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Resilience and Sustainability in the Congo Basin

Retracing the Past, Looking to the Future

Science Panel for the Congo Basin

Panel Scientifique pour le Bassin du Congo

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Resilience and Sustainability in the Congo Basin

Retracing the Past, Looking to the Future

With 150 Figures and 42 Tables

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Preface

I am honored and profoundly moved to write the foreword to this historic report of the Science Panel for the Congo Basin. The Congo Basin deserves every superlative that we can muster, and the Science Panel has done justice to this remarkable part of humanity's biological heritage. As this report makes profoundly clear, the roughly 3.56 million km^2 of the Congo Basin is home for 130 million people in Central Africa, the habitat for tens of thousands of species, and a vital regulator of the Earth's climate and biophysical systems at continental and planetary scale.

The Science Panel for the Congo Basin is itself a remarkable creation, following in the path of the Science Panel for the Amazon. Both Science Panels and their third companion, the Science Panel for Borneo, are built on one main idea. The vital expertise regarding the history, management, and sustainable future of the great rainforest biomes lies with the scientists of each region, of course, in partnership with the global scientific community. The Science Panels seek to empower each region's scientists to take the lead in proposing science-based solutions for the sustainable management of the respective biomes. While outside experts play a highly constructive role, it is the scientists of each region who must be the guides and stewards of the rainforests. As such, the Science Panels serve directly the people and governments of the region, as well as the whole human community.

Moreover, the term "serve" is also on point, since the scientists are generously donating significant amounts of time as well as their unique expertise to this effort. A remarkable volume of work has been mobilized through the spirit of public service of the scientists involved. The Science Panel for the Congo has thereby gone a vast distance in producing the most comprehensive and up-to-date scientific study of the Congo Basin of recent years, and probably ever.

One hundred Eighty scientists have contributed to this report, enabling its comprehensive and panoramic perspective. This report discusses the geological history of the Congo Basin, and every aspect of the science of this wondrous ecosystem: geology, geodynamics, hydrology, climate, soils, biodiversity and its evolution, ecology, cultural diversity, land-use systems in agriculture, pastoralism, forestry, hunting, fishing, mining, and other activities, drivers of deforestation, protected areas, urbanization, and much more.

The aim of the Science Panels, of course, is not only to produce excellent science but also excellent public policy. This report fulfills that aim. After a remarkably deep,

holistic, and up-to-date scientific report on the state of the Congo Basin and the main drivers of human-induced change, this volume proceeds to holistic solutions. Our aim is not merely sustainability (in the environmental sense) but sustainable development, meaning the combination of environmental sustainability with economic well-being and social justice in the region. Farming, forestry, fisheries, mining, and other activities must continue to contribute to livelihoods and economic opportunity, but in a manner that is compatible with the environment, not contrary to it. With millions of degraded hectares of forest land, for example, the Congo Basin can be an enormous sink for carbon through regeneration of the forests. With the right incentives, through carbon markets and other mechanisms, the Congo Basin should receive tens of billions of dollars for carbon storage that recovers degraded lands, builds new livelihoods and strengthens biodiversity. The wisdom of the Science Panel is to propose win-win-win solutions, whereby local communities, biodiversity, and global humanity are all beneficiaries of the ethical, science-based, and forward-looking stewardship of the Congo Basin. The Science Panel for the Congo Basin will be a key leader in that grand initiative, supported by the wisdom in this volume.

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Congo Basin Resilience and Sustainability: From the Past to the Future

Summary for Decision-Makers

Congo Basin Resilience and Sustainability: From the Past to the Future, the 2025 Congo Basin Assessment Report, is the first ever, collective, and multidisciplinary work by 192 scientists active in the region. It was brought together by the Science Panel for the Congo Basin (SPCB), convened by the United Nations Sustainable Development Solutions Network (UNSDSN), and was inspired by the Science Panel for the Amazon. It features 40 chapters, which are organized into four sections dedicated to the region's geological history, the emergence of humans and their impact on the Congo Basin's ecosystems, the emergence of sustainable development models post-Rio, and a vision for the future.

The Congo Basin, as defined in the report, covers an area of 3,462,806 km^2, representing the world's second largest tropical rainforest ecosystem, composed principally of the lowland wet and dry "Guineo-Congolian" rainforests, along with extensive swamp, mangrove, and Afromontane forests, bordered to the north and south by a mosaic of transitional rainforests and secondary grasslands.

The Congo Basin encompasses extensive areas in six nations: Cameroon, Central African Republic, Democratic Republic of Congo (DRC), Equatorial Guinea, Gabonese Republic and Republic of Congo (RoC), and smaller areas in a further six: Angola, Burundi, Nigeria, Rwanda, South Sudan, and Uganda.

It includes 73% of the Congo River Basin, which extends into areas of wooded savanna in Tanzania, Zambia, and Angola, as well as the entire catchments of the Ogooué, Sanaga, and numerous smaller rivers. The outer limits of the biome today are somewhat subjective because they represent a transition from wetter to drier forests, which is continually changing as a function of climate variability and human activities. The eastern limit is the eastern edge of the Afromontane forests of the African Rift Valley, while the western limit is the Cross River in Nigeria.

The Congo Basin plays an important role as a regional entity in the Earth system, the African continent's "green heart," a critical natural life support system, driving atmospheric moisture recycling, which generates 60–70% of the rainfall in the region and sends moisture to the Sahel, the Angolan Highlands and Ethiopia.

The Congo Basin is the largest tropical carbon sink on Earth and is proving more resilient to climate change than the Amazon. It includes the Cuvette Centrale

peatlands, the largest tropical peatland complex covering about 145,500 km^2, which store around 30 billion tons of carbon (110 billion tons of CO_2).

It is one of the most biodiverse ecosystems on Earth, with over 10,000 species of vascular plant, 400 mammal, 1000 bird, and 700 fish species and includes the entire range of the bonobo and the two species of gorillas, and is home to three of the four subspecies of chimpanzee. Among these species, some are endemic to the Congo Basin and have very limited ranges, making them critically important for conservation. It is the only region where an intact megafauna survives, perhaps because of the long history of humans living in the forests, estimated to be at least 650,000 years.

The Congo Basin is a rich socio-ecological system where more than 600 languages are spoken. The languages encode complex taxonomies for plants, animals, and landscapes reflecting a deep place-based understanding of the environment. Traditional ecological knowledge extends beyond mere identification of species to include an understanding of ecological relationships, such as the seasonal movements of animals, the medicinal properties of plants, and the spiritual significance of certain forest locations, such as sacred forests, which are widely prevalent throughout the basin. This oral transmission of knowledge ensures that ecological literacy is embedded within cultural practices, with stories and rituals functioning as living manuals of forest stewardship, crucial for maintaining sustainable use of natural resources.

The shift from exclusively hunter-gatherer to early agricultural societies began about 4000 years ago. Human impacts on the forests increased markedly with the arrival of iron smelting and Bantu-speaking communities from the north, and the development of slash and burn agriculture from 2500 years ago. Between 2000 and 1000 years before present, there was a period of rapid human population growth, forest fragmentation, and widespread development of secondary vegetation across the Congo Basin, as human societies became ecological engineers, creating "cultural forests" shaped by their selective management of useful species, such as the native oil palm. There was a marked decline in human population between 1400 and 1200 BP, which lasted to about 800 BP, when populations recovered and expanded again.

European explorers and traders arrived from the fifteenth century onward resulting in increased trade. The Atlantic commerce in ivory, ebony, pepper, rubber precursors, and enslaved persons intensified the exploitation of natural resources. The introduction of firearms altered hunting efficiency, exacerbating pressures, particularly on elephants and other megafauna.

The arrival of European traders and the gradual penetration of trade routes and infrastructure into the Congo Basin resulted in epidemics of diseases to which people had not previously been exposed. Millions perished from diseases such as bubonic plague, smallpox, syphilis, cholera, measles, and chickenpox, compounding the social impacts of the slave trade.

The late nineteenth-century "Scramble for Africa" radically reshaped the Congo Basin. Colonial administrations, especially in the Belgian Congo and French Equatorial Africa, imposed concessionary systems that turned vast tracts of forest into rubber, timber, and mining concessions. Villages were forcibly relocated to serve as

forced labor for extraction sites, transport corridors, and plantations. Country borders were decided arbitrarily without taking sociological realities into account. In some cases, these borders separated populations belonging to the same tribe into different countries (e.g., Cameroon, Gabon, Equatorial Guinea). Forced labor was used to exploit mineral and timber resources, which were shipped to Europe for processing.

The colonial economic model was to extract natural resources which were exported to Europe, where they fed the industrial revolution and the growth of wealth, a model that continues to this day. As African development came to be seen as a threat to species and ecosystems, the colonial authorities imposed a model of "fortress" conservation, creating protected areas by banishing human populations by force.

The period between 1960 and 1992 saw the progressive independence of the Congo Basin nations and rapid urbanization. Logging and mining remained the principal economic activities but were largely replaced in the Western Congo Basin countries by oil.

The early 1990s saw significant social-ecological transformations, including the beginning of the political transition to multi-party democracy. A political vision championing the principles of sustainable development gradually emerged on the road to the Rio Earth Summit in 1992, where leaders from Congo Basin states played a key role in shaping global commitments to sustainable development, bringing both the legacy of colonial and post-colonial extraction and the enduring traditions of stewardship and ecological knowledge that had characterized the region for millennia to the table.

Forestry, historically one of the region's most destructive extractive industries, underwent significant transformations. In the 1990s and early 2000s, governments began to introduce forestry laws that required companies to operate under long-term sustainable management plans. Environmental and Social Impact Assessments (ESIAs) were gradually institutionalized, embedding safeguards into planning processes. Voluntary forestry and timber certification schemes emerged as tools for both governance and market access. The Forest Stewardship Council (FSC) became the gold standard, and countries such as Cameroon, Congo, and Gabon emerged as leaders in Africa in certifying concessions under FSC standards.

While challenges remain in ensuring compliance and addressing illegal logging, these initiatives place Central Africa at the forefront of tropical forest management and certification worldwide. More recently, there has been a move to increase local transformation and even to ban the export of unprocessed timber from the region, to maximize local economic growth and job creation. These reforms mark a profound shift from the colonial-era extract-and-export model toward one that aspires to reconcile economic use with ecological sustainability, while maximizing local economic returns and job creation.

Even as forestry has moved toward sustainability, other resource sectors have remained firmly extractive. Mining remains a significant contributor to deforestation, pollution, biodiversity loss, and social disruption. While environmental regulations and Environmental and Social Impact Assessments are now formally required, enforcement is uneven, and artisanal mining continues to devastate river systems

and forests. Industrial agriculture—particularly oil palm and rubber—has also expanded since the 1990s, often encroaching on forest frontiers and undermining biodiversity commitments. Smallholder agriculture is technologically unsupported by states, allowing widespread landscape degradation through outdated slash and burn practices to continue and intensify.

Overall, these trends illustrate the contradictions of post-Rio development: formal sustainability frameworks exist and perform well when used, but business-as-usual extractive logics also endure. Sustainable land-use planning tools are in place on paper, but weak governance, overlapping land rights, poor agricultural practices, and international demand for minerals and commodities perpetuate ecological degradation. Strengthening governance and cross-sectoral institutions is vital for ensuring resource security and aligning extractive sectors with sustainable development pathways.

Hunting and fishing remain vital for livelihoods and nutrition, but the scale and intensity of exploitation have grown since the 1990s. The wild meat trade now supplies both urban and rural markets, with an estimated 1.6–11.8 million tons consumed annually. Inland fisheries continue to provide a crucial source of protein, particularly in the DRC, but overfishing and habitat degradation have reduced catches. Customary management systems such as taboos and seasonal bans, once widespread, have eroded under the pressures of market demand and weak governance. The "empty forest syndrome," where forests remain structurally intact but devoid of large fauna, has become emblematic of these pressures, although protected areas often still preserve viable populations, preventing extinction and species becoming lost to nations forever.

Community-based management is emerging as a modern African conservation model, but success is uneven, often due to the level of degradation of wildlife communities, and to the inadequacy of alternative rural food systems. There is a growing evidence base for community management models that do deliver sustainable harvest and these could be scaled up across rural areas, but if underlying food systems are not improved, stemming biodiversity loss will remain challenging.

The key to peace and security, sustainable development and prosperity in the region are strengthened democracies, improved governance, including governance of natural resources, elimination of illegal exploitation of natural resources and better rule of law, as well as an efficient, objective, independent justice system able to fight corruption. These vital foundations for society are crucial to tackle challenges to attract the long-term investment needed to implement local processing of natural resources and to attract finance to invest in logistical infrastructure needed to optimize supply chains and ensure profitability in the private sector.

To attract the responsible investors and affordable finance needed to drive sustained economic growth, continued and accelerated improvements in democratic process, governance, rule of law, justice, and equity are needed in the Congo Basin nations. Political stability and elimination of illegality in the natural resource extraction industries are crucial to encourage international confidence and investment. Furthermore, integration and strengthening of local community involvement and rights in integrated spatial plans are also needed. International agreements such as

the African Union's Agenda 2063 and the UN Sustainable Development Goals (SDGs) can help to chart a path but need to be adapted to local circumstances through regional leadership.

There is a need to foster affordable, dependable finance and equitable investment in sustainable development for the Congo Basin nations, to provide dignified, sustainable livelihoods for their people, while continuing to supply the global ecological services that benefit all of humanity.

Preservation and enhancement of nature-based solutions provides a critical foundation to boost sustainable development and climate resilience of nations and economies. The Congo Basin countries are leading the world through the development of economies that depend on sustaining ecosystem services, banishing the model of using Africa simply as a source of cheap raw materials that provision nations far from the continent, as was the case during colonial rule.

Africa is the continent that is most susceptible to climate change because of the vulnerability of its more arid ecosystems and lack of technological and financial capacity to adapt. The ecological stewardship and environmental resilience of the Congo Basin is critical for the region and for many other parts of Africa, whose weather patterns are impacted by moisture from the "heart and lungs of the continent," the Congo Basin rainforests. Nature preservation and nature-based solutions need to be integrated into ecosystem management, urban environments, and national planning, to ensure maximal climatic resilience for ecosystems, agriculture, and people in the coming century. This is by far the most efficient and effective way of reducing the costs of adaptation, while contributing to global climate change mitigation.

Looking to the future, harnessing all possible technological advances to optimize the preservation, management of natural resources, and monitoring of local and regional changes is critical for the future of the Congo Basin. It is hard to manage something that is not well understood, and many knowledge gaps remain. There is a need to promote the formal training and capacity building for scientists, sociologists, and natural resource managers to establish effective management systems that maximize ecological resilience and benefits for the region's economies and people and to promote interdisciplinary collaboration. The Science Panel for the Amazon and its precursor, the Large-Scale Biosphere-Atmosphere Experiment Programme, provide powerful models that can be adapted to the Congo Basin.

The Congo Basin stands at a decisive crossroads. It is the world's second-largest tropical forest system, a vast carbon sink, and home to unparalleled biodiversity, but it is also a region of rapid population growth, particularly in Cameroon and DRC, persistent poverty, weak governance, and competing demands for development. Strengthened governance, equity, and justice; reliable finance and sustainable economies; technology and capacity; and ecological stewardship and stability are the four key foundations for the future emergence of the region. They will decide if the region's young population could become a competitive advantage.

In conclusion, the Congo Basin is a critical component of our planetary biosphere: a treasure house of biological and cultural diversity that provides key environmental services at local, regional, and global scales. After centuries of

extraction and degradation, there is real potential for a different future: one of genuine sustainable, locally led development for the welfare and benefit of its peoples and communities, where resources are sustainably managed and preserved and contribute to both African and planetary resilience in the face of inevitable impacts of climate change. Many challenges remain, including both needs and opportunities to reinforce good governance, strong institutions, and political accountability. Science, scientific institutions, and scientists themselves have important roles to play to monitor, generate evidence, and inform decision-making by those responsible for solving of collective problems and development of transformative solutions. Africa is facing a unique set of circumstances and opportunities to ensure a vibrant future. Many of these depend on the resilience of the Congo Basin's ecosystems.

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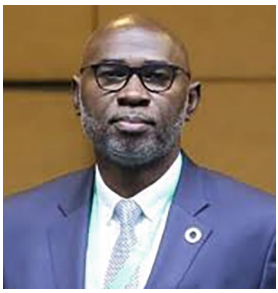

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Introduction: Congo Basin Resilience and Sustainability: From Past to Future

1

Bila-Isia Inogwabini, Birgit Ricquier, Aida Cuni-Sanchez, Bonaventure Sonké, Lydie-Stella Koutika, Stephanie Rupp, and Lee J. T. White

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Abstract

This chapter introduces the 2025 Congo Basin Assessment Report, discusses the multiple definitions of the Congo Basin, defines the limits of the Congo Basin covered by the report, discusses issues of indigeneity, and describes the regional scientific capacities. The chapter argues that the best way to define the Congo Basin is to use the regional ecological features rather than focusing on the political delimitation or focusing narrowly on the basin of the Congo River itself. Broadening the question of who indigenous communities are and who they are not, the chapter argues that the name Pygmy is contested and that the politics of identity is both complex, contextual, layered, plural, and varied; calling, therefore, for caution in ways they should be used. Rather than going into detailed contents, the chapter briefly summarizes the biodiversity metrics in the Congo Basin, presents the four sections of the report and overall spirit that guided the writing up process, and provides the current status of the available capacities to conduct research in the Congo Basin.

Keywords

Congo Basin · Geographic extent · Autochthonous and Indigenous People · Biodiversity · Research capacity

Introduction

Congo Basin Resilience and Sustainability: From Past to Future is the 2025 Congo Basin Assessment Report synthesizing existing scientific knowledge, including that of Indigenous Peoples and Local Communities, on the functioning of and threats to the Congo Basin and its ecosystems. The assessment is made of four parts that total 39 chapters, each describing the current status of an area of knowledge. This introduction covers cross-cutting issues that reoccur throughout the whole book and clarifies operational definitions that different authors have used. It is important to note that operational definitions used here were produced after long debates; they reflect the consensuses reached for each hotly debated subject, among which the most important were the definition of the Congo Basin itself, the question of which communities qualify as Indigenous people, and where to lay the lower limit of the montane forests.

Geographic Extent of the Congo Basin

There are multiple diverging political, hydrological, geological, and ecological definitions of the Congo Basin (Fig. 1a–c). The Science Panel for the Congo Basin uses an ecological (not political) definition of the Congo Basin, based on the seminal

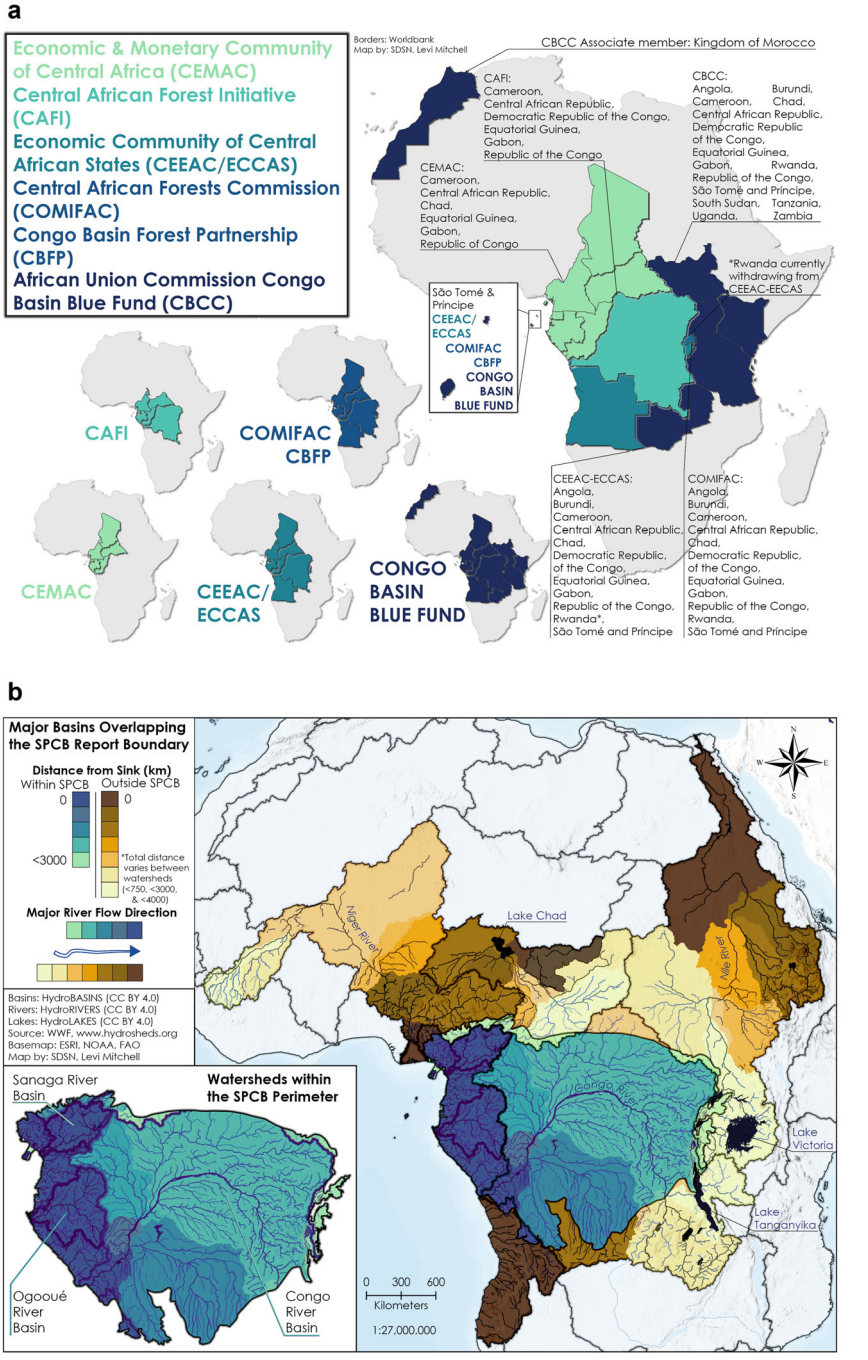

Fig. 1 (**a**) Various political definitions of the Congo Basin/Central African region; (**b**) watersheds constituting the Congo Basin; (**c**) the extent of the Congo Craton, neighboring Cratons, and the Congo Basin

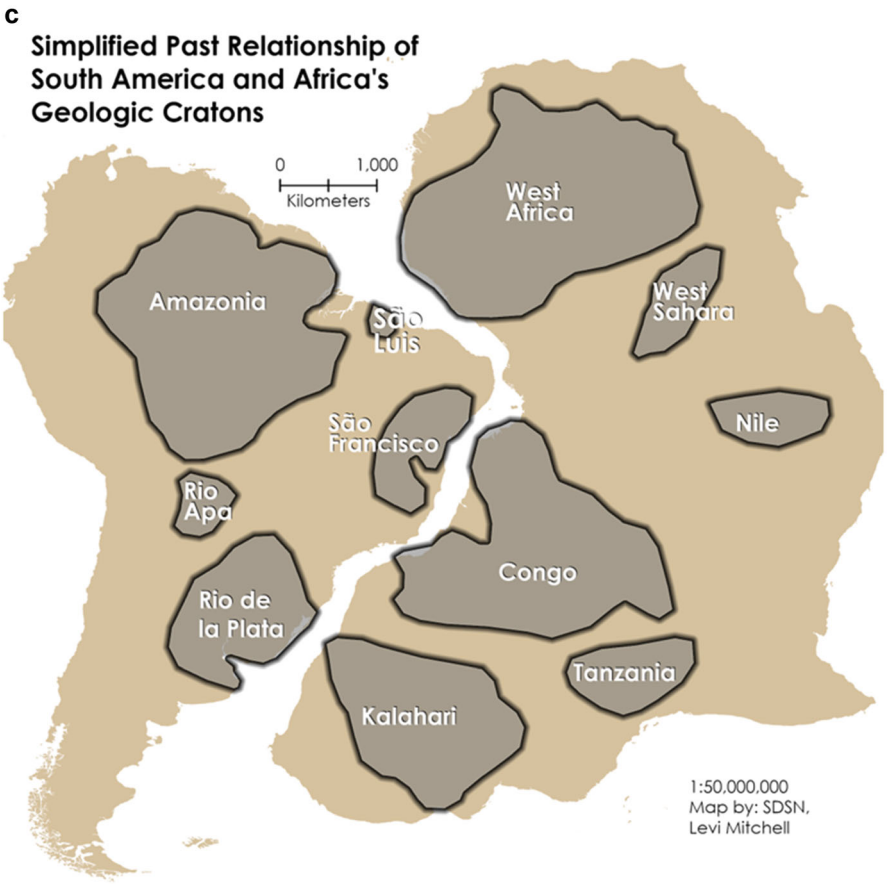

Fig. 1 (continued)

work on the vegetation of Africa by Frank White (1986), along with the ecoregion analysis. Figure 1a shows the political definitions of the Central Africa/Congo Basin forest countries—as defined by the Central African Forest Commission (COMIFAC) and the Economic Community of Central African States (ECCAS—which have the same definition), the Economic and Monetary Community of Central Africa (CEMAC), the African Union's Congo Basin Commission and Blue Fund (CBCC), and the Central Africa Forest Initiative (CAFI). All except CAFI are definitions adopted by subsets of African nations in the Congo Basin region. Figure 1b shows the principal river basins that fall within the Congo Basin, notably the Congo, Ogooué, and Sanaga as well as the adjacent river basins. Finally, Fig. 1c shows the relative location of the principal African and South American continents and their principal Cratons in the Early Cretaceous as the Pangea supercontinent broke apart and the Atlantic Ocean opened up.

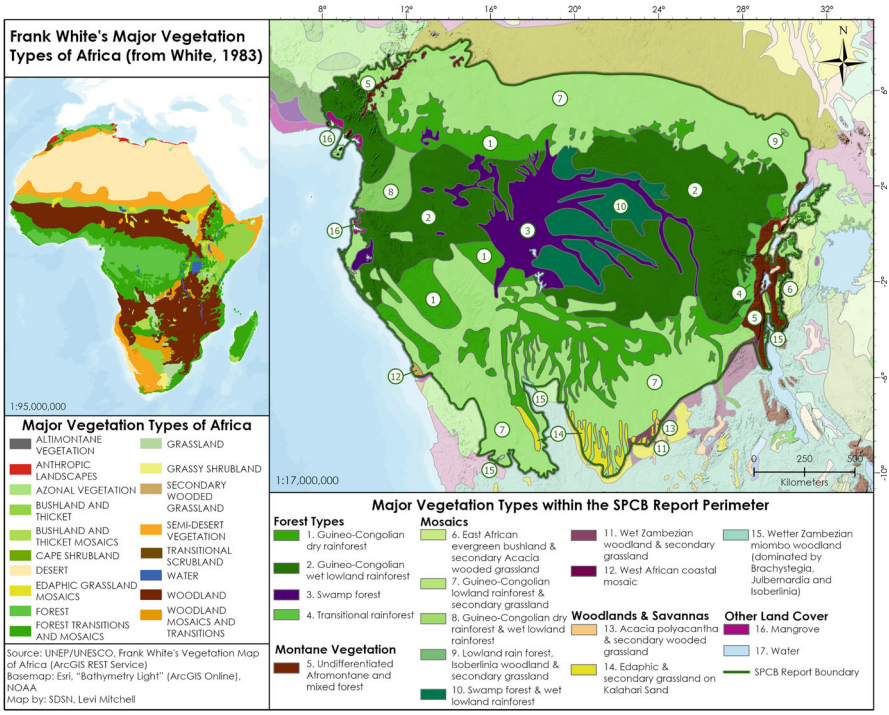

Fig. 2 The geographic limits of the Congo Basin as defined by the SPCB

The Congo Basin as defined by the Science Panel (Fig. 2) covers an area of 3,462,806 km^2. It is composed principally of the lowland wet and dry Guineo-Congolian rainforests (covering 28% and 16% of the total area, respectively), along with extensive swamp (13%), mangrove (0.3%), and Afromontane forests (2.2%), bordered to the north and south by a transitional rainforest and secondary grassland mosaic (39%), as defined by White (1986; Fig. 2). The outer limits of the biome today are somewhat subjective, because they represent a transition from wetter to drier forests, which is continually changing as a function of climate variability and human activities. It includes extensive areas in six nations: Cameroon, Central African Republic, Democratic Republic of Congo (DRC), Equatorial Guinea, Gabon, and Republic of Congo (Fig. 3), and smaller areas in a further 6: Angola, Burundi, Nigeria, Rwanda, South Sudan, and Uganda. The eastern limit is the eastern edge of the Afromontane forests of the African Rift Valley, while the western limit is the Cross River in Nigeria. It does not include the volcanic islands of Sao Tomé and Principé, which have never been connected to the African continent but does include Bioko, which was connected to the mainland by a land bridge during the last Ice Age 12,000 years ago.

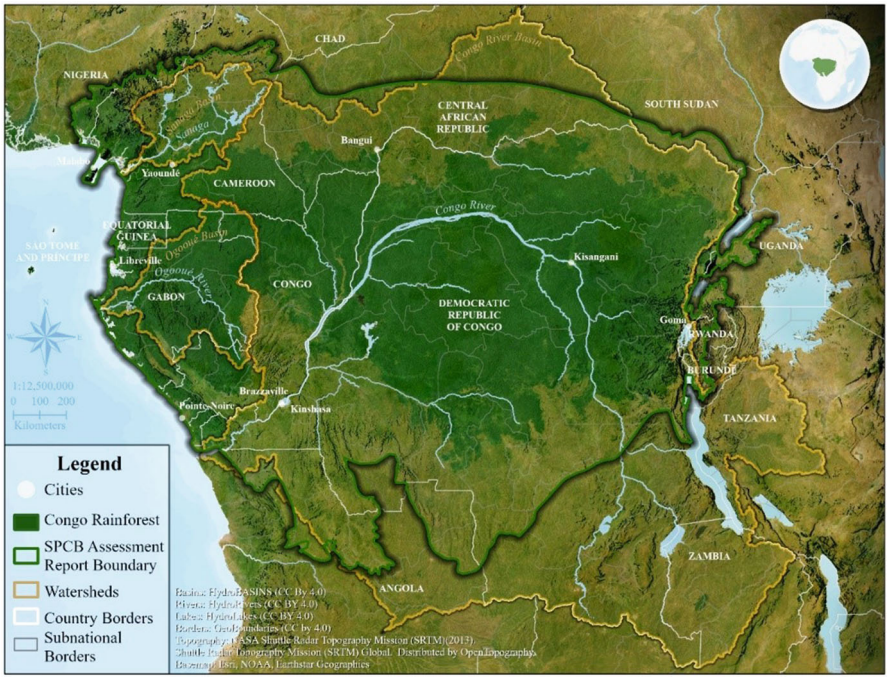

Fig. 3 The Congo Basin in its geographical context

The Issue of Indigenous, Autochthonous, and Local Communities and Peoples in the Congo Basin

Homo spp. have lived in the Congo Basin for at least 650,000 years and probably longer. *Homo sapiens* has been present for hundreds of thousands of years. During the process that led to the production of this report, questions emerged as to who should be identified as Indigenous, autochthonous, and how to name largely marginalized communities throughout the document. Some have simplistically argued that the distinction between Bantu and Nilotic people and "Pygmies" (or hunter-gatherers) in Africa is analogous to the definition of Indigenous People used by the Science Panel for the Amazon, while others feel the context in the Congo Basin is much more complex and nuanced. Vansina (1990) argued that the differentiation between pygmies as the first dwellers of the forests of the Congo Bantu has been essentially imposed from the outside; in some areas, there might also have been other (non-pygmy) peoples present before the arrival of Bantu "farmers." Then, if so, why would pygmies be considered "indigenous" and not Bantu?

The current usage of the word "Pygmy" is contested among scientists, as it is sometimes used pejoratively by non-Pygmy ethnic groups to indicate "backwardness," being less than human, or for warning someone about their unacceptable

behavior (Boyette et al. 2022). However, some Pygmy groups use the term to refer to their unique identity vis-à-vis "non-Pygmies" (e.g., Takeuchi 2014), and the term is still widely used in academic and nonacademic circles and the popular press. Some authors prefer to use the term "foragers" or "hunter-gatherers" rather than Pygmy, to refer to their traditional main subsistence mode, the way their societies are organized, other core cultural features, and how they relate to nature (see ▶ Chap. 9, "Critical Interconnections Between Cultural and Biological Diversity in the Congo Basin"). Today, not all Pygmy groups remain hunter-gatherers; some are extensively engaged in farming. We use concrete ethnic group names (e.g., Aka, Baka, Balumbe, Batswa, Mbuti, Okandé, and Téké) whenever possible, but for purposes of generalization, in some chapters authors use the word "Pygmy," given that this term is more widely known by nonacademics outside the Congo Basin.

The discussion on the usage of the word "Pygmy" led to the discussion about the cultural and political identities of forest communities throughout the Congo Basin. It was affirmed that both are complex, varied, and often fraught. The ways that any given person self-identifies are plural, layered, and contextual. Furthermore, forest communities form multiethnic, multilingual clusters, in which local identities are shaped by relationships that traverse and entangle many different social boundaries of similarity and difference, and are shaped by complex dynamics of mutuality as well as tension. Finally, the ways that peoples identify themselves and the ways that they are identified by others, and particularly by institutions, do not always align.

Since early colonial times, outside observers have used contrasting categories to distinguish the tremendous cultural, economic, and political diversity of the region: pygmies versus non-pygmies; hunter-gatherers versus farmers versus pastoralists people; and Indigenous people versus those (presumed to) have migrated into the forest. These etic (outside) categories offer conceptual handles for making sense of, and create policies for, forest communities throughout the region. At the same time, forest people identify themselves in a variety of layered, culturally and contextually specific ways; such emic (inside) identities may reflect language, clan, historical heritage, contemporary alliances, and other meaningful, dynamic, and shifting ways of expressing the self and its relations to others. Importantly, these emic identities may also include etic, outside identities such as "pygmy"—perhaps in alignment with the institutional, political, or outside expectations of the qualities, but in other cases with meanings that diverge, complicate, or even contradict and fill the category with cultural meanings that are specific to a local context in time and place. Whether a forest dweller or entire forest community is classified as a "pygmy" or a "non-pygmy," these terms flatten out a universe of salient features of ancestry, ecological connection, ritual participation, economic pursuit, marriage and alliance, and many other features of sociality that shape identities.

Administrative and academic categories have histories of their own; they are not neutral, stable, uncontested, or original categories for forest peoples themselves. Thus, as useful as such categories, "pygmy" or "hunter-gatherer" on the one hand, or "villager" or "farmer" on the other, may be to facilitate institutional or external understandings of the Congo Basin as a region, it is important to bear in mind that these categories represent just one valence of identity, a layer that is highly abstract,

imprecise, and does not fully capture the local meanings and complexities of people's identities.

Since early colonial times, and in some cases reaching back to much earlier expeditions of exploration, simplified identity categories have been used to make sense of who was who, to identify which people and communities were sought for particular purposes of observation or contact, and to control the movements, activities, and rights of different groups, in the complex, fluid social spaces of the Congo Basin (Bahuchet 1993a; Rupp 2011). Such categories allowed, and continue to allow, outside or institutional observers more easily to identify differences within forest communities who occupy the same space or adjacent spaces, and to compare social, economic, and political patterns across space. Indeed, the creation of these categories and their continued use illustrates a fundamentally significant social reality: Within the Congo Basin, communities live in complex, flexible social configurations. The local complexities of ethnicity and belonging make simple categories of delineation extremely useful, even if they are not always especially accurate. For example, throughout the basin today as in the past, not only communities tagged as "hunter-gatherers" engage in hunting and gathering as a primary economic pursuit, but also at the same time, people identified as "hunter-gatherers" often engage in, and have engaged in, horticulture, fishing, and trade over time. Furthermore, communities throughout the basin have a much longer history of economic and social diversification than reductive categories imply.

From an analytical perspective, to understand the identities, social relations, and political configurations of communities, it is essential to understand each group in relation to its neighbors. Looking holistically at the particular, local contexts of multiethnic, multilinguistic communities throughout the basin, it becomes evident that neighboring groups—even if they can be administratively slotted into contrasting categories such as "hunter-gatherers" or "villagers"—have much more in common with each other and share contemporary realities locally, than either administrative group may share with "pygmy" or "villager" groups in some other region of the vast Congo River Basin. While local divisions and tensions also may well exist, it is essential to understand the local iterations of competition and cooperation, and not to assume that social identities all map neatly onto intellectual and administrative categories derived by external, institutional, and often (but not always) Euro-American observers. To take one group within a plural setting as the object of investigation or policy is to offer a partial, or incomplete, understanding and to the risk of designing and implementing a partial, or biased, policy.

Today, the politics of identifying who counts as an "indigenous person" is similarly fraught, particularly when conventions on "indigenous people" offer rights of access to protected areas of the forest, or rights to hunt in particular ways, to some forest peoples and not all. The diverse and dynamic human history in the Congo Basin renders such simplistic demarcations of "indigenous" and "non-indigenous" both impossible and foolish. While linguistic and genetic research demonstrates that certain language communities that have been identified as "pygmy" groups since the mid-nineteenth century were the first human inhabitants of the Congo River Basin, such ancient origins do not preclude movement within the basin over time. Furthermore, being identified as a "pygmy" group in a particular region does not necessarily

mean that the community is an autochthonous or Indigenous person in the particular region where they live today. "Pygmy" communities, for example, the Baka and Aka, also have histories of displacement, migration, arrival, and contact with preexisting forest communities in the particular areas of the basin where they live today (Bahuchet 1992, 1993b). Furthermore, the deep histories of Bantu-language speaking forest communities (a linguistic group that also includes numerous "pygmy" communities) span at least 5000 years. Is habitation of a region for 5000 years by one's ancestors not "long enough" to be considered Indigenous? Identifying who counts as "indigenous" is a contrived and politically motivated exercise, which has more to do with the politics of resource allocation than with accurate understandings of Congo Basin history. It is also frequently undertaken in efforts to align the Congo Basin with the Amazon, where there is a complex sociopolitical relationship between communities who arrived some 10,000–15,000 years ago and others who arrived around 500 years ago and thereafter. The reality is that human societies have existed in the Congo Basin since our species emerged from other hominins and their collective histories are much more complex than those of inhabitants of the Americas.

Reliance on static, homogenizing categories of social and political identities leaves outside observers with the impression that the people of the Congo River Basin, and the forest itself, can be reduced to archetypes, and furthermore that these distilled simplifications of identity are sufficient, even appropriate, to use as categories to designate political and economic policies that impact and regulate the complex realities of forest peoples today. Outside observers, whether they are fellow national citizens and officials living in cities and towns rather than forests, academic scholars and students, policymakers and nongovernmental organization staff, or officers of international bureaucracies that administer ecological resources in the forest context, fall back on these archetypal identities for the sake of expediency and clarity. Forest people themselves today often assume such categories of identity for themselves and apply them to others in contexts where they are useful for a variety of reasons: to align with policies that might offer preferential access to resources; to make oneself and one's community visible and understandable to institutions; and to celebrate or denigrate particular social relations, playing on the stereotypical values that inhere in a category such as "pygmy." The identity politics of forest communities throughout the Congo River Basin region are complex, dynamic, and varied.

In this report, we use reductive categories of identity sparingly and only where they offer value in synthesizing information that pertains across communities; otherwise, we refer to forest communities simply as "forest communities," "communities," or simply "people," to avoid layering in distilled categories of identity that can have administrative, political impact on the people of this vast forest region.

A Diversity of Ecosystems

The Congo Basin includes an extraordinary variety of ecosystems. The region is the world's second-largest tropical rainforest and supports more than 400 mammal species, 1000 bird, and 1200 fish species, about 300 species of reptiles and

amphibians, countless insect species, and over 10,000 plant species (Harrison et al. 2016). It is home to both species and all four subspecies of gorillas, Cross River gorillas (*Gorilla gorilla diehli*), Western lowland gorilla (*Gorilla gorilla gorilla*), Eastern lowland gorilla (*Gorilla beringei graueri*), and Mountain gorilla (*Gorilla beringei beringei*); it also shelters three subspecies of chimpanzees, Nigeria-Cameroon chimpanzee (*Pan troglodytes ellioti*), Central chimpanzee (*Pan troglodytes troglodytes*), and Eastern chimpanzee (*Pan troglodytes schweinfurthii*), and the Bonobo (*Pan paniscus*), found exclusively in DRC. Congo Basin's other notable species include forest elephants (*Loxodonta cyclotis*), which are found across the forested area (while African savanna elephants (*Loxodonta Africana*) are present at the edges of the Northern Congolian Forest-Savanna Mosaic) and the okapi (*Okapia johnstoni*).

The region's fish species form a crucial ecosystem component that are important in the wildlife food chain, nutrient cycling, and human food security. As with other taxa, many fish species are regionally endemic. Recent studies have identified at least 280 species of reptiles within the Congo Basin, including the dwarf crocodile (*Osteolaemus tetraspis*), the critically endangered slender-snouted crocodile (*Mecistops cataphractus*), various monitor lizards (*Varanus* spp.), and snakes, such as the Gabon viper (*Bitis gabonica*). Thompson (2024) compiled studies describing new species from the region (e.g., Hart et al. 2012; Tilbury and Tolley 2015; Hughes et al. 2017; Giarla et al. 2020; Freitas et al. 2022; Prozorov et al. 2023) and noted that in 10 years running from 2013 to 2023, some 742 species new to science were discovered in the Congo Basin.

Efforts to mitigate the decline in biodiversity and global poverty of the Congo Basin human populations go hand-in-hand with efforts to preserve biodiversity on which most people living in the basin depend. The most prominent aspect of these efforts consists of 199 protected areas (Fig. 4) of all categories that governments of the Congo Basin countries have set aside to protect biodiversity and to sustain human economic development.

The Basin plays a vital role in global climate regulation, biodiversity conservation, and sustaining the livelihoods of millions of people (Shapiro et al. 2021). While Dyer et al. (2017) showed how inextricably connected the Congo Basin is to both Atlantic and Indian Oceans in terms of its moisture and precipitations, recent studies also have shown the critical role this region plays in providing rainwaters that sustain other regions of Africa, such as the Ethiopian highlands (e.g., Gebrehiwot et al. 2018). While habitats within the Congo Basin are still relatively better preserved compared to many other African ecosystems, they are undergoing rapid

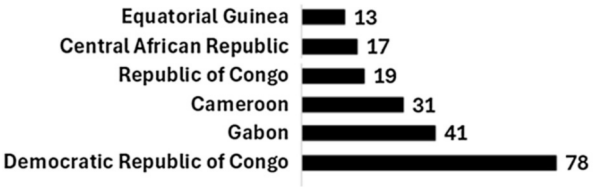

Fig. 4 Protected areas in each country of the Congo Basin. (Data from OSFAC Database 2025)

transformation due to human activities (James et al. 2013; Fonteyn et al. 2023; Beekmann et al. 2024). Human activities that are detrimental to the Congo Basin's wealth of biodiversity and the regional sustainability are described in section "Geographic Extent of the Congo Basin" of this report.

The Contents of This Report

This report, prepared by the Science Panel for the Congo Basin (SPCB), documents existing knowledge and identifies critical gaps in our understanding. It does not include new field data, but rather it is a meta-analysis of published materials and ongoing research on the Congo Basin, a synthesis of most available knowledge on various aspects of the Congo Basin ecosystems. The themes of this report are not restricted to the ecosystems that exist in the Congo Basin but also document aspects of human history and economics needed to understand the past, present, and future of the region.

The report assesses the knowledge the scientific community possesses on the Congo Basin in 2025 as well as knowledge gaps. However, it is more than a simple compilation of dispersed published materials. It brings together diverse knowledge from various areas of scientific inquiry and assembles them in a coherent set of new metaknowledge which we hope will help to guide future decisions that will impact the Congo Basin. The report assesses the past and present conditions of the Congo Basin; it assembles available knowledge on the long-term geological and ecological history and processes in the region and explains how that history led to the present. Beyond the history and current state of the Congo Basin, the book examines possible likely future pathways if current trends remain constant. In this perspective, the Congo Basin scientists provide scenarios to help policymakers ensure that economic activities are not detrimental to essential ecological functions and the vibrancy of the cultural diversity of the Congo Basin.

The report consists of four sections. Section One covers the long-term geological, ecological, and human history, examining the processes that have shaped the Congo Basin we encounter today. It presents biological and cultural diversities as they developed before human activity began to drive change in nature. Section Two gathers peer-reviewed knowledge on the positive and negative effects human activities have had on biological and cultural diversity and presents the current status of biodiversity in the Congo Basin. Section Three models future trajectories the Congo Basin might take given current knowledge and management options. Section Four strives to show how science can help decision-makers formulate ecologically, climatically, culturally, socially, and poverty-sensitive practices to sustain the development of the Congo Basin.

State of Knowledge and Scientific Capacity in 2025

In writing this report, we have been able to identify gaps in knowledge, which has proven to be one of the key features of all areas covered in this book. Despite the contributions of more than 180 authors, it is clear that we are currently constructing

the future of the Congo basin on the basis of fragmented and incomplete scientific knowledge. Indeed, the broad conclusion emerging from the development of this report is that scientific capacity and knowledge in the Congo Basin remains inadequate and needs to be greatly developed in the coming decade, if the region aspires to achieve sustainable management of its resources based on sound scientific knowledge. This conclusion is in line with and further supports the conclusions of a paper published by a group of leading scientists and politicians from the region in the lead in the Glasgow Climate COP (White et al. 2021).

During the inception phase, the UN Sustainable Development Solutions Network (UNSDSN) undertook an exercise to identify scientific initiatives, networks, institutions, and scientists involved in research in the Congo Basin. An effort was undertaken to compile a list of all researchers whose names appear on traditional peer-reviewed papers featuring the Congo Basin. The place where researchers are currently based was taken to be the affiliations they included in their publications, which may have changed over time, and their main fields of expertise were noted. Using a minimum H-Index as an indication of scientific productivity, 447 researchers with an H-Index of 10 or more were identified. Slightly more than 25% of these were from the Congo Basin region (Fig. 5).

Put simply, close to 74% of researchers in the Congo Basin reside outside of the basin itself. The majority (88%) of the researchers based in the Americas (Central and Northern) are found in the USA. This can be explained by the fact that research bodies in the USA were, until a very recent past, given significantly more resources than most other countries to conduct research in the Congo Basin. Initiatives such as the Congo Basin Forest Partnership, the Central African Regional Program on Environment, and the International Branch of the US Forest Service were funded by the US Government; the access to the funds disbursed via these mechanisms made easier for US-based institutions to access and work in the Congo Basin, which may at least partially explain the predominance of the US-based organizations as hosting establishments for research on the Congo Basin.

In Europe, Belgian and French researchers, when combined, make about half (50.7%) of the researchers from outside, but when combined with UK, they become a much larger majority (ca 85%). That Belgian and French researchers make up 50.7% of the researchers is hardly surprising, given the colonial legacy of these two countries in Congo Basin. They colonized the largest area of the Congo Basin and began conducting scientific research therein at least a century ago. The surprising element of the figure is that UK comes above of both countries. In the Congo Basin itself, there are many more recorded scientists essentially in DRC and Cameroon.

Lumping things from H-index >20 as it is done above does not say much about differences between researchers based outside of the Congo Basin and scientists of the Congo Basin. Decomposing the higher tier (H-index >20) (Fig. 6) gives some important lessons about how the scientific careers evolve in the Congo Basin for the scientists of the region.

While the distribution of the top scientists is even for scientists from North America and Europe combined, a larger proportion of the scientists from the Congo Basin is packed within the bracket of H-index = 21–25. Several reasons may explain this situation; among the most important are the facts that many young

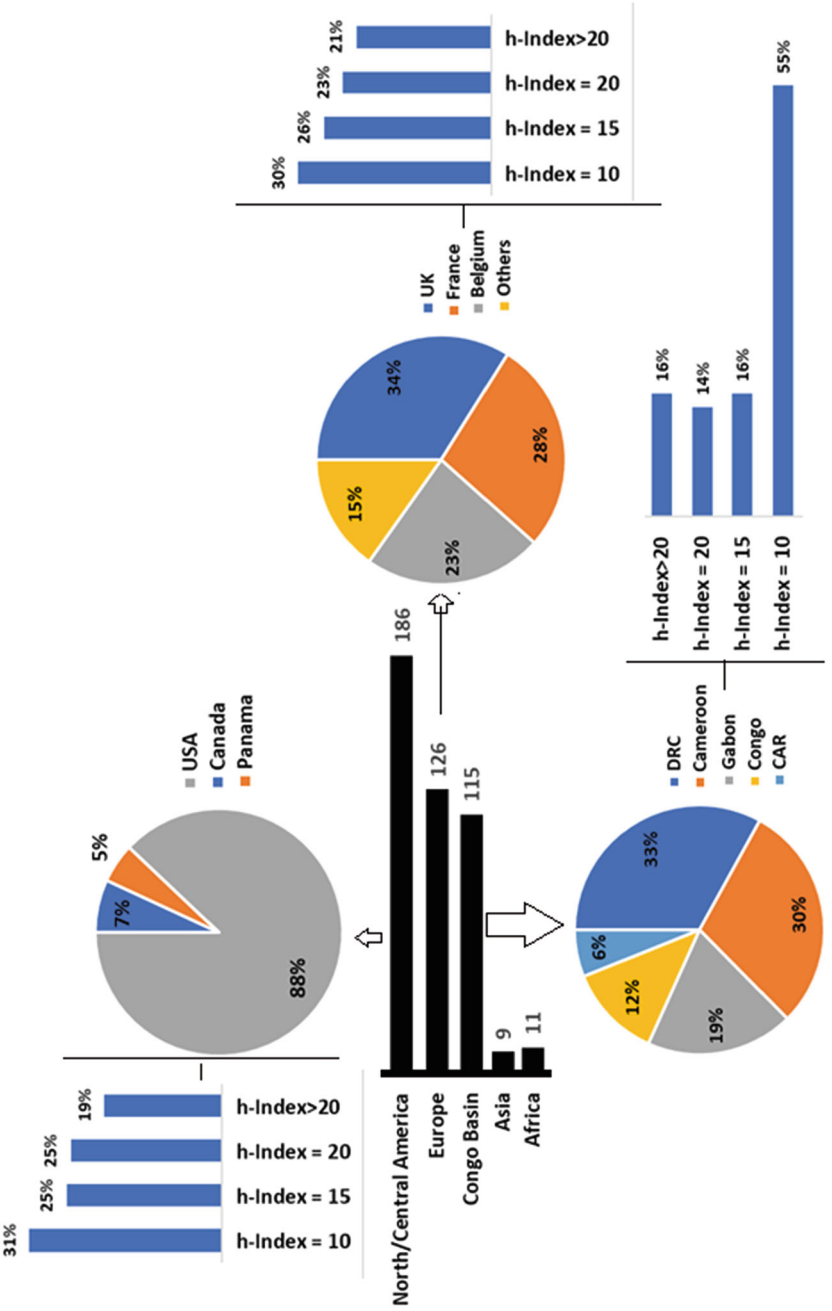

Fig. 5 Number of scientists working in the Congo Basin (sorted by H-Index ≥10). (Source: Inogwabini 2023)

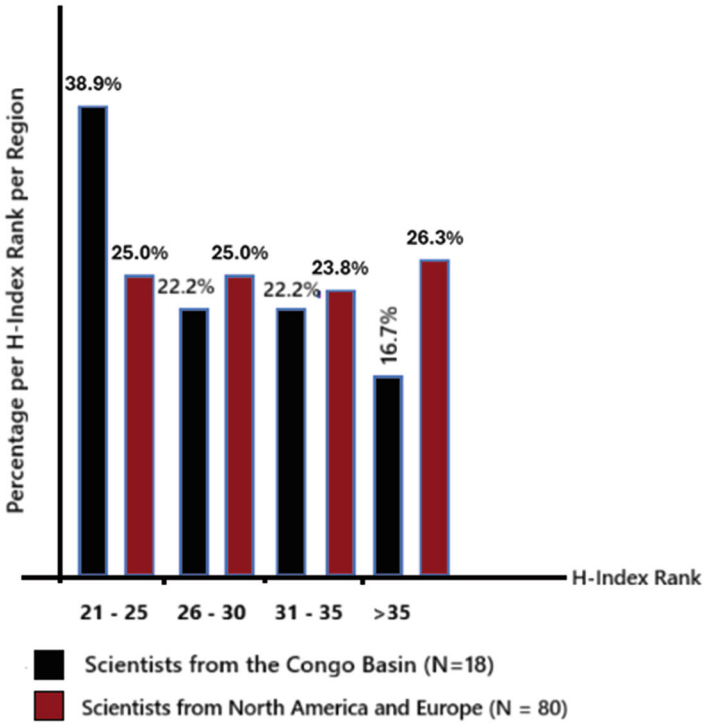

Fig. 6 Decomposed proportions of scientists with H-Index ≥20 in the Congo Basin. (Source: Inogwabini 2023)

scientists come back with a PhD and are immediately appointed to an administrative position; lack of a formal system of postdocs, where young scientists are paid to focus on further developing their experience and getting more publications out; and very little funding for science; so it is mostly only people who manage to develop international collaborations and those that work with international biodiversity conservation structures that are successful. The other important factor is the use of English to publish in most important scientific journals, which prevents most scientists from the Congo Basin whose language is principally French to publish continuously after they graduate (although modern translation and AI tools are helping with this issue today).

While we did not conduct a similar analysis of scientists active in the Amazon, the Large-Scale Biosphere-Atmosphere Experiment in Amazonia program, known as the LBA, comprised 1700 participants, 990 of whom were Brazilians (White et al. 2021), indicating that there is probably at least an order of magnitude of more native South American scientists active in the Amazon. The UNSDSN assessment of scientific knowledge of the Congo Basin demonstrated that significant gaps in knowledge and capacity exist. It was this that motivated the creation of the Science Panel for the Congo Basin (SPCB), following on from the success of a similar

initiative in the Amazon, as well as its sister organization, the Congo Basin Science Initiative (CBSI).

It is our hope that this first effort led by the SPCB, with 180 coauthors, including a majority of Congo Basin nationals, will paint as comprehensive as possible a picture of the state of knowledge of the formative processes that have created the Congo Basin as we know it today, as well as the environmental, social, and economic changes underway that will shape it in the future. Furthermore, by identifying critical gaps in both capacity and knowledge we hope to set in motion a process of scientific endeavor and training such that future assessments will be more comprehensive and authoritative, resulting in the preservation and sustainable management of the Congo Basin, one of Earth's critical life support systems and havens of biodiversity and people.

Competing Interest Declaration The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

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Section I

The Function of Congo Basin Ecosystems as a Regional Entity, and Their Influence on the Changing Earth System

Geology and Geodynamics Evolution of the Congo Basin

2

Jean-Jacques Braun, Etienne Kadima Kabongo, Stéphane Audry, Franck Delpomdor, Damien Delvaux, Pascal Mambwe, Mathieu Nouazi, and Denis Thiéblemont

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Abstract

The Congo Basin is a vast intracratonic sedimentary basin in Central Africa, covering about 3.7 million km^2. It plays a critical role in global biodiversity and carbon storage, supporting the world's second-largest rainforest and a major tropical peat carbon reserve. This chapter offers an overview of the basin's geology and geodynamic evolution, focusing on its formation, structural features, and sedimentary processes. The basin's geological history is tied to major tectonic events, including the Pan-African orogeny (~600–500 Ma), the breakup of Gondwana, and later extensional tectonics. It is underlain by an Archean to Mesoproterozoic basement formed through successive orogenic cycles. The Congo Basin developed as an intracratonic depression influenced by rifting and subsidence, resulting in thick sedimentary accumulations from the Meso-Neoproterozoic to the Cretaceous. Geophysical data reveal a complex internal structure marked by tectonic reactivation. Lateritic covers and regolith formations provide insight into long-term weathering and erosion, important for reconstructing past climate and environmental changes. The basin is also rich in geological resources, including hydrocarbons, metals, and weathering-derived deposits of economic value. This synthesis highlights the need for an interdisciplinary approach to studying the Congo Basin, integrating geological, hydrological, and ecological dimensions. A deeper understanding of its evolution is vital for sustainable resource management, conservation, and evaluating its role in global biogeochemical cycles.

Keywords

Congo Craton · Intracratonic basin · Pan-African orogeny · Greenstone belts · Sedimentary sequences · Neoproterozoic belts · Regolith · Geological resources

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Introduction

The Congo Basin is a vast, multifunctional region defined in three interrelated ways: as a central African rainforest with exceptional biodiversity (~1.6 million hectares); as a major watershed—second only to the Amazon—known as the Congo River Basin (CRB); and as a large intracratonic sedimentary basin rich in mineral resources, termed the Intracratonic Congo Basin (ICB). This complexity underscores the need for an interdisciplinary perspective integrating ecology, hydrology, and geology.

Geologically, the Congo Basin spans ~3.7 million km^2 across Central Africa, mostly within the Democratic Republic of the Congo, and lies within the stable interior of the African Plate. Despite its cratonic location, geophysical evidence suggests reactivation of ancient structures.

Its evolution has been shaped by major tectonic events. The Pan-African orogeny (~600–500 Ma) defined the basement structure, followed by extensional phases linked to Gondwana's breakup (Carboniferous–Cretaceous). The opening of the South Atlantic further influenced the basin's morphology, producing an east-to-west gradient with uplift and erosion in the east and sediment accumulation in the west.

This chapter explores the basin's geological and geodynamic evolution, emphasizing its role in shaping the Congo River system, sustaining tropical rainforest ecosystems, and storing a significant share (~28%) of global tropical peat carbon.

Geological Diversity of the Congo Basin

Basement Complex

Central Africa in the Gondwana Background

The Congo Basin is underlain and surrounded by Precambrian blocks amalgamated and stabilized during Paleoarchean to Neoproterozoic times (c. 3.5–0.54 Ga) (Fig. 1).

This basement reached is final configuration at the end of Precambrian, through the amalgamation of former cratons of Archean to Mesoproterozoic age, as the result of the Neoproterozoic Pan-African orogeny (Fig. 2).

A large piece of mainly crystalline rocks covering most of Central Africa and designated as the Congo Craton forms the main and central part of this basement (Fig. 2). It was initially part of the west Gondwana supercontinent.

The Congo Craton consists of three main Archean sub-units (De Wit and Linol 2015; Fig. 3): (i) the Southwestern Congo Craton (SWCC), uniting the Kasai-Cuango and Chaillu-Ntem blocks; (ii) the Northeastern Congo Craton (NECC), including the Bomu-Kibalian, West-Nile, and Uganda blocks; and (iii) the Central Congo Craton (CCC), buried beneath Congo Basin sediments.

These cratonic blocks form the oldest basement units of the Congo Basin, shaped by successive geological events that remobilized early cratons and accreted peripheral orogens. Post-Archean orogenic belts developed during three main periods:

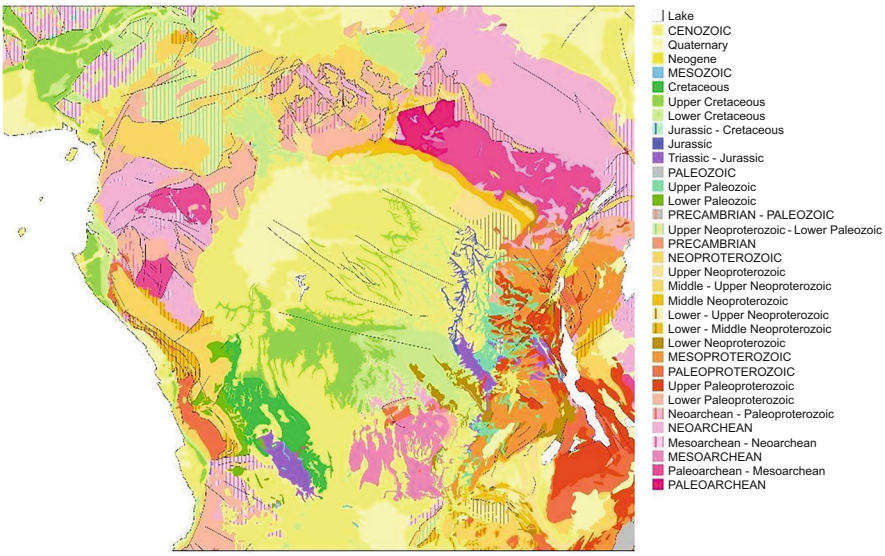

Fig. 1 Geological map of the Congo Basin prepared from the 3rd edition of the Geological map of Africa at 1/10,000,000 scale (Thiéblemont et al. 2016). Terrains are classified according to their age. Note that the precision in the age is variable from one unit to another according to the quality of the available geochronological data. For instance, terrains reported as "Neoproterozoic" may belong to any period of this era. On the other hand, terrains reported as "Upper Neoproterozoic" are indeed Neoproterozoic but with a higher degree of resolution in the determination of their age. Note that many new ages have been published since the publication of this map that have not been considered as they would require a new edition of the map to be prepared, which is beyond the scope of this chapter

(i) the Paleoproterozoic West-Central African Belt; (ii) the Mesoproterozoic Kibaran Belt; and (iii) Neoproterozoic belts including the Lufilian (Katanga), West-Congo, and Oubanguides (Central African) systems (Fig. 3). These are detailed chronologically in the following sections.

Archean Blocks

The underlying figure (Fig. 4), derived from the 3rd edition of the Geological map of Africa at 1:10,000,000 scale (Thiéblemont et al. 2016), classifies the Archean terrains of Central Africa according to their lithology and age on the basis of the geochronological data available before 2016.

Archean terrains are dominated by TTG-type (tonalite–trondhjemite–granodiorite) granitoids and orthogneisses, with greenstone belts as the second principal component. These belts—elongated volcanic-sedimentary units composed mainly of basic to ultrabasic rocks—contain banded iron formations (BIF), key for iron and gold exploration. While greenstone belts are intensely deformed, their metamorphism varies widely, from greenschist to granulite facies, as seen in the Chaillu–Ntem Block (Thiéblemont et al. 2009).

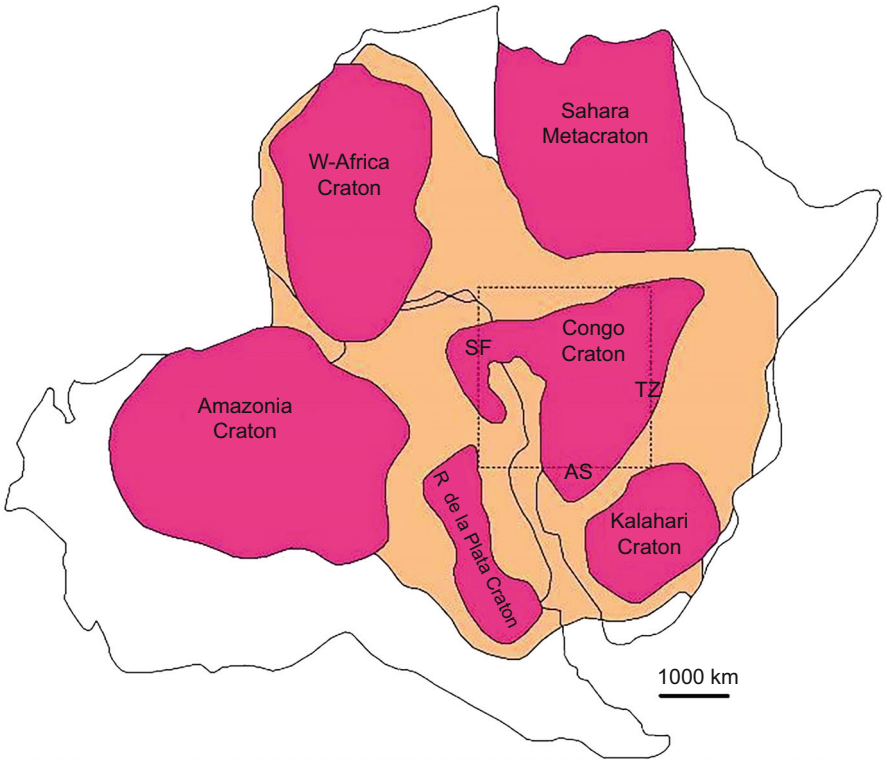

Fig. 2 Simplified geological sketch showing the outline of western Central Africa (rectangle in the middle of the figure) relative to cratonic blocks (pink) and Pan-African belts (ocher) issued from Gondwana amalgamation. (Redrawn from Tack et al. 2024). In South America, the Congo Craton extends to the São Francisco Craton (**SF**). East of the Congo Craton, the Tanzania Craton (**TZ**) was amalgamated to the Congo Craton during Mesoproterozoic (see text). South of the Congo Craton, the Angola Shield (**AS**) stands as a southward extension of the Congo Craton of mainly Paleoproterozoic age

The nature of TTG–greenstone relationships remains debated. Greenstone belts often show lower-grade metamorphism than surrounding TTG plutons, suggesting they were emplaced atop older TTG basement. However, intrusive TTG bodies also cut across some belts (e.g., Thiéblemont et al. 2009; Akame et al. 2020). Poor geochronological resolution for greenstone lithologies further complicates interpretation.

In northeastern DRC, Archean geological mapping has seen little revision since the 1:2,000,000 national map (Lepersonne 1974; Fernandez-Alonso et al. 2016), constrained by limited pre-1980s geochronological data (Cahen et al. 1984). Two main crustal blocks are recognized (Fig. 4): The W-Nile Block—depicted as undifferentiated Neoarchean gneisses—and the NE-Congo Block, composed of a Paleoarchean Bomu Block in the west and a Paleo- to Mesoarchean domain to the east.

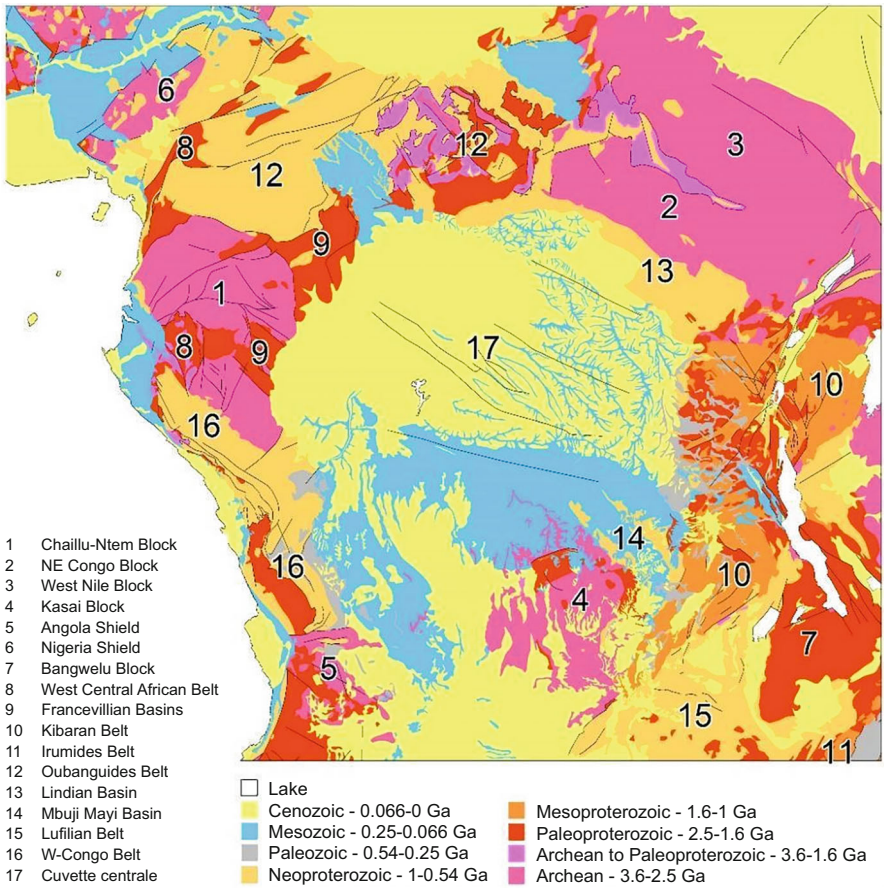

Fig. 3 Simplified geological map of the Congo Basin prepared from the 3rd edition of the Geological map of Africa at 1/10,000,000 scale (Thiéblemont et al. 2016). Precambrian terrains are classified according to their era and the geological domains described in this note are listed and identified by numbers

Recent U-Pb zircon dating (Turnbull et al. 2021) reveals two plutonic episodes in the NE-Congo Block: a potassic-poor phase (2670–2600 Ma) and a potassic-rich phase (2600–2530 Ma). In the W-Nile Block, ages of 2720–2620 Ma have been reported, along with a single 3200 Ma gneiss, but overall geological understanding remains limited due to sparse field data.

To the west, the Chaillu–Ntem Block is well mapped in Gabon, Cameroon, and northern Congo (Thiéblemont et al. 2009; Delor et al. 2021; Blein et al. 2024), with detailed work refining the Ntem Complex in Cameroon (Akame et al. 2020). At the continental scale, three Archean units are distinguished: (i) a Paleo- to Mesoarchean TTG basement (3000–2800 Ma), (ii) Meso- to Neoarchean greenstone belts, and (iii) Neoarchean granitoids (2700–2600 Ma). Greenstone emplacement in Cameroon and Gabon is dated between 2883 ± 20 Ma and 2750 Ma (Chombong and Suh 2013).

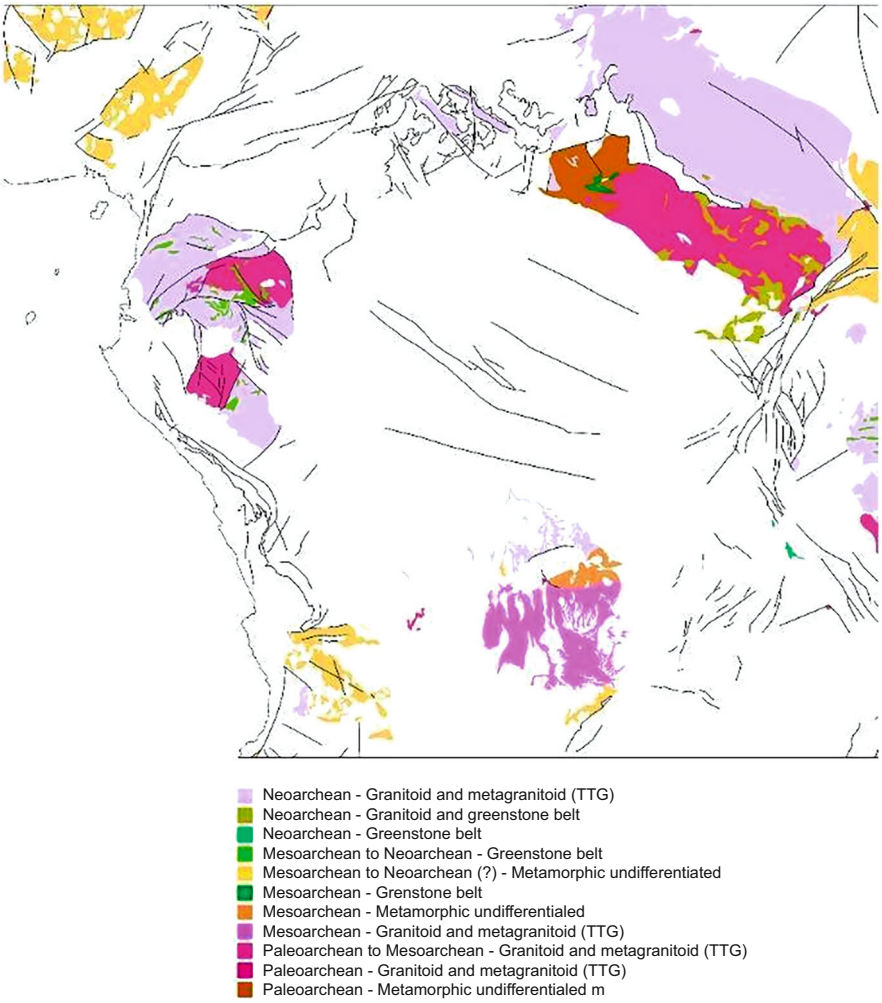

Fig. 4 Broad lithological classification of Archean terrains localized in the Congo Craton distinguished according to their age

The Chaillu–Ntem Block's simplified evolution includes TTG basement formation, greenstone belt emplacement, and later tectono-metamorphism with granitoid intrusions.

Further south, the Kasaï Block comprises undifferentiated granito-gneissic complexes—Mesoarchean in the south, Neoarchean in the north—along with high-temperature charnockitic intrusions. These lithologies correlate with those in the Chaillu–Ntem Block, supporting the grouping into a unified Southwestern Congo Craton (De Wit and Linol 2015). No greenstone belts are yet identified in the Kasaï Block.

The Central Congo Craton, a major basement element of the Congo Basin, remains poorly constrained due to thick sedimentary cover. A possible late Neoproterozoic mobile belt (Kiri High) has been hypothesized beneath the basin (Delvaux et al. 2021; Maddaloni et al. 2021), though tomographic data (Raveloson et al. 2015) suggest the absence of Proterozoic lithosphere. In the absence of direct field data, the Central Congo Craton is inferred to host TTG-type gneisses, metavolcano-sedimentary sequences, granitoids, and mafic intrusions, similar to surrounding Archean blocks.

Paleoproterozoic Belts

Paleoproterozoic terrains are widespread in Central Africa's Precambrian basement, primarily in two major zones (Fig. 3):

- The West-Central African Belt (WCAB)—a 3000-km-long orogenic belt extending from Angola to the Central African Republic, including associated foreland basins such as the Francevillian and Sembé-Ouesso basins
- The Bangweulu Block in the southeastern region, composed of plutonic and volcano-sedimentary rocks emplaced between 2000 and 1800 Ma (De Waele et al. 2006)

Other Paleoproterozoic exposures include the Kasaï region, near the Archean basement, and the Kibara Belt, where they form the basement beneath Mesoproterozoic cover sequences.

In the West-Central African Belt, attributed to the Eburnean orogenic cycle (~2.0 Ga), an east-west transect across Gabon reveals the following:

- Foreland basins, such as the Francevillian series, unconformably overlying the Archean Chaillu–Ntem Block. These unmetamorphosed sedimentary-volcanic sequences (up to 2.5 km thick) show limited deformation.
- A folded and metamorphosed internal domain, where Paleoproterozoic supracrustal rocks and Archean basement were buried to ~25 km, reaching P–T conditions of ~8 kb and 550 °C, with widespread granitic intrusions.
- An innermost zone comprising reworked Archean basement intruded by Eburnean granitoids (c. 2.0–2.1 Ga).

High-temperature metamorphism at ~2.5 Ga in internal zones suggests a long-lived reworking from 2500 to 2000 Ma.

Northward, the WCAB extends into Cameroon, where it forms the basement of the Pan-African Belt. Here, Archean gneisses and greenstone belts (Delor et al. 2021) experienced Paleoproterozoic metamorphism (Toteu et al. 1994), but without equivalents to the metamorphosed Paleoproterozoic series of Gabon.

However, the **foreland Francevillian basins** extend into the Republic of the Congo, Cameroon, and the Central African Republic (Rolin 1995), where deformation once linked to late Eburnean events may instead relate to the Mesoproterozoic

Kibaran orogen (Fullgraf et al. 2024). These formations typically overlie Archean TTG-type rocks, except in the CAR, where they rest on supracrustal rocks (2900–2450 Ma) intruded by Eburnean granites (~2150 Ma).

To the south, the WCAB continues along the Atlantic margin in SW-Gabon, Congo, DRC, and Angola (e.g., Callec and Fullgraf 2015), forming the crystalline basement of the Pan-African West Congo Belt (Fig. 3).

In the **Kasaï Block** (Figs. 3 and 5), despite minimal changes since the original mapping (Lepersonne 1974), three Paleoproterozoic units are distinguished:

- The Lueta Complex (~2400 Ma), a deep-seated gabbronoritic unit (~200 km long).
- The Luiza Group (~2000 Ma), resting on Lueta, composed of quartzites, micaschists, BIFs, and rare conglomerates.
- The Lulua Group (~2000 Ma), resting unconformably on Archean rocks, comprising quartzites, schists, and tholeiitic volcanics indicating rift settings.
- Eburnean granites (2135–2040 Ma) occur both along the Archean margins and as large plutons (~20–30 km wide) within the block.

These supracrustal units extend southwest into **Angola (Cuango Craton)**, where the Lovua (lower) and Upper Groups correlate with the Luiza and Lulua groups, respectively (Pereira et al. 2003). Both Kasaï and Cuango are intruded by dolerite dykes, ultramafic bodies, and diamondiferous kimberlites (Batumike et al. 2008).

Paleoproterozoic rocks also dominate the eastern Congo Basin margin, forming the basement for younger orogenic belts. The **Kibara Belt** basement may correlate with the Luiza–Lulua unit (Debruyne et al. 2019), while the **Lufilian Belt** basement likely corresponds to the Eburnean Bangweulu Block (De Waele et al. 2006).

Mesoproterozoic Belts

The main Mesoproterozoic domain in the crystalline basement of the Congo River Basin is the Kibaran orogen (Figs. 5 and 6), a south-southwest-north-northeast-oriented belt of some 1500 km long forming the eastern flank of the basin.

The Kibara Belt comprises a thick sedimentary sequence (10,000–20,000 m; Cahen et al. 1984) divided into two groups separated by an unconformity and a decrease in metamorphism (Kokonyangi et al. 2006). Felsic volcanism accompanied deformation of the basal group, while mafic rocks and ophiolitic remnants are absent (Tack et al. 2010). The succession spans ~450 Ma (ca. 1400–950 Ma), constrained by crosscutting granites (Cahen et al. 1984), and includes four granite suites: two synorogenic and two post-orogenic. Major magmatic events occurred at ca. 1400–1350 Ma, ~1200 Ma, and ~1000–950 Ma (Tack et al. 2010). Structurally, the belt features NE-trending, west-verging folds and thrusts formed under moderate P–T conditions. Two main tectonic phases are inferred: an early northward thrusting (~1380 Ma) and a later folding phase (~1080 Ma) preceding emplacement of economically significant tin-bearing granites.

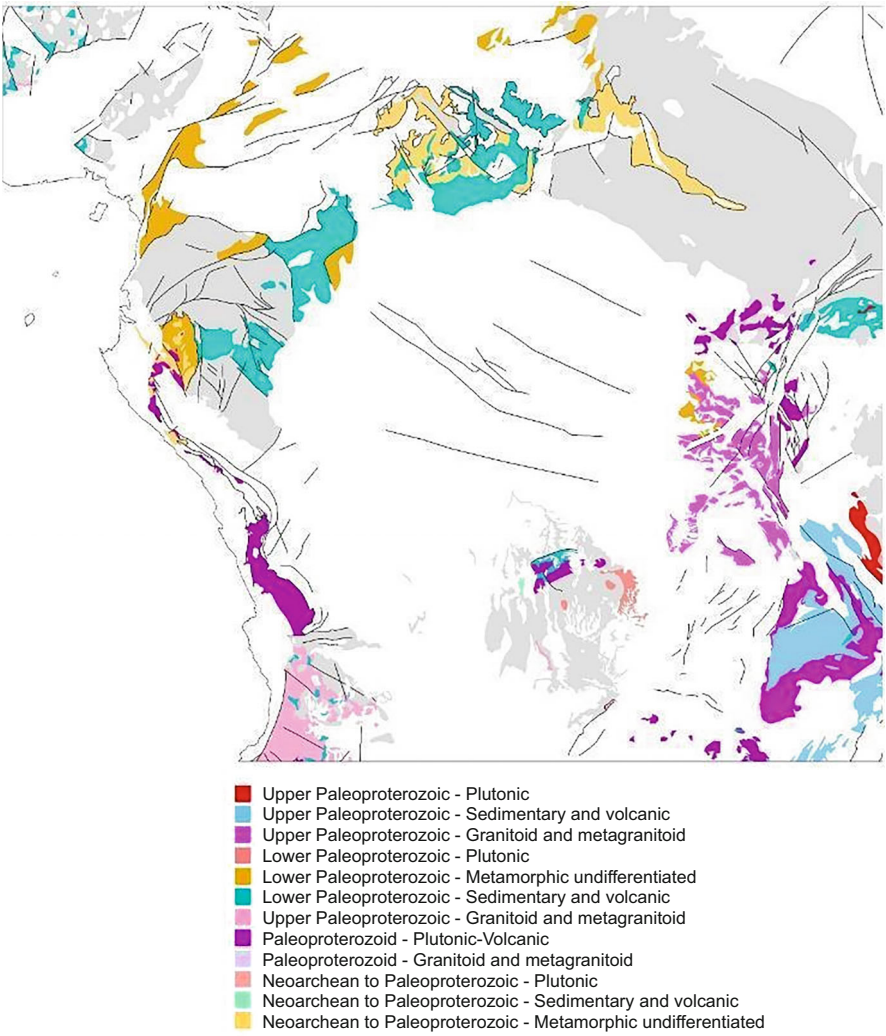

Fig. 5 Broad lithological classification of Paleoproterozoic terrains localized in the Congo Craton distinguished according to their age. Undistinguished gray zones correspond to Archean terrains preexisting to Paleoproterozoic

Neoproterozoic Belts

The Neoproterozoic fold belts underlying the Congo River Basin were formed in response to the Pan-African orogenic cycle, a major tectonic event that led to the amalgamation of African cratons during the assembly of West Gondwana (Fig. 2). Although these belts formed during the same overall geodynamic context, they exhibit marked differences in their structural, metamorphic, and magmatic histories, reflecting distinct geodynamic evolutions.

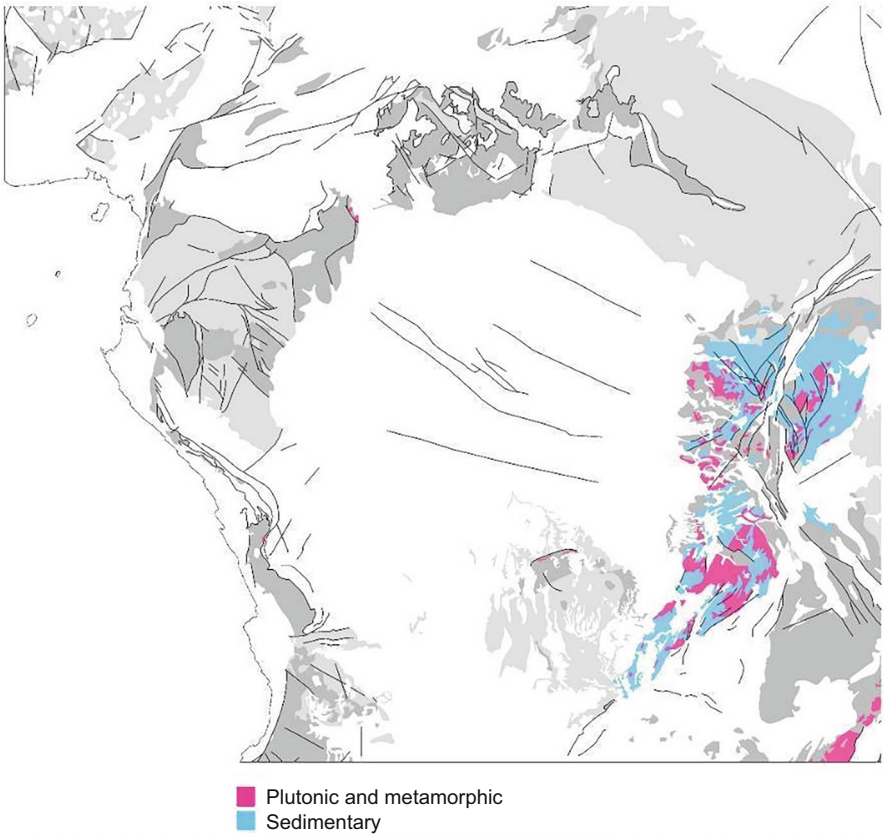

Fig. 6 Broad lithological classification of Mesoproterozoic terrains localized in the Congo Craton distinguished according to their age. Gray zones correspond to terrains preexisting to Mesoproterozoic: light gray, Archean; medium gray, Paleoproterozoic

To the north of the basin, the Central African Orogenic Belt (CAOB)—also known as the Oubanguide Belt (Figs. 3 and 7)—extends across Cameroon and the Central African Republic. It formed as a result of the collision between the Congo Craton (south) and the Saharan Metacraton (north) (Fig. 2). This belt is characterized by high-temperature metamorphism and intense syn- to post-tectonic plutonism, indicative of a deep crustal orogenic system involving substantial crustal thickening and thermal input.

In sharp contrast, the West Congo Belt on the western margin of the basin (Figs. 3 and 6) and the Lufilian (or Katanga) Belt in the southeastern corner exhibit moderate metamorphism and lack tectonically related plutonic intrusions. These differences suggest that, while all three belts participated in the Pan-African convergence, they did so under varied tectonic settings—ranging from continental collision with deep crustal melting (CAOB) to foreland fold-and-thrust dynamics (West Congo and Lufilian Belts).

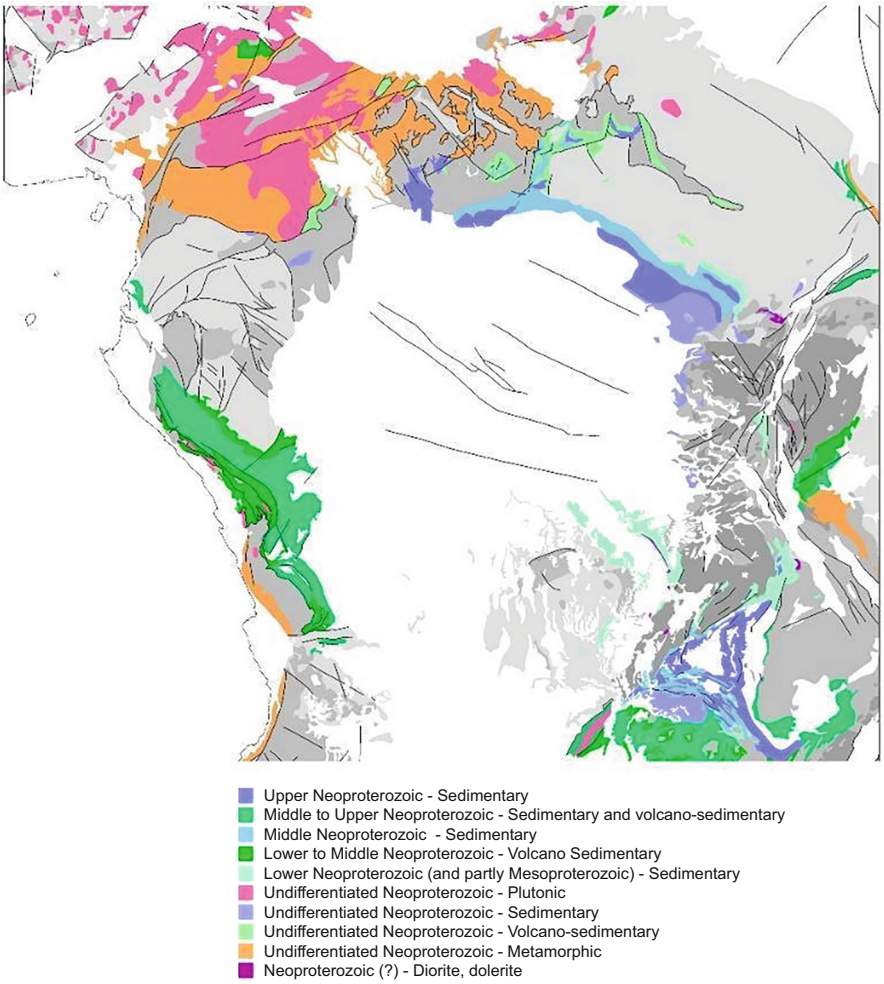

Fig. 7 Broad lithological classification of Neoproterozoic terrains localized in Central Africa distinguished according to their age. Gray zones correspond to terrains preexisting to Neoproterozoic belts: light gray, Archean; medium gray, Paleoproterozoic; dark gray, Mesoproterozoic

The presence of high-temperature metamorphic rocks, particularly granulites, in the Central African Fold Belt and the adjacent Chaillu–Ntem Craton (Fig. 3) has been recognized since the earliest geological surveys. Initially, these rocks were attributed to a widespread Archean "basal complex" believed to extend across southern Cameroon and the Central African Republic (Mestraud 1964). However, subsequent isotopic dating confirmed that the Ntem Complex in southern Cameroon is of Mesoarchean age (Lasserre and Soba 1976).

To the north of the Chaillu–Ntem Craton, the metamorphic terranes of the Oubanguide Belt were reinterpreted as part of a Neoproterozoic orogenic system,

with geochronological data confirming high-temperature metamorphism of Neoproterozoic age (Pin and Poidevin 1987). These granulitic rocks, extending from the Central African Republic into Cameroon, reflect a crustal-scale south-verging nappe system formed during the thrusting of the Central African Fold Belt onto the Congo Craton (Rolin 1992).

Despite advances, the overall geodynamic architecture of the belt remains debated (Delor et al. 2021; Toteu et al. 2022). Key features contributing to current geodynamic models include the following:

- **Extreme metamorphic conditions**: Peak temperatures of 600–800 °C and pressures of 9–12 kbar suggest deep burial (~25–35 km) under a high thermal gradient, followed by tectonic exhumation via thrusting.
- **Prolonged magmatic activity**: A sequence of magmatic events spanning ~500 million years (c. 1050–550 Ma), reflecting long-lived crustal evolution (Delor et al. 2021).
- **Relicts of older basement**: Inliers of Archean to Paleoproterozoic rocks embedded within Neoproterozoic units suggest the presence of a **crustal block** located between the **Congo Craton** and the **Saharan Craton or Metacraton** (Toteu et al. 2022).
- **Discontinuous ophiolitic remnants**: Found along the contact between the basal Pan-African nappe and the Chaillu–Ntem Block, these suggest the former existence of a **now-closed oceanic domain** to the north (Kundu et al. 2022).
- **Arc-related magmatism**: The occurrence of volcanic rocks with **subduction-related geochemical signatures** in northwestern Cameroon supports the hypothesis of a **north-directed subduction zone** during Neoproterozoic orogenesis (Toteu et al. 2022).

Together, these elements point to a **complex, multiphase tectonic evolution**, involving ocean closure, continental collision, deep burial and exhumation, and crustal-scale thrusting—hallmarks of a **high-grade collisional orogen** formed during the Pan-African event.

The **West Congo Belt** is a prominent Neoproterozoic orogenic belt that stretches parallel to the Atlantic coast (Fig. 7). It is morphologically and structurally divided into two distinct domains. To the west, the Mayombe Massif forms a high-relief internal domain composed of deformed and metamorphosed rocks. To the east, the Niari–Nyanga Basin constitutes a low-lying foreland domain made up of slightly deformed sedimentary rocks. These sedimentary sequences rest unconformably on the Congo Craton and are locally overlain by younger sediments of the Cuvette Centrale in southern DRC and Angola.

Crystalline rocks of Eburnean age crop out at the western margin of the Mayombe Massif and are considered to represent the basement of the internal domain (Callec and Fullgraf 2015; Thiéblemont et al. 2018). At the northern boundary of the belt, the sedimentary units of the Niari–Nyanga Basin are in direct contact with cratonic rocks, suggesting that the orogen resulted from the closure of an intracontinental rift basin, with no evidence of an intervening oceanic domain (Tack et al. 2001).

The Neoproterozoic formations of the West Congo Belt are grouped within the so-called West Congo Supergroup, although a consistent lithostratigraphic framework remains elusive, particularly in the internal domain. In the Republic of the Congo and DRC, the lower part of this supergroup begins with a granitic magmatic phase dated to ~1.0 Ga, followed by clastic sediments and a thick basaltic unit (~1600–2400 m) dated to ~920 Ma. Although this unit was once interpreted as ophiolitic, more recent studies affirm a within-plate, rift-related setting (Tack et al. 2001).

Above the basalts lies a thick sequence (3000–4000 m) of volcanoclastic and felsic volcanic rocks, emplaced between 920 and 910 Ma, followed by a second basaltic phase. In Gabon, similar but less extensive magmatism occurred between ~905 and 875 Ma, contemporaneous with volcano-sedimentary formations that constitute a large part of the Mayombe Massif.

The upper part of the West Congo Supergroup is dominated by sedimentary rocks, including two glaciogenic diamictites that correspond to the Sturtian (~740 Ma) and Marinoan (~650 Ma) glaciations. These are followed by post-glacial carbonate and detrital sequences that filled the Niari–Nyanga Basin, which formed in a foreland position east of the Mayombe Massif. This infill includes a basal carbonate platform along the margins and a central clastic succession, reflecting the synclinorial structure of the basin.

Structurally, the West Congo Belt is a classic fold-and-thrust belt, with deformation intensity and metamorphic grade increasing from the external to the internal domain. In the Mayombe Massif, metamorphic conditions reached mesozonal grades (biotite–garnet paragenesis). Ar–Ar ages indicate that peak metamorphism ended before ~566 Ma (Frimmel et al. 2006). Detrital zircon and illite K–Ar ages from the upper clastic units suggest sedimentation continued into the late Neoproterozoic, during the uplift and exhumation of the Mayombe Belt, in a foreland molasse setting (Callec and Fullgraf 2015).

To the southeast of the Congo Basin lies the **Lufilian Belt**, an arcuate Neoproterozoic orogen extending across southwestern DRC and northern Zambia, and hosting the world-class Central African Copperbelt (Cailteux et al. 2005). The Lufilian Arc, to the south, curves from the Irumide Belt in the east to the Kibara Belt and Kasaï Block in the west, while the Kundelungu Plateau in the north represents a foreland basin bounded by the Bangweulu and Kibara belts (Figs. 3 and 7).

The Lufilian Belt exposes the Katanga Supergroup, a volcano-sedimentary succession 5–10 km thick, deposited atop a Paleoproterozoic basement (~2.05–1.85 Ga). The supergroup is classically divided into four groups (from oldest to youngest):

- The **Roan Group**, consisting of alternating siliciclastic, dolomitic-carbonate, and pyroclastic rocks, with minor hematite and cherts
- The **Nguba Group**, which begins with a glacial diamictite overlain by a cap carbonate and transitions to siliciclastics

- The **Kundelungu Group**, also glacially initiated and capped by carbonates, followed by fine- to medium-grained siliciclastics
- The **Biano Group**, comprising coarse-grained conglomerates, arkoses, and sandstones

Tectonically, the belt is a north-verging fold-and-thrust system, subdivided into three structural zones. The Kundelungu foreland forms a triangular, relatively undeformed northern zone. South of this, the intermediate zone displays the most complete stratigraphy of the Katanga Supergroup, deformed by thrusts and low-grade metamorphism. The internal zone, to the south, contains basement inliers and experienced higher-grade metamorphism (up to amphibolite facies), suggesting the presence of nappes that juxtapose metasediments and basement rocks (Eglinger et al. 2016).

The tectono-metamorphic evolution of the Lufilian Belt spanned ~500 million years, from early Neoproterozoic sedimentation (1000–800 Ma) through successive orogenic phases (800–500 Ma), with major deformation events between 800 and 710 Ma (Kampunzu and Cailteux 1999). Recent geothermobarometric and geochronological data reveal a Cambrian high-pressure metamorphic event (~530 Ma), with P–T conditions up to 13 kbar and 750 °C, interpreted as the result of continental collision during the terminal stages of belt evolution (Eglinger et al. 2016). This interpretation challenges the traditional view of the Lufilian Belt as a solely rift-related fold-and-thrust system and points to a more complex orogenic history involving deep crustal processes.

Sedimentary Basins

The Congo Basin, also known as the Cuvette Centrale, developed atop the Archean-Paleoproterozoic Congo Craton, which comprises Archean blocks amalgamated by Paleoproterozoic and Mesoproterozoic belts and bordered by Neoproterozoic mobile belts (De Wit and Linol 2015).

Its internal structure was first investigated during major exploration campaigns in 1952–1956 and the 1970s, involving seismic, gravity, magnetic surveys, and four deep boreholes (up to 4560 m). These studies formed the basis for several syntheses of the basin's tectonic and stratigraphic evolution (Kadima et al. 2011; Delvaux et al. 2021).

The basin originated as a NE–SW-oriented failed rift, extending into the Kasaï region where the Mbuji-Mayi Supergroup (1174–888 Ma) crops out (Delpomdor et al. 2013; François et al. 2023). This Stenian–Tonian age is considered the initiation stage of the basin. Sedimentation ceased in the Late Cretaceous, with an estimated post-depositional erosion of ~1000 m (Sachse et al. 2012). The basement depth is estimated between 8 and 12 km based on seismic and gravity data (Maddaloni et al. 2021).

The stratigraphy is divided into four major seismo-stratigraphic sequences (Delvaux et al. 2021):

- Stenian–Tonian: Rift-related clastics and carbonates of the Mbuji-Mayi Supergroup, overlain by glacial diamictites in the south (Delpomdor et al. 2013, 2015).
- Neoproterozoic: Post-rift subsidence carbonates, clastics, evaporites, and Cryogenian siliciclastics of the Lindi Supergroup—linked to the Rodinia breakup.
- Paleozoic–Triassic: After the Pan-African orogeny, deposition of red sandstones (Banalia Group) from Cambrian to Devonian correlated with the Inkisi Group (West Congo Supergroup) and Biano Group (Katanga Supergroup) (Cailteux and De Putter 2019). A sedimentary gap occurred during the Gondwana glaciation. Sedimentation resumed in the late Carboniferous with deglacial lacustrine deposits, followed by Triassic sandstones and mudstones of the Karoo Supergroup.
- Jurassic–Cretaceous: After a major unconformity (800–1200 m depth), deposition resumed in the Late Jurassic (Kimmeridgian) with fluvial-lacustrine sediments, followed by Cretaceous calcareous sandstones, black shales, marls, limestones, and chromiferous kimberlites of the Congo Supergroup (Caillaud et al. 2017).

Lateritic Regoliths and Landform Evolution of the Congo Basin

The Congo Basin, located within the latitudinal band of 27°N–27°S known as "Low Africa" (Doucouré and de Wit 2003), hosts one of the most extensive and well-preserved lateritic regolith mantles in the tropical belt (Burke and Gunnell 2008; Jones et al. 2013; Chardon 2023). Sustained by warm, humid climates, this deep weathering mantle underpins a vital bio-geosystem—supporting soil resources (Jones et al. 2013), groundwater (Trigg and Tshimanga 2020), mineral deposits (Milési et al. 2006), and tropical rainforests (Shapiro et al. 2021).

The complex lateritic capping system offers a unique record of regolith–landform evolution and has important implications for critical zone processes, such as land degradation, rejuvenation, and geohazards. Laterites extend from lowland interior plains on cratonic and Pan-African terrains to highland plateaus (up to 2000 m) shaped by mantle-driven uplift (Guillocheau et al. 2017; Nouazi Momo et al. 2024).

Lowland terrains, dominated by rainforest, exhibit gently rolling etchplains and pediplains formed under limited mechanical erosion and low denudation (10–200 $t/km^2/yr$) (Regard et al. 2016; Moquet et al. 2021). Here, in situ geochemical weathering and iron accumulation predominate (Temgoua et al. 2002; Bitom et al. 2004), with climate seasonality driving Holo-Pleistocene sedimentation and pedogenesis, especially in floodplains such as the Cuvette Centrale, which covers ~32% of the Congo Peneplain (Bwangoy et al. 2010; Runge et al. 2013).

In contrast, highland swells—including the Adamaoua and CAR swell (north), Mayombe and Bié swells (south), and the Albertine Rift shoulder (east)—feature dissected topographies with multi-level lateritic sequences (Guillocheau et al. 2017; Grab 2016). On the Adamaoua Plateau, five stepped lateritic surfaces between ~1300 and 800 m reflect alternating phases of weathering and incision, largely climate

driven. In the Albertine region, uplift-induced base-level drops led to rapid dissection and the development of successive regolith benches (Nouazi Momo et al. 2024).

The best-preserved surfaces—thick Al-rich laterites (bauxites and kaolinites)—form remnants of the "African Surface," a Paleogene weathering surface developed during greenhouse conditions between ~59 and 45 Ma (Guillocheau et al. 2017; Nouazi Momo et al. 2024). Its incision was associated with major geological, climatic, and topographic changes that influenced Central African biodiversity (Couvreur et al. 2020).

Beneath these bauxitic caps, subsequent post-Eocene seasonal climates promoted mechanical erosion, leading to duricrusts of varied geochemical signatures (ferricretes, Al-Fe crusts), as observed across sequences such as the Adamaoua Plateau (Burke and Gunnell 2008) (Figs. 8 and 9).

Structural Features

The current morphology of the Congo Basin, largely inherited from the Miocene, is shaped by the Congo River watershed and enclosed by elevated morpho-tectonic provinces forming prominent plateaus (Fig. 10). These include the following:

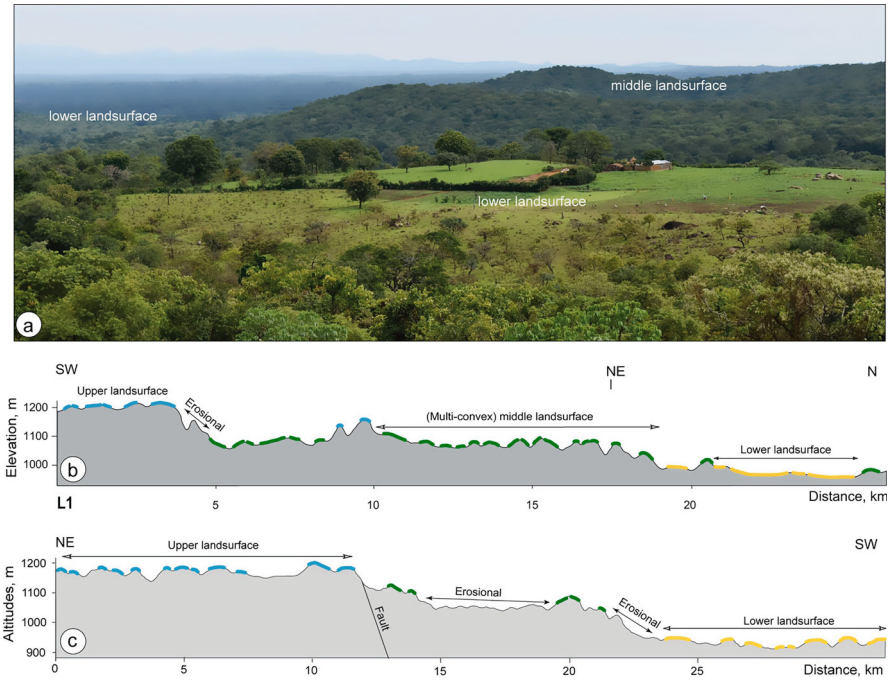

Fig. 8 (**a**) Landscape of Adamaoua highland with the middle and the lower land surface. (**b** and **c**) Topographic sections across successive lateritic land surfaces of the Adamaoua highland over granitic basement. (Adapted from Nouazi Momo et al. 2024)

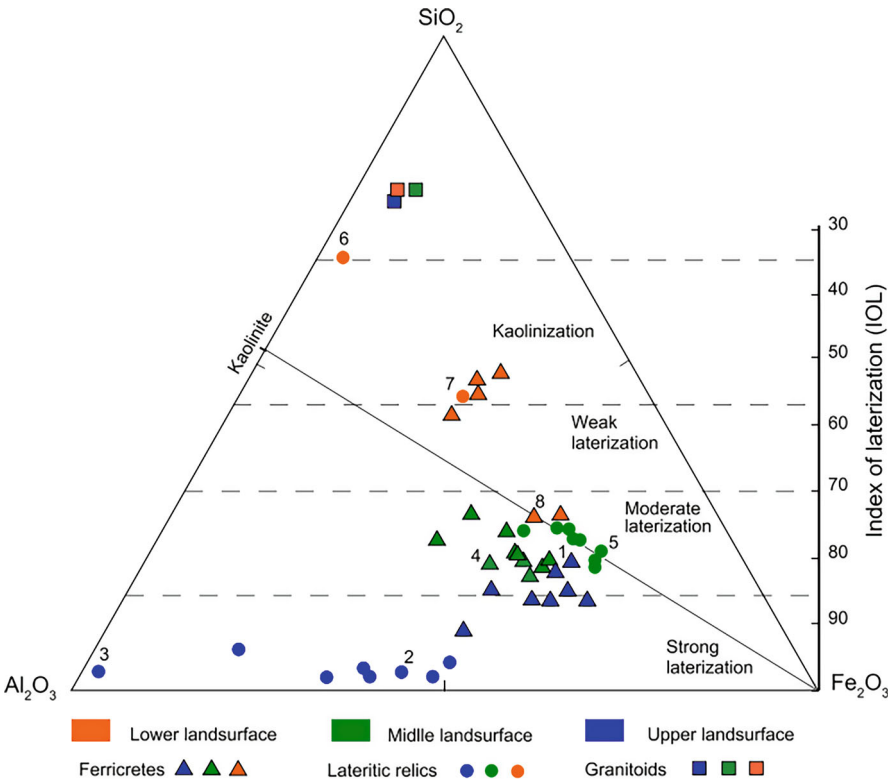

Fig. 9 Composition diagram (SiO_2-Al_2O_3-Fe_2O_3) for parent rocks and lateritic duricrusts sampled in regolith of three land surfaces, including the vertical IOL. (Adapted from Nouazi Momo et al. 2024)

- The Adamalia and Congo-Nile plateaus (NW and NE)
- The East African bulge (east)
- The crustal uplifts of North Zambia, Bié, and Mayombe (SE to W) (Burke and Gunnell 2008)
- Within the basin, the central structural pattern has been inferred from drainage anomalies and lineament analyses (Deffontaines and Chorowicz 1991), revealing two main conjugate sets of structural directions:
  - Northwest–southeast lineaments: Associated with Meso- to Neoproterozoic tectonics, as seen in the Mbuji-Mayi Basin (SW) and Lindi Basin (NE).
  - Northeast–southwest structures: Linked to the Pan-African orogeny, Atlantic opening (in the west), and SREA-related deformation (in the east) (Kadima et al. 2011).

In the southern basin, an additional pattern of ESE–WNW structures overlain by NE–SW trends has been interpreted as evidence of tilted crustal blocks within the southwestern Congo Craton, reflecting complex reactivation histories.

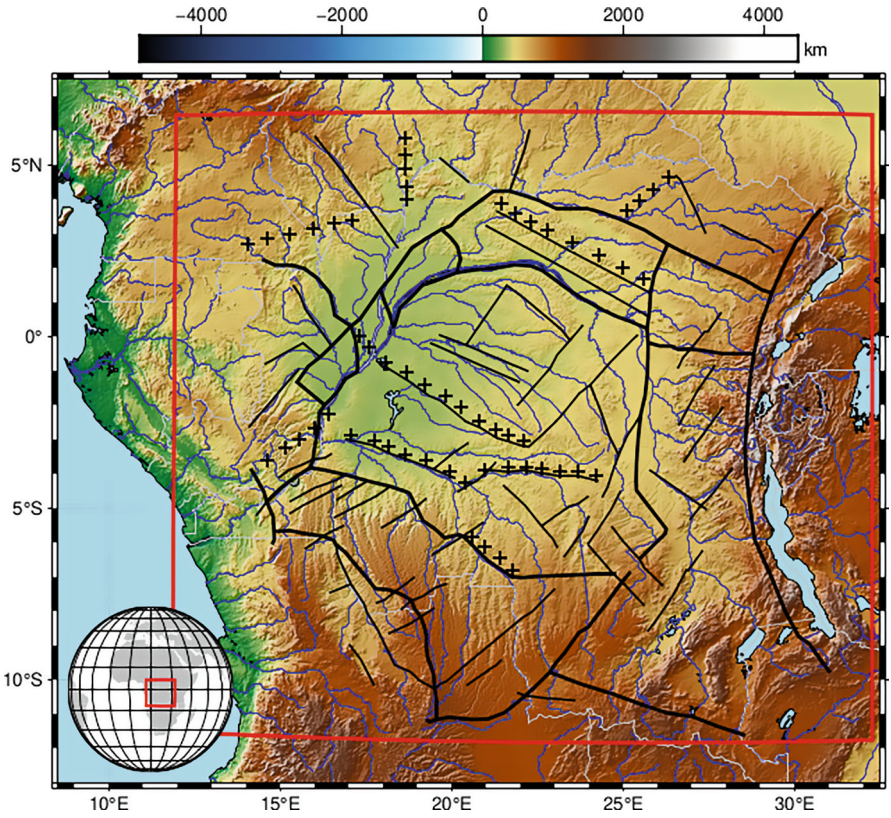

Fig. 10 The current shape of the Congo Basin, inherited from the Miocene, is shaped by the Congo River watershed and is surrounded by morpho-tectonic provinces

Internal and External Geodynamics of Central Africa

Craton Formation

Among the Archean blocks of the Congo Craton, the Chaillu–Ntem Block is the best-studied, thanks to detailed national mapping at 1:200,000 scale and extensive geochronological data acquisition.

The block is dominated by a widespread TTG-type (tonalite–trondhjemite–granodiorite) basement, emplaced between ~3000 and 2850 Ma. This gray granitoid crust contains mafic enclaves, indicating early injection of mantle-derived magmas. Zircons dated up to ~3500 Ma—notably from the Bomu Complex at the western edge of the NE-Congo Block (Cahen et al. 1984)—suggest continental crust formation may have begun in the Paleoarchean.

Following TTG crust formation, several key events reshaped the block (Thiéblemont et al. 2009):

- Transformation of TTG into charnockites via high-temperature metamorphism
- Intrusion of potassic pink granites as large massifs or smaller-scale veins
- Emplacement of greenstone belts

Geochronological constraints indicate these three events occurred nearly synchronously, between ~2850 and 2800 Ma, likely during a phase of crustal extension and injection of mantle-derived magmas.

A later regional tectonometamorphic event (~2750 Ma) further deformed the greenstone belts, imposed a second metamorphic overprint on the crystalline basement, and triggered the intrusion of a second generation of potassic granites (~2700–2500 Ma).

Proterozoic Mobile Belts and Pan-African Orogeny

Paleoproterozoic Belts

The best-exposed Paleoproterozoic belt around the Congo Basin is the West Central African Belt (WCAB), with its full section preserved in Gabon. Its current configuration results from east-directed thrusting of metamorphic units over a foreland basin, followed by erosion.

The WCAB evolved through alternating extensional phases, marked by sedimentation, and compressional phases, responsible for deformation and metamorphism (Thiéblemont et al. 2009). It shows similarities with modern orogens, including: (i) a metamorphic-to-undeformed gradient from core to foreland (e.g., Francevillian basins), (ii) an orogenic prism of stacked nappes, and (iii) a remobilized continental block intruded by abundant granites, reflecting intense crustal exhumation.

These features support its interpretation as a continental collision zone, formed by convergence between the Congo Craton (east) and the São Francisco Craton (west) (Weber et al. 2016).

Geochronological data suggest a protracted evolution spanning ~500 million years (c. 2450–2000 Ma)—twice the duration of typical Wilson Cycle orogens. Unlike many modern orogens, the WCAB lacks preserved ophiolites and high-pressure/low-temperature metamorphic rocks (e.g., blueschists, eclogites), indicating a different tectonic style.

Paleoproterozoic units elsewhere in the Congo Basin have been reworked during later orogenies and remain poorly constrained. Nonetheless, Feybesse et al. (1998) noted structural and lithological analogies between the WCAB and Paleoproterozoic terranes of the Kasaï Block, suggesting similar tectonic histories.

Mesoproterozoic Belt

The Kibara Belt is the only Mesoproterozoic belt identified in the Congo Basin region (Fig. 6). Its geodynamic evolution remains debated, with two contrasting models:

- A subduction–collision model involving eastward subduction of oceanic crust, largely consumed without leaving high-pressure/low-temperature metamorphic evidence (Kokonyangi et al. 2006; Debruyne et al. 2015).
- An intracontinental deformation model (Cahen et al. 1984; Tack et al. 2010) suggesting the ~1375 Ma Kibaran event reflects bimodal magmatism and crustal extension within an intracratonic setting, followed by mild compression possibly linked to distant tectonic forces.

Both models fall within a plate tectonic framework, differing chiefly in whether oceanic subduction was involved in the orogenic process.

Neoproterozoic Belts

Despite attributed to the same orogenic cycle (Pan-African orogeny), the three belts, Central African, Lufilian, and West Congo, display strongly different features: (i) intense metamorphism, widespread syn- to post-tectonic plutonism, and crustal scale thrusting in the first case; (ii) limited magmatism but important sediment accumulation in the second; and (iii) important pre-tectonic magmatism and limited tectonic exhumation in the third.

Two of these belts are interpreted because of craton amalgamation (Fig. 3): (i) between the Congo Craton and Sahara Metacraton for the Central African Belt and (ii) between the Congo Craton and the Kalahari Craton for the Lufilian Belt. On the other hand, the West Congo Belt is attributed to the closure of an intracontinental rift.

Nevertheless, the timing is the same for the three belts, with a common interval of about 450–500 Ma from the first extensive movements (sediment deposition and/or rift-related magmatism) to the completion of convergence.

Considering the huge quantity of work so far accumulated in a recent mountain belt such as the Western Alps, and the questions still remaining open, one can infer the considerable work remaining to do on African orogens, with high-scale geological mapping being probably the first priority.

Erosion and Chemical Weathering

Critical Zone Observations in the Humid Tropics: Lessons from the Nyong River Basin

The critical zone (CZ)—Earth's outer layer where rock, soil, water, air, and life interact—regulates essential processes such as chemical weathering, erosion, carbon cycling, and water flow. Understanding these interactions requires long-term, integrated monitoring of hydrological and hydrochemical parameters. While critical zone observatories (CZOs) have expanded over the past 25 years, few are located

in the humid tropics, despite their importance as biodiversity hotspots, carbon reservoirs, and regions experiencing rapid land use change.

Since 1994, such monitoring has been conducted in the Nyong River basin (Cameroon), on both local (<1 km^2) and regional (18,500 km^2) scales, as part of the M-TROPICS CZO network (https://mtropics.obs-mip.fr/). Located on the periphery of the Congo Basin but within the same geological unit, this long-term dataset provides rare insight into tropical critical zone processes.

Studies based on the M-TROPICS data have the following:

- Characterized water reservoirs in humid tropical catchments (Boeglin et al. 2003; Viers et al. 1997, 2000)
- Identified key controls on chemical weathering and physical erosion, including the role of organic matter (Oliva et al. 1999) and colloids (Dupré et al. 1999)
- Quantified elemental fluxes, saprolite production, and denudation rates (Braun et al. 2005, 2012; Cary et al. 2005; Regard et al. 2016)
- Modeled streamflow partitioning among hill aquifers, marsh runoff, and groundwater (Maréchal et al. 2011)
- Identified marsh zones as hotspots of weathering activity
- Revealed non-conservative behavior of chloride in tropical rivers (Viers et al. 2001)
- Contributed to carbon budgeting and greenhouse gas emission estimates (Borges et al. 2015; Boeglin et al. 2004; Brunet et al. 2009)
- Traced Fe and Zn cycling across the soil–plant–water continuum using isotope geochemistry (Poitrasson et al. 2008; Akerman et al. 2014; Viers et al. 2007)

These datasets offer a foundation for future assessments of climatic impacts, including droughts and extreme monsoons, and for predictive modeling of elemental transport under global change scenarios (temperature shifts, monsoon variability, land use change).

However, the Nyong CZO also reveals the challenges ahead. Over the past 25 years, solute concentrations at the outlet of a small tributary have shown non-stationary behavior, likely linked to evolving hydrology and land use—underscoring the need for continued long-term monitoring.

This need is especially acute in the Congo Basin, where the paucity of hydrochemical data severely limits our ability to understand and predict the region's response to global environmental change.

Issues, Gaps, and Challenges

Geological Resources

The mineral and energy resources of the Congo Basin are closely linked to the geological evolution of both its sedimentary cover and Precambrian basement. Various commodities formed during distinct geological events and tectonic phases, reflecting the complex history of the basin and its surrounding cratonic margins.

Sedimentary units of the Congo Basin and ancient Karoo rifts host hydrocarbon resources such as coal and bituminous shales.

The Archean to Neoproterozoic basement encircling the basin contains a wealth of mineral deposits, including the following:

- Archean greenstone belts—gold (Au), iron (Fe)
- Early Neoproterozoic granites and pegmatites—lithium (Li), tin (Sn), tantalum (Ta), niobium (Nb), tungsten (W)
- Neoproterozoic alkaline-carbonatite intrusions—rare earth elements (REE), zirconium (Zr), niobium (Nb), phosphorus (P)
- Neoproterozoic sediments—copper (Cu), cobalt (Co), uranium (U), gold (Au)
- Carboniferous–Permian deposits—coal
- Jurassic strata—bituminous shales
- Cretaceous kimberlite pipes—diamonds, later dispersed by fluvial transport

Tectonic reactivations over geological time enhanced fluid circulation and led to the remobilization and concentration of elements such as Au, Cu, and Co. Subsequent Cenozoic weathering and denudation further oxidized sulfide deposits and produced supergene enrichment in Mn, Cu, Co, and Al.

Hydrocarbon Resources

The hydrocarbon potential of the Congo Basin remains controversial, with past claims of prolific oil reserves largely speculative and aimed at attracting investment. Current data do not support the existence of an active, commercially viable petroleum system (Delvaux and Fernandez 2015).

Five stratigraphic levels with potential source rocks have been identified (Sachse et al. 2012; Delpomdor et al. 2018):

- Mbuji-Mayi Supergroup (Stenian–Tonian) and Alolo Subgroup (Neoproterozoic): Rich in Type I–II kerogen but now thermally overmature with low organic content; they are considered fossil systems.
- Lukuga Group (Permo-Carboniferous): Contains Type III–IV kerogen with very limited gas potential, in early maturity stage.
- Stanleyville Group (Upper Jurassic): Composed of lacustrine argillites with excellent Type I kerogen and high oil-generating capacity. However, the rocks are immature to early mature and often exposed at the surface or at shallow depths.
- Loia Group (Lower Cretaceous): Contains Type I–II kerogen, but similarly immature, with limited generation.
- Bituminous shales of the Stanleyville Formation, between Kisangani and Ubundu, exhibit high oil potential—generating up to 980 mg HC/g TOC with up to 25% organic carbon. Deposited in a lacustrine setting above the Basal Jurassic unconformity, these rocks remain thermally immature and have not been economically mined.

In contrast, **coal resources** are more substantial. Mining has occurred at the following:

- **Kalemie (Lake Tanganyika)**
- **Luena Basin (Katanga)**

where several seams at the base of the **Karoo Supergroup** (Late Carboniferous–Early Permian) were exploited for rail transport and cement production (Jamotte 1950).

Mineral Resources

The Congo Basin is underlain and bordered by Archean to Neoproterozoic basement rocks (Kadima et al. 2011; De Wit and Linol 2015; Debruyne et al. 2019), which host world-class deposits of critical and base metals (e.g., Cu, Co, Ta, Nb, W, Sn, Fe, Mn, Ni, Au), nuclear minerals (Th, U), precious stones (diamond, ruby, sapphire, beryl), and industrial materials (mica, olivine, dolostone, limestone) (Milési et al. 2006; Thiart and de Wit 2015; Dewaele et al. 2013; Villeneuve et al. 2022; Mpaka et al. 2024). These mineralizations are linked to distinct global tectonic events and metallogenic epochs (Robb 2004).

The Central African Copperbelt, spanning southeast DRC and northern Zambia, represents the world's largest sediment-hosted Cu-Co (Ni, U) province. The region is estimated to hold over 5 billion tons of Cu ore and 6 million tons of Co ore—accounting for ~53% of global cobalt reserves. Mineralization in the Neoproterozoic–Cambrian Katanga Supergroup followed a multistage evolution, from early diagenesis (~800–650 Ma) to syn-orogenic (~560–500 Ma) and post-orogenic (~475–470 Ma) phases (Muchez et al. 2015; Mambwe et al. 2023, 2024). Cu-Pb-Zn mineralization in the Nguba and Kundelungu Groups is dated between 454 ± 14. Sulfide ores (e.g., chalcopyrite, carrollite, bornite, chalcocite, sphalerite, pyrite) underwent supergene alteration in weathering zones, producing secondary minerals such as malachite and heterogenite.

The Shinkolobwe deposit is historically the most important deposit hosted the U, and producing >50,000 t of U_3O_8 between 1921 and 2004 in the Katanga Supergroup. The mineralization occurred with breccias enriched in Co, Ag, Ni, Bi, and As and genetically linked to Cu-Co ores (Decrée et al. 2014). Two distinct U remobilization phases have been identified:

- Pre-orogenic phase (~876–652 Ma): Related to the opening of the Katanga Basin and early proto-oceanic rift development, with U remobilized by hydrothermal fluids during early basin evolution and early Lufilian orogeny.
- Syn-orogenic phase (~530 Ma): Linked to tectonic inversion and collision between the Congo and Kalahari cratons, further remobilizing U during orogenesis (Loris et al. 1997).

Smaller Cu-Pb-Zn occurrences are also found in the Neoproterozoic West Congo Belt of the DRC and Republic of Congo (e.g., Boko-Songho, Mfouati, Mindouli,

Mbamba-Kilenda) (Kampunzu et al. 2009). In the West Congolian and Niari basins, Cu-Pb-Zn mineralization was structurally controlled by late- to post-Pan-African faulting and later Mesozoic rifting related to the opening of the Atlantic (Dewaele et al. 2016).

Special attention is given to cassiterite, wolframite, and columbo-tantalite, which form significant placer and eluvial deposits, as well as primary mineralization in granitoids along the Mesoproterozoic Kibara Belt (e.g., Manono-Kitotolo) and Karagwe–Ankole Belt (e.g., Kalima) in the DRC (Dewaele et al. 2013). Although these deposits are currently exploited through artisanal and small-scale mining (ASM), notably, they have not yet been reported within the Congo Basin itself. Nevertheless, the presence of Archean and Proterozoic basement rocks—the known source of these ore minerals—highlights the high exploration potential for critical metals in Central Africa (Thiart and de Wit 2015).

The DRC accounts for approximately 8.3% of global tin production, with the Bisie mine (Walikale district, eastern DRC) ranking as the third-largest tin-producing mine globally (~6% of world production), containing an estimated 165,000 t of tin reserves. In the same region, the Manono deposit hosts around 220,000 t of tin ore, along with substantial lithium reserves. The Kivu Province also contains 60–80% of global niobium-tantalum (Nb-Ta) reserves.

Primary Sn–Nb–Ta–W–Li mineralization in the Kibara and Karagwe–Ankole belts is associated with pegmatites related to the differentiated G4 granite, emplaced during the early Neoproterozoic (990 ± 1–923.3 ± 8.3 Ma), while the earlier G1–G3 granites are typically barren. The mineralization occurred through mixing of magmatic and meteoric fluids, triggering oxidation and precipitation of ore minerals like cassiterite (Makutu et al. 2024). Pegmatites and related Sn–Nb–Ta–W veins were emplaced in fault zones within metasedimentary rocks and dolerites during the late Kibaran orogenic phase. Mineral deposition was driven by magmatic-hydrothermal processes, particularly fractional crystallization (Ngulube 1994; Dewaele et al. 2016).

Iron (Fe) and nickel-chromium (Ni-Cr) mineralization in Central Africa is primarily associated with Neoarchean greenstone belts and Proterozoic banded iron formations (BIFs). In the DRC, Fe and Ni-Cr are chiefly mined from the Kibalian greenstone belt (2630–2625 Ma) on the northeastern margin of the Bomu Complex, with notable deposits including Karagba, Chauffeur, and Durba for Fe; Kanda Kanda (BIF-hosted); and Nkoko for regolith-hosted Ni-Cr in the central Kasai Block (Makutu et al. 2024).

In the Republic of the Congo, the Zanaga deposit is among Africa's largest high-grade Fe ore bodies, with 2.1 billion tons at an average 33.9% Fe. The Mayoko-Moussondji deposit holds 383 million tons at 34.5% Fe, including 22.1 million tons of high-grade colluvial hematite.

Gabon's Belinga deposit is one of the most significant untapped high-grade iron ore reserves globally, with over 1 billion tons grading >60% Fe. In the DRC, major BIF-hosted deposits occur in the Upper Ituri Basin (900 Mt @ 45% Fe) and Upper Uele Basin (1350 Mt @ 68% Fe) near the headwaters of the Uele and Kibali Rivers.

Banded Iron Formations (BIFs) are the principal host rocks for Fe mineralization across the DRC, the Republic of the Congo, and Gabon, formed between 3.5 Ga and 500 Ma by chemical sedimentation, involving oxidation of Fe^{2+} to Fe^{3+} and precipitation of hematite and magnetite alongside quartz. The simultaneous presence of Fe and Si reflects their origin from Fe- and silica-saturated ocean water. At Zanaga, Belinga, and in the Kasai and Bomu regions, BIFs were metamorphosed into itabirite (Mpaka et al. 2024).

Though Ni-Cr deposits in the southern Congo Craton (DRC) are not currently exploited, they represent a strategic reserve. At Nkoko, mineralization is hosted in a 37-m-thick regolith profile developed over serpentinized ultramafic rocks, resulting from prolonged climate-controlled weathering. Indeed, the distribution and grade of Ni and Cr are strongly controlled by lateritic profile development (Mukonki et al. 2018).

Gabon holds over 25% of the world's manganese reserves (~150 million tons), ranking second globally after South Africa. The Moanda Mine in Haut-Ogooué Province is the country's major Mn-producing site. In the southeastern Kasaï Block of the DRC, both primary and supergene Mn deposits—such as the Kisenge deposit—occur in Paleoproterozoic metasedimentary rocks (De Putter et al. 2015). The formation of these supergene Mn ores coincides with the alteration of Cu-Co-(Pb-Zn) sulfide ores into supergene minerals (e.g., chrysocolla, malachite, heterogenite) during the Cenozoic, indicating a regional-scale weathering event across the southeastern Congo Basin.

In Gabon, five uranium deposits—Boyindzi, Mikouloungou, Mounana, Okélobondo, and Oklo—occur in the Francevillian Basin, hosted by Paleoproterozoic unmetamorphosed sandstones. Between 1961 and 1999, these deposits produced a total of ~26,000 t. Notably, the Oklo site hosted a natural nuclear fission reactor, making it unique in the geologic record.

The genesis of U mineralization in the Francevillian Basin differs markedly from that of the Katanga Basin and involves two key stages (Bankole et al. 2015; Lecomte et al. 2020):

- Diagenetic stage: Quartz dissolution and hydrofracturing during burial and uplift create the porous reservoir.
- Mineralization stage: Hydrocarbon generation from black shales leads to mixing with U-bearing brines, promoting thermochemical sulfate reduction (TSR) and co-precipitation of U, Cu, and Fe sulfides.

Additional U occurrences have also been documented in the Bakouma region of the Central African Republic, including Berbérati and Bangassou.

Gold placer deposits in the Congo Basin are primarily reported in three key areas:

- Eastern DRC, near major goldfields such as Kibalian, Karagwe–Ankole, and Kivu, with notable deposits at Kilo-Moto, Kamituga, Twangiza, Namituga, Namoya, and Imonga-Saramabila (De Groote et al. 2023).

- The Ngounié Province in Gabon, around Eteke, where ~40 t of proven alluvial gold reserves are concentrated in Quaternary sediments.
- The northeastern Gabon Mountain Complex, where gold placers are associated with world-class iron ore deposits.

At Eteke (Gabon), primary gold mineralization occurred via hydrothermal fluid migration during the Eburnean orogeny, with sulfidation and carbonation processes leading to gold precipitation along breccias, fractures, and faults (Bouchot and Feybesse 1996). In the Bomu Complex (DRC), gold is hosted in meta-conglomerates, associated with pyrite, suggesting early diagenetic precipitation during initial basin development (Mpaka et al. 2024). A subsequent fold-thrusting phase induced by tectonic inversion enhanced fluid migration and led to syn-orogenic gold precipitation. Hydrothermal remobilization and multi-phase alteration along fault zones linked to successive brittle deformation events are commonly observed. A multistage model for gold mineralization has thus been proposed for the Congo Craton, encompassing the DRC, the Republic of the Congo, Gabon, and Cameroon, with gold emplacement spanning diagenetic to syn-orogenic stages (Mpaka et al. 2024).

In the Congo Basin, diamond and gold are the primary mineral resources (De Wit and Jelsma 2015). The region hosts extensive alluvial systems formed through erosion and incision of basement terrains, particularly where kimberlite intrusions and goldfields are exposed. These processes have generated widespread placer deposits, which continue to form today within the Congo River drainage system (e.g., Kwango; Kosman et al. 2016). In addition, eluvial diamond deposits have developed in and around the subsurface zones of kimberlite bodies (De Wit and Jelsma 2015; Mukonki et al. 2022).

Two main kimberlite regions are recognized in the DRC:

- Plateau de Kundelungu (Katanga foreland, Katanga Supergroup): (1) Kimberlite pipes here are generally barren or low-grade, intruding Paleoproterozoic basement and Neoproterozoic sediments (conglomerates, sandstones, shales) and (2) radiometric dating places the intrusions in the Eocene–Oligocene, e.g., Mafwa and Katalwa (~32.3 ± 2.2 Ma) and Katuba (~23 ± 1.8 Ma) (Batumike et al. 2009, 2019).
- Kasai Province (Bakwanga Kimberlite Field): (1) These Upper Cretaceous kimberlites (~70 Ma) have high diamond potential, especially in pyroclastic facies; epiclastic facies are typically barren (Mukonki et al. 2022) and (2) the pipes intrude both Archean basement of the Kasai Craton and the overlying Neoproterozoic Mbuji-Mayi Supergroup (Batumike et al. 2009).

Diamonds formed in the upper mantle were transported by kimberlitic magma to the surface, crystallizing within ultramafic kimberlite rocks following volcanic emplacement (Robb 2004). Beyond primary deposits, widespread placer diamond deposits are documented across the southern and central DRC, northern Angola, Gabon, eastern and western Cameroon, and parts of the Central African Republic,

even in areas without known kimberlite pipes. These occurrences reflect the role of mechanical and chemical weathering, erosion of kimberlite host rocks, and subsequent transport and concentration of diamonds in alluvial systems (De Wit and Jelsma 2015). In Angola, a clear relationship exists between diamond placer distribution and the Upper Cretaceous Calonda Formation, composed of gravels, conglomerates, and sandstones, which serve as the main host for diamond-bearing placers (Pereira et al. 2003; Jelsma et al. 2004; Kjarsgaard et al. 2022).

The industrial aggregate and construction minerals such the gravels to sand materials and carbonates rocks (dolostone and limestone) constitute a second group of resource potential in the Congo Basin.

Regolith

Early regolith mapping efforts in Central Africa (e.g., Boulvert 1976; Jamet and Rieffel 1976; Muller and Gavaud 1979; Martin 1981) in countries such as Congo, Cameroon, Gabon, and the Central African Republic provided foundational data on regional regolith distribution and characteristics. These pioneering studies—later complemented by the Africa Soil Atlas (Jones et al. 2015)—highlighted petrographical, geochemical, and pedogenetic processes shaping soil evolution across various landscapes.

While these datasets remain valuable, they are fragmented and often lack resolution, with most high-resolution regolith maps available only for localized areas. Such maps detail regolith attributes at hillslope scale (e.g., lateritization, geochemistry, texture, mineralogy), which are difficult to generalize regionally due to sparse and inconsistent coverage.

Existing maps and regolith project data—many available online or upon request—offer a useful base for both technical and non-technical applications. However, developing an interactive regolith information system for the Congo Basin will require the following:

- Integration of additional field and analytical data
- Consideration of anthropogenic impacts on regolith dynamics
- A regional coordination of efforts across political and institutional boundaries

This initiative must begin with capacity building, ensuring local expertise in standardized data acquisition, analytical methods, and data management. Despite dependence on external funding, Central African geological research institutions should collaborate under transparent national frameworks to build a unified regolith database.

Such a database would be instrumental in the following:

- Linking mineral distribution to regolith profiles under tropical conditions
- Understanding bio-geosystem dynamics
- Supporting geotechnical assessments in rapidly urbanizing environments

Tectono-Sedimentary Evolution and Depocenter Migration of the Congo Basin

The Congo Basin is an intracratonic basin characterized by long-term subsidence and a progressive migration of its depocenter over geological time. Stratigraphic logs from four key boreholes and regional geological mapping reveal this evolution.

- The basin originated during Neoproterozoic rifting, a regional event that also initiated surrounding peripheral basins.
- Through the Cambrian to early Paleozoic, the region remained relatively flat, resulting in the coexistence of Cambrian and post-Cambrian sedimentary units across different sub-basins.
- By the end of the Paleozoic, south-eastern tilting led to the progressive deposition of Permo-Carboniferous (Karoo) and Triassic units in the south, southeast, and east of the basin.

During the mid-Mesozoic, higher sedimentation rates occurred in the central-eastern sector, depositing the following:

- Jurassic Kisangani Formation (central)
- Cretaceous Loia Group (east)

From the Oligocene onward, the SREA (Sub-Regional Epeirogenic Activity) began influencing basin filling, which became concentrated first in the central zone and more recently in the western part of the basin.

Tectonically, the basin currently lies in a compressional regime, resulting from the differential movements of the following:

- Continental rifting to the east (East African Rift System)
- Atlantic Ocean widening to the west

The shift of the active depocenter westward reflects a faster eastward extension compared to westward opening—an observation supported by the distribution of Tertiary to Recent sediments.

Synthesis

Multidimensional Definition of the Congo Basin

- It is an extensive rainforest ecosystem, a major global watershed, and a significant intracratonic sedimentary basin.
- Its geological evolution has directly influenced the biodiversity and hydrology of Central Africa.

Tectonic and Geological Evolution

- The Congo Basin developed as a stable intracratonic depression within the African Plate.
- Major tectonic influences include the following:
  - The **Pan-African Orogeny (~600–500 Ma)**, which shaped the regional basement structure
  - The **break-up of Gondwana**, leading to extensional tectonics and subsidence
  - The **Cretaceous Rifting Event**, which further influenced basin sedimentation and structural reactivation

Basement Geology and Structural Features

- The basin is underlain by Precambrian cratonic blocks (Congo Craton) that amalgamated over billions of years.
- It is structurally framed by Neoproterozoic and Proterozoic mobile belts, with ancient faults periodically reactivated.
- Basement heterogeneity has implications for mineralization and fluid migration.

Sedimentary Evolution and Basin Architecture

- The Congo Basin contains multiple sedimentary sequences deposited from the Neoproterozoic to the Cretaceous.
- Four key stratigraphic sequences have been identified as follows:
  - Stenian–Tonian (late Mesoproterozoic-early Neoproterozoic) sediments from failed rift systems (~1.1 Ga)
  - Neoproterozoic sequences, including post-rift carbonate and evaporite deposits
  - Paleozoic-Triassic deposits, representing fluvial, deltaic, and glacial sedimentation
  - Jurassic-Cretaceous sequences, which include hydrocarbons and diamondiferous kimberlite intrusions
- The central basin is filled with sediments up to 8–12 km thick, with significant tectonic subsidence recorded.

Geodynamic Processes and Surface Evolution

- Long-term weathering has led to extensive lateritic covers, influencing soil fertility and mineral resource distribution.
- The landscape has been shaped by mantle-driven uplift and erosion cycles.

Natural Resources and Economic Significance

- **Mineral deposits**: Includes gold, diamonds, copper, cobalt, iron, lithium, niobium, tantalum, and rare earth elements.
- **Hydrocarbons**: Potential but controversial petroleum reserves exist, mainly in Mesozoic formations.

- **Regolith resources**: Extensive bauxite and lateritic deposits result from prolonged tropical weathering.
- **Groundwater and ecosystem services**: The basin plays a key role in regional hydrology and carbon sequestration.

Challenges and Knowledge Gaps
- Limited hydrocarbon exploration and uncertain petroleum viability.
- Poor geophysical and geological data in remote areas.
- Need for an integrated approach combining geology, climate science, and biodiversity conservation.
- Importance of long-term monitoring to assess environmental changes and geohazards.

Conclusion

The Congo Basin represents a geologically complex and ecologically vital region that has evolved through a series of tectonic and climatic events. Its sedimentary and tectonic history holds critical insights into continental evolution, resource formation, and environmental stability. A multidisciplinary approach is essential for future research, sustainable resource management, and conservation strategies.

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Climate of the Congo Basin

3

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Abstract

This chapter provides an overview of the current understanding of the key features of the Congo Basin's climate. It presents the main features that characterize the dynamics of air masses, the hydrological cycle, and the spatial and temporal variability of precipitation. The lower tropospheric circulation is dominated by low-level westerlies, which transport moisture from the Atlantic Ocean inland and sustain deep convection and rainfall throughout the year. This moist air converges with dry easterly air along the Congo Air Boundary, marking the southern limit of convection. Mass convergence causes ascent and warming of moist air parcels, destabilizing the atmosphere and causing upward motion. This is balanced by a mid-tropospheric easterly flow, leading to a shallow east-west overturning circulation known as the Congo Basin cell. Although the cell does not regulate rainfall, it may play a role in rainfall distribution through the position of the rainfall maximum. Mesoscale convective systems (MCSs) are the principal rainfall producers, accounting for up to 80% of annual precipitation and contribute to exceptionally high lightning activity. The hydrological cycle is strongly modulated by evapotranspiration and rainfall recycling, with evidence that local vegetation contributes significantly to atmospheric moisture supply. Regional climate variability reflects complex teleconnections with Atlantic, Indian, and Pacific Ocean sea-surface temperature, though the strength and consistency of these links remain debated. A persistent challenge is the scarcity of reliable, long-term observational data, particularly

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rainfall and upper-air records, which undermines model validation and projection accuracy. Addressing these gaps is essential for improving climate prediction and informing sustainable management of this critical climate-regulating region.

Keywords

Congo Basin · Precipitation recycling · Low-level westerlies · African Easterly Jet · Congo Basin cell · Precipitation · Shallow meridional circulation

Introduction

At the heart of the world's second-largest tropical rainforest lies the Congo River, Africa's second longest, flowing through vast floodplains, swamps, and dense forests. This river system and the surrounding rainforest exert a powerful influence not only on local weather but also on regional and global climate (Balas et al. 2007; Nicholson and Dezfuli 2013; Dezfuli and Nicholson 2013; Siam et al. 2013; Akkermans et al. 2014; Sorí et al. 2017). From the cooler, humid equatorial core to the warmer transitional zones merging with savannah grasslands, where thermal lows develop seasonally (Longandjo and Rouault 2024), the Basin encompasses diverse climatic conditions shaped by multiple land–atmosphere–ocean interactions.

Understanding the climate of the Congo Basin is critical for over 100 million people who depend on vulnerable, rain-fed agriculture and other water-related activities, making them highly sensitive to changes in rainfall magnitude and variability. Yet despite its significance, the Congo Basin remains one of the least studied tropical regions, largely due to a persistent lack of observational data (Nicholson et al. 2019).

This chapter examines the main controls of rainfall, regional and large-scale circulations, and temperature contrasts, while exploring their connections to surrounding and global systems. It establishes a foundation for understanding how the Basin's climate influences natural processes across multiple timescales and how its stability will shape environmental and socio-economic futures.

Main Meteorological and Climate Features

Atmospheric Circulation

This section summarizes the current state of knowledge on atmospheric circulation and the hydrological cycle. It presents the main winds that dominate atmospheric circulation from the lower to the upper atmosphere, as well as their interaction in modulating key elements of the water cycle in the Congo Basin.

Lower-Level Westerlies

The climate of the Congo Basin results from a complex interplay of regional and global drivers, with low-level westerlies (LLWs) emerging as a key local factor.

These winds transport moisture from the Atlantic Ocean into Central Africa, forming a crucial control on rainfall variability throughout the year (McCollum et al. 2000). Although LLWs are present year-round (Fig. 1), their intensity peaks between July and September, when they deliver the greatest moisture influx into the Basin. This period coincides with the region's second and main rainy season in September–October, during which maximum rainfall is observed (Moihamette et al. 2022).

The low-level moisture flux from the Atlantic Ocean is a primary control of the moisture content of the entire atmospheric column (Pokam et al. 2012) and in turn rainfall regime over the Congo Basin. By strengthening the zonal circulation, LLWs favor ascent through the effect of orographic uplift of the highlands next to the coastal region, leading to an increase in rainfall in these regions (Vondou et al. 2010).

Pokam et al. (2014) identified two mechanisms controlling LLW. North of 6°N, LLWs primarily result from rotational flow within a cyclonic circulation driven by the heat low of the West African monsoon. This northern branch is prominent from June to August, associated with the rainy season over the northernmost Congo Basin but diminishes during the dry season (December to February). South of 6°N, LLWs are

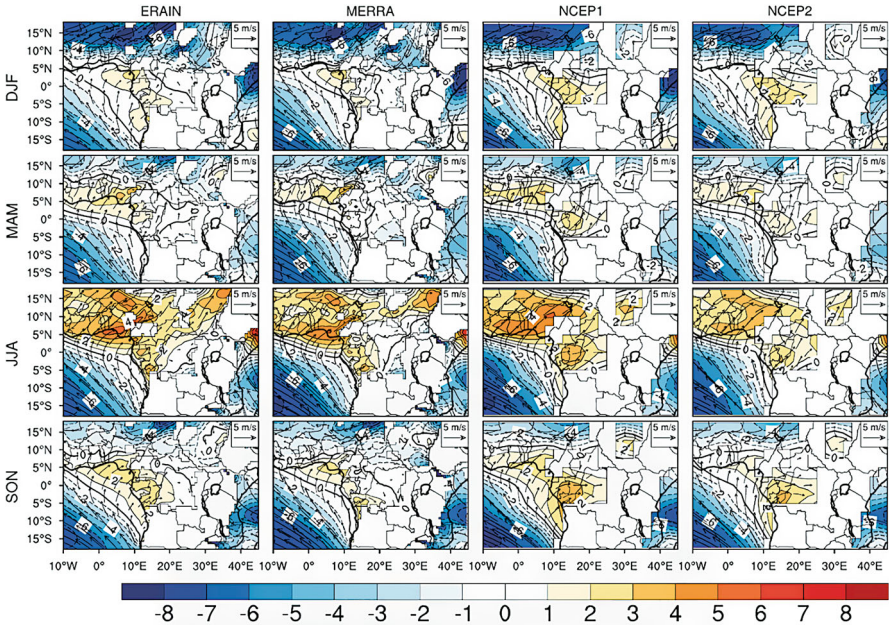

Fig. 1 Seasonal means of the circulation at 925 hPa for (left)–(right) the European Centre for Medium-Range Weather Forecasts Interim Re-Analysis (ERAI), the Modern-Era Retrospective Analysis for Research and Applications (MERRA), the National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis (NCEP1), and the NCEP–US Department of Energy Atmospheric Model Intercomparison Project phase 2 reanalysis (NCEP2 for the period 1989–2003). Contours and shading indicate the zonal wind speed, with westerlies shown in red and easterlies in blue. The zero contour indicates the boundaries of westerlies (positive values on solid lines). Inland white areas indicate grid points below the topography. (Figure from Pokam et al. 2014)

influenced by the temperature contrast between the cooling ocean and the warming Congo Basin. The seasonal variability of LLWs in this region is primarily controlled by the strength of this heating contrast between the cooling associated with the heat sink over the southeast Atlantic Ocean due to the prevalence of stratocumulus cloud and heating driven by latent heat release by condensation within the deep convection over the Congo Basin. LLWs are weakest in MAM, strengthen in JJA, and remain stronger in SON. LLWs penetrate the continent as far as the Rift Valley Highlands, forming the lower branch of zonal overturning circulation cells over the Congo Basin.

Shallow Overturning Circulations in the Mid–Lower Troposphere: The Congo Basin Cell and the Shallow Meridional Circulation (SMC)

Many papers (Neupane 2016; Cook and Vizy 2016; Longandjo and Rouault 2020, 2024) report that deep and shallow east-west overturning circulations coexist over the Congo basin year-round, due to its position that spans from the Sahel to southern Africa and from the Atlantic Ocean to the Rift valley highlands. In the zonal direction, the zonal surface pressure gradient—between the warm vegetated Central Africa landmass and the cold Atlantic Ocean—triggers the LLWs. These LLWs therefore constitute the lower branch of both the shallow and deep east-west overturning circulations that develop over Central Africa (Fig. 2a). While moving further into the landmass, mass convergence is produced over the Congo Air Boundary, such that it provides an upward motion to warm moist air parcels and destabilize the atmosphere over Central Africa (Fig. 2a). This forms the upward branch of both the shallow and the deep overturning cells (Fig. 2a). To balance the deep convection associated with the saturation and associated rainfall, the easterly jet forms at mid-levels as the mechanical work (Longandjo and Rouault 2020), constituting the return branch of the shallow circulation (Fig. 2a). Aloft, the convection is further reinforced to form the east-west overturning cell (Fig. 2a). Over the cold Atlantic, the subsiding branch closes the shallow circulations. This zonal shallow circulation is referred to as the Congo Basin cell. This distinct, unique, closed, counterclockwise zonal shallow overturning circulation operates throughout the year, with its maximum intensity and width in August/September and a minimum intensity and width in May (Longandjo and Rouault 2020). This shallow cell extracts the energy from the warm Central Africa landmass and advects it into the cold Atlantic Ocean. Although the Congo Basin cell does not regulate the rainfall over Central Africa, it may play a role in rainfall distribution through the position of the rainfall maximum. All this indicates that both the zonal shallow and deep east-west overturning cells coexist over Congo Basin (Fig. 2a), with the shallow mode associated with the Congo Basin cell.

On the other hand, in the meridional direction, due to the local evaporative cooling effect related to the Congo Basin rainforest, the foot of the ascending branch of meridional overturning (Hadley) cells occurs over the Sahel heat low, where the temperature is the warmest (Longandjo and Rouault 2024). This results in the distortion of the southern Hadley cell, forming its bottom-heavy structure (Fig. 2b). As a consequence, one can see that both the deep and the shallow Hadley cells are superimposed over Central Africa (Fig. 2b). The deep mode is associated

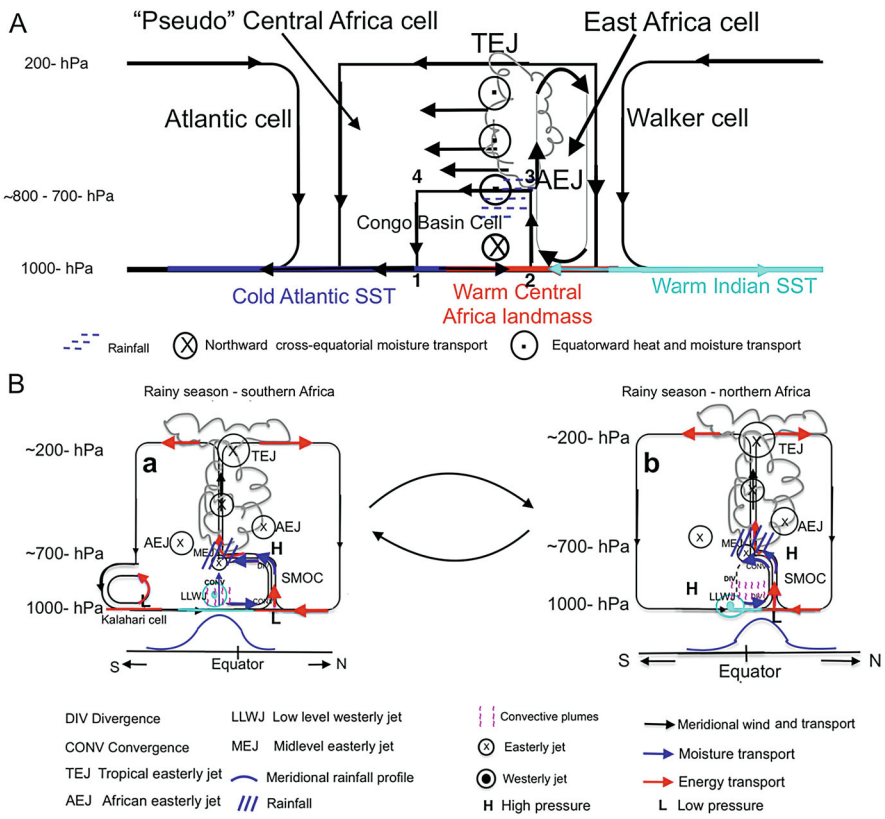

Fig. 2 Schematic diagram representing the (**a**) longitude-height and the (**b**) latitude-height large-scale circulations over Congo Basin. (Figure adapted from Longandjo and Rouault 2020, 2024)

with the poleward transport of atmospheric energy at the upper troposphere (Fig. 2b). The shallow mode is characterized by a shallow meridional circulation, with its moisture transport vanishing and converging in the mid-troposphere rather than the lower troposphere (Longandjo and Rouault 2024). However, Zhai and Boos (2017) found that this SMC may limit the rainfall amount by drying up the mid-troposphere through the equatorward advection of dry air into the convective region. This SMC can strengthen or shrink should the convective region and its associated rainfall maximum be in the southern or northern hemisphere (Fig. 2b).

African Easterly Jet

African Easterly Jets (AEJs) are major mid-tropospheric climate features located over the African continent (Cook 1999; Adebiyi and Zuidema 2016; Kuete et al. 2019) composed of the North African Easterly Jet (AEJ-N) and the South African Easterly Jet (AEJ-S). AEJ-N is discernible year-round at 700 hPa with a meridional migration ranging from 3°N in January to around 12°N in August, while AEJ-S appears from September to November at 600 hPa and has its axis around 8°S

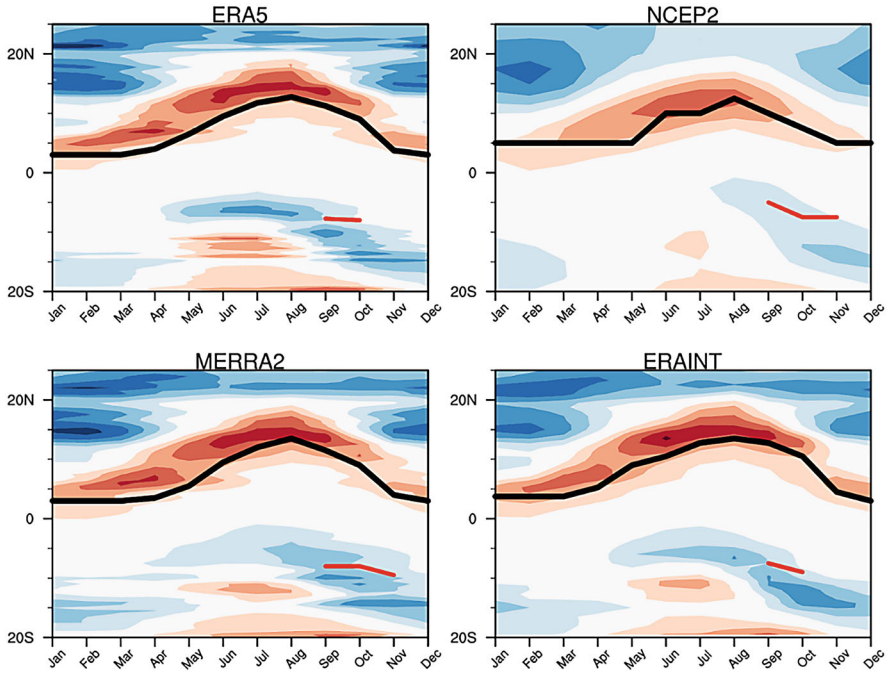

Fig. 3 Latitude/time evolution of the 925 hPa surface temperature gradient (shading) with overlay mean locations of AEJ components core. The black solid line in the north represents AEJ-N and the red solid line in the south is the AEJ-S. All variables are averaged between 12°E and 24°E. (Figure from Kuete et al. 2019)

(Fig. 3). Studies have highlighted the critical role of both AEJ components in shaping the climate of the Congo Basin. During the September–November rainy season, when the highest rainfall amount is recorded over the Congo, these jets play a key role in the region's convective rainfall regime by influencing mid-tropospheric circulation and moisture advection (Pokam et al. 2012; Dyer et al. 2017). The AEJ components also contribute to interannual rainfall variability over the Congo region, with research indicating that wetter years are typically associated with a weaker AEJ, while drier years correspond to a stronger jet (Nicholson and Dezfuli 2013; Dezfuli and Nicholson 2013). Moreover, the jet-streak-like circulation associated with the AEJ-S creates strong convergence that contributes to the intense storms occurring in the Congo Basin (Jackson et al. 2009).

The strength and location of the AEJ components are determined by a complex interplay of factors, with the atmospheric baroclinic thermal structure characterized by temperature gradients and differential heating being a key component (Nicholson and Grist 2003). This thermal structure varies significantly across Africa, influencing the AEJ-N through the strong and positive temperature contrast between the hot, arid Sahara and the more humid Congo Basin, while the AEJ-S is shaped by the negative thermal differences between the semi-arid Kalahari and the sub-humid Congo region (Kuete et al. 2019).

The AEJ-S has received less attention than AEJ-N. Kuete et al. (2019) demonstrate that AEJ-S is dominated by rotational circulation and is maintained by a mid-level high that forms over the Kalahari region from September to November. At the core of this high, anticyclonic circulation is induced and maintained, AEJ-S is located at the northern flank of the high. The AEJ-S is influenced by the Kalahari thermal low, which is characterized by intense surface heating, associated uplift, and dry convection (Attwood et al. 2024). This dry convection is superimposed by upper-level subsidence, leading to mid-level divergence. From September to November, strong positive vorticity reinforces this mid-level divergence circulation. An analysis of the atmospheric energetics shows that the Coriolis divergence is less pronounced in the AEJ-S region than in the AEJ-N region. Consequently, the strength of the AEJ-N is mainly determined by other factors, such as the well-developed North African divergence centers over the Chad-Sudan region.

A significant difference between the dynamics of the AEJ-N and AEJ-S over the Congo region resides in the shape of the African continent. As the southern component region is relatively smaller compared with its northern counterpart, less surface instability is produced. In Northwest Congo, the AEJ-N generates synoptic atmospheric disturbances known as African Easterly Waves, which modulate the convection and, in turn, rainfall regime, in that region, and Atlantic tropical cyclone genesis (Fischer et al. 2024). But, the AEJ-S is less likely to exhibit significant easterly wave patterns. However, the AEJ-S does respond to extratropical westerly waves crossing southern Africa and which are able to disrupt the strong AEJ-S and in turn modulates the Congo rainfall during SON (Kuete et al. 2019).

Tropical Easterly Jet

The Tropical Easterly Jet is a key feature of the general atmospheric circulation in the tropics. The jet is located in the upper-troposphere (150–200) hPa over Africa and the Asian sector, reaching its core speed around 35–40 $m.s^{-1}$ between July and September (Nicholson and Klotter 2020). It owes its existence to the temperature gradient between the warm land masses of Asia and Africa and the colder Indian Ocean (Chen and Yen 1993). Although the Tropical Easterly Jet is an important component of the general circulation, studies of this jet and its influence on climate in Africa, particularly its influence on rainfall variability in equatorial Africa and the Congo Basin, are very limited. Its influence on rainfall in equatorial Africa is generally associated with other climatic features of the regional circulation, such as the African Easterly Jet and the Low-level Westerly circulation (Dezfuli and Nicholson 2013; Nicholson and Dezfuli 2013). The jet regulates rainfall over equatorial Africa through upper tropospheric divergence, which in turn generates thunderstorms and convective systems (Nicholson 2018). This upper tropospheric divergence is important because it is associated with low-level moisture convergence from the Atlantic westerlies, thereby controlling rainfall seasonality. Intensification of the TEJ has also been observed during wet years in equatorial Africa (Dezfuli and Nicholson 2013).

Congo Air Boundary

From August to November, the southern edge of the Central African rain belt is characterized by an extreme gradient in near-surface dew point temperature along a southwest to northeast (Fig. 4) oriented on a line known as the Congo Air Boundary (CAB). Moist, tropical air with dew points typically in the low 20 °C advected by northerly flow converges with the dry easterly flow where the dew point is near zero. The convergence line typically lies on the high ground of the Katanga plateau along the Zambian-DRC border (Howard and Washington 2019). It curves northward along the Albertine Rift, suggesting that topography has an important effect on the line. The CAB is an example of a feature that has erroneously been identified as the Inter Tropical Convergence Zone, a term which is not appropriate to the circulation characteristics of Africa (Nicholson 2018). The CAB demarcates the southern limit of Congo Basin convection. At intraseasonal timescales, the CAB is not a steady-state feature (Torrance 1979; Taljaard 1986). Prior to the onset of tropical rains in southern Africa, the CAB breaks down several times, before reforming after 2–3 days. The breakdown has been traced to breaking Rossby waves in the circumpolar westerlies over southern Africa (Knight and Washington 2024). By December the CAB is no longer evident as a circulation feature. Future drying trends projected for the southern edge of the tropical rain belt have been traced to a later breakdown of the CAB in the seasonal cycle (Howard and Washington 2020).

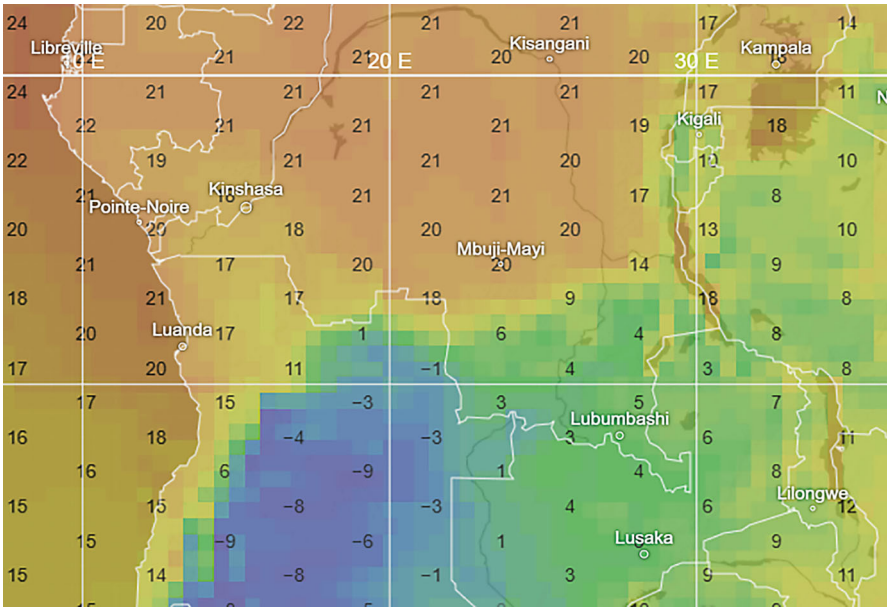

Fig. 4 Surface dew point temperatures at 0300 UTC on 5 September 2024 from the fifth-generation European Centre for Medium-Range Weather Forecasts reanalysis (ERA 5)

Hydrological Budget

Evapotranspiration and Precipitation Recycling

Across the Congo Basin, the variability in evapotranspiration (ET) is influenced by factors such as forest density, land cover changes, and seasonal climatic conditions. During the wet season, higher ET rates are typically observed, which significantly contribute to local rainfall patterns and sustain the forest's hydrological cycle. Conversely, in the dry season, reduced ET levels result in a lower recycling rate, making the region more dependent on external moisture sources, such as the Atlantic and Indian Oceans.

The Central African forest is predominantly concentrated in the equatorial part of the Congo Basin (Burnett et al. 2020) and plays a significant role in supplying the region with a substantial amount of water vapor (Worden et al. 2021) through the process of ET. It can be reasonably inferred that rainfall recycling makes a significant contribution to the total amount of local rainfall.

Over the last few decades, many studies have been carried out to assess moisture recycling and its role in the hydrological cycle of the Congo Basin. The first attempt to assess moisture recycling in a regional framework was made by Shem (2006) using the CAM3/CLM3 coupled climate models and found a recycling rate between 15% and 20%. Pokam et al. (2012) made the first assessment of the spatial and temporal variation of moisture recycling for the Congo Basin. They used the general 2D bulk recycling model and found a recycling rate of 38%. Following this study, research on the contribution of recycling to total precipitation has intensified. Dyer et al. (2017) used the water tagging capability of the National Center for Atmospheric Research's Community Earth System Model version 1.2 (CESM1.2) to assess the impact of different moisture sources on the water cycle in Central Africa. They found a recycling rate of more than 24%. Meanwhile, Sorí et al. (2017), who also assessed moisture sources in the Congo River Basin, used the Lagrangian model FLEXPART and found that recycling provides more than 50% of the total water vapor contributing to local rainfall. Applying the same method to a study of the spatiotemporal variability of droughts in the same region, Sorí et al. (2022) confirmed the key role of recycling in the basin's water balance. They found that the region contributed almost 60% of the total water vapor that is locally precipitated. More recently, Worden et al. (2024) assessed the net surface water flux using the water balance approach and found a recycling rate of over 70%. This provides further evidence for the substantial recycling of moisture in the Congo Basin. The sensitivity of the results to the models and data used to perform the water balance simulation could probably explain the significant differences in the recycling rates observed in each of these studies.

Burnett et al. (2020) employed the water balance method to estimate evapotranspiration in the Congo Basin. They observed a strong correlation between the seasonal cycles of ET and precipitation. Nevertheless, a notable discrepancy was identified in the seasonal patterns of ET and rainfall. In contrast to the expected peak during the September to November season, ET exhibited a maximum in the March to May season. This discrepancy in the seasonal characteristics of these two key water

fluxes was also been observed by Crowhurst et al. (2020). Indeed, they identified tree transpiration as a significant contributor to the total ET in the Congo Basin. Transpiration accounts for a large portion of the seasonal variability, driving the differences in ET rates between the March–May and September–November seasons. Furthermore, they found that factors like forest cover, tree species, and soil moisture significantly influence transpiration rates. This highlights the critical role of vegetation in shaping ET dynamics and indicates that deforestation or land use changes could substantially alter the seasonal water cycle, potentially affecting regional climate patterns and water availability.

In a related study, Worden et al. (2021) found that the deficit in ET moisture supplied during the second rainy season in comparison to the first is a consequence of increased moisture advection from the ocean during the September to November rainy season. This seasonal shift suggests that while local ET is critical for maintaining atmospheric moisture, external moisture sources become increasingly important later in the year, influencing the timing and distribution of rainfall across the region.

Atmospheric Moisture Convergence

The seasonal cycle of the atmospheric moisture flux convergence is strongly correlated with that of precipitation over the Congo Basin (Cook and Vizy 2022). Cook and Vizy (2022) and Longandjo and Rouault (2024) showed that precipitation does not follow a bimodal cycle in the North-equatorial (0–10°N, 7–33°E) or in South-equatorial Central Africa (0–15°S, 7–33°E)—instead, the bimodal annual cycle results from averaging over an area spanning the equator. Nicholson (2022) and Mba et al. (2022) also argued the existence of a bimodal rainfall regime over the equatorial band of 2°N–2°S. Indeed, North Central Africa features a rainy season spanning from April to October and dry conditions for the remainder of the year. During the wet season, moisture convergence predominates in the region, with monthly precipitation amounts exceeding the monthly total evaporation rate. Conversely, dry conditions feature moisture divergence with monthly rainfall amounts smaller than the monthly total evaporation rate. South Central Africa features wetness from September to April and dryness for the remainder of the year, in association with patterns of moisture convergence.

Cook and Vizy (2022) decomposed atmospheric moisture flux convergence into convergence and advection terms. They found that throughout the Congo Basin, the convergence term is the main conveyor of atmospheric moisture flux convergence during rainfall peaks. In April, moisture convergence north of Central Africa (5–10°N) is sourced from the Central Congo Basin, in association with strong low level ($\leq$900 hPa) meridional northward moisture transport. Western convergence (~15°E) originates from the Atlantic Ocean and southerlies. In the upper layers (800–500 hPa), moisture convergence caps low-level divergence, driven by meridional moisture transport. In October, zonal low-level moisture convergence from west to east crosses the basin and characterizes the region. Local moisture convergence enhances and differentiates between the wetter character of October

compared to April. The upper layer of October's moisture convergence and transport are similar to those of April.

It is now clearly established that the Inter Tropical Convergence Zone paradigm is not the driver of rainfall seasonality in Central Africa (Nicholson 2018). Longandjo and Rouault (2024) highlighted the controlling role of a shallow meridional overturning circulation on the alternation of seasons. They showed that mid-layer moisture divergence overlays low-level moisture convergence over the Sahel throughout the year. However, the dry season over the Sahel from November to March is associated with westward advection of dry air that balances low-level moisture convergence. Simultaneously in North Central Africa, low-level moisture convergence is stronger than mid-tropospheric divergence, thereby triggering shallow convection that induces low rainfall. Over South-Central Africa where it is the rainy season, the shallow meridional overturning circulation expands and induces atmospheric instability, thereby deepening the convection through rising moist air which feeds mesoscale convective systems. When it is the rainy season over North-Central Africa from April to October, the southern component of the shallow meridional overturning circulation displaces northward across the equator and causes low-level moisture divergence over Central Africa. During this time, the return outflow of the shallow meridional overturning circulation induces important mid-tropospheric moisture convergence, triggering intense convection. The wet season over the Sahel from June to September features a shrunk shallow meridional overturning circulation in association with strong low-level moisture convergence. Subsequently, surface warm moist air uplifting is blocked by mid-layer moisture divergence through mid-tropospheric horizontal advection, thereby limiting the convection. Although the same situation applies to South-Central Africa, the mid-tropospheric moisture convergence is too weak to initiate convective rainfall, leading to low rainfall.

Moisture convergence feeding strong convection mainly originates from the mid-troposphere over Central Africa, in association with a top-heavy structure of the vertical velocity. This moisture convergence is the main conveyance of the total moisture flux convergence over convective regions, and its seasonality mimics that of the shallow meridional overturning circulation. Shallow convection is associated with moisture advection and its seasonality is driven by the zonal circulation.

Convective Processes

Convection is a dominant process over the Congo Basin. It is essentially a cooling mechanism to deal with the large, positive net radiation budget of the tropics and is also the key rainfall producing process. Convective Available Potential Energy, which is proportional to the kinetic energy that drives updrafts in thunderstorms, is typically non-zero in nearly all parts of the basin during the rainfall seasons (Fig. 5), reflecting the high values of near surface specific humidity and temperature. Not surprisingly, the basin is one of three key regions of tropical diabatic heating (Webster 1983), the other two being the Amazon and the warm-pool region of the West Pacific. In other words, the Congo Basin is one of three key areas that drives the tropical and subtropical circulation system of the planet. The intensity of convection

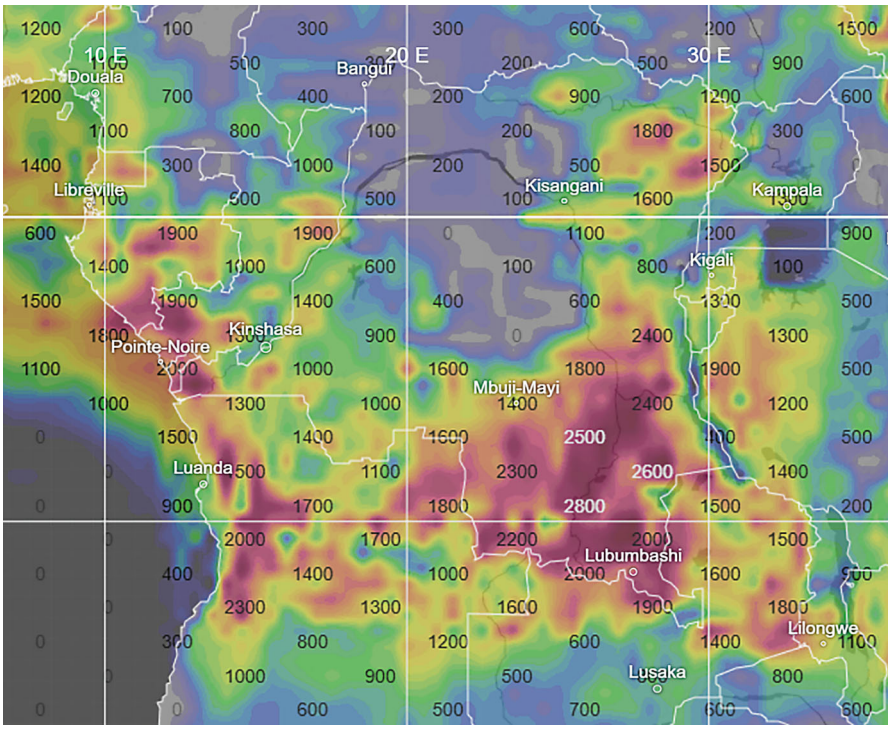

Fig. 5 Convective Available Potential Energy in $J.kg^{-1}$ at 1500 UTC on 6 April 2024 from Global Forecast System. Purple indicates low Convective Available Potential Energy values while dark red indicates high values

is reflected in the fact that 50% of the planet's top 500 locations for highest lightning frequency occur in the basin (Albrecht et al. 2016).

A key characteristic of Congo Basin convection is the extremely high frequency of occurrence of mesoscale convective systems (MCSs) (Nesbitt and Zipser 2003; Jackson et al. 2009). MCSs produce between 70% (Nesbitt et al. 2006) and 80% (Andrews et al. 2024) of the basin's rainfall. Whereas thunderstorms tend to cover tens of kilometers and last for about 2 hours, MCSs cover hundreds of kilometers with a duration of longer than 6 hours. They are extremely efficient forms of energy cycling.

MCS initiation occurs frequently downwind of topographical features, for example, the highlands west of the lee of the Great Rift Valley, the Cameroon highlands, and the Lake Victoria region, with a peak between 1500 and 1800 UTC (Laing et al. 2011; Hartman 2021; Tikeng et al. 2024). Storms have an east to west phase speed of 8–16 $m.s^{-1}$ (Laing et al. 2011). Rainfall peaks at 1500 UTC (Andrews et al. 2024).

Rainfall associated with MCSs also exhibits a diurnal cycle, with a significant peak at 15:00 UTC (Andrews et al. 2024). As the systems expand, stratiform rain begins to dominate over convective rain (Jackson et al. 2009), with a secondary rainfall peak at around 04:00 UTC, though this varies seasonally and meridionally. A minimum in activity occurs at 10.00 (Andrews et al. 2024).

Clouds

Over Western Central Africa (WCA) bounded by 5°S–8°N and 8°E–25°E, Vondou (2012) found that the peak at 220 K (Fig. 6) corresponding to deep convective clouds is observed at 16LST with the lowest percentage. During nighttime, a second peak is observed at 265 K corresponding to mid-level clouds (Fig. 6) followed by a decreasing underpinning a transition toward clear sky. Overall, all the graph exhibit peak between 280 K and 300 K, therefore a threshold of 285 K was proposed to detect cloudy pixels.

The spatial pattern of the deep convective and high-level clouds is controlled by the topography: the highest values are observed over West Cameroon highlands and the Mandara mountains and the lowest values over the Adamaoua and south Cameroon plateaus (Vondou et al. 2010). Therefore, topography plays an essential role in cloud formation through air lifting on its slopes through the southwest monsoon flow crossing the region and moisture convergence at low level. Minima of deep convective clouds are observed over the Atlantic Ocean, the Benue and Niger valleys and the Lac Tchad (Vondou 2012).

The spatial structure of low clouds over western equatorial Africa (WEA) bounded by 5°S–5°N and 8°E–18°E (Fig. 7) reveals a predominance of low stratiform clouds with high frequency on the Atlantic seaboard extending up to 15°E (Gabon, South Congo, Equatorial Guinea, Cameroon coast) during the June–September season (Dommo et al. 2018). This reduces solar radiation to the point where the region receives the least amount of sunlight during the dry season, in contrast to the interior of equatorial Africa where the main dry season is the brightest (Philippon et al. 2019).

With a peak diurnal cycle between 04LT and 07LT (Dommo et al. 2018; Champagne et al. 2023) over the coast and windward slopes, low clouds over WEA also

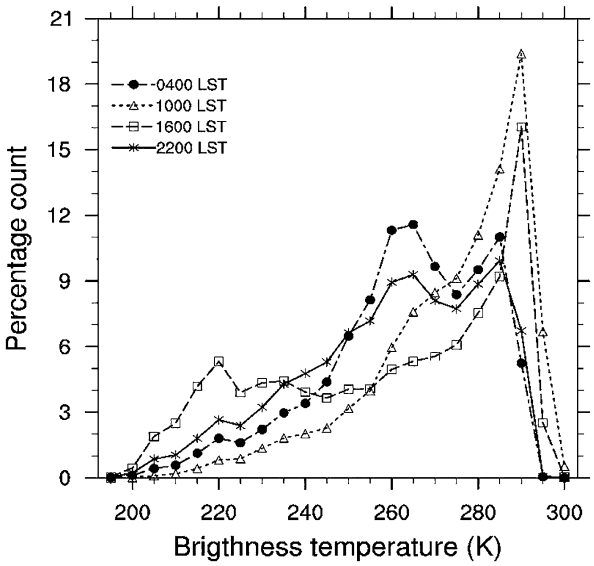

Fig. 6 The evolution graph of the percentage for which brightness temperature occurred within each 5 K interval, between 190 and 300 K during the daytime and the nighttime, over Western Central Africa bounded by 1°N–8°N & 1°E–17°E for June–August 1998–2002 (Vondou 2012)

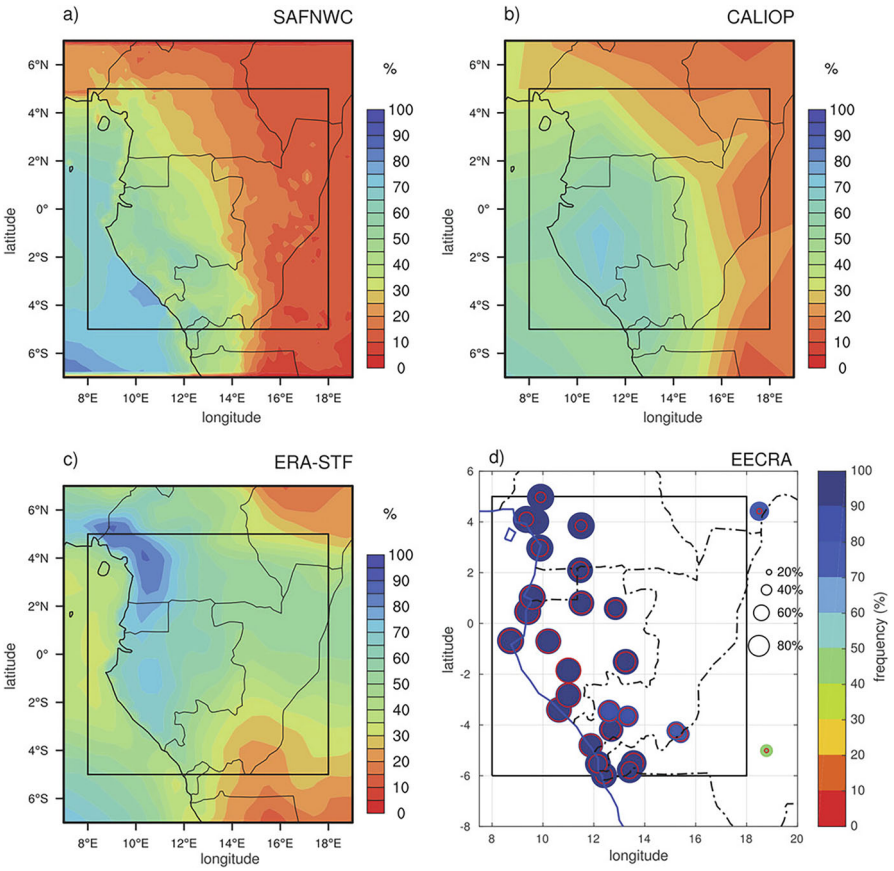

Fig. 7 Low-level cloud frequency (%) in June–September for nighttime and daytime, from the (**a**) Satellite Application Facility for Supporting Nowcasting and very short-range forecasting (SAFNWC) (2009–14), (**b**) global climate model-oriented *Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations* (CALIOP) (2007–15), (**c**) European Centre for Medium-Range Weather Forecasts interim reanalysis (ERASTF) (2009–14), and (**d**) the Extended Edited Synoptic Cloud Reports Archive (EECRA) (1971–2009). In (**d**), the circle size is proportional to the frequency. The total low clouds (blue disks) and the low stratiform clouds only (red circles) are marked (Dommo et al. 2018)

exhibit an east to west gradient with a high frequency of occurrence over the coastal region and a lower frequency inland (Dommo et al. 2018). Previous studies mentioned the influence of topography on the spatial distribution of the low clouds over WEA which exhibits a significant reduced low cloud frequency over the plateaus in the afternoon. Dynamic processes show that, during nighttime, the formation of low cloud over WEA is associated with moisture flux related to low level westerlies, strong convergence in the lower layer (below 1000 m, e.g. ~900 hPa) and turbulent upward mixing of moisture (Dommo et al. 2022). The reinforcement of the radiative cooling at the cloud top helps to maintain the cloud deck once it has been formed.

During daytime, latent and sensible heat flux from the surface, due to downward shortwave radiation, contributes to increase the vertical turbulence and deepen the boundary layer and thus, combined with decreasing relative humidity in low levels ~1000 m mostly due to the diurnal warming, acts to partly destroy the cloud deck and decrease the cloud fraction.

At the interannual scale, Moron et al. (2023, 2025) show that mechanisms driving low level clouds over WEA are associated to the meridional shallow overturning cell and a strong cold tongue over the equatorial Atlantic. Processes operating at intraseasonal cycle, involve tropical waves (Moron et al. 2025).

Although considerable progress has been made in understanding the structure of clouds, accurately representing them in climate models over WCA remains challenging, particularly for low clouds (Camberlin et al. 2023). This unrealistic representation contributes to the large uncertainties noted in regional and global climate projection (Dufresne and Bony 2008).

Nature of the Precipitation Regimes

The rainfall data available for the Congo are inadequate for assessing the mean spatial pattern of rainfall. Figure 8 shows the spatial pattern based on NIC131 and based on the CHIRPS satellite rainfall dataset. Both are in excellent agreement with each other and with a map produced by Bultot (1971) for 1930–1959, a time when over 100 stations were available.

Inland, three rainfall maxima are clearly apparent. The largest are over the Cuvette Centrale and just west of Lake Victoria, where in both maps, mean annual rainfall exceeds 2000 mm. As for the latter maximum, orography enhances rainfall as the easterlies flow over the Rwenzori and Mitumba Mountains in the Rift Valley highlands. In the former, rainfall appears to be enhanced by evaporation from the Congo River and the wet regions around it (Nicholson et al. 2021). The third maximum lies north of the one near Lake Victoria. It also appears to be related to orography, in particular the Blue Mountains. At the northern and southern extremes of the region, roughly 10°N and 10°S, rainfall is around 1000 mm. It increases steadily toward the central basin, being on the order of 1750–2000 mm over most of the region.

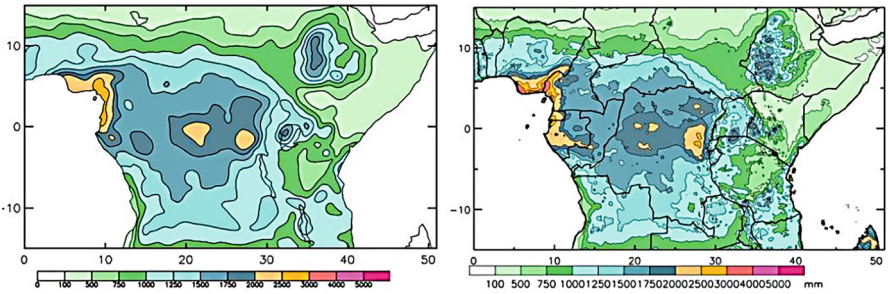

Fig. 8 Mean annual rainfall (mm) based on gauge data (left) for the period 1945–1984 and CHIRPS data (right) for the period 1981–2019 (Nicholson 2022)

Figure 9 shows the seasonal cycle of rainfall in each five-degree grid cell. To the north, from 5 to 10°N, rainfall has a unimodal seasonal cycle with maximum rainfall in June-to-August or July-to-September. In the northern Congo Basin, from the equator to 5°N, two peaks are generally evident, but in most grid cells rainfall is also high in summer, mainly off the coast. Thus, the bimodal nature is not well developed. It is better developed in the southern Congo (equator to 5°S), but even there the dry season between the two maxima is not very dry, so the two rainy seasons are not extremely distinct. Over these two latitudinal bands, the bimodal cycle is more pronounced over the coastal region. Therefore, this bimodal character of annual rainfall is not obvious when averaging rainfall along each latitudinal band (Longandjo and Rouault 2024). In general, September–November seems to be the wetter period of the year. Farther south, most grid cells have a clear summer rainy season, although in some two peaks are evident.

The month of maximum rainfall (Fig. 10) changes progressively from March in the far south, around 10°S to August in the far north at roughly 7°N. The driest month shifts abruptly from June or July south of 0 to 2°N to January in northern hemisphere sections.

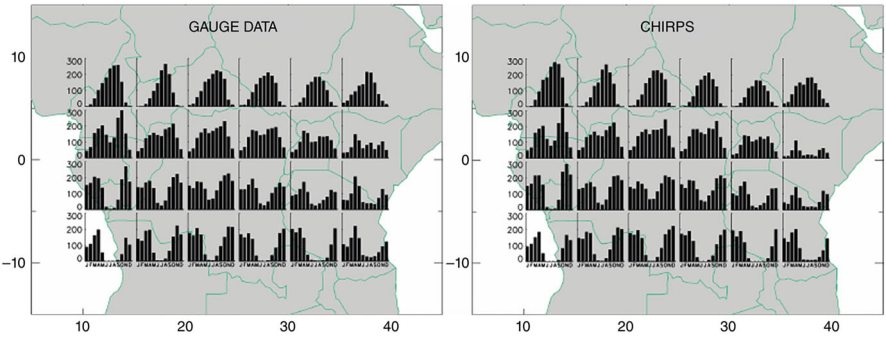

Fig. 9 The seasonal cycle of rainfall, with bar graphs indicating mean rainfall in each month (Nicholson 2022). Based on gauge data averaged for the period 1945–1984

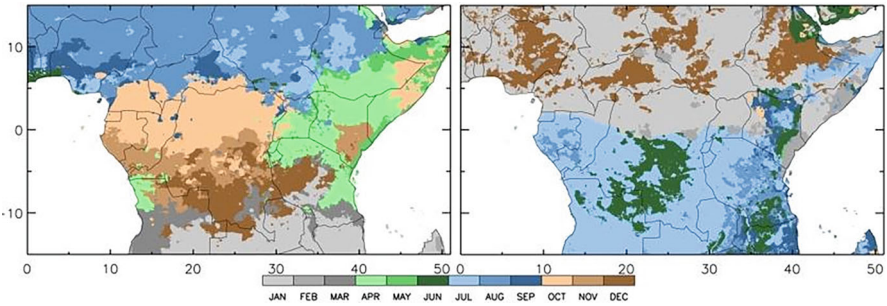

Fig. 10 Months of maximum rainfall (left) and minimum rainfall (right), based on CHIRPS data for the period 1981–2019 (Nicholson 2022)

Most of the rainfall in the Congo Basin (70–80%) is associated with mesoscale convective systems (Feng et al. 2021). These tend to form in the late afternoon but persist through the night, producing short-lived convective rainfall in the afternoon but long-lived stratiform rainfall at night. Consequently, there is a nocturnal rainfall maximum in many areas. Consequently, the diurnal cycle of precipitation exhibits two peaks due to MCSs (the first peak in the afternoon and the second at night) compared to a single peak for days with no mesoscale convective systems (only one peak in the afternoon) (Tikeng et al. 2024).

The Congo Basin experiences the highest frequency of lightning in the world. Within the region there are two very pronounced maxima, co-located with the two regions of maximum rainfall: just west of the highlands and over the central basin. The small village of Kifuka experiences the absolute highest number of flashes per year, 158/km^2 (Kalair et al. 2013). Mesoscale Convective Systems are responsible for the intensity of lightning activity in the region, mainly close to the equator (Jackson et al. 2009).

An unusual characteristic of Congo Basin rainfall is the lack of spatial coherence of rainfall variability and spatial teleconnections. Throughout most of Africa both characteristics are strong, and teleconnections extend across the continent. However, studies based on 90 climatic regions (e.g., Nicholson et al. 2012a, b) show that both characteristics are lacking over the Congo Basin, with very low correlation among station for the Congo during both rainy season clearly evident in Fig. 11.

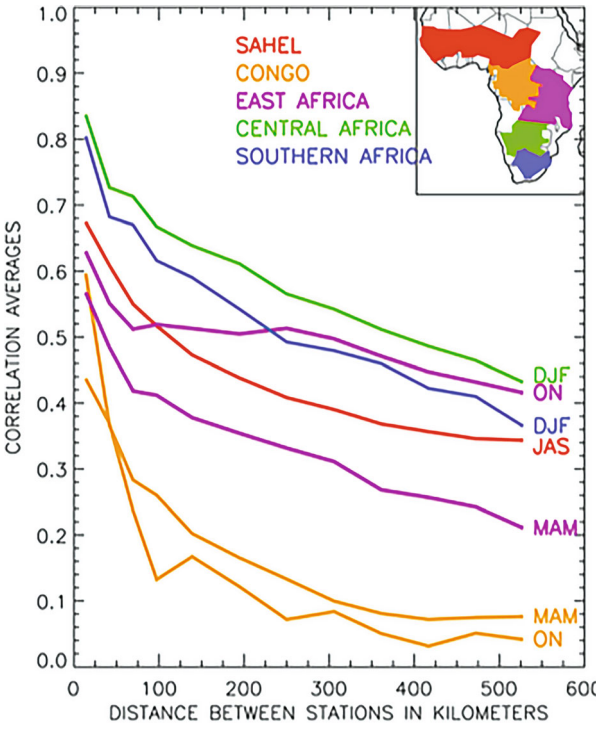

Fig. 11 Inter-station correlation during the period 1930–1989 as a function of distance between stations in five geographical sectors in Africa (Jackson et al. 2009)

Regional Drivers of Climate Variability

Establishing the long-term interannual variability of rainfall over the Congo Basin is difficult because of the decline of the station network since the 1970s. Precipitation from various datasets for the Congo Basin tends to disagree with each other, which can be attributed to the various interpolation approaches used by the observations, temporal availability, and satellite-only to blended data (Dallmann 2023). This makes it difficult to establish the relevant forcings. Conclusions of various studies are to some extent contradictory.

Interannual variability was examined by several studies. Balas et al. (2007) concluded that the large-scale factors controlling interannual rainfall variability vary greatly from region to region and from season to season. They also concluded that links to global SSTs and ENSO were quite weak. In some areas/seasons a weak link to El Niño but not La Niña was evident; in others the reverse was true. Dallmann (2023) likewise concluded that ENSO and large-scale SSTs were not factors in interannual variability in the Congo Basin.

In contrast, Hua et al. (2016, 2018) found linkages with the Indo-Pacific SSTs. They concluded that the principal factors associated with the long-term drying trend in April–June (Fig. 12) were an enhanced and westward extension of the tropical

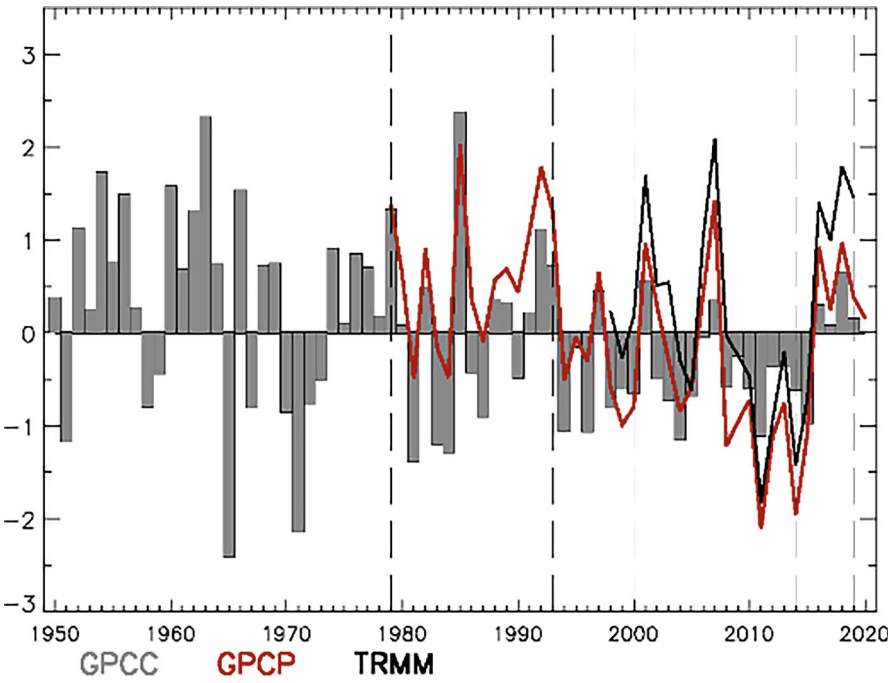

Fig. 12 Time series of April–May–June areal averaged (10°S–8°N, 14–32°E) rainfall 1950–2019 based on GPCC (bars), GPCP (red dashed line), and TRMM 3B43 (black dashed line). (From Nicholson et al. 2022b). Rainfall is expressed as a standardized departure. Vertical lines delineate recent wet and dry periods

Walker circulation, an anomalous anticyclonic circulation in the lower troposphere over southern Africa, weakened ascent over Central Africa, and reduced low-level moisture transport. These appear to have been triggered by changes in SSTs in the Indo-Pacific sector, in particular decreasing temperatures in the equatorial Pacific but increasing temperatures over the tropical Atlantic and Indian Oceans and the western Pacific.

Nicholson et al. (2022b) examined two wet periods during the AMJ season, 1979–1993 and 2016–2020 (Fig. 12). They concluded the first wet period was related to a warmer central and eastern pacific and a cooler western Pacific, compared to the dry phase between 2000 and 2014. Changes in moisture flux and the Walker circulation were also involved. In contrast, during the second wet period, warming was more pronounced in the central and eastern Pacific compared to the western Pacific, which decreased the trans-Pacific SST gradient in the 2016–2020 period compared to either prior period. For this episode, the major factors appear to be an increase in Convective Available Potential Energy and in total column water vapor.

The Indian Ocean provides a significant amount of atmospheric moisture for rainfall to the Congo Basin (Dyer et al. 2017). Dezfuli and Nicholson (2013) and Nicholson and Dezfuli (2013) found only weak associations but found a tendency for dry/wet conditions over Congo Basin to be associated with abnormally warm/cold Indian ocean temperatures. However, in recent decades, the influence of the Indian Ocean Dipole on the Congo Basin rainfall during September–December has increased (Jiang et al. 2021). Positive/negative Indian Ocean Dipole events are associated with enhanced/reduced moisture transport and wet/dry conditions over the Congo Basin. This influence is more pronounced south of the equator (Moihamette et al. 2024).

The western part of the Congo Basin is the region most sensitive to SST variations in the tropical Atlantic Ocean. Warmer/colder than normal SSTs in the equatorial and southern Atlantic together are associated with wet/dry conditions in the region along the coast during the AMJ season (Nicholson and Dezfuli 2013). However, Congo Basin's coastal rainfall strongly connects with the local SST along the Benguela coast, resulting in rainfall increases under the effect of warm SST anomalies on the Benguela coast (Nicholson and Dezfuli 2013). Wetter years also tended to be associated with strongly developed westerlies in the lower troposphere (Pokam et al. 2014). During the JJA/SON seasons, the Atlantic Niño causes increased rainfall, leading to wet conditions over the Democratic Republic of the Congo (DRC), Congo, and north Angola, whereas Cameroon and the Central African Republic experience dry conditions. This pattern is reversed when stronger upwelling in the equatorial Atlantic produces cold SST anomalies in these regions (Balas et al. 2007). The South Atlantic Ocean Dipole (Nnamchi et al. 2011) also influences Congo Basin rainfall. A colder-than-normal SST off the coast of South America, but warmer-than-normal SST along the west/central coast of Africa causes a convergence (divergence) of moisture flows over the southern Atlantic coast (inland the Congo Basin) resulting in increased (decreased) rainfall in these regions of the Congo Basin in the JJA season. An inverse pattern results in opposite rainfall

variability (Nana et al. 2023). The Madden-Julian Oscillation also has an impact on rainfall in the Congo Basin (Raghavendra et al. 2020).

Extreme Weather and Climate Events

Extreme Rainfall

Extreme rainfall is an event that is of very high magnitude with a very rare occurrence at a particular place (IPCC 2021). Extreme rainfall is one of the most frequent and widespread severe weather hazards to affect Congo Basin countries (Igri et al. 2015; Tanessong et al. 2017; Kenfack et al. 2024). Often, a significant amount of precipitation occurs in only a few hours, leading to severe flooding and risk of landslides.

The interannual variability of precipitation during October and November reveals recent precipitation extremes, particularly in 2019 and 2023. (Fig. 13). From the spatio-temporal variability of the southern Congo (10°S–0°) in October 2019 and 2023 (Figs. 14a, c), two very wet years over Equatorial Africa (Nicholson et al. 2022a; Nana et al. 2025), rainfall extremes are primarily over the western region. In November 2019 and 2023, rainfall extremes are over all regions. Spatio-temporal variability of the northern Congo (0–10°N) in October 2019 (Fig. 14b) shows more extreme rainfall and in a greater longitudinal extent than October 2023 (Fig. 14d). November 2019 shows larger rainfall extremes only in the eastern Congo and only for half of the month. November 2019 shows more rainfall extremes across latitudes

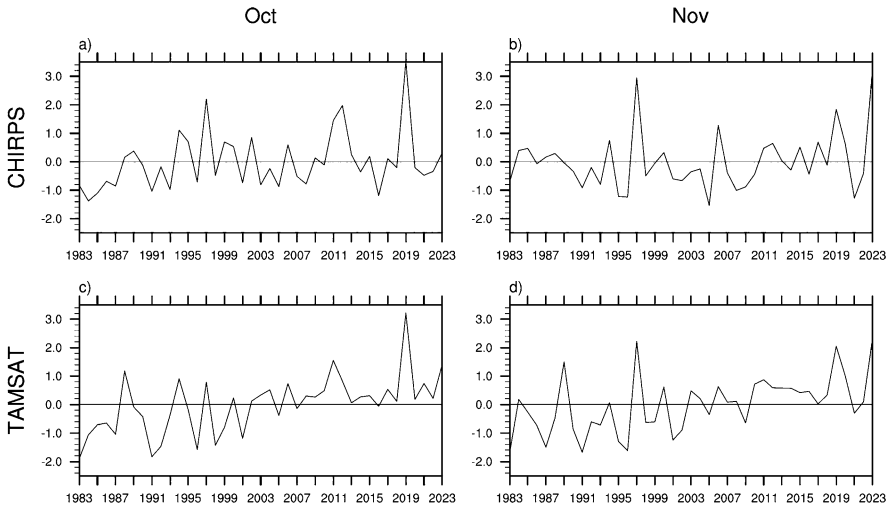

Fig. 13 Time series of monthly rainfall over the Congo Basin (10°S–10°N, 10°E–40°E) for the standardized anomalies (1983–2023) during October and November from (**a** and **b**) CHIRPS and (**c** and **d**) TAMSAT

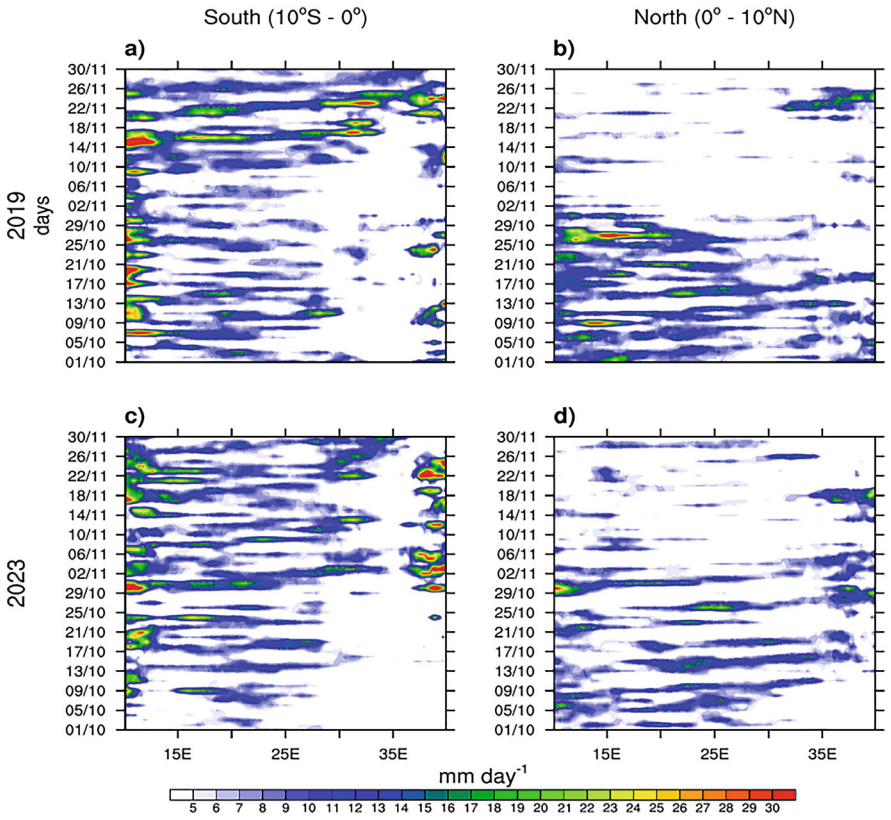

Fig. 14 Daily rainfall from CHIRPS, averaged over 10°S–0° (first column) and 0°–10°N (second column), for (**a** and **b**) 2019 and (**c** and **d**) 2023

compared to November 2023. Figure 14 shows that the southern Congo rainfall extremes are more consistent with each other in both months compared to the northern Congo rainfall extremes.

Nicholson et al. (2022a) investigate the unprecedented October and November 2019 rainfall extremes in equatorial Africa, putting them in their historical context and analyzing the juxtaposition of forcings needed to explain them. The mechanisms underlying these extremes of rainfall are not straightforward. The Indian Ocean Dipole and the associated moisture provision to equatorial Africa contribute to wetter conditions over the Congo Basin (Moihamette et al. 2022). SST variability of the Atlantic Ocean may also contribute. However, over the Congo Basin, the lack of a homogeneous response of rainfall variability suggests that local factors may play a significant role in extreme rainfall. The prevalence of low wind shear over the Congo Basin prevents random convective outbreaks in the region from organizing into large-scale propagation systems, leading to this heterogeneous response in rainfall patterns. Then, Convective Available Potential Energy and total column

water vapor appear to be the main factors for the occurrence of extremes over the Congo Basin (Nicholson et al. 2022b).

Meteorological Drought

Meteorological drought is defined as a period when precipitation is significantly below the long-term average. Few studies are based on improving mathematical tools to accurately determine meteorological drought in the areas of the Congo Basin. The Standardized Precipitation Index (SPI) remains the most used because it has the most advantages, such as being flexible, depending on a single variable (precipitation which is the most easily accessible), and can describe drought at several time scales (Batool et al. 2025). However, it requires modeling the distribution of data by a statistical function, which is generally assigned to the gamma distribution. Recent studies have shown that such an assumption induces errors in the characterization of drought (Guenang et al. 2019) and propose selection by decision test, the most appropriate distribution in a sample of functions. Very few studies have looked into solving this problem. In the particular case of Central Africa, improvements in the calculation of this index may be found in Fotse et al. (2024).

Mabrouk et al. (2022) shows an increase in drought risk in the Congo River Basin. The reasons are awarded to the vulnerability and population rise in that region (Ahmadalipour et al. 2019). This drought can affect Congo Basin by reducing forest photosynthetic as shown by Zhou et al. (2014). Other studies focused on particular countries. Kapiri et al. (2023) focused on the study of drought from the 1970s to the 1990s and its influence in the Tropical City of Beni, Eastern DR Congo. Results show that the city of Beni has suffered from drought during the years 1970 to 1990. Guenang and Kamga (2014) also found that many localities in Cameroon recorded severe to extreme drought during the 1980s. Some agroecological zones of the country are expected to suffer from these drought categories in the future decades of the end of the twenty-first century (Guenang et al. 2024).

Possible mechanisms for drought in Central Equatorial African were examined by analyzing the circulation changes related to sea surface temperature (SST) variation (Hua et al. 2016). It was found that drought for the season April–May–June was correlated to atmospheric circulation and SST variation. This finding was confirmed by Nicholson et al. (2022b) studying rainfall conditions in the Congo Basin. Ndehedehe et al. (2019) also examined the impacts of global multi-scale climatic drivers on hydro-climatic extremes over the Congo Basin and found that drought was correlated to the phenomena of ENSO, QBO, MJO, and AMO. Additionally, increases in evapotranspiration will offset increases in precipitation where rainfall amounts are expected to increase and exacerbate drought severity in regions where precipitation is expected to decrease (Karam et al. 2022). Nicholson (2022) suggested that lower moisture flux convergence and lower relative humidity are responsible for drier conditions over the Congo Basin as compared to other tropical rainforests. It was observed that the occurrence of drought over the Congo Basin

coincide with flood over the Amazon and vice versa (Eltahir et al. 2004); this phenomenon is defined as a see-saw oscillation was observed at a decadal scale between the Amazon and Congo Basin (1945–1955, 1960s, and 1970s).

Heat Waves

Recent trend of surface temperature over northern Congo Basin have shown an increase greater than average global warming (Engelbrecht et al. 2015), as a result of anthropogenic global warming. As a consequence, the Congo Basin experiences increases in extremes of heat and in turn heat waves, mainly in the northern and western part of the region (Kaissassou et al. 2023). This presents a growing challenge for the region. Strong heat stress is experienced over the region from November to February. Moderate heat stress is observed from April to June. The average length of heat waves in northern Congo Basin varies between 4.8 and 5.2 days, growing longer with time and associated with an increased trend of maximum temperature (Hu et al. 2019).

The synoptic feature driving these heat wave events involves the occurrence of an anomalous convergence center in the upper troposphere and a divergence center in the lower troposphere, inducing strong subsidence anomalies, which leads to warming through greater solar insolation. This enhancement of the solar radiation induced by strong subsidence anomalies is the major contribution to the occurrences of HW events over northern Congo Basin.

Issues, Gaps, and Challenges

A serious limitation in developing an understanding of the mean climate of the Congo and its interannual variability is a dearth of recent observational data. During much of the twentieth century, rainfall records for the Congo were plentiful. Some 500 stations were operative in the Democratic Republic of the Congo (DRC) during the 1940s through 1960s (Bultot 1971). When economic conditions worsened and political conditions changed, the number of stations rapidly declined, especially during the 1970s. By the early twenty-first century, only 12 gauges were operative in the DRC.

This decline is illustrated in Fig. 15 (left), which shows the total number of months with rainfall records in each grid box in the NIC131 dataset (Nicholson et al. 2019) during the period 1995–2012. Clearly there are few records available in the Democratic of the Congo during that period. The results are similar for GPCC, but with fewer station months in almost every grid point with available data. Figure 15 (right) shows the stations available in four multi-year periods.

Gridded datasets have been produced to cover the recent years. However, these are not independent datasets because all contain more or less the same records until about 1998. These include NIC131 (Nicholson et al. 2018), NIC131-gridded (Nicholson et al. 2019), GPCC of the Global Precipitation Centre in Offenbach, Germany

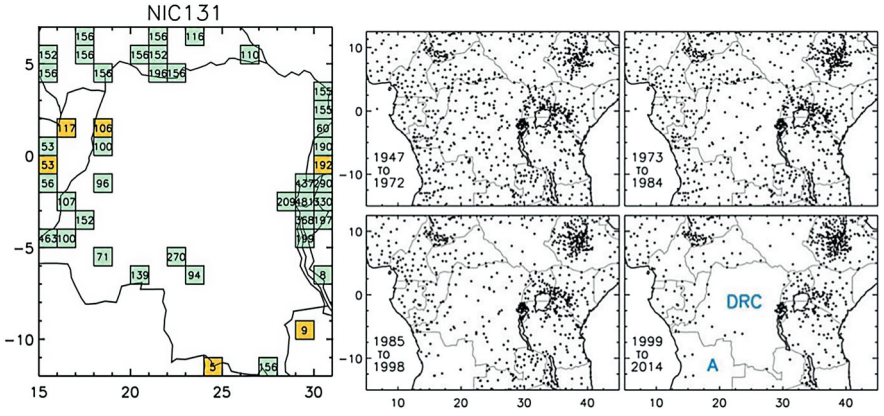

Fig. 15 Left: Total number of months with available rainfall records during the period 1995–2012 for any grid box with data in NIC131 (Nicholson et al. 2019). Grid boxes in orange are those with a greater number of records in GPCC. Right: Station network around the Congo Basin in four time periods. (From Nicholson et al. 2018). Country boundaries are shown. In the map for 1999–2014, the letters DRC and A, respectively, identify the Democratic Republic of the Congo and Angola

(Schneider et al. 2015); CRU of the University of East Anglia (Harris et al. 2014); and the University of Delaware (Willmott and Matsura 2000). It should be noted that the decline in station records affects all of these sources. Many of the sources continued providing records post-1998 by using the data available through the Global Telecommunications System (GTS), but the GTS provides very little data.

Numerous satellite precipitation datasets cover the Congo region. While, in principle, satellite data provide the needed spatial detail, their reliability is dependent on the quality and density of ground station records. Several validations found large discrepancies between gauge and satellite data over the Congo. Nicholson et al. (2019) found that the various available satellite datasets differed greatly in their ability to accurately estimate rainfall over the Congo. They concluded that the most reliable satellite products over the Congo region are CHIRPS2, GPCP2.3, and PERSIAN-CDR. Meanwhile, reanalysis datasets are inconsistent with each other in their spatio-temporal rainfall estimates and likely do not adequately represent rainfall within the Congo Basin (Nicholson and Klotter 2021; Hua et al. 2019).

The dearth of rainfall data is matched by an absence of upper air data from radiosondes, which are necessary to capture the thermodynamics associated with key rainfall systems, notably MCSs. Key metrics such as CAPE have been shown to contain misleading trends in reanalysis data (Benestad et al. 2022).

The unreliability of observation data hampered efforts to constrain climate model results, which directly impacted the ability of the model to represent regional climate. There is significant variation in the representation of rainfall climatology among global climate models (Creese and Washington 2016). In some months the difference is up to a factor of 5. Although the coarse resolution and the parametrization of these models contribute to these biases, the poor skill of those models in

representing the strength of LLWs or the location of AEJ components lead to rainfall biases over the Congo Basin (Creese and Washington 2018; Kuete et al. 2023). To overcome this issue of coarse resolution, the ability of regional climate models to represent regional climate processes has been assessed (Tamoffo et al. 2023, 2024). Increasing model resolution does not always lead to improved climate simulation (Vondou and Haensler 2017; Wu et al. 2020) with reasons behind finer scale model biases similar to those of global climate models, including misrepresentation of regional teleconnection, land–sea thermal atmospheric circulation, and land–atmosphere feedback leading to error in the regional hydrological cycle (Mba et al., 2022; Akinsanola et al. 2025). The direct consequence is the lack of agreement between climate models on the sign and magnitude of future change in the Congo Basin (Creese and Washington 2018).

In recent years, significant pan-African (TAHMO) and regional (WASCAL, SASSCAL) investments have been made to bridge the gap in ground-based meteorological data availability. However, the Congo Basin remains data defficient with sparse network coverage.

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Competing Interest Declaration The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

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The Evolution of Congo Basin Ecosystem Diversity

4

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Abstract

The Congo Basin is a biologically diverse and dynamic terrestrial region composed of a central rainforest block flanked by savanna-forest ecotone. Embedded within this region are the Congo, Ogooué, and Sanaga which constitute the most biodiverse river systems in Africa. Although the Congo Basin is dominated by lowland forest, it also harbors a variety of terrestrial and freshwater ecosystems. Forests and associated savannas have been shaped by both abiotic and anthropogenic influences and differ in terms of their hydrology, elevation, and soil type. Current species distributions are complex and are thought to have been shaped by both historical and ecological factors. Major drivers of speciation are thought to have resulted from either geographic isolation through past refugia, riverine barriers or divergence across environmental gradients. Both genetic and genomic tools can help to refine taxonomy, identify unique evolutionary lineages, and understand the historical and ecological factors that have led to the rich biodiversity that we see today. Genetic tools are increasingly being applied to conservation efforts, including tracking and curbing the illegal wildlife trade. Genomic techniques also offer powerful means to preserve biodiversity in the face of climate change and identify populations with the greatest potential to adapt. This approach can inform placement of new protected areas to enhance species resilience and reduce extinction risk. Despite the potential of genomic tools, their integration into conservation planning remains in its infancy and will require expertise and long-term investment. Future efforts should focus on developing a road map for incorporating genomic data into conservation strategies along with fostering stronger communication between researchers and practitioners. Lastly, many species in the Congo Basin await discovery and for most groups, there is a backlog of species awaiting description. Developing regional expertise is needed to address this taxonomic impediment.

Keywords

Rainforest · Ecosystem · Congo basin · Biodiversity · Speciation · Genomics

Biogeographical History of the Congo Basin

Forest Ecosystems

Lowland rainforest constitutes the main ecosystem of the Congo Basin, covering approximately 1.7 to 1.8 million km^2 (Hansen et al. 2000; Mayaux et al. 2013; Verhegghen et al. 2012a) (Fig. 1) and a high density of aboveground carbon (Fig. 2). It is generally characterized by a tall, closed canopy, with a complex multi-layered vertical structure, so that the understory is usually dark, except in forest gaps. An estimated 8.5% of its area has been lost between 1990 and 2020 (Yuh et al. 2024).

Renowned for their high biodiversity, central African rainforests vary in their floristic composition at different spatial scales, leading to different classification schemes. From a phytogeographic perspective, White (1983) distinguished three regional centers of endemism: Upper Guinea (West Africa), Lower Guinea (western Congo Basin), and Congolia (eastern Congo Basin; Fig. 3). This subdivision is supported by quantitative analysis of the whole flora of the region (Droissart et al. 2018), although other analyses have distinguished moist and wet forest, based on the amount and seasonality of rainfall (Fayolle et al. 2014). Forests are also classified according to the relative dominance of deciduous tree species (i.e., trees shedding

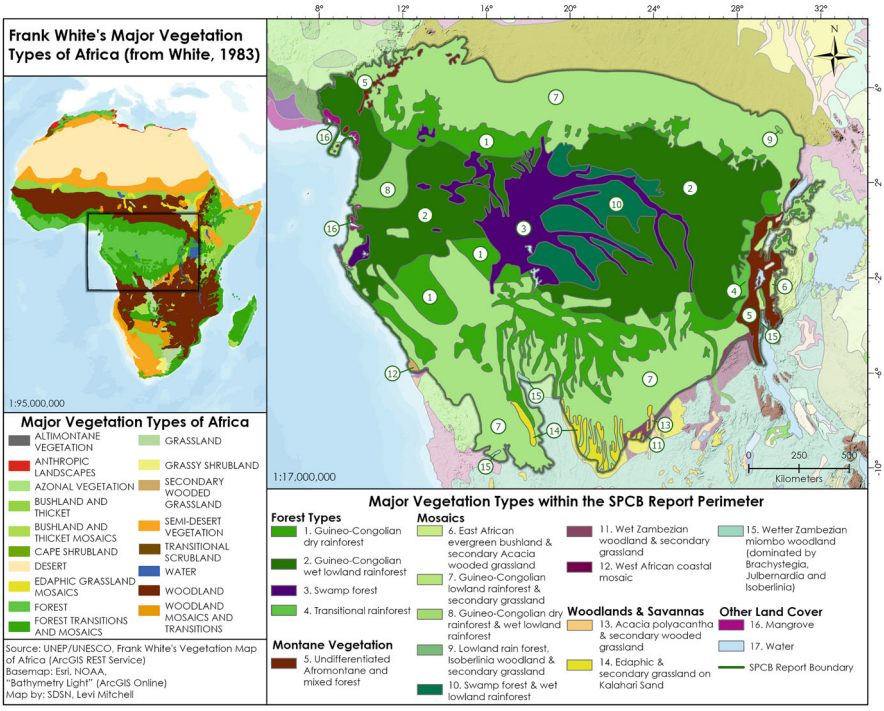

Fig. 1 Major Congo basin vegetation types. (Adapted from Verhegghen et al. (2012b))

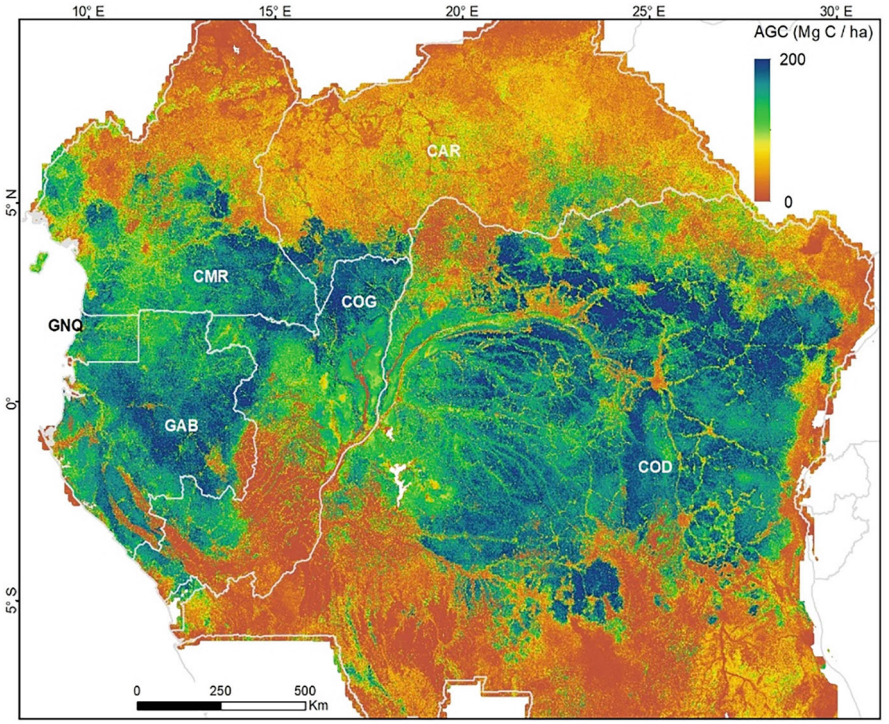

Fig. 2 Spatial distribution of the aboveground carbon density (AGC, Mg C/ha) of the Congo basin rainforest at 1 ha resolution for the year circa 2020 obtained by combing air- and space-borne remote sensing data and the-state-of-the-art gradient boosted regression trees. Key: *CMR* Cameroon, *GNQ* Equatorial Guinea, *GAB* Gabon, *COG* Republic of the Congo, *CAR* Central African Republic, *COD* Democratic Republic of the Congo. (Adapted from Xu et al. (2017), (2021); Sagang et al. (2024))

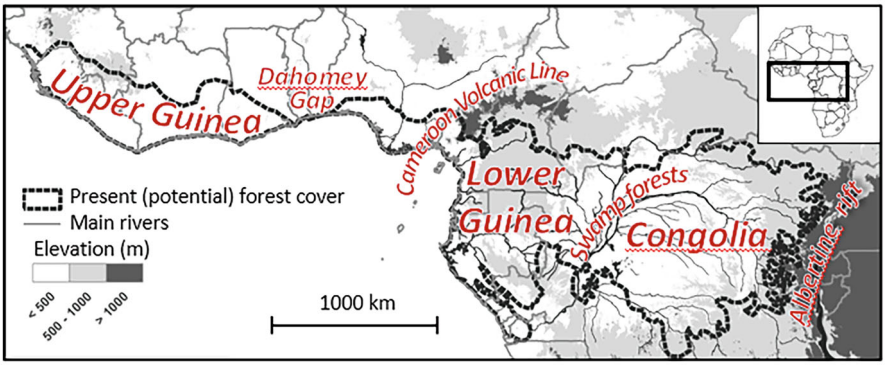

Fig. 3 Major biogeographical regions and patterns of elevation in West and Central Africa. (Adapted from Hardy et al. (2013))

their leaves during the dry season), distinguishing deciduous, semi-deciduous, and evergreen forests, whose distribution is closely related to the total amount of rainfall, cloud cover, as well as the duration and severity of the dry season (Philippon et al. 2019). One of the most recent broad-scale classifications based on forest inventories in the Congo Basin distinguish ten forest types (Réjou-Méchain et al. 2011), which differ in the relative dominance of key functional traits (wood density, deciduousness, and maximum diameter). Satellite images are also used to produce vegetation maps distinguishing different forest types (Gond et al. 2013; Verhegghen et al. 2012a), notably 20 m resolution images from Sentinel-2 satellites allowed a regionally harmonized typology of 15 forest types (Dalimier et al. 2021).

At a more local scale, forest types are distinguished according to (i) species dominance (monodominant versus mixed forest); (ii) water table depth (swamp forest, temporally inundated forest, *terra firme* forest), which is closely related to the topographic position; and (iii) the degree of disturbance (primary versus secondary forest). Previously, scientists often assumed that primary forests were devoid of human influence. However, scientists now recognize that humans have influenced the floristic composition of African forest for about three millennia through slash and burn agriculture and other cultural practices (Morin-Rivat et al. 2017; Oslisly et al. 2013; Yasuoka 2013). In some regions, extensive slash and burn farming centuries ago still has profound impacts on dominant canopy trees today, such as in the mahogany forests of Northern Congo (White and Oates 2001), the forests of the Ntem Valley in Cameroon (Carrière 2003), the *Aucoumea klaineana* stands in Gabon (Engone Obiang et al. 2014), and Cameroon's coastal forests (Morin-Rivat et al. 2017).

The existence of monodominant forests (forests where at least 60% of the canopy is made of a single species) is unusual, since tropical rainforests are usually characterized by a large number of tree species at relatively low density. Some monodominant forests are made up of pioneer tree species and are considered to be a transient state. One example are the *Sacoglottis gabonensis* and *Aucoumea klaineana* forests of coastal Gabon and the Republic of the Congo which emerged 500 to 1000 years ago. These forests are thought to be a product of recolonization following coastal deforestation in response to swidden agriculture (Delègue et al. 2001), the slave trade (White et al. 2000), or salt production from boiled seawater, an extensive practice along the Atlantic coast of Gabon in the sixteenth century (Hymas 2016). *A. klaineana* is endemic to Gabon and Equatorial Guinea and is by far the most important timber species exploited in Gabon. This species colonizes savannas and abandoned fields, forming a dense high forest after one or two centuries. These dense stands are scattered throughout Gabon near village sites that were forcibly abandoned during the colonial policy of regroupment, which forced villages to relocate to roadsides (Walters et al. 2025). However, *A. klaineana* is unable to regenerate by itself and is replaced by mixed forest in the long term (Engone Obiang et al. 2014). Only a handful of tree species can form stable (climax) monodominant stands, which can be as small as 0.1 ha or cover several km^2 as is the case for the timber species *Gilbertiodendron dewevrei* (Tovar et al. 2019). The high density of their foliage seems to inhibit establishment of seedlings by most other species except *G. dewevrei* seedlings which are particularly shade-tolerant (Peh et al. 2014).

The limit of lowland rainforest can be gradual, as is the case for the transition toward submontane forest, which occurs around 700–900 m (Cheek et al. 2000; Senterre 2005), or abrupt, as seen in the transition to savanna, which tends to occur when annual rainfall falls below about 1580 mm (Staal et al. 2016), but sometimes less (1300 mm in Lopé, Gabon). In fact, forest and savanna ecosystems can coexist over a broad climatic envelope (900–1900 mm), even up to 3000 mm on well-drained deep sandy soils, such as in the Plateaux Batéké, but exclude each other on a local scale, leading to alternative stable states (Aleman et al. 2020). Where climatic and soil conditions allow both ecosystems to persist, it is common to find a mosaic landscape where forest occupies humid areas like valleys, and savanna the drier ones, like elevated plateaus. Rainfall, herbivory, or fire can then shift the spatial distribution of the forest-savanna transition zone. However, in many cases in the forest-savanna mosaic, fire is unable to maintain the boundary and forest encroaches savanna (Jeffery et al. 2014).

The extent of rainforest in Africa has continuously changed over geological time, depending on orbital processes, plate tectonics, and climatic conditions (Kissling et al. 2012; Zachos et al. 2001). Six major "geo-climatic" periods have impacted the biodiversity of tropical Africa since the extinction of dinosaurs, 66 million years ago (Couvreur et al. 2021). Rainforest may have dominated Africa during the mid-Eocene (c. 55 million years ago), possibly covering c. 22 million km^2 according to a paleogeographic vegetation reconstruction (Kissling et al. 2012), but its extent globally declined, with an abrupt reduction during the last ten million years (Couvreur et al. 2021; Kissling et al. 2012). The last two million years (Quaternary) have been marked by glacial-interglacial cycles at higher latitudes. Fossil pollen records from marine sediments from the Gulf of Guinea show a decay of lowland forest pollen taxa concomitant with glacial episodes, especially during the last 1.1 million years. Therefore, forest cover during glacial maxima might have been much more reduced and probably fragmented than today (Maley and Brenac 1998). However, Pleistocene paleo-vegetation data is generally lacking from the Congo Basin. This hinders estimates of the past distribution of lowland rainforests (Elenga et al. 2004), making it difficult to tease apart the different hypotheses proposed for the distribution of Pleistocene forest refugia (Anhuf et al. 2006; Aubreville 1949; Hamilton and Taylor 1991; Kingdon 1980; Maley and Brenac 1998). Although precipitation was higher in tropical Africa during the Holocene, (deMenocal et al. 2000), two climatic crises affected the Congo basin about 4300 and 2500 years ago, the latter coinciding with the expansion of slash-and-burn agriculture (Maley et al. 2018), probably mediated by Bantu populations (Bostoen et al. 2015; Grollemund et al. 2015).

Peat Ecosystems

Forested wetlands are an important habitat within the Congo Basin. Also known as swamp forests, these have been estimated to cover 360,000 km^2 of the "central depression" or Cuvette Centrale of the Congo Basin (Bwangoy et al. 2010); see Fig. 1.

This habitat spans the northern-eastern Republic of the Congo (ROC) and western Democratic Republic (DRC) of the Congo Basin. Swamp forests occur across large interfluvial basins between rivers, such as between the Ubangi and Likouala-aux-herbes Rivers in the Republic of the Congo (ROC) and in the river valleys of the middle reaches of the Congo River and various left-bank tributaries, including the Ikelemba and Ruki Rivers in the Democratic Republic of the Congo (DRC) (Bwangoy et al. 2010; Crezee et al. 2022). Other sizeable wetlands in the Congo Basin region include near the Lomami River in central DRC, and the Minkébé wetlands in northwest Gabon, plus various coastal wetlands, such as those associated with the Ogooué River in Gabon (Fluet-Chouinard et al. 2015). Small areas of wetland also occur elsewhere, typically close to rivers, streams, lakes, or in small depressions (Gond et al. 2013).

Compared to *terra firme* forest, forested wetlands tend to be composed of shorter stature trees and have lower tree biomass and lower tree biodiversity (Bouillenne et al. 1955; Dargie et al. 2017; Évrard 1968; Gond et al. 2013). In all these regions, animal diversity is largely unexplored, except charismatic megafauna. Central African forested wetlands are known to have dense populations of forest elephants and western lowland gorillas in the large interfluvial basins of the ROC (Fay and Agnagna 1991; Rainey et al. 2010). However, the once thriving Minkébé elephant population has been reduced by ~25,000 individuals due to poaching (Poulsen et al. 2017).

The most striking recent finding is that the Congo Basin contains the world's largest tropical peatland complex (Dargie et al. 2017). Approximately half of the Cuvette Centrale wetland area forms peat. In many locations, the high organic matter input from the forest into the soil, coupled with waterlogging impeding decomposition, has led to peat deposits slowly building up over thousands of years, forming peat soil beneath the forest (Dargie et al. 2017). These peat swamp forests are exceptionally high-carbon storage ecosystems. They are also vulnerable to a loss of this carbon if the peat dries, since decomposition processes accelerate and the carbon in the peat is released to the atmosphere (Dargie et al. 2017; Garcin et al. 2022).

The most recent ground-verified estimate indicates that there are 167,600 km^2 of peat swamp forest in the central Congo Basin, representing 36% of the world's tropical peatland area (Crezee et al. 2022). Peat is found in both interfluvial basins (Dargie et al. 2017), which form peat-domes (Davenport et al. 2020), and in river valleys in the Cuvette Centrale (Crezee et al. 2022). The interfluvial peatlands appear to be waterlogged due solely to topography and rainwater, while the river valley peatlands include water from adjacent rivers, and run-off from adjacent higher ground (Georgiou et al. 2023). Peat depth is shallow at the edges, becoming consistently deeper with distance from the peatland edge (Crezee et al. 2022). The maximum peat thickness was 5.9 m, found in the center of a large interfluvial peatland (Dargie et al. 2017). Peat has been accumulating for at least 20,000 years in places (Garcin et al. 2022; Hawthorne et al. 2023), with ages of more than 10,000 years documented in several locations across the region (Dargie et al. 2017). These findings have transformed scientific understanding of central Congo

Basin wetlands and reveal that DRC and ROC are now the second and third most important countries in the tropics for peatland area, respectively, after Indonesia (Xu et al. 2018).

The forest overlying the peatlands is of three types. The most widespread is the hardwood swamp forest, in which *Uapaca paludosa*, *Carapa procera*, and *Xylopia rubescens* are often common, covering ~55% of the peatland area. The second is another common palm-dominated peat swamp forest dominated by *Raphia laurentii*, a trunkless palm with fronds that reach the canopy, covering ~44% of the peatlands. Finally, there is a much rarer (<1%) palm-dominated peat swamp forest, dominated by *Raphia hookeri* that occupies abandoned river channels (Dargie et al. 2017).

The newly mapped central Congo peatlands are estimated to store an average of 1712 ± 634 Mg C ha^{-1} in the peat (1 Mg = 1 metric ton), when extrapolating to the whole region, making the peatlands some of the most carbon-dense ecosystems on Earth (Crezee et al. 2022). The maximum estimate was 3970 Mg C ha^{-1}, which is approximately 20 times the carbon storage of the trees in a typical African humid tropical forest. In total, the peatlands are estimated to store 29.0 billion metric tons of carbon (Crezee et al. 2022). This is approximately 28% of the world's tropical peat carbon.

Peatlands have a long history of vegetation change. The first analyses of preserved pollen from peat cores show that peat began accumulating at the center of the interfluvial peatland ~19,600 calibrated years BP (Hawthorne et al. 2023). The peatland margins were much younger, initiating between ~9500 and 10,500 BP, suggesting that the peatland expanded over time. The peatland first formed in a grass- and sedge-dominated floodplain environment, with frequent fires, followed some seven thousand years later by a forest dominated by the genus *Manilkara* (~12,640 cal. yrs BP), then after a further three thousand years a transition to a more mixed swamp forest (~9670 cal. yrs BP), which stayed until the present day. Rainfall and/or its seasonality correlated with change in the species composition of the forest over this time. Thus, the peatland vegetation seen today is influenced by both succession and the annual extent and level of waterlogging (Hawthorne et al. 2023).

The globally important stock of carbon in peat is more vulnerable to release into the atmosphere because the region is only just sufficiently wet to accumulate peat, unlike, for example, the peatlands in the Peruvian Amazon or in Southeast Asia which occur under much wetter climates (Garcin et al. 2022). Therefore, environmental changes that reduce rainfall, increase rainfall seasonality, or increase temperatures could reduce the water table allowing the peat to dry out (Young et al. 2023). Such drying would result in an increase in the decomposition rate of the peat, with oxidation occurring and carbon being released to the atmosphere. This has happened in the past. The hydroclimate history of the region has been determined using preserved plant waxes from peat cores from the central Congo Basin. The hydrogen isotopes of plant waxes indicate whether they were formed during wetter or drier conditions. These analyses indicate a drying trend from ~5000 cal. yrs BP until about 2000 cal. yrs BP (Garcin et al. 2022). This occurred at the same time as evidence of a major loss of peat, documented as only very decomposed peat remaining, and a lack of peat thickness remaining at the site at that time (Garcin et al. 2022). There was

also a switch from the dominance of swamp forest species to forest species associated with drier conditions (Garcin et al. 2022; Hawthorne et al. 2023). The authors suggest that as the climate dried, there was a regional drop in the water table, resulting in a near-complete mineralization of several meters of previously accumulated peat. Subsequently, the drier conditions abated, at ~2000 BP, and the peatland stabilized, with peat accumulation resuming and typical swamp forest species becoming abundant again, all conditions that continue to the present day (Garcin et al. 2022; Hawthorne et al. 2023; Young et al. 2023). The drought event and peat carbon loss, likely related to Earth axial precession, shows the ecosystem's high sensitivity to changes in precipitation and/or its seasonality.

Savanna Ecosystems

The largest savanna systems in Central Africa occur at the margins or as large incursions into the forest block (Fig. 1). Savannas to the north of the forest block are part of the Guinea-Congolia/Sudania Regional Transition Zone, while those to the south are classified as Guinea-Congolia/Zambezia Regional Transition Zone (White 1983). This vegetation has been shaped over time by both climatic and anthropogenic factors (e.g., fire). Savannas provide important ecosystem services, from livelihoods to cultural values and biodiversity. However, they remain poorly understood as they were previously considered as degraded areas rather than the ancient and biodiverse savannas (Bond 2016).

Savannas vary in age and have responded to many human and climatic processes (Oslisly et al. 2013). While those of the Plateaux Batéké (stretching from Gabon, across ROC to DRC) are estimated to have first formed 30,000 to 70,000 years BP (Schwartz 1988), other savannas are younger. The savannas in the Mouila-Ndende (Gabon) area are thought to have been present 20,000 years BP, then converted to forest, only to reappear 6000 years BP (Schwartz and Lanfranchi 1991). Those of Lopé and Mouila-Ndendé (Gabon) likely reformed about 2500 years BP during a dry climatic period (De Foresta 1990; Maley et al. 2018). However, those of Lopé's savanna marshes (Gabon) could be as old as 9000 years (Bremond et al. 2021) and represent a large enclave of savanna contained within the forest block. Coastal savannas of Gabon originated approximately 3000 years ago and were colonized by *A. klaineana* and *Sacoglottis gabonensis* over large areas (Delègue et al. 2001). The littoral savannas situated directly behind the beach are also in part formed by changing sea levels, with former beaches now located just inland in long dunes, parallel to the sea (Giresse and Kouyoumontzakis 1990).

Recent research on African savannas provides evidence of their ancient origins (Bond 2016). These biomes often have species compositions that are influenced by anthropogenic and natural fire regimes (Demichelis et al. 2020). These old-growth savannas are characterized by high herbaceous species richness, high endemism, and unique communities (Veldman et al. 2015) and can be distinguished by the presence of endemic pyrogenic geoxylic suffrutices that form underground forests and/or forbs with underground storage organs or flowering stimulated by fire (Bond and

Zaloumis 2016). These indicators have been found in the Plateaux Batéké savannas (Walters et al. 2022), but other Central African savannas remain to be studied.

Forests and savannas co-exist as alternative stable states in Central Africa even under the same rainfall regime (Aleman et al. 2020). In general, climate fluctuation between arid and moist periods favored savanna and forest expansion at different times. An arid period favored savanna formation 40,000–70,000 years BP, followed by a wet period of "forest revival" around 30,000 years BP, then by an arid period until 18,000 years BP where savanna resurged, and finally by a wetter period 3000 years BP (Giresse 1978). Overall, for the past 1000 years, savannas in southern ROC and northwestern and central Cameroon have largely been stable while others have shown changes in forest island density with a few converting from savannas with forest islands to forests with savanna islands (Giresse et al. 2023).

Encroachment of the forest into savanna is active in southern and central Cameroon (Sagang et al. 2022), in the coastal forest of ROC (Favier et al. 2004) and at the forest edge of the Plateaux Batéké in Gabon (Walters 2010). Forest advances into Congolese Mayombe savanna have occurred at a rate as high as 50 m per century (Schwartz et al. 1996). Fire slows forest progression but does not stop it and active protection of the forest edge can speed up forest colonization (King et al. 1997). Management fires in humid savannas are not able to stop forest colonization in the Lopé (Jeffery et al. 2014) and ecotonal forests stop fire spreading from the savanna into the forest (Cardoso et al. 2021).

Despite the presence of large savanna kingdoms along coastal Central Africa, including large urban centers of the Loango Kingdom, and the associated smelting processes which required wood, Giresse et al. (2023) found no evidence that human presence led to changes in vegetation. Their synthesis further shows that over the past 1000 years, Central African forests and savannas have been long inhabited and have undergone local disturbance, except for the forest crisis of 2600 years BP (White and Oates 2001).

Beyond climate, fire is an important factor shaping savannas. Fire structures the savanna woody vegetation including recurrent fires creating cooler fire regimes which favor increased tree growth, maintaining its open habitat, and dominant, fire-dependent tree species, such as *Hymenocardia acida* in the Batéké Plateaux (Walters 2012). Savannas contain species with fire-related traits such as fire-resistant tree bark and underground storage organs that release leaves post-fire (Menaut 1983; White 1993) and post-fire resprouting (Lamont and Downes 2011). Forb diversity varies across savannas (Walters 2012) with some being fire dependent (Walters et al. 2022). Herbivory by native and domesticated browsers also plays a role in shaping many savannas. Cattle densities can be high in some areas of Central Africa, where people such as the Fulani have high stocking rates (Boutrais 1994). In other savannas of Central Africa, buffalo (Taylor et al. 2023), duikers, and elephants play stronger roles.

Riparian and Freshwater Ecosystems

During the Cenozoic Era (66 Ma, i.e., million years ago), the evolution of the Congo Basin was significantly marked by tectonic uplift and climatic changes that

influenced its landscape and hydrology. The Early Miocene epoch (23–16 Ma) was marked by warm and humid conditions favorable for extensive wetlands, shaded rivers, and a much more cosmopolitan continental ichthyofauna. During this time, the hydrological systems were predominantly stable, with rivers and lakes maintaining relatively consistent water levels due to abundant precipitation, which supported various aquatic habitats.

The Middle Miocene Epoch (16–11 Ma) saw profound changes, particularly with the Congo River's headwaters shifting southward, which reorganized existing drainage patterns and diverted river systems such as the Fwa and Inkisi (Flügel et al. 2015). This period also corresponded with increasing sedimentation rates driven by climatic fluctuations, enhancing erosion and reshaping the geological configuration of the basin (Guillocheau et al. 2015). There was a marked retraction of rainforests and emergence of more open savanna landscapes, indicative of increasing aridity (Couvreur et al. 2021; deMenocal 2004; Plana 2004). This transition influenced hydrology by altering river flow patterns and lake levels, potentially leading to the abandonment or rerouting of certain river courses and changes in wetland extents, thereby impacting the habitats available for aquatic species (Lévêque 1997). In approximately the Middle Miocene, the Central African Atlantic Swell formed a low mountain range stretching from South Cameroon to South ROC (Guillocheau et al. 2015; Schefuß et al. 2016) contributing to the divergence of Lower Guinea and Congo freshwater fauna (Lévêque and Paugy 2017).

Simultaneously, the Albertine Rift, located along the western margin of the East African Rift System, played a critical role during this period (Guillocheau et al. 2015). The ongoing tectonic activity caused notable uplift and volcanic activity in the region, which directly influenced the hydrography of the Congo Basin and surrounding areas (Guillocheau et al. 2015). Initially, by the Late Miocene (11–5 Ma), the area that would become Lake Tanganyika was characterized by a mosaic of shallow, temporary lakes, and wetlands instead of a singular, large lake basin (Cohen et al. 1997). Global cooling began to take hold, contributing to further aridification. Precipitation patterns became more erratic, leading to lower water levels in rivers and lakes, which may have resulted in seasonal wetlands and increased isolation of aquatic environments (Cohen et al. 1997). This drying trend would have introduced new ecological dynamics, as species adapted to fluctuating water availability, shifting the evolutionary pressure on aquatic organisms.

Transitioning into the Pliocene (5.3–2.6 Ma), the uplift of the Congo and Angolan margins accelerated, facilitating extensive geomorphic transformations (Savoye et al. 2009). Tectonic uplifting activities in the Albertine rift (Lezzar et al. 2002) severed an east-west river linking the eastern Congo basin from the Tanzania plateau, the remnants of which can be seen in the Lukuga and Malagarasi rivers, respectively West and East of lake Tanganika (Cohen et al. 1997; Goodier et al. 2011). The favorable conditions of this era supported the expansion of tropical rainforests, which likely contributed to a rise in water levels across various lakes and rivers (Runge 2022; Weiss et al. 2015). The enhanced rainfall conditions resulted in more substantial hydrological connectivity among various water bodies, facilitating the movement of aquatic species and likely reducing isolation among populations (Van Steenberge et al. 2020).

By the Late Pliocene, the region's uplift had caused approximately 500 m of elevation changes (Goodier et al. 2011). This uplift contributed further to the intricate topography of the basin, altered precipitation patterns leading to the establishment of incised valleys and a more complex network of river systems reflecting both dendritic and linear characteristics. The Pliocene-Pleistocene transition introduced increased climatic variability characterized by glacial and interglacial cycles (deMenocal 1995; Plana 2004). The consequent fluctuations in climate had significant effects on the hydrology of the Congo Basin, leading to oscillating lake levels and changing river flows over time. During wetter periods, rivers could expand and create extensive floodplains and wetlands whereas during drier phases, lakes and rivers might have receded or fragmented, resulting in isolated pockets of water that acted as refuges for various freshwater species (Bragança and Costa 2019). The Pleistocene (2.6–0.012 Mya) witnessed ongoing adjustments to river channels due to tectonic influences associated with the East African Rift system, enhancing the sensitivity of these systems to geological disruptions (Guillocheau et al. 2015). By the Late Pleistocene, the three main basins that had existed since the Miocene had coalesced to the modern single basin of Lake Tanganyika (Weiss et al. 2015).

The origins of the Congo River can be traced back to earlier configurations, which were defined during periods when the basin was shaped by both tectonic activity and climatic regimes conducive to sediment deposition and erosion (Guillocheau et al. 2015). Importantly, for reconstruction of historical biogeography there is considerable ambiguity concerning the events and chronology forming today's main channel of the Congo River (Stankiewicz and de Wit 2006; Takemoto 2023). A vast body of literature, much outside the public domain, supports unequivocally the existence of a river flowing into the Atlantic at or near the present-day outlet for the past 30 mya (Burke et al. 2008). There is some disagreement of whether the antecedent river emptied into the sea 200 km North (Karner and Driscoll 1999; Uenzelmann-Neben 1998) prior to the Pliocene. The turbite sediment transport path of the Congo Fan attests that the Congo River fed into the Atlantic at its present course by the Early Pliocene (Anka et al. 2009).

Palynological records from the Congo fan provide further insights into the river's history and climate in the Congo Basin. These records indicate that the Congo River had assumed its present course by the Middle Pleistocene. The pollen data also reveal fluctuations in forest cover, with *Podocarpus* (Afromontane) forests expanding during cool, humid glacial stages (1.05–0.6 Ma) and swamp assemblages dominating during warmer inter-glacial periods. Megadroughts occurred at 135 and 75 kya that exceeded the aridity of the Last Glacial Maximum and a major rise in rivers at 70 kya (Dupont et al. 2001; Scholz et al. 2007). The blackwaters of the Cuvette Centrale formed only around 17.5 kya, highlighting the millennial-scale dynamics of landscape evolution that remain obscured for most of the Congo Basin.

Montane Ecosystems

Submontane and montane forest ecosystems represent about 2.8% and 0.8% of the forested area of the Congo Basin, respectively. They are found essentially in two

regions separated by about 2000 km at the western and eastern limits of the Congo Basin: (1) the Cameroonian Volcanic Line (CVL) stretching from the islands of the Gulf of Guinea to the Adamawa plateau in northern Cameroon and (2) the Albertine Rift situated across the border between DRC, Uganda, Rwanda, Burundi, and Tanzania (Fig. 3, areas above 1000 m elevation).

Montane forests of Cameroon are part of the West Africa Biodiversity Hotspot (Myers et al. 2000). These forests are not only exceptional for their plant richness and endemism, but also for their faunal diversity (Denys et al. 1999; Muafor et al. 2011). In addition, they provide a wide range of ecological services, vital for local populations as a source of water, and offer many forest products such as firewood, timber, medicinal plants, and fruits (Fogwe and Kwei 2015). Afromontane forests are patchily distributed, bounded at higher elevation by Afroalpine grasslands and an ericaceous belt, and at lower elevation by sub-montane forests and savannas, which form the transition between lowland rain and seasonal forests. *Podocarpus latifolius*, the emblematic tree of these Afromontane forests, is found between 850 and 2900 m altitude on the CVL, where it can form large monospecific stands, as on Mount Oku (the Kilum-Ijim forest). It is also found on isolated massifs and inselbergs all along the west coast of Africa, from Angola to Cameroon/Nigeria, in populations rarely exceeding a few dozen individuals. Located within or on the fringes of densely populated regions, Afromontane forests are at serious risk from anthropogenic pressure. For example, in Cameroon the Kilum-Ijim forest which covered 20,000 hectares has lost 62% of its area, which was converted into cropland and became increasingly fragmented between 1978 and 2001 (Solefack et al. 2012).

Montane forests of Cameroon have long been considered as contemporary relicts occupying refugial areas in response to an exceptionally favorable climate in the recent past (White 1993). Based on the presence of distant populations of *Podocarpus*, White (1981) postulated a connection between East, South, and West African Afromontane forests. Recent genetic studies confirm past connections between East and West Africa (Migliore et al. 2022) but also show a barrier to gene flow across the Equator in western Central Africa.

The vegetation history of the montane forests is better known than that of the lowland forest of the Congo Basin because many montane forests are found in regions where volcanic crater lakes offer ideal conditions to accumulate pollen in their sediments, providing continuous pollen records up to about 90,000 years (Lézine et al. 2019). Late Quaternary pollen data (Lézine et al. 2019, 2023) in the northern sector of the CVL point to the long-term persistence of montane populations with fluctuating sizes according to climate change: expansion during interglacial periods and reduction during glacial maxima. They show that the upper tree line was particularly unstable, shifting substantially in response to climate change, whereas the transition between the montane and lowland forests remained remarkably stable. In the southernmost sector of the CVL (Lézine et al. 2025), a slightly different scenario emerges with *Podocarpus* populations comparatively slightly more developed during the last glacial and dramatically reduced during the Holocene. Interestingly, *Podocarpus* is today absent from the Manengouba Massif and Mount Cameroon. Only relict, poorly developed, populations persist in

this sector such as in Mount Kupé and the Ebo forest of Cameroon. A similar evolution seems to have occurred in some areas of the Congo Basin, such as in the Bois de Bilanko in Congo (Elenga and Vincens 1990), where forest trees (*Podocarpus*, *Olea*, *Ilex*) may have spread to low elevations during the last glacial and then disappeared during the Holocene. However, no such environmental change is recorded in the glacial sequences of Ngamakala in Congo (Elenga et al. 1994), showing that the biodiversity of the central forest massif was far from homogeneous at that time. Marine cores (Dupont et al. 2000) also note the presence of *Podocarpus* populations during the last climatic cycle in equatorial West Africa but point to strong regional disparities. While a remarkable and continuous expansion of *Podocarpus* populations is recorded in Gabon except for the Holocene (core GIK 16876), successive phases of development/contraction of *Podocarpus* populations are recorded in Congo (core GeoB 1008).

All these cores show that, despite major changes in diversity, the Central African forest has not undergone major phases of retraction during the last climatic cycle. It is only at the edge of the forest massif to the north (lakes Bosumtwi in Ghana (Talbot et al. 1984) and Barombi Mbo in Cameroon (Maley and Brenac 1998) that the massive expansion of grasslands at the expense of the forest during the last glacial is recorded. These results partly confirm the hypothesis (Aubreville 1949) that the northern limit of the Guineo-Congolian forest may have shifted southward during the last Ice Age.

In response to the abrupt increase in rainfall at the last glacial-interglacial transition (Weldeab et al. 2007), montane forests gradually developed to reach an optimum between 9.5 and 8.5 ka (Lézine et al. 2025). The Holocene forest expansion lasted until 3.3–3.0 ka, depending on altitude, when montane forests collapsed (Lézine et al. 2013). This collapse most certainly originated in the Middle Holocene, when rainfall seasonality was established (Vincens et al. 2010), resulting in the gradual destabilization of the forest block. While montane forest has partially recovered from the 3.3 ka environmental crisis at higher altitudes, this is not the case on the Adamawa plateaus, where montane forest has massively retreated. In the lowlands, the impact of this crisis was more a change in forest composition and density than the replacement of forests by a grass-dominated landscape (Vincens et al. 1999). This conclusion was recently confirmed by isotopic studies on soil profiles from Cameroon (Desjardins et al. 2020) and in the Congo basin (Bremond et al. 2017).

During the last few millennia, the forest cover remained roughly unchanged in the lowlands of the central forest massif (Lézine et al. 2023). In contrast, both high- and low-elevation sites from the western sector of the equatorial forest show a marked forest recovery that began in the early years of the little ice age and accelerated around 1450 CE. The forest expansion in this region occurred despite increased human presence. In the absence of sufficient archaeological and paleo-botanical data, the impact of neolithic populations on the natural environment is still the subject of intense debate. It is however probable that rather than a massive destruction of forest, people have used periods of climate-induced clearance events to develop agriculture (Ngomanda et al. 2009; Lézine et al. 2013).

Bais and Other Rare Ecosystems

In addition to major ecosystems, the Congo Basin hosts relatively rare ecosystems stretching over narrow areas but hosting a unique flora and/or fauna, such as inselbergs (Parmentier et al. 2005), cave systems (Labadie et al. 2025), mangroves (Ajonina et al. 2008), and swampy forest clearings or baïs. Generally in Central Africa, the term "baï" is used by indigenous peoples of the region to describe this environment. This term bai is now widely used to describe these forest clearings.

These botanically remarkable azonal biotopes are a real magnet for forest fauna. For example, at Langoué in the south of the Ivindo National Park (Gabon), the Wildlife Conservation Society has recorded nearly 1080 elephants and 52 gorillas that regularly visit the clearing. One of the largest and best known bais is Dzanga Bai (CAR) has been the site of long-term elephant studies spanning several decades. These clearings thus offer the opportunity to study large mammal behavior and represent a vital asset for the development of ecotourism.

Deuse (1960) carried out the first ecological and phyto-sociological study of the esobe vegetation in the eastern region of Lake Tumba. This study distinguished a number of groups and associations. An open-water aquatic grouping, with a depth of between 10 cm and 1 m and a bottom composed of muddy peat. A semi-aquatic group characteristic of the lower parts of the esobe that are periodically flooded. An exundated peaty grouping that develops at the head of springs and in the beds of the streams that flow from them. A *Rhynchospora corymbosa* association that is established on waterlogged peat of around 50 cm and forms tight clumps. An association between *Bulbostylis laniceps* and *Xyris vanderystii*, which is established on firm peat, 10–50 cm thick. An association between *Stipularia africana* and *Syzygium* aff. *cordatum*, a shrubby formation scattered along the small watercourses of the baï.

More recently in ROC, Lejoly and Lisowski (1997) carried out a study of the vegetation of clearings on hydromorphic soil in Odzala National Park and described three new associations and one grouping. In Gabon, no in-depth botanical study had yet been carried out on these particular biotopes until Temgoua (2006) carried out a detailed characterization of marshy clearings in the Ivindo National Park. More recently, Boupoya (2010) completed his thesis on the flora and vegetation of these environments in Ivindo National Park, identifying 229 species in 175 genera and 72 families across 133 phyto-sociological surveys. The overall flora of the clearings is dominated by Cyperaceae, Rubiaceae, and Fabaceae.

Biodiversity Patterns

Species Distribution Models

The Congo Basin contains more than 10,000 plant species, among which at least 2264 are tree species, 1966 shrub species, 1384 liana species, and 3510 herb species (Sosef et al. 2017). About 30% of those species are endemic to the Congo Basin.

Although plants and vertebrates are the best studied organisms, the degree of botanical exploration shows many geographical gaps, in particular in some countries like ROC, CAR, and large areas within DRC (Sosef et al. 2017). Therefore, new species are regularly described (Lachenaud et al. 2018), and genetic markers can greatly help to delimit closely related species, for example, in trees (Bouka et al. 2024; Dainou et al. 2014). It is likely that the majority of extant species in the Congo Basin have been formally described for groups like plants, birds, and mammals. However, this is probably not the case for arthropods (Stork 2018). Therefore, huge efforts are still needed to describe existing species of the Congo Basin.

The geographic distribution of species varies widely from widespread species to narrow endemic species. For example, Texier et al. (2022) have shown that about 15% of the endemic flora of western central Africa has a known range size of less than 10 km^2. Species distributions depend on numerous factors, but a few interlinked factors are particularly important: (i) the distribution of the habitat(s) to which the species is adapted, (ii) the species dispersal ability in relation to potential barriers to dispersal (oceans, mountains, rivers, savannas), (iii) species interactions (e.g., prey-predator relationships, diseases, parasitic relationships but also mutualisms like plant-pollinator, plant-seed disperser, or plant-mycorrhizal relationships, which can be more or less specific and obligatory), and (iv) the history of environmental and biotic factors affecting the distribution of a species.

In the Congo Basin, many species are adapted to only one of its constituent ecosystems (e.g., lowland forest, montane forest, savannas, etc.), and sometimes to a particular component of an ecosystem (e.g., periodically inundated forest). The distribution of species with good dispersal and competitive abilities tends to follow quite closely the distribution of habitats to which they are well adapted and can be modeled reliably using gridded environmental layer data like Climate Research Unit (Harris et al. 2020) or WorldClim (Fick and Hijmans 2017). However, species with poor dispersal abilities, or adapted to a highly fragmented habitat type (e.g., montane ecosystems), may only occupy a subset of their potential habitats. The distribution of forest species with limited dispersal ability, such as *Begonia* plants, can potentially reveal the position of Pleistocene forest refugia (Sosef 1994). Even within the relatively continuously distributed lowland forest of the Congo Basin, barriers like major rivers can delimit the range of some species including many primates and artiodactyls (Anthony et al. 2007; Colyn et al. 2001; Fonteyn et al. 2023; Kingdon 1989). By contrast, rivers usually do not represent major barriers for plant species. Finally, given that environmental conditions are always changing, though at varying paces, species ranges are not explained by the current distribution of habitats or barriers but by past environmental and biotic conditions so that their current ranges reflect just a moment in their slow colonization or retreat. For such cases, species distribution models must be interpreted cautiously as they can miss the actual drivers of a species' range.

Community Patterns of Diversity

Species assemble in communities whose composition depends on different ecological and evolutionary processes (Chesson 2000; Thompson et al. 2020;

Vellend 2010). Among the main drivers of species assemblages are (i) selection through habitat filtering, (ii) biotic interactions (competition, predation, parasitism, mutualism), (iii) dispersal, and (iv) ecological drift (stochastic fluctuations of population sizes due to their finite size). At deep temporal scales, speciation and adaptive evolution also matter, constituting the ultimate sources of diversity. The development of large public databases of species occurrences (e.g., GBIF, https://www.gbif.or) has benefitted from better quality controls (Brooks et al. 2001) for African vertebrates (Dauby et al. 2016) for African plants and has greatly facilitated large-scale community ecology studies (Silva de Miranda et al. 2022). A big challenge to addressing the ecology of species-rich communities is that there is little knowledge of species' individual ecology, making it difficult to understand the proximal mechanisms underlying species assembly. Functional ecology and the analysis of phylogenetic structure of communities can circumvent this challenge to some extent.

Studies in the Congo Basin generally highlighted the importance of environmental filtering, for example, in fishes (Walsh et al. 2022). The analysis of functional traits and their inter-correlation can also reveal a continuum of opposing strategies favoring coexistence through niche partitioning. For example, in rainforest trees, large-statured, light-demanding, deciduous and wind-dispersed species dominating the canopy coexist with small-statured, shade-tolerant, evergreen and animal-dispersed species found in the understory (Loubota Panzou et al. 2018). Tree species with the most original functional traits tend also to be the rarest so that the analysis of functional traits can guide conservation priorities to favor functional originality rather than redundancy (Kearsley et al. 2019).

Community phylogenetics integrates phylogenetic relationships among species into the analysis of communities. When species assemblages are mostly driven by environmental filtering, we expect that related species will tend to occur in the same habitats, a pattern known as phylogenetic clustering, while if competitive exclusion dominates, we expect the most related species to exclude each other, leading to a pattern known as phylogenetic overdispersion (Hardy and Senterre 2007). Species phylogenies are much easier to obtain thanks to advances in DNA sequencing tools and access to public DNA databases (e.g., GenBank) and large DNA-based phylogenies for some broad taxonomic groups, like angiosperms (Janssens et al. 2020). The most often encountered pattern in the Congo Basin is a phylogenetic clustering of species in local communities, suggesting that habitat filtering is more important than competitive exclusion, at least in plants (Hardy and Senterre 2007; Parmentier and Hardy 2009; Parmentier et al. 2014). Broad-scale patterns of phylogenetic diversity can also identify areas where paleo- or neo-endemism occurs. For plants, the Guineo-Congolian lowland rainforest region is characterized by widespread and old lineages while mountainous areas are centers of both neo- and paleo-endemism (Dagallier et al. 2020), highlighting the importance of conserving their unique biodiversity where evolutionary processes are very active. Finally, community phylogenetics reveals the legacy of evolutionary constraints: studying tropical African woody species, Gorel et al. (2022) showed that most forest and savanna species were adapted to one of six bioclimatic subgroups, wet forest, moist forest, dry forest, cold savanna, hot savanna, and a coastal group intermediate between

forest and savanna groups. Despite a general trend of climate niche conservatism during speciation over the last 50 mya, biome shifts occurred from forest to savanna in about 5.2% of cases and from savanna to forest in about 1.8% of cases, indicating that most woody lineages originate from the forest biome, probably because the rainforest was much more widespread in Africa for most of the Cenozoic before the Pleistocene (Kissling et al. 2012). Furthermore, climate niche was much more labile in some families (e.g., Fabaceae and Rubiaceae) and some genera (e.g., *Combretum*, *Ficus*, *Cola*) and highly conserved in some large clades, like the order Magnoliales, which rarely adapted to savanna (Gorel et al. 2022).

Drivers of Diversity Patterns: Pleistocene Refugia, Riverine/Landscape Barriers, and Environmental Gradients

In an era of unprecedented anthropogenic environmental change, informing conservation strategies with an understanding of the mechanisms that drive population structure and the formation of new species is vital. Conservation strategies should aim to preserve the evolutionary processes that generate and maintain this genetic variation. The hope is that some of the genetic variation those processes have produced will enhance species' "evolvability," i.e., ability to mount an *in situ* evolutionary response to threats like climate warming and habitat disturbance.

The evolutionary processes responsible for speciation in African rainforests have continued to engender debate (Moritz et al. 2000b). Typically, these discussions have centered on the importance of geographic isolation versus ecological gradients. Historically, emphasis was focused on isolation driven by lowland glacial refugia (Haffer 1969; Mayr and O'Hara 1986). Notably, the role of Pleistocene glacial refugia (Fig. 4) in isolating previously contiguous rainforest populations and driving rainforest diversification (Haffer 1997). Other allopatric speciation models included isolation on mountains during glacial periods (Fjeldsa and Lovett 1997; Moreau 1966; Roy 1997) or major riverine barriers to gene flow (Moritz et al. 2000b).

Lacking, however, are attempts to distinguish the actual mechanism(s) of divergence and speciation. Typically, if divergence was found in allopatry, genetic drift was assumed to be the likely cause (Roy 1997), though selection might be an equally parsimonious explanation. Moritz et al. (2000a) emphasized the importance of testing alternative mechanisms, including measuring the relative roles of selection and drift in promoting divergence and speciation.

In addition to the role of geographic isolation in allopatric speciation, there is mounting evidence for the role of natural selection along environmental gradients in driving ecological speciation. Early studies (Endler 1982a, b; Gentry 1989) emphasized the dominant role of natural selection in parapatry—in which adjacent populations inhabit different environmental regimes—might play in rainforest speciation. Empirical studies that followed showed evidence in a wide array of taxa (Ogden and Thorpe 2002; Orr and Smith 1998; Schluter 2009). Studies suggesting that parapatric speciation along environmental gradients may be common are further bolstered by theoretical models showing that this mode of speciation can readily

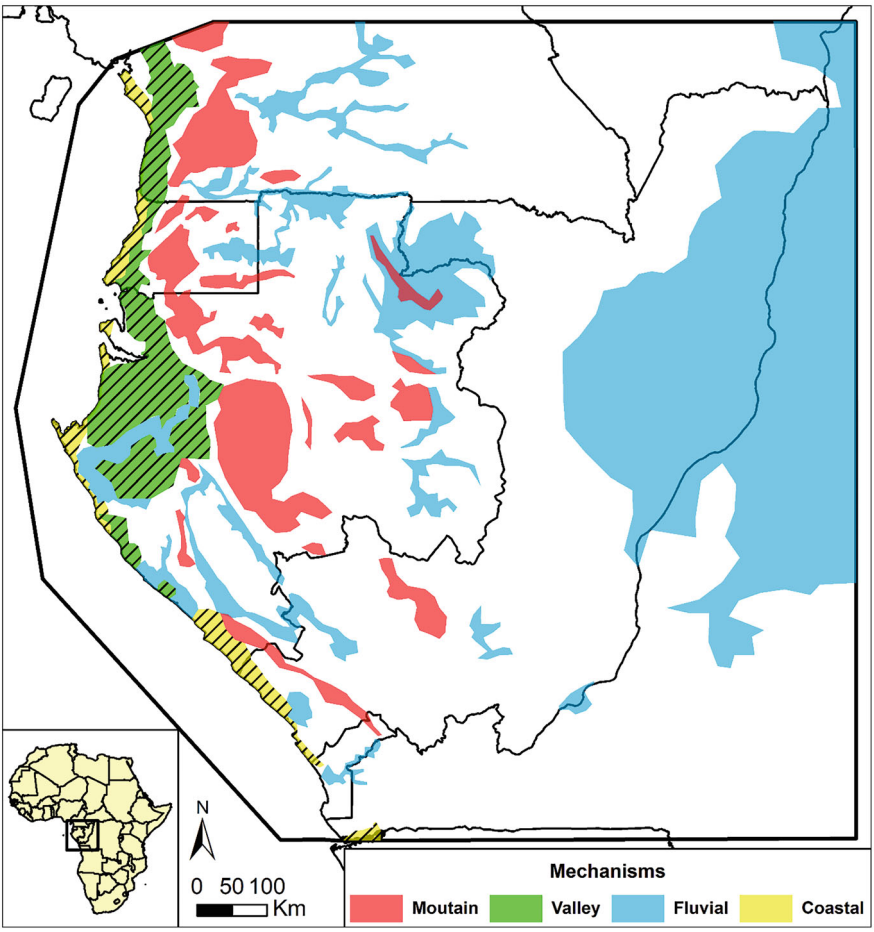

Fig. 4 Putative schematic locations of forest refugia in western Central Africa during the Last Glacial Maximum. The four colors indicate the main hydrological mechanism on which the existence of putative forest refugia is based and the hatched parts symbolize territories where only microrefugia would have persisted over a small surface of the colored part. (Adapted from Texier (2021))

occur (Doebeli and Dieckmann 2003; Gavrilets et al. 2000). Hindering progress is a lack of robust tests of these competing hypotheses. The importance of allopatric and parapatric speciation may depend on time scales and the type of organisms. Moreover, geographic isolation and selection can act together, such as in the "vanishing refuge model" (Barratt et al. 2018; Couvreur et al. 2021), where climate change would firstly isolate a population in a temporary micro-refugium and then force adaptation to new environmental conditions, eventually leading to speciation.

African rainforests are severely at risk due to a myriad of anthropogenic threats, including climate change. This makes addressing this long-standing debate critical

for making informed conservation decisions. Genetic studies of diverse African rainforest species, including birds (Smith et al. 2000; Zhen et al. 2017), mammals (Anthony et al. 2007; Gonder et al. 2011; Ntie et al. 2017), reptiles (Allen et al. 2021; Freedman et al. 2023), amphibians, and plants (Hardy et al. 2013; Jongsma et al. 2018), have revealed varying degrees of population structure. Rough geographic concordance between patterns of genetic differentiation and hypothesized rainforest refugia are used to support arguments for allopatric isolation in ancient forest refugia as the primary generator of rainforest biodiversity. However, only a few studies have attempted to test the refugial model's fit to genome-scale data (Barratt et al. 2018; Jaynes et al. 2022; Pineiro et al. 2017). Moreover, molecular clock estimation of population divergence are often much more ancient than the last glacial cycle and can vary greatly (Matvijev et al. 2022; Migliore et al. 2020; Pineiro et al. 2021), even among species displaying similar phylogeographic structures (Demenou et al. 2020), so that it is usually not possible to assess whether populations diverged in response to glacial cycles or other drivers. At the inter-specific level, dated species phylogenies of plant and animal taxa indicate that diversification occurred mostly from the Late Miocene to Pliocene (Couvreur et al. 2021), so that the contribution of Pleistocene climate change to the species diversity today would be restricted to a few clades, for example, in some mammals, e.g., fruit bats (Nesi et al. 2021), forest duikers (Johnston and Anthony 2012), cercopithecine monkeys (Guschanski et al. 2013), and a few plants, e.g., *Begonia* (Plana 2004).

Although there is direct pollen evidence from oceanic cores that major vegetation changes in the Congo Basin followed the glacial-interglacial rhythm, at least since 1.05 million years (Dupont et al. 2001), the hypothesis that the lowland forest of the Congo Basin was fragmented during the Pleistocene glacial periods has been mainly supported by indirect evidence. Moreover, the impact of low atmospheric CO_2 concentration during the glacial peaks is also difficult to establish due to the absence of similar conditions in today's vegetation (Dupont et al. 2001). There is some support for the periodic fragmentation of rainforest into refugia from palaeoecological studies (Anhuf et al. 2006; Maley 1996; Maley and Brenac 1998), detailed plant genetic investigations, and current distribution patterns of areas of endemism of forest plant taxa (Sosef 1994; Texier 2021). Texier (2021) explored different mechanisms maintaining rain or moist forests during glacial periods based on the accessibility of water to plants through shallow water tables and low stratiform clouds in drier climates, suggesting that in addition to some permanent forest blocks such as those proposed by Maley (1996, 2001), many areas in Lower Guinea could have remained suitable for forest species, possibly within forest-savanna mosaic landscapes. It should be stressed however that claims for the importance of refugia in the diversification of forest taxa have often been made despite few efforts to examine possible roles of environmental gradients, genetic divergence by environmental variation, or analyses of adaptative phenotypic variation. An alternative hypothesis, namely, parapatric speciation (Smith et al. 1997), cannot be adequately tested without such data. Consequently, the refugia hypothesis can become an implicit null model without the evidence to justify it. For speciation along the African rainforest-savanna gradient, evidence has been indirect and often

many decades old and based on data such as the frequency of contact zones between forest and savanna habitats versus those between refugia (Endler 1982a, b).

In contrast, many recent studies have found that divergent natural selection across environmental gradients may be an essential generator of African rainforest biodiversity (Freedman et al. 2023; Smith et al. 1997; Zhen et al. 2017). These studies rely on either differentiation in phenotypic traits involved in local adaptation or evidence for isolation-by-environment or IBE (Wang and Bradburd 2014), in which allele frequency-environment correlations cannot be explained solely by geographic distance alone. While these studies indicate diversifying natural selection may contribute to an ongoing process of genomic divergence, none of them have demonstrated that speciation across the gradient has occurred. However, a recent study that employed a panel of tens of thousands of SNPs found evidence for speciation along the rainforest-savanna gradient in a rainforest lizard that was likely driven by local adaptation (Freedman et al. 2023). More integrative investigations across multiple species are needed to elucidate general patterns concerning the role of local adaptation via diversifying selection and to disentangle adaptation from isolation such as that which might arise in putative refugia. General patterns concerning the relative contribution of adaptation, isolation via refugia, and divergent selection among refugial represent a gap in our knowledge of the mechanisms that generate and maintain biodiversity in African tropical forests.

Several other alternative historical scenarios of diversification and speciation of rainforest and savanna taxa have received relatively little attention but should be the focus of future studies. For example, there is limited evidence to suggest that the isolation of savanna remnants during warmer interglacial periods may have played a role in driving intra-specific diversification in central African grassland rodents (Mboumba et al. 2011). Similarly, the role of the seasonal inversion in rainfall patterns either side of the equator in driving species diversification has been documented in plants but has received little attention in other central African taxa (Hardy et al. 2013; Helmstetter et al. 2020; but see Blatrix et al. 2017). There is also a general lack of knowledge of the role that riparian areas could have played in providing microrefugia during drier glacial periods (Leal 2001, 2004) and deserves further attention.

Evolutionary-Informed Approaches to Conservation Decision-Making

Phylogenetics and Phylogenomics

Phylogenetic systematics is the study of evolutionary relationships between organisms and has been applied to a wide range of issues such as resolving taxonomic issues, estimating phylogenetic diversity, dating species radiations and inferring evolutionary specific units or ESUs (Avise 2000; Ksepka et al. 2015; Pellens and Grandcolas 2016). Phylogenetic methods have also been used extensively to map the geographical distribution of evolutionary lineages (phylogeography) and infer

biogeographical history (Avise 2008; Matvijev et al. 2022). Although molecular phylogenies have traditionally been based on a handful of markers, there is increasing interest in using genome-wide approaches (phylogenomics) to more accurately estimate phylogenies. Lastly, DNA sequence data has been used in DNA barcoding approaches to identify species from reference databases and in DNA-based surveys of environmental samples (DeSalle and Goldstein 2019).

Phylogenetic analyses of species radiations within the Congo basin have been carried out in a wide range of taxa. Africa was an island continent from the mid-Cretaceous to early Miocene leading to approximately 75 million years of isolation and a complex migration history (Gheerbrant and Rage 2006). A number of groups that either originated or are endemic to the Congo Basin region include mammals within the superorder Afrotheria (Springer et al. 1997; Stanhope et al. 1998), artiodactyls (Johnston and Anthony 2012; Rakotoarivelo et al. 2024), birds (Huntley et al. 2018; Huntley and Voelker 2016; Nana et al. 2014), rodents (Nicolas et al. 2005; Pradhan et al. 2021), crocodilians (Shirley et al. 2014), and amphibians (Blackburn 2008; Zimkus et al. 2010). Despite its lower plant diversity compared to the Neotropics or South-East Asia, tropical Africa also hosts many plant lineages that diversified locally (Couvreur et al. 2021; de la Estrella et al. 2020; Ojeda et al. 2019).

Species radiations associated with CVL, Albertine Rift, and Eastern Arc mountains have also been documented and are associated with high levels of endemicity (Cable and Cheek 1998; Cheek et al. 2000; Dolinay et al. 2021; Greenbaum et al. 2015; Voelker et al. 2009). All of these areas are considered to be biodiversity hotspots based on their high levels of endemicity and degree of threat (Myers et al. 2000). Phylogenetic studies have also been used to trace patterns of diversification across the oceanic islands of the Gulf of Guinea (Bell et al. 2014; D'Haijère et al. 2022). Indices of phylogenetic diversity have also been used to rank sites for biodiversity (McGoogan et al. 2007; Smith et al. 2000). These approaches have also been applied to plant communities to infer ecological and evolutionary processes in the Congo Basin at local (Hardy and Senterre 2007; Parmentier et al. 2014) and continental (Dagallier et al. 2020) scales.

Previous studies have shown that divergence times of many species predate the Pleistocene (Hassanin et al. 2018; Migliore et al. 2018; Rakotoarivelo et al. 2024; Shirley et al. 2014) and in plants may be associated with shifts in karyotype (Farminhão et al. 2021). However, climate oscillations within this epoch have most likely played an important role in recent speciation and/or intra-specific diversification (Duminil et al. 2013; Gaubert et al. 2016; Huntley et al. 2018). Similarly, intra-specific diversification across the CVL has been documented in a number of species groups (Demenou et al. 2020; Migliore et al. 2020).

Phylogenetic systematics and DNA barcoding have also helped document biodiversity, reveal cryptic lineages, and resolve taxonomic relationships (Decru et al. 2016; Delabye et al. 2019; Ntie et al. 2010; Sonet et al. 2019). However, the lack of robust reference databases and resolution of individual species can hamper DNA barcoding efforts (Johnston et al. 2011; Parmentier et al. 2013). Lastly, DNA barcoding tools have been applied to wildlife forensics and the tracking of the timber trade (Mascarello et al. 2023; Mwale et al. 2017), providing promising avenues for international regulation of illegal trafficking.

Population Genetics, Single Nucleotide Polymorphisms (SNPs), and Genomics

Population genetics is the study of patterns of population genetic variation and evolutionary diversification at the intraspecific level (Riddle and Jezkova 2019). In Congo basin animals, hypervariable mitochondrial DNA sequences and nuclear microsatellite analyses have been traditionally used to quantify genetic variation, assess genetic structure, infer demographic history, and interpret phylogeographic patterns (Anthony et al. 2007; Gonder et al. 2011; Mitchell et al. 2015a; Nicolas et al. 2011; Ntie et al. 2017). Chloroplast DNA sequences, nuclear loci, and microsatellites have been typically used in plants (Hardy et al. 2013; Ley et al. 2017; Matvijev et al. 2022; Vanden Abeele et al. 2023). Generally, these studies point to the importance of Pleistocene refugia and/or riverine barriers in intraspecific diversification. However, competing models of diversification resulting from selection across environmental gradients or isolation in riparian refugia have received relatively little attention.

More recently, population genetic studies have been refined to include the development of single nucleotide polymorphisms (SNP) arrays, restriction-associated DNA or RAD sequencing, and whole plastome or mitochondrial DNA sequencing (Faye et al. 2016; Jones et al. 2018). For example, whole chloroplast genome sequencing revealed signatures of large-scale range expansion starting 200,000–300,000 years ago for three tree species characteristic of different vegetation types: *Staudtia* in the Congolian rainforest (Matvijev et al. 2022), *Brachystegia* in Miombo savannas (Boom et al. 2021), and *Podocarpus* in montane forests (Migliore et al. 2020). Whether these range expansions were truly synchronous and resulted from a period of major vegetation changes throughout tropical Africa remains to be tested. Generally, genome-wide studies have revealed the underappreciated role of ecological gradients in driving intraspecific diversification and highlight the importance of using rigorous statistical approaches to differentiate between competing models of diversification (Freedman et al. 2023; Miller et al. 2024). Gene-environmental associations (GEAs) have also been explored in several studies using RAD sequence data to identify candidate loci that might be targets of selection (Morgan et al. 2020; Smith et al. 2021). These studies and others (Miller et al. 2024) also point to the potential use of indices of "genomic vulnerability" or "genomic offset" that measure the degree to which populations will have to adapt to future climate change.

In general, most studies of medium- to large-sized animals have been based on non-invasive genetics using hair, feces, or museum specimens to generate mitochondrial, nuclear microsatellite, or major histocompatibility complex data (Mitchell et al. 2015a, b; Ntie et al. 2017; Weber et al. 2023). However, few studies have been able to tackle genome-wide studies without access to tissue or blood samples. Genomic analyses of non-invasively sampled species are still undergoing development, but approaches based on SNP arrays (Bourgeois et al. 2018; Laguardia et al. 2021) or targeted exon capture of non-model organisms (Jones and Good 2016) are developing rapidly and provide promising avenues for future work.

Population genetic approaches can also be used to differentiate patterns of gene flow between the two sexes. In animals, these studies have generally relied on comparing data from mitochondrial data (maternal) and either Y chromosomal (paternal) or nuclear microsatellite (biparental) markers. In plants, these questions have been addressed by comparing chloroplast DNA (maternal) to pollen (paternal) data (Petit et al. 2005). Population genetic approaches have also been used to delineate evolutionary significant units (ESUs) for conservation or in recommendations for the translocation and maintenance of evolutionary lineages of animals in captivity (Soto-Calderon et al. 2015). Forensic genetics have also been used to understand the geographic origin of confiscated samples and patterns of illegal trade (Tinsman et al. 2023; Wasser et al. 2015; Yeo et al. 2024). Lastly, species distribution models have been used to identify patterns of niche differentiation and its role in species evolution (Sesink Clee et al. 2015). Hind-cast modeling can also be used to predict the location of hypothesized refugia and help disentangle the effects of Pleistocene-era refugial dynamics from other potential drivers of genetic differentiation (Miller et al. 2024; Morgan et al. 2020).

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The Hydrology of the Congo Basin

5

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Abstract

The chapter provides a comprehensive review of the hydrology of the Congo River Basin (CRB), emphasizing its physical features, current data and models, hydrological processes, environmental pressures, and the evolving scientific understanding. Water resources of the CRB support vital ecosystem and societal services that include agriculture, fisheries, hydropower, navigation, water supply, biodiversity conservation, and maintenance of vulnerable ecosystems such as peatlands and flooded forests that are crucial for carbon storage and climate resilience. The CRB hydrology is shaped by its diverse physiographical and geomorphological features, linked through a complex river network encompassing wetlands, lakes, and groundwater systems. Connectivity between headwaters, the Cuvette Centrale, and major tributaries (Kasai, Lualaba, Oubangui, and Sangha) plays a central regulatory role. Our current understanding of these processes remains very limited, which restricts our ability to implement policies for water security and address the impacts of change on physical systems

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and society. Increasing pressures from deforestation, mining, land use, and climate change threaten hydrological stability, livelihoods, and ecosystem resilience. Heightened vulnerability to hydro-climatic extremes, such as floods, droughts, and landslides, and biological risks like Ebola outbreaks raises concerns of an approaching hydro-ecological tipping point. The chapter calls for urgent investment in monitoring networks, remote sensing, data integration, and predictive modeling to support sustainable water resources management and development. **Fifteen major hydrological research challenges are identified**, underscoring the need for robust scientific investment. Beyond the CRB, findings will enhance global understanding of tropical forest hydrology and reinforce the basin's critical role in the Earth System.

Keywords

Congo River Basin · Hydrological processes · Environmental pressures · Data and models · Scientific challenges

Introduction

The contemporary history of the Congo River Basin (CRB) that we know to date includes the expedition of Henry Morton Stanley in early 1875 for the exploration of the great Congo River (Stanley 1890; Baker 1894; Wack 1905). It also includes the role of the Congo River in the transaction of goods between Arabs and the inhabitants of the Congo Basin in the nineteenth century, the slave trade, and the colonialism by western powers. The history is also shaped by early migrations of peoples who colonized the river banks of the basin (Vansina 1990; Tshimanga 2009). In February 1885, the General Act of the Berlin Conference provided the status of the Congo Basin in terms of its geographical extent, but also the freedom for trade and shipping across the Congo River to its mouth in the Atlantic Ocean and the ban on the slave trade. "This basin is bounded by the watersheds (or mountain ridges) of the adjacent basins, namely, in particular, those of the Niari, the Ogowé, the Chari, and the Nile, on the north; by the eastern watershed line of the affluents of Lake Tanganyika on the east; and by the watersheds of the basins of the Zambesi and the Logé on the south. It therefore comprises all the regions watered by the Congo and its affluents, including Lake Tanganyika, with its eastern tributaries."

The Congo River rises from the tributaries of the Lualaba and Lufira Rivers, in the southeast of the Katanga in the Democratic Republic of Congo (DRC), and flows 4700 km before emptying its average annual flow rate of about 41,000 m^3/s into the Atlantic Ocean, covering a drainage area of 3.7 million km^2. The riparian countries of the CRB include DRC (62%), Central African Republic (11%), Angola (8%), Republic of Congo (7%), Zambia (5%), Tanzania (4%), Burundi, and Rwanda (0.49%). The tropical forest of the Congo Basin extends to the northwestern part of the topographic hydrographic boundary of the CRB, encompassing six riparian countries: Cameroon, Central African Republic, DRC, Gabon, Guinea Equatorial,

and the Republic of the Congo. This review focuses on the topographic hydrographic boundary of the CRB.

Historically, the Congo River served as the artery of colonial economic networks, enabling the export of minerals, timber, rubber, and other goods. Hydrological studies of the Congo Basin evolved largely to support these economic needs, particularly ensuring safe navigation for exports and assessing rainfall variability critical to agriculture.

A landmark in hydrological monitoring was the establishment of the Kinshasa gauging station in 1903 (4.30°S, 15.31°E), followed by over 400 flow gauges, 150 climate stations, and 1000 rainfall gauges between 1903 and the 1960s (Tshimanga 2022). This network provided robust hydrological data. However, after independence in the 1960s, monitoring networks declined due to limited state capacity and shifting political priorities. The implication is that there is a good coverage of hydrological records for the period before 1960, which are not sufficient to represent the current conditions of environmental changes in the basin.

The challenge of data quality necessary to foster adequate understanding of the hydrological functioning of the CRB and enable predictive capacities prompted large-scale experiments to collect new field data (Borges et al. 2019; Tshimanga 2022; Bates et al. 2023) and application of new robust approaches for hydrological predictions in the basin or validation of satellite missions (Alsdorf et al. 2016; Papa et al. 2022). There have also been efforts toward the use of global datasets, including global climate (both reanalysis and satellite-based) and physical basin properties datasets as well as satellite altimetry for prediction of water level and discharge (Kitambo et al. 2022; Paris et al. 2022). However, there are several challenges for performing such studies, including the uncertainty in modeling approaches and satellite estimates (Washington et al. 2013) and the lack of adequate in situ data to validate satellite-based information. Jointly, they pose difficulties to develop locally relevant predictive approaches that can effectively support water resources development in the basin.

The hydrology of the Congo Basin remains poorly understood, limiting effective water resource management and forecasting of environmental change impacts. Meanwhile, the basin faces escalating pressures from pollution (mining, industry, plastics, urban waste), river fragmentation, and deforestation, disrupting hydrological regimes and degrading aquatic habitats. Recent years have seen more frequent and intense extreme hydro-climatic events, including floods and landslides, signaling major shifts in basin dynamics (Tshimanga et al. 2016; Bola et al. 2022a). Research highlights a growing trend of hydrological drought in the Cuvette Centrale, threatening biodiversity and the survival of sensitive ecosystems like peatlands and permanently inundated forests, with profound ecological and socio-economic consequences Ndehedehe et al. (2022).

All these extreme events and the emergence of infectious diseases (Ebola, monkey pox) translate a disruption in the functioning of the Congo Basin ecosystem. What are the causes? Are we close to a tipping point in the Congo Basin? Demands for water resources are expected to increase from the other drought-plagued countries of Africa, which need the availability of information to establish sustainable

water resources management strategies. As human pressures grow, these ecosystems are at risk, and all the potential economic and environmental benefits they provide, including fluvial navigation and the blue economy, hydropower and renewable clean energy, agriculture for food security, and maintenance of endemic species and vulnerable ecosystems such as peatlands (Trigg and Tshimanga 2020).

There are major challenges for hydrological research and water resources management in the CRB (Alsdorf et al. 2016; Tshimanga 2022), which necessitate urgent attention in terms of investment for new data collection with experimental field work, remote sensing, and robust process based and predictive models, including artificial intelligence. This chapter provides a review of what we know to date on the hydrology of the CRB, current and future impacts, and it identifies possible knowledge gaps to inform future investment for hydrological science research and water resources management strategies in the Congo Basin and the region of central Africa.

Dominant Features of the Hydrology of the Congo Basin and Connectivity

Congo River Catchment and Its Evolution

The CRB is located within 10°N, 12°E to 14°S, 34°E (Fig. 1) and shares its drainage divides with other large river and lake basins of Africa, including the Zambezi basin in the south, the Nile basin in the east, and the Lake Chad basin (through the Chari River) in the north, all of which drain in opposite directions, thus emphasizing the complexity of regional drainage patterns. The extent of the Congo Basin tropical forest encompasses a number of other watersheds that include Kouilou-Niari, Ogoué, and Sanaga and drain their water into the Atlantic Ocean. Within the CRB itself, there is no single classical mode of drainage pattern which emphasizes the heterogeneous nature of the underlying geology. The CRB is approximately circular, ringed by topographic highs, also called "Swells" (Kadima et al. 2011) or "Rises" (Runge 2008), with a large central depression, an internal drainage basin known as the *Cuvette Centrale* (Bwangoy et al. 2010). These topographic highs include the Atlantic Rise on the western ridge of the basin, the Asante Rise on the northern ridge, the Mitumba Mountains on the eastern ridge, and the Lunda Rise (Shaba and Angola swells) in the southern ridge. The main rivers generated from the Atlantic Rise are known as the Sangha, Likouala Mossaka, Likouala Aux Herbes, Kouyou, Alima, Lefini, Nkeni, Foulakari, Mponzo, Luozi, and Inkisi. The Asante Rise encompasses the streams that drain the CRB starting from its drainage divides with the Chari (Lake Chad) and Nile Basins to the main trunk of the Congo River. This drainage unit is known as the Oubangui basin, the name of the main stream that connects all the upstream north-eastern tributaries to the main trunk of the Congo River (Nguimalet 2022). The Mitumba Mountains mark a clear drainage divide between the Congo and the Nile basins and constitute the source of the main rivers that provide substantial flow contributions to the Congo River at Kisangani and the lower

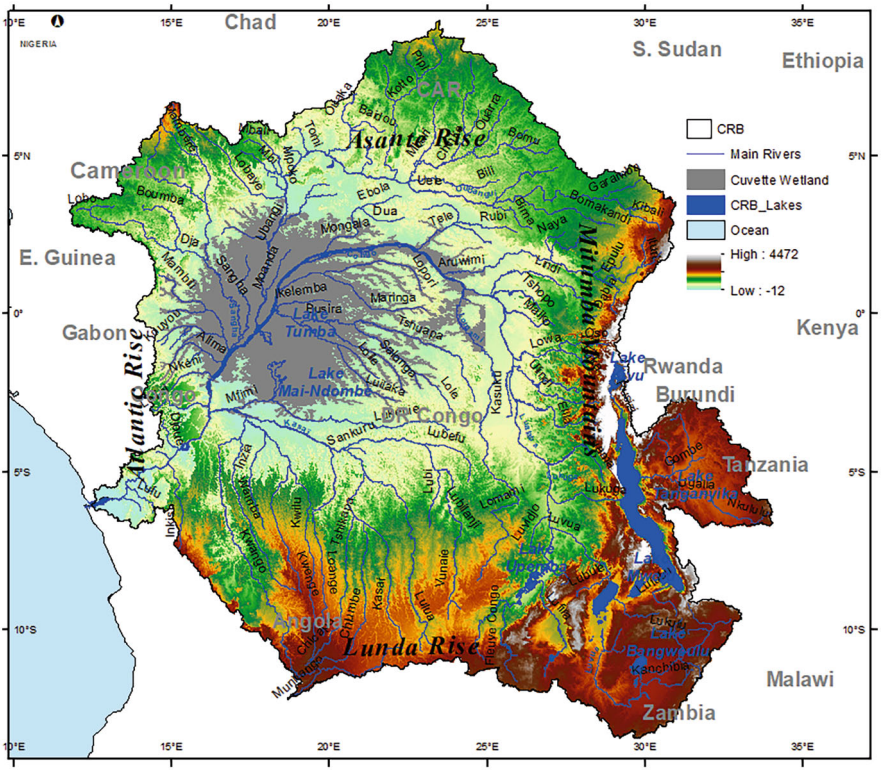

Fig. 1 Physiographic setting of the Congo River Basin

part of Lualaba. The southern rim of the CRB is flanked by the Lunda Rise, which is shaped by the Angolan highlands in the south-west and the Shaba, or north Zambian swell in the south-east. The main rivers of the southern CRB, notably the Kasai and Lualaba Rivers, rise in the highlands of the Angolan and Shaba Swells (Lunda Rise), respectively.

The Congo River's unique arc-shaped course is a result of the basin's ancient geological and tectonic history, combined with its location across the Equator. This distinctive path is largely influenced by the Congo Craton, an ancient, stable continental crust in central Africa, which creates a bowl-shaped depression (the Cuvette Centrale) that directs the river in a sweeping arc across the region (Flugel 2014). This unusual course allows the river to cross the Equator twice, leading to its bimodal flood pattern and relatively stable year-round discharge with relatively small amplitude range for such a large river (Kitambo et al. 2022). The Congo's path also contributes to its extensive drainage network, which includes many large tributaries from both north and south of the Equator. This complex network results in consistent water flow, as the alternating wet and dry seasons in different parts of the basin integrate into the main channel to provide a continuous source of water to the river

throughout the year. Further west, the Congo passes through regions with varied topographies, including the Malebo Pool (formerly Stanley Pool), a wide, lake-like section where Kinshasa and Brazzaville sit on opposing banks (Kechnit et al. 2024). As the river approaches the Atlantic, it descends rapidly through the Livingstone Falls, a series of rapids that present a dramatic drop in elevation at the of its journey from the interior of Central Africa to the coast, where the river has no delta and instead carves a canyon into the sea floor (Talling et al. 2022).

Two main theories explain the Congo River's geomorphology and flow direction (Tshimanga 2012). The first posits a southeastward flow into the Indian Ocean during the Late Cretaceous–Paleogene, redirected by East African highlands uplift in the Oligocene/Eocene (Stankiewicz and de Wit 2006). Marine deposits in southeastern valleys support this, though some argue they reflect northern marine intrusions (Giresse 2005). Alternatively, Giresse suggests initial northward drainage via the Chari Basin into Lake Chad. Despite differing views, both theories agree the basin was once landlocked or a deep-sea fan, with current Atlantic drainage being recent, shaped by long-term channel modifications (Runge 2008).

Large River Channels Morphology

The Congo River ranks second largest in the world after the Amazon, and first in the African continent, in terms of discharge and drainage area. Meanwhile, within the CRB itself, there are tributaries of second and third order which surpass all other African major rivers in terms of their area and discharge. Table 1 shows some comparative characteristics for the major river basins of Africa.

The hydrographic network of the CRB features a complex geomorphology that is vital for understanding ecosystems' distribution. The Congo River's course is characterized by significant hydrographic features, including expansive lakes, floodplains, wetlands, peatlands, and islands. Tshimanga et al. (2022a) identify three major reaches of the Congo River's course. The upper reach begins at the Katanga Plateaus and flows north to Boyoma Falls at Kisangani. This segment, known as the Lualaba, is followed by the middle reach, which extends approximately 1740 km from the city of Kisangani to the city of Kinshasa. The middle reach ends at the Pool Malebo, a significant fluvial-lacustrine system (Kichnit et al. 2024a) before the Congo River advances downstream toward the Atlantic Ocean (see Fig. 2). There are major tributaries, including Kasai River in the southern hemisphere, and Oubangui and Sangha Rivers in the northern hemisphere that join the Congo River in its middle course. The influx of water from these tributaries influences flow dynamics, leading to variations in river velocity and sediment transport patterns. This interaction fosters diverse habitats that support a wide range of aquatic species, enhancing the overall biodiversity of the Congo River system. Understanding the interactions of these tributaries is crucial for effective management and conservation strategies, particularly in the face of environmental changes and human activities.

The hydrodynamics of the Congo River are shaped by bathymetry and morphology, with stark contrasts between the Chenal and multithreaded reaches. The Chenal

Table 1 Major river basins of Africa and their drainage area and discharge characteristics

No.	River Basin	Drainage area (*1000 km^2)	Discharge (m^3/s)
1	Congo	3700	41,000
1.1	*Kasai*	900	11,020
1.2	*Lualaba*	970	8940
1.3	*Oubangui*	604	5320
1.4	*Sangha*	220	2570
2	Niger	2300	5589
3	Zambezi	1330	3500
4	Nile	3400	2830
5	Chari	600	1059
6	Senegal	337	650
7	Okavango	721.258	475
8	Orange	973	365
9	Limpopo	413	170

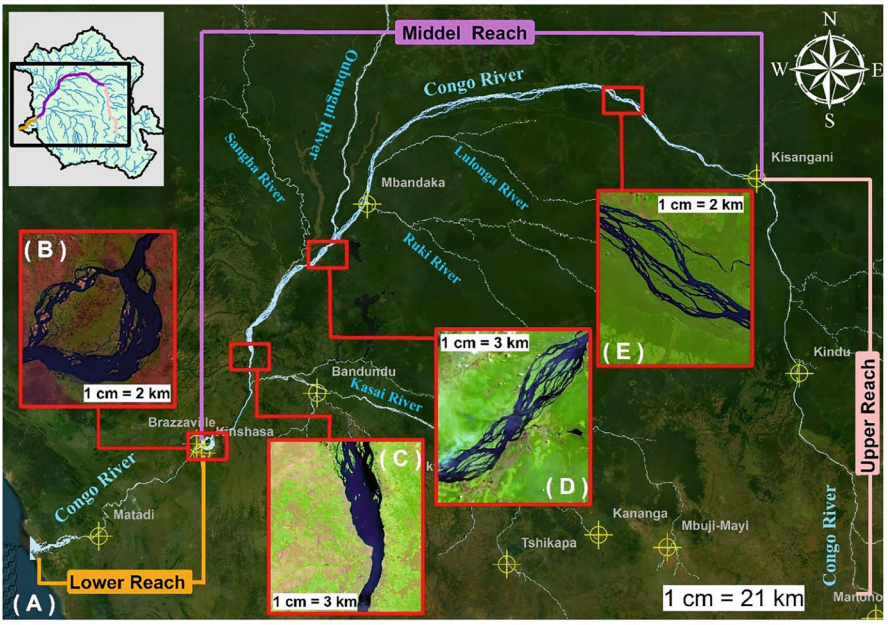

Fig. 2 Overview of the Congo River Reaches, including (**a**) various reaches, (**b**) Pool Malebo, (**c**) the Chenal reach at Tshumbiri, and multithreaded reaches in (**d**) Lukolela and (**e**) Bumba. (River course from Landsat 8_9. Source: https://earthexplorer.usgs.gov/)

reach, with greater depths, supports higher velocities due to reduced friction and better hydraulic efficiency. In contrast, the multithreaded reaches between Kisangani and Kinshasa feature numerous islands that split the channel, disrupting flow and

causing turbulence and sediment deposition. As only 20% of the middle reach maintains a single channel (Alsdorf et al. 2016), flow velocities are markedly lower. These dynamics critically influence sediment transport and ecological processes, highlighting the strong link between river morphology and hydrodynamic behavior.

Headwater Catchments

The CRB is structured around four dominant headwater catchments, namely, the Oubangui (Northeast), Sangha (Northwest), Kasai (Southwest), and Lualaba (Southeast), with the Plateaux Batékés extending the Cuvette Centrale in the west (Moukandi N'kaya et al. 2022). These upstream units are large, varying from 212,400 km^2 (Sangha) to 961,648 km^2 (Lualaba), drain steep topographies, and form the Congo River's major tributaries (Fig. 3). A catchment classification system is required in this area to help synthesize our understanding of the interaction between climate variability, catchment characteristics (e.g., vegetation, soils, topography), and the resulting hydrological responses (Sivakumar et al. 2015).

Tshimanga et al. (2022b) developed a framework delineating 1740 catchment units, based on topography (199), socio-economic and anthropogenic factors (204),

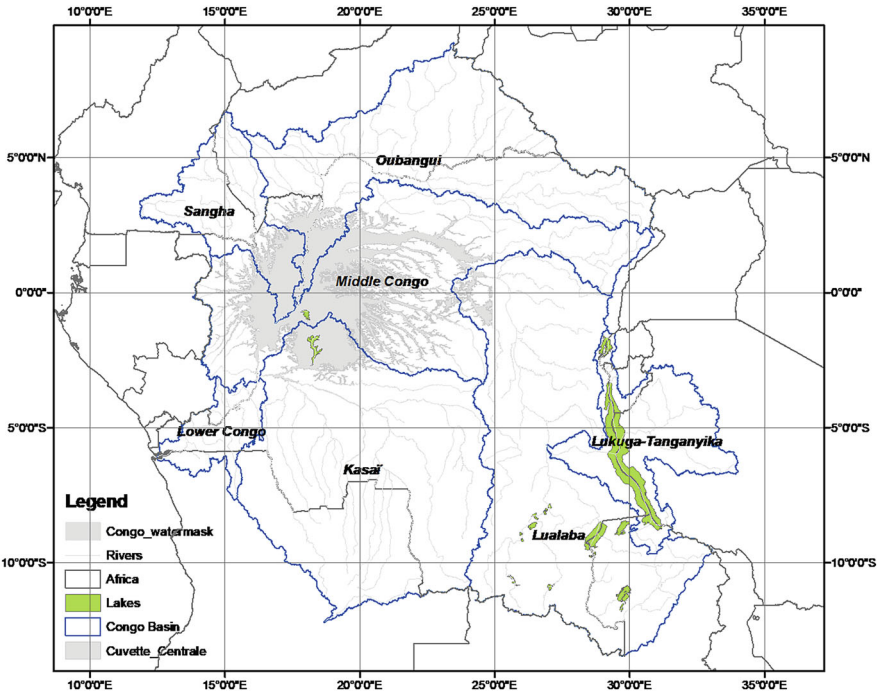

Fig. 3 Major drainage units and headwater catchments of the CRB

and traditional hydrological nomenclature (1337). These units provide standardized descriptors of physical and socio-environmental attributes. This framework underpins the Congo Basin Catchment Information System (CB-CIS, www.cbcis.info), offering 128 attributes across seven management themes: governance, climate, physiography, hydrology, risks, water uses, and external linkages. CB-CIS enhances data availability and scalability, supporting integrated water resource management, policy decisions, and transboundary cooperation.

Wetlands, Peatlands, and Lakes

The CRB hosts several wetlands, peatlands, and natural lakes of global significance, including various Ramsar sites (wetlands of international importance; see section "Wetland, Peatland, and Lake Dynamics and Functions" for details). These water bodies are predominantly distributed across the south-eastern rim of the basin, in the Lualaba drainage system; in the central part of the basin characterized by the Cuvette Centrale; and in the coastal region of the basin with a large extent of mangroves (Hughes and Hughes 1987; Bwangoy et al. 2011; Hughes et al. 2013; Kabuya et al. 2020; Dargie et al. 2017; CRREBaC 2022). Figure 4 shows the geographical distribution of what we know to date in terms of wetlands, peatlands, and natural lakes of the Congo Basin. It should be stressed that there is quite a good number of water bodies of great relevance in terms of the storage volume and aquatic ecosystem services in the Congo Basin, but which remain unclassified due to a lack of adequate studies (Tshimanga et al. 2022b).

Groundwater

The CRB holds significant groundwater resources (Tourian et al. 2023), distributed in four major hydrogeological units, which influence significantly the spatial variability in groundwater storage anomalies (GWSA) (Kitambo et al., 2025). These include the unconsolidated sedimentary aquifer composed of coarse alluvial sediments reaching up to 120 m thick, the cretaceous consolidated sedimentary intergranular aquifer consisting mainly of semi-continuous sandy loam and soft sandstone, the consolidated sedimentary one dominated by fracture flow composed mainly of sandstone and calcareous rocks, and the Precambrian basement aquifer often consisting of basalt and granite (UNEP 2011; Africa Groundwater Atlas 2019).

Currently, little is known and understood about the characteristics (i.e., the size of the aquifers, recharge rates, or interactions between groundwater and surface water), the spatiotemporal variability of groundwater resources, and the way they link to climate variations within the basin, leading to a significant gap in the scientific knowledge of the Congo Basin's groundwater resources. Despite the recent advances in characterizing groundwater storage anomaly changes (Crowley et al. (2006), Richey et al. (2015), Becker et al. (2018), Tourian et al. (2023),

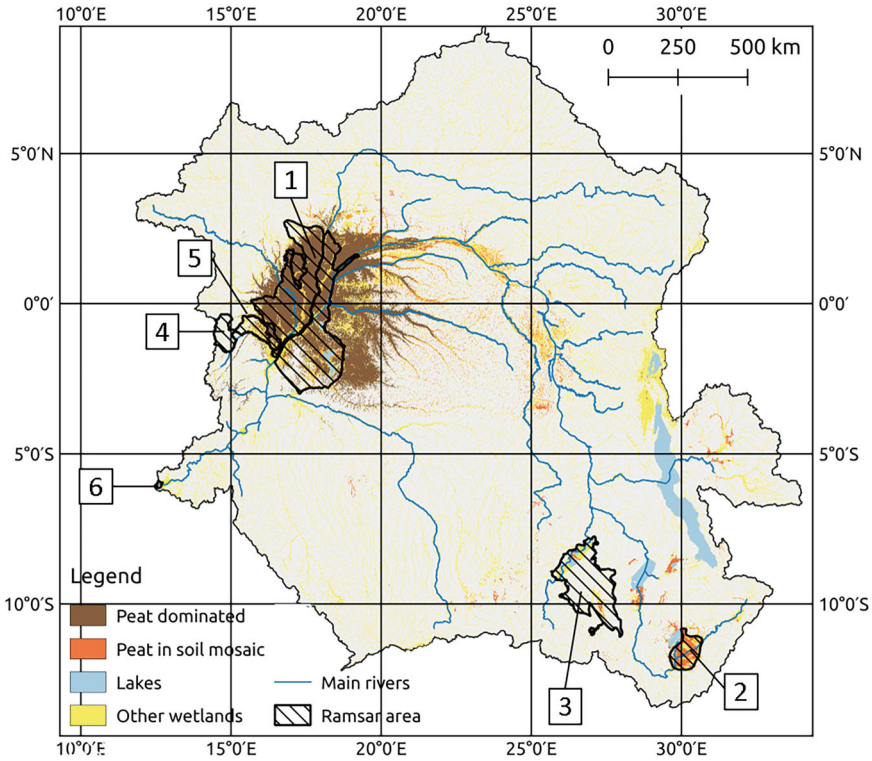

Fig. 4 Distribution of wetlands, including peatlands, with areas declared as Ramsar sites (1) flooded Cuvette Centrale; (2) Bangweulu Wetlands; (3) Basin de la Lufira; (4) Leketi-Mbama; (5) Tchikapika-Owando; (6) Parc national des Mangroves). (Data sources: Global Peatland Map 2.0, Ramsar sites (https://rsis.ramsar.org), Global Lakes and Wetlands Database, Cuvette Centrale peat distribution from Crezee et al. (2022))

Mouakoumbat et al. (2022)), its knowledge at the large scale is still inadequate. A recent study performed by the Congo Basin Water Research Center (CRREBaC) and its international partners (i.e., Laboratoire d'Etudes en Géophysique et Océanographie Spatiales, University of Stuttgart) helped to characterize the dynamics of groundwater storage at the basin and subbasin scales (Kitambo et al., 2025). The study revealed that GWSA consists of 24%, 42%, 42%, 29%, 16%, and 19% of the total water storage anomaly from GRACE satellite, respectively, in Sangha, Oubangui, Kasaï, Middle Congo, Lower Congo, and Lualaba subbasins (Fig. 5) (Kitambo et al. 2025). This work enhanced our understanding of groundwater dynamics in the basin through Earth Observation and field integration. A groundwater storage database using GRACE, remote sensing, and monitoring networks are vital to assess climate impacts, understand groundwater–surface water interactions, identify recharge zones, and strengthen integrated resource management.

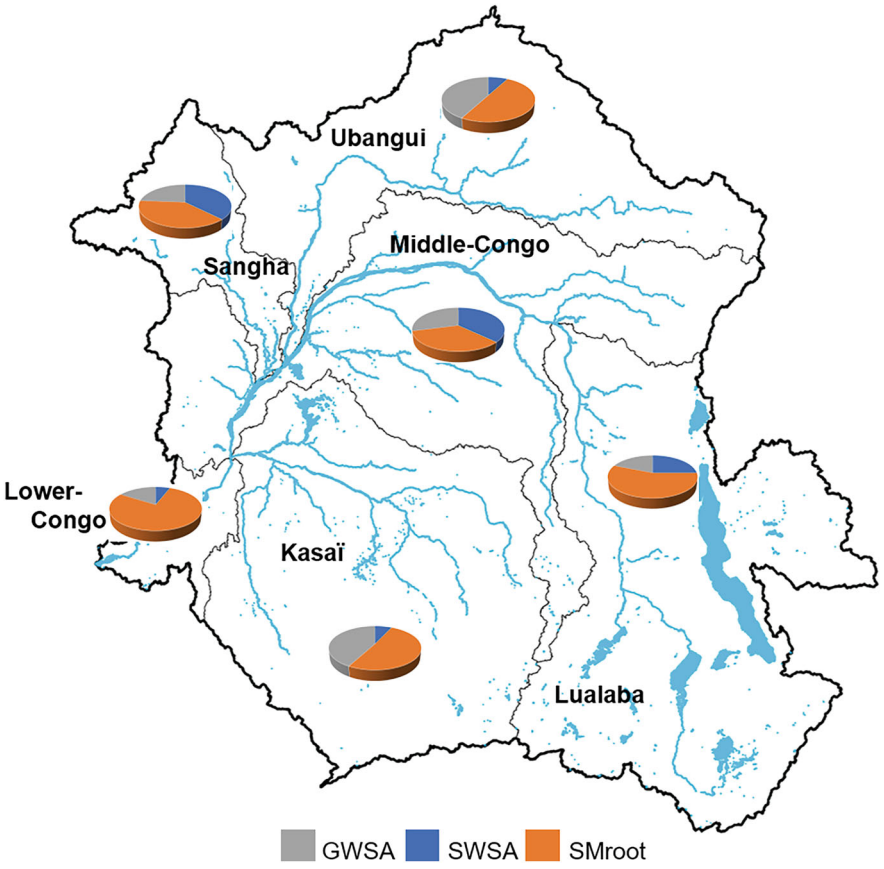

Fig. 5 Contribution (%) from surface water storage anomaly (SWSA), root zone soil moisture (SMroot), and groundwater storage anomaly (GWSA) reservoirs to Total Water Storage Changes from GRACE for each subbasin in the CRB

Measurements, Remote Sensing, Modeling, and Decision Support System

In Situ Measurements

Since the 1960s, many riparian countries of the CRB have been marked by a drastic decline in the hydro-meteorological stations, so that, within the CRB, no more than 15 gauging in situ stations are considered operational today (Tshimanga 2022). Figure 6 shows the quality and distribution of the existing streamflow monitoring gauges in the Congo Basin that spans 3.7 million km^2. Comparatively, this is critically far beyond the hydrometric monitoring network of the United Kingdom, which encompasses more than 1400 gauges over 230,000 km^2 of the surface area.

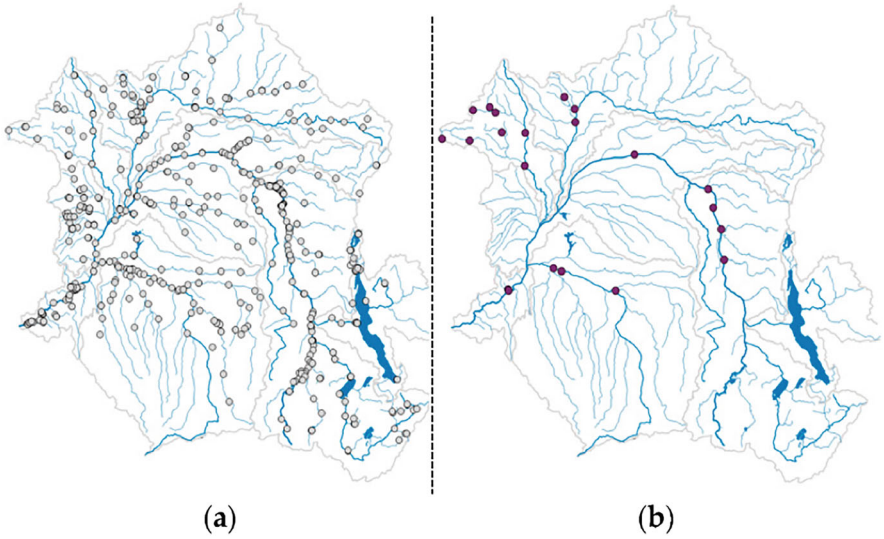

Fig. 6 Decline in the hydrological monitoring stations of the Congo Basin, (**a**) before 1960s and (**b**) current situation

Also, as a comparison, the Brazilian portion of the Amazon River Basin currently has around 60 operational river gauges (Moreira et al. 2023). At present, and still in the absence of any real National Hydrological Service, it is the river navigation services of the Congo and CAR (GIE-SCEVN—Groupement d'Intérêt Economique—Service Commun d'Entretien des Voies Navigables) and then the DRC (Regie des Voies Fluviales) that have inherited part of the data from the former hydrometric networks.

During the last decade, scientists endeavored a number of meso- and large-scale field experiments aiming at enhancing the quality and availability of in situ data (Borges et al. 2019; Tshimanga et al. 2022a; Bates et al. 2023). One of these initiatives is the Congo River users Hydraulics and Morphology—CRuHM project (2016–2022, Bates et al. 2023), which focused on carrying out several cross sectional ADCP measurements over the main navigable reach of the Congo Basin (1700 km long), between the towns of Kisangani and Kinshasa, as well as the lower reach of the Kasai River from the town of Bandundu to its outlet in the Congo River (Fig. 7).

ADCP Measurement

The first ADCP measurements in the Congo River were carried out in July 2008 (Oberg et al. 2009). RVF and GIE-SCEVN initiated other numerous ADCP measurements, which remain unpublished. Between 2017 and 2019, the CRuHM project conducted ADCP measurements over 29 cross sections along the middle reach of Congo River (Tshimanga et al. 2022a). The measurements targeted both single and multi-thread channel styles in the middle reach of the Congo River (Fig. 8).

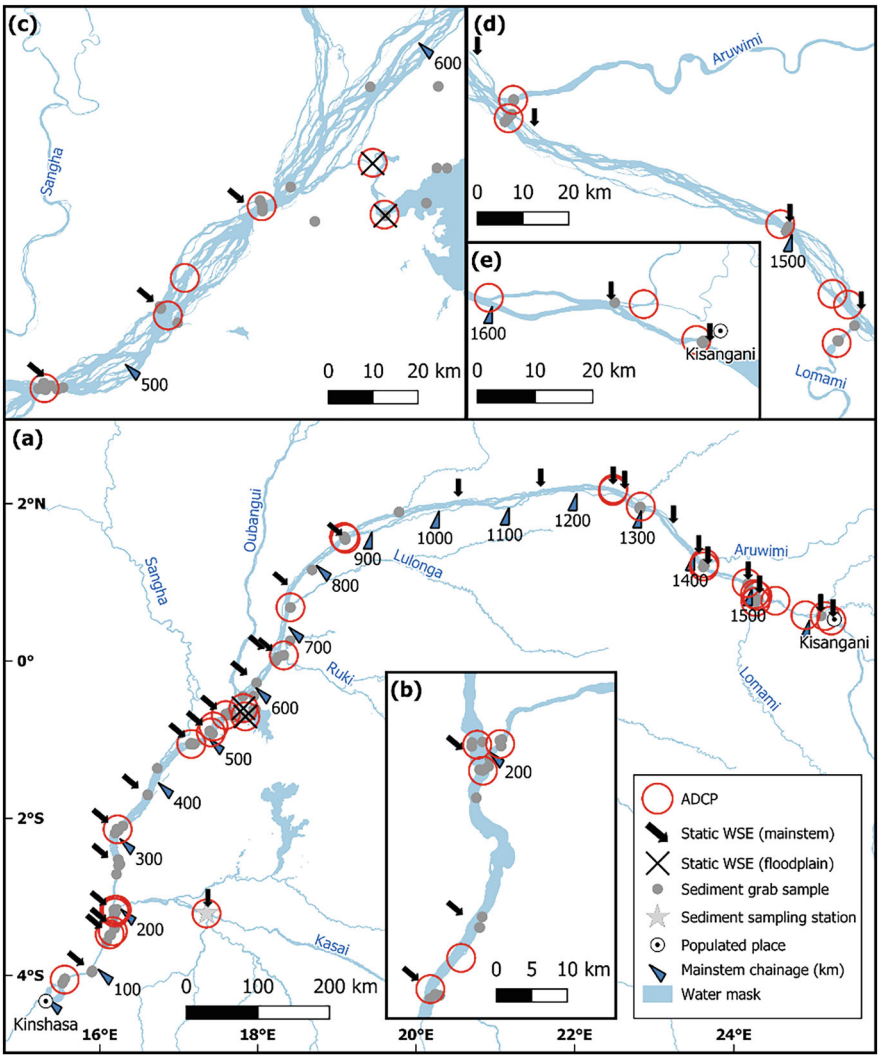

Fig. 7 Study reach and locations of measurements (Chainage calculated from the navigation path used with the CRuHM boat)

Water Surface Elevation and River Bathymetry

Measuring elevation in the Congo River Basin (CRB) is challenging due to sparse benchmarks and limited cellular networks. To address this, the CRuHM team used Precise Point Positioning (PPP) with GNSS equipment in 2019, collecting continuous Water Surface Elevation (WSE) data every 50 m along the Congo River between Kisangani and Kinshasa (Fig. 9). This dataset is indispensable for the determination of the longitudinal profile and the hydraulic gradient, which are important characteristics in the optimal use of a river. Taking into account the longitudinal profile, this allows the identification of locations with similar hydro-sedimentary characteristics.

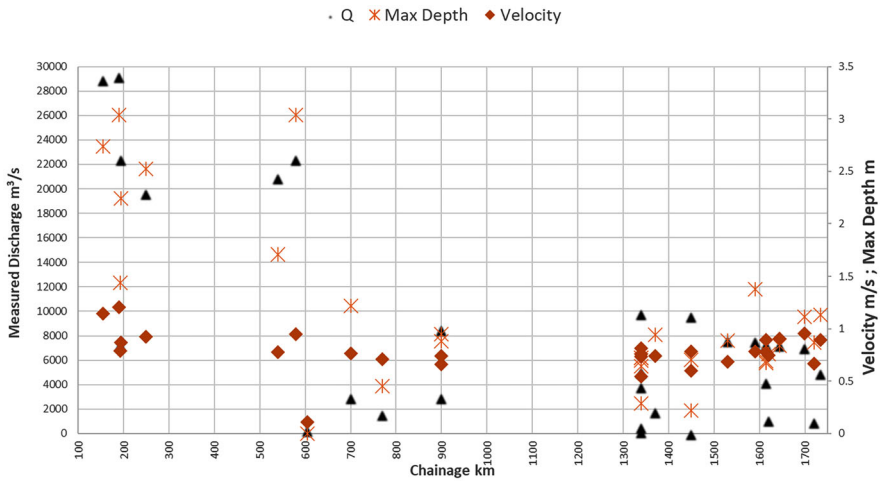

Fig. 8 Measured discharge, channel hydraulic depth, and velocity for 29 cross sections along the Congo River main stem (max depth values divided by 10 to fit the scale) (Tshimanga et al. 2022a)

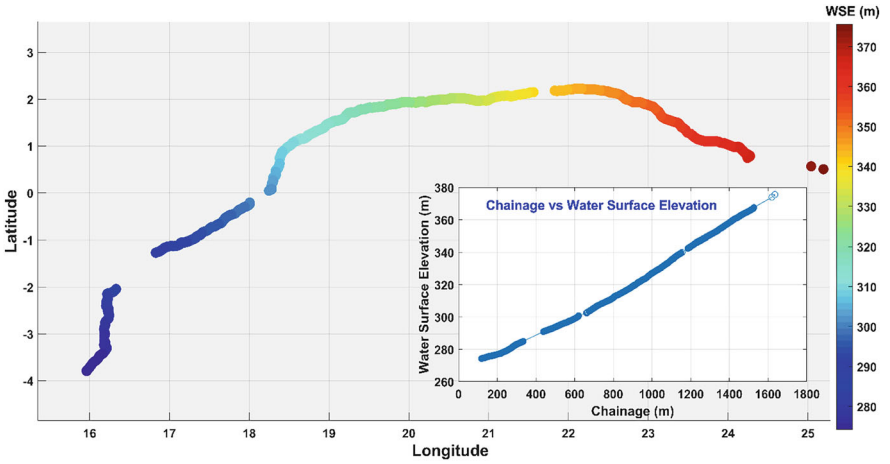

Fig. 9 Continuous water surface elevation measurements along the middle reach of the Congo River using GNSS (Tshimanga et al. 2022a)

Through a longitudinal profile, slope variations can be observed that can indirectly provide information on past climates, structural controls, eroding and deposition sections, sediment transport capacity, and upstream-downstream flow dynamics.

Figure 9 illustrates the WSE data along the studied river reach and its relationship with chainage (distance along the river). The longitudinal profile of WSE reveals a clear and consistent increase in water levels from the upstream to the downstream end of the reach. This systematic downstream rise in WSE is attributed to the river's slope and flow characteristics, which influence the longitudinal variation in water surface elevation. Analysis of the data highlights a significant range in WSE within

the studied river reach, with maximum values reaching approximately 370 m and minimum values around 270 m. This variation is a critical parameter for establishing accurate boundary conditions in hydraulic models and informing effective water resource management decisions.

Several initiatives have been undertaken to measure the bathymetry of the middle reach of the Congo River, as highlighted in studies by Alsdorf et al. (2016), Carr et al. (2019), and Tshimanga et al. (2022a). While earlier measurements did not comprehensively cover the entire reach, data from the PANAV project has effectively encompassed the middle reach, particularly the Chenal reach, which extends from 50 km to 250 km along the river. In this segment, data were collected at 100-meter intervals between each cross-section, providing a detailed understanding of the river's depth and topography, which is crucial for navigation and environmental management. In contrast, the multithreaded reach, extending from 250 km to 1600 km, presents unique challenges that require a different measurement strategy. Here, data collection occurred at 1-km intervals due to the river's complex geomorphology, characterized by numerous islands and extensive cross-sectional areas. These geological features complicate the maintenance of consistent measurement intervals, thereby impacting the precision and reliability of the bathymetric data.

Figure 10 shows the map of the interpolated bathymetry for the main channel of the Congo River and its singularities (Ketchnit 2024). The in situ dataset for a 1740 km stretch of the river consists of cross sections spaced at 1 km intervals.

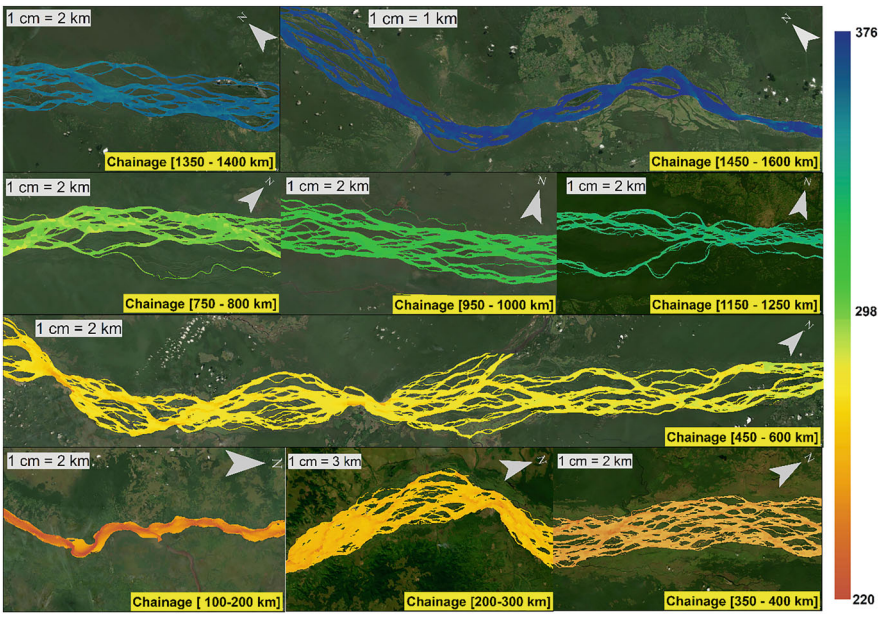

Fig. 10 Interpolated bathymetry along the middle reach of the Congo River

Overall, the WSE and bathymetry measurements taken along the middle reach of the Congo River between 2017 and 2019 have revealed that the variability in water surface slope is greater than previously thought. Such variability is important for characterizing the hydraulic behavior of river reaches (Montazem et al. 2019). The variability appears to be the result of changes in bathymetry, especially as the Congo River enters the C*henal* and is joined by the Kasai tributary. Initially, the water surface slope becomes relatively steep (8 cm/km) as it approaches the entrance to the *Chenal*.

Sediments and Carbon

Coynel et al. (2005) published the results of 6-year experiment, including TSS, particulate organic carbon (POC), and dissolved organic carbon (DOC), for the main stem of the Congo River near Brazzaville-Kinshasa station, and the Oubangui, Mpoko, and Ngoko-Sangha tributaries, where they noted a clockwise hysteresis pattern in relation to river discharge. The results obtained in this study are in the same order of magnitude, most specifically for TSS, although it is currently difficult with instantaneous samples taken over one low flow season to derive variability and establish a comprehensive pattern.

Alsdorf et al. (2016) and Richey et al. (2022) provide a comparative summary of the river discharge-controlled carbon fluxes in the Congo and Amazon basins. They identified that Congo River has an exceptionally low TSS yield, which however has a high POC content and ranks fifth in terms of annual POC flux to the oceans. With respect to DOC, the Congo River is a major global exporter with a total flux estimated at between 11.5 and 12.4 Tg C/yr. Combining the DOC and POC loads, the Congo River exports 14.4 Tg C/yr of organic carbon to the Atlantic Ocean and is the second major exporter of terrestrial organic carbon on Earth after the Amazon.

During 2019, the research team under the CRuHM project conducted a number of samplings together with ADCP cross sectional measurement (Tshimanga et al. 2022a). These data encompass total suspended sediment (TSS) and organic matter (OM) for the sections with ADCP measured discharge (MD). The results are representative of the low flow season during the month of August 2019 along the main channel of the Congo River between Kisangani and Kinshasa.

Basically, these observations, while highlighting the role of these major tropical river basins of the world in the dynamic of aquatic carbon fluxes, also lead to many hypotheses that should be investigated through a combined approach that include field measurements, laboratory analyses, and modeling to establish the geographic distributions and magnitude of the riverine carbon fluxes. To date, there is little knowledge of the spatial distribution of these fluxes across the hydrographic continuum of the Congo Basin, including wetlands and lakes, headwater catchments, and their small streams that currently undergo major land use changes. Furthermore, there is a lack of information on how the change in hydrological regime, including rainfall, streamflow, and sediment loads influences these dynamics.

Remote Sensing

A number of satellite-based products necessary for assessing basin-wide water balance or improving hydrological predictions are now available at the global scale, encompassing the region of the CRB (Papa et al. 2022). These products have been used in many studies such as temporal changes in river water levels derived from radar imagery (Rosenqvist and Birkett 2002), seasonal and long-term trends of terrestrial water storage from Gravity Recovery and Climate Experiment (GRACE, Crowley et al. 2006), and temporal changes in water surface elevations and connectivity between the mainstem and floodplain channels evaluated from space-borne radar (Jung et al. 2010). Satellite altimetry has been used to infer hydrologic variables and evaluate water sources and sinks along wetlands using multiple remote sensing measurements such as GRACE, satellite radar altimetry, GPCP, JERS-1, SRTM, and MODIS (Lee et al. 2011; Becker et al. 2014; Kim et al. 2019; Carr et al. 2019). Landsat imagery has been used to characterize the hydraulics of the middle reach of the Congo River (O'Loughlin et al. 2013), and hydrologic modeling of the CRB has used various sources of satellite derived rainfall as input (Paris et al. 2022; Wongchuig et al. 2023). While the benefits of these satellite-based products are of no doubt, it is important however to recognize the difficulty of validation and associated uncertainties in some large areas of the CRB where there is a complete lack of ground-based historical observations (Washington et al. 2013).

Current efforts to leverage the use of these products and take into account uncertainty have led to the validation of a quite good coverage of satellite derived products, including ~2300 surface water level virtual stations, covering the period 1995 to 2020 and spatially distributed across the Congo Basin, with a total number of 323 VSs (Virtual Stations) from ERS-2; 364 and 342 VSs for ENV and ENV2 (new orbit of ENVISAT since late 2010), respectively; 146 and 98 VSs for Jason 2 and Jason 3, respectively; 358 VSs for SRL; 354 VSs for Sentinel 3A; and 326 VSs for Sentinel 3B. Figure 11 shows the map of the existing virtual stations with long-term time series of water level.

The current knowledge based on the use of these products reveals a persistent trend of drought over the central part of the Congo Basin, the distribution of the water availability throughout the basin, the quantification of the TDWS, and the spatial and temporal dynamics of the extent of episodic and seasonal inundation, wetlands, rivers, lakes, reservoirs, and floodplains (Kitambo et al. 2022, 2023; Wongchuig et al. 2023; Kechnit et al. 2024). However, the scientific community is still uncertain about the causes of the observed changes and how they would evolve in the future. Observed ground data are required to constrain predictive models to help improve our understanding of the processes, impacts, and causal relationships.

Evaluation of Hydrologic Model Applications in the Congo Basin

The advent of hydrological modeling in the Congo Basin is relatively recent, given the need to address the many challenges of water resources management in the basin.

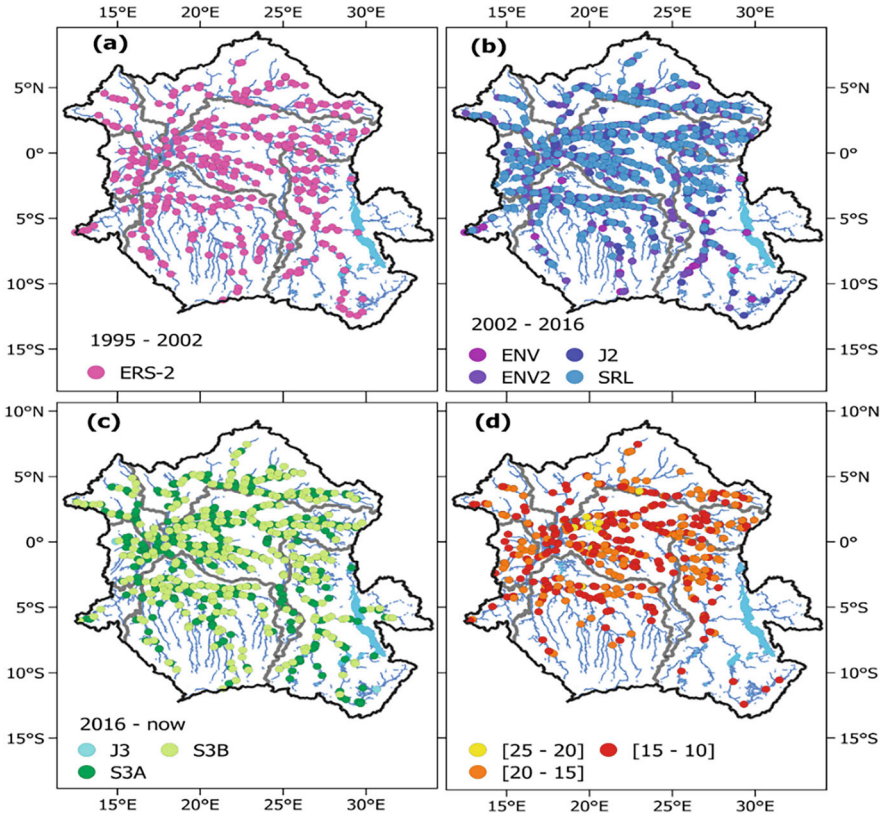

Fig. 11 Locations of ~2311 Virtual Stations (VSs) from multi-satellite missions validated by Kitambo et al. (2022)

In a review of two decades of hydrological modeling in the Congo Basin, Tshimanga (2022) showed that there has been a great deal of efforts from the past modeling studies to address both data issues and process understanding and to establish models that represent the basin's hydrologic processes. The analysis also shows that there are still numerous issues and uncertainties that should attract the attention of future modeling studies—*right modeling for the right reason.* Modeling in the Congo Basin has evolved to encompass rainfall-runoff, hydrodynamic, and water allocation models. However, development has often focused on testing model viability rather than meeting operational needs of basin stakeholders. Key modeling systems include the following:

- Hydrologic Modeling System (HMS)—Source-to-sink approach for flow routing at continental scale. Applied to both the Congo and Nile Basins, but only Nile Basin gauging sites were used for validation (Asante 2000).

- River-Transfer Hydrologic Model (RiTHM)—Rainfall-runoff model applied to 11 major world basins, including the Congo. Successful elsewhere, but Congo calibration yielded a negative Nash Efficiency due to systematic overestimation of flows (Ducharne et al. 2003).
- PITMAN-GW—Semi-distributed rainfall-runoff model for the entire Congo Basin (99–403 sub-basins). Incorporation of storages (canopy, wetlands, lakes) and improved routing enhanced performance, calibrated with 31 gauging stations (Tshimanga et al. 2011; Hughes et al. 2013). Used for climate change impact studies, and informed WEAP, MIKE-HYDROBASIN, and later Lisflood-FP wetland parameterization (Kabuya et al. 2020).
- LISFLOOD-FP—4 km resolution hydraulic model combining in situ and modeled flows. Provided insights into Congo River discharge seasonality, floodplain interactions, and flood wave propagation (O'Loughlin et al. 2020).
- SWAT—Daily rainfall-runoff model for the whole basin, calibrated with 20 gauging sites. Successfully assessed water availability, climate change scenarios, and uncertainty from sparse hydrometric networks (Aloysius and Saiers 2017; Sridhar et al. 2022).
- Hillslope River Routing (HRR)—Daily model calibrated with four sites to simulate total water storage, validated against GRACE-derived storage changes (Beighley et al. 2011).
- Geospatial Streamflow Model (GeoSFM)—Daily rainfall-runoff model using satellite rainfall estimates. Initial results prompted model/data refinements, improving performance (Munzimi et al. 2019).
- Large Basins Model (MGB)—Hydrologic–hydrodynamic model calibrated with in situ and remote sensing data, with improved lake representation and assimilation of discharge/water level observations (Paris et al. 2022).

These modeling efforts are significant but still face structural and operational limitations. Many models are not directly usable by water managers due to lack of stakeholder integration and data input constraints. The absence of a catchment classification system has further limited model transferability and generalization (Tshimanga et al. 2022b).

Understanding Hydrological Processes and Functions in the Congo Basin

The processes that take place at the Congo Basin scale are under the influence of many internal and external factors of the climate dynamics, land use and land cover, soil types, and the geology of the terrain. Figure 12 provides a schematic of our conceptual formulation of these processes. They include surface and sub-surface response to rainfall at the small scale but also include storage and attenuation effects of wetlands, floodplains, natural lakes, and the channel systems of large rivers. An adequate conceptual representation of storages such as forest canopy interception, soil moisture, groundwater, lakes, and wetlands as well as space-time variations in

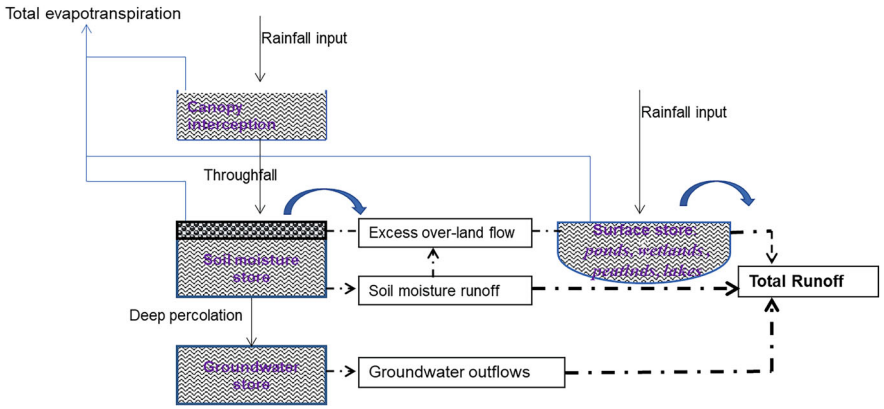

Fig. 12 Conceptual dominant hydrologic processes for the CRB

quantities such as interflow, soil moisture flow, recharge, runoff, transmission losses, and evaporation would be a true representation of the hydrologic behavior of the CRB hydro-system.

Rainfall Input

► Chapter 3, "Climate of the Congo Basin," of this book provides a comprehensive review of rainfall process over the Congo Basin. Mean Annual Precipitation over the Congo Basin is estimated to 1700 mm. Overall, there are three dominant modes of annual rainfall recycling over the Congo Basin (Worden et al. 2021):

- Transport of moisture flux from the Atlantic Ocean into the Congo Basin, which plays a critical role in determining the climate variability of the region throughout the year (Pokam et al. 2012).
- Transport of moisture flux from the Indian Ocean into the Congo Basin (Dyer et al. 2017).
- A significant part of rainfall recycling in the Congo Basin is vegetation-sourced, which accounts for up to 52% of the annual rainfall from local evapotranspiration (Smith et al. 2023). This process has been identified as a key modulator of the Congo Basin water recycling, suggesting that the Congo rainforest could be an important source of moisture for initiating the rainy season.

During the wet season, higher evapotranspiration rates are typically observed, which significantly contribute to local rainfall patterns and sustain the forest's hydrological cycle. In the dry season, reduced evapotranspiration levels result in a lower recycling rate, making the region more dependent on external moisture sources, such as the Atlantic and Indian Oceans. Part of the amount of the moisture recycled over the Congo Basin is transported to other regions of Africa, contributing

to rainwater supply to those regions. This has huge implications for livelihood of about 100 million of rural famers who depend direct on red-fed agriculture in the Congo Basin and a further 300 million of rural famers from the Sahel region and Ethiopian highlands who benefit from rainfall through atmospheric moisture recycling from the Congo Basin forests (Barimalala et al. 2023).

Analysis of historical ensemble precipitation data for the Congo Basin rainforest region shows a decreasing precipitation trend with about −90 mm per decade and an increasing dryness index of about 0.05 per decade (Wongchuig et al. 2025). This has also affected the trend in river flow. However, we are currently uncertain to whether this trend is induced by deforestation or change in the ocean sourced moisture flux to the Congo Basin. Deforestation in the Congo Basin affects not only the mean rainfall in the basin and neighboring countries, but also the spatial distribution and the temporal characteristics of the rain, such as the onset, cessation, and length of the rainy seasons. These have crucial implications in the agricultural sectors. The projected overall Congo Basin forest loss between 2015 and 2100 is estimated to induce a rainfall decline of 8% to 10% in the basin itself. The deforestation will also have large effects on neighboring regions as a result to its impact on rainfall patterns, which despite large uncertainties is believed to be potentially substantial. The indirect effect of deforestation on agriculture through the effect on rainfall is likely to be large, as there is a strong dependency on rain-fed agriculture in Africa.

Forest Canopy Interception and Evaporative Losses

The tropical rainforest of the Congo Basin plays a key role in the hydrological cycle of the basin and the African continent. This role includes local rainfall recycling, but also regional moisture recycling, which further ensure rainfall supply to as far as the Sahel and Ethiopian highlands region. It is unfortunate that this role remains poorly understood to date, which undermines conservation efforts as well as promotion of the ecosystem services. It is understood that the massive forest canopy of the Congo Basin constitutes a major atmospheric storage that intercepts a significant amount of rainfall, which then undergo direct evaporative losses to the atmosphere without reaching the ground. Variability in land cover composition for the basin implies variability in surface canopy which will also affect the variability in rainfall interception storage across the basin. The type and structure of the forest canopy determine the amount of rain water that is captured and subsequently released to the atmosphere. Associated with the types of vegetation cover are litter depths and types, rooting depth, and densities, all of which have effects on the water balance and runoff generation mechanisms (Chappell et al. 2008). Some studies in the basin have been able to use proxy data to model the interception loss through forest canopy (Tshimanga and Hughes 2014). Adequate quantification of these processes could help understand the impact of the loss of forest canopy, through deforestation, on river runoff and

flooding, soil erosion, and sediment transport. Similarly, the forest cover plays a significant role in the infiltration processes, which remains understudied in the Congo Basin. In light of the heightened pressure from land use change in the basin, the findings of these studies are particularly pertinent.

Evapotranspiration and Surface Air Temperature

There are relatively fewer studies that address Evapotranspiration (ET) and Surface Air Temperature in the Congo Basin, compared to precipitation (Alsdorf et al. 2016; Tshimanga 2022). An analysis based on 229 reference stations for the years 1950 to 1959 shows the annual average daily maximum, mean, and minimum temperatures for most of the Congo Basin are 30 °C to 31 °C, 23 °C to 25 °C, and 18 °C to 20 °C, respectively (Bultot 1972). The actual ET varies from region to region, from "a little more than 800 mm in Katanga to a little less than 1,200 mm in Uele" (Katanga is a region in the southernmost Lualaba Basin, and the Uele region occupies the eastern portion of the Oubangui Basin). For the entire Congo Basin, the actual ET "generally measures between 75% and 85% of the annual precipitation." Potential evapotranspiration (PET) peaks at about 1500 mm/yr near the equator, with lower values further north and south (Nicholson et al. 1997).

Storage

Storage here refers to surface water stores such as lakes, wetlands and peatlands, and the subsurface stores in soil and groundwater. Our current understanding of these processes in the CRB is limited due to experimental challenges related to the measurement of these processes. However, the advent of satellite derived products such as total water storage variations from GRACE and inundation extent are enabling these measurements.

For instance, using satellite data, Tourian et al. (2023) show that currently the Congo Basin's Total Drainable Water Storage (TDWS) lies within a range of 476 km^3 to 502 km^3, unevenly distributed throughout the region, with 63% being stored in the southernmost sub-basins, Kasaï (220–228 km^3) and Lualaba (109–169 km^3), while the northern sub-basins contribute only 173 $\pm$ 8 km^3. The Kasaï sub-basin has the highest capacity, storing 220 $\pm$ 4 km^3 or about 43% of the total drainable water of the Congo Basin. Sangha, Oubangui, and Middle Congo contain in total 173 $\pm$ 8 km^3, equivalent to 63% of the Kasaï sub-basin. The Middle Congo, with its Cuvette Centrale, stores 90 $\pm$ 6 km^3 of TDWS, only 40% of the Kasaï estimates. Such a difference is expected, as both Kasaï and Middle Congo receive similar annual precipitation, but the latter is a shallow watershed with much larger discharge (498 $\pm$ 20 mm/yr) and evapotranspiration. The Lualaba sub-basin accounts for approximately 21% of the basin TDWS with 109 $\pm$ 4 km^3 (sum of its subbasins North, South and Lukuga), but most of the storage (61%) is concentrated

in the Lualaba-South (67 ± 2 km^3). Over the Lualaba-Lukuga the TDWS is 20 ± 1 km^3, for which the storage of Lake Tanganyika was subtracted from Total Water Storage Anomaly (TWSA).

Tourian et al. (2023) emphasize that the water amount of 476 ± 10 km^3 TDWS of the Congo Basin corresponds to 133 ± 3 mm of equivalent drainable water height, i.e., the level at which the discharge reaches zero. This means that when the Congo reaches its minimum drainable storage in August—40 mm (137 km^3), the basin could still be drained by about 339 km^3 (476–137 km^3). Conversely, when both the water storage and the discharge reach their maximum in December, the basin holds a water volume of 613 km^3.

Comparing the estimates over the Congo and Amazon basins, a ratio of about 25% between Congo's TDWS 476 ± 10 km^3 to Amazon's TDWS 1766 ± 47 km^3 is obtained. This is roughly equivalent to the ratio estimated between their mean annual discharge to the ocean (Congo 40,000 m^3/s, Amazon 209,000 m^3/s) and the ratio between the amplitude of their water storage anomaly (Congo 40 mm, Amazon 170 mm) as well as the ratio between their recharge (P-ET), e.g., Congo 300 mm/yr and Amazon 1100 mm/yr. Other attempts to characterize the surface water storage of the Congo Basin include the studies by Lee et al. (2011); Yuan et al. (2017); Becker et al. (2018); and Kitambo et al. (2023).

River Discharge and Flow Variability

The Congo River is distinguished by its exceptional discharge characteristics, with an average annual flow rate of approximately 41,000 m^3/s recorded at the Brazzaville-Kinshasa hydrological stations (Tshimanga et al. 2022a; Moukandi N'kaya et al. (2022). The river, situated at the equator, displays a weakly contrasting equatorial flow regime, exhibiting low seasonal discharge variability. The ratio between the highest monthly mean discharge of 75,500 m^3/s and the lowest of 23,000 m^3/s is only 3.3, indicating a relatively stable seasonal flow pattern. According to Laraque et al. (2020), Paris et al. (2022), the hydrological year starts in August and features two high-flow periods (October–January and April–May) alternating with two low-flow periods (February–March and June–September) (Fig. 13). A spatial analysis of discharge variability across the Congo River Basin reveals that local and regional factors exert a significant influence on the hydrological regime. For instance, discharge and rainfall patterns at specific locations such as Bangui, Ouesso, and Kisangani exhibit considerable variation, suggesting that discharge characteristics are not uniform throughout the basin (Bola et al. 2022b). Significant variations in river discharge have been observed over the years. Between 1960 and 1995, fluctuations were noted, with the river only recently returning to its long-term average. For Kinshasa/Brazzaville station, discharge increased by 21% between 1960 and 1970, 4.5% from 1971 to 1981, followed by a 5.3% decrease from 1982 to 1993, compared to the 1902–1959 average.

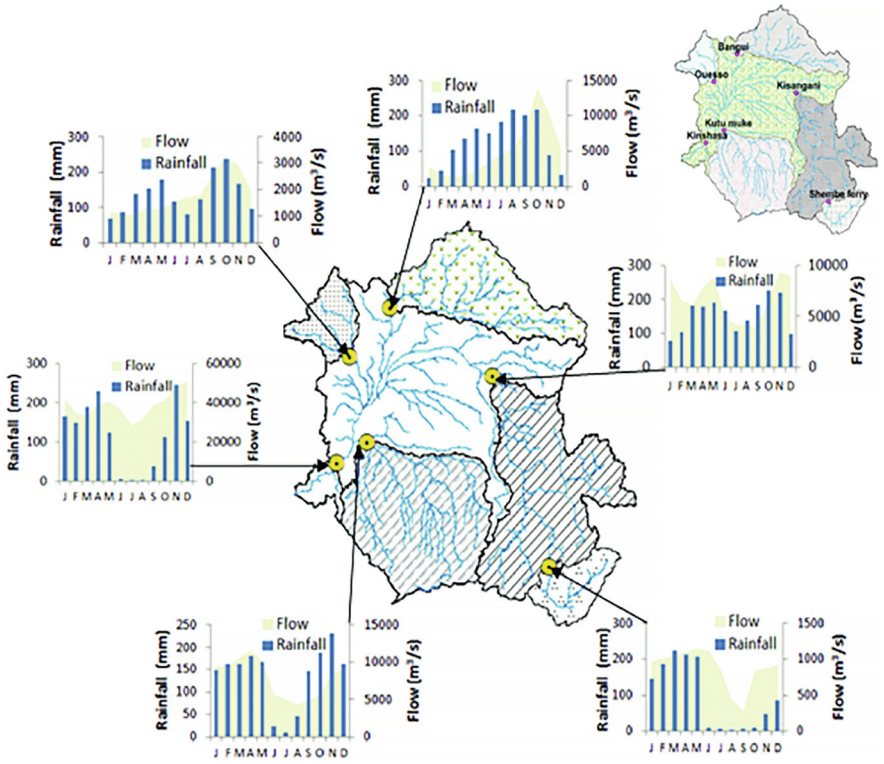

Fig. 13 Rainfall-runoff relationship in specific stations of the Congo Basin (Bola et al. 2022b)

Wetland, Peatland, and Lake Dynamics and Functions

A combination of available in situ measurements, hydrological modeling, and satellite observations is used to gain insights into these dynamics. A mass balance analysis by Yuan et al. (2022) estimated that river-wetland exchange accounts for less than 20% of the wetland inflow, while hydrological modeling by Datok et al. (2022) suggested a 69% contribution of the Congo River (33%) and tributaries (25% RoC and 11% DRC) to the wetland inflow, with remaining water input coming from precipitation. Georgiou et al. (2023) mapped the spatial distribution of the main water source for a subregion of the Cuvette Centrale. They found that 27.5% of the wetlands in the subregion received river or groundwater input. O'Loughlin et al. (2020) found that more than 16% of the river channel network actively exchanges water with wetlands and identified river-wetland exchange as a crucial feature in the propagation of Congo River flood waves. Interfluves co-occur with floodplains along the Likouala-Mossaka and Sangha Rivers, and floodplains are also found next to the Congo River, east/upriver along the left bank tributaries, and north and east of Lac Mai-Ndombe (Biddulph et al. 2021).

The dominant feature of the Bangweulu system is the seasonal flooding regime, which influences every aspect of the local environment and economy. By January each year, vast areas of the Bangweulu floodplains are inundated from local rainfall and runoff. Peak water levels occur in March when the inflow from the Chambeshi and other rivers draining the surrounding catchment spills across the seasonally flooded plains (6800 km^2) and into the permanent deepwater swamps (5000 km^2). Waters recede slowly during the dry season, reaching their lowest level in October/November, leaving only the central basin permanently under water. The mean annual outflow to the Luapula River is about 440 m^3/s. The extent of the floodwater inundation and the rate with which it rises and recedes varies from year to year. The climate is divided into three distinct seasons: a cool dry season from April to August, a hot dry season from August to October, and a warm wet season from November to April (Chundu et al. 2024). The wetland is fed by 17 major rivers from a catchment area of 190,000 km^2 but is only drained by one river, the Luapula River (Kamweneshe et al. 2003).

The wetlands associated with the Lufira River create extensive floodplains, papyrus, and other marshes, especially in the Upemba National Park region. The Lufira rises in the Shaba plateau south of Likasi. The river was dammed in 1926 at Mwadingusha near Likasi to form Lake Tshangalele, a reservoir for a hydroelectric generator supplying power for copper smelting. It flows northward through the Bia Mountains for about 500 km, joining the Lualaba in Lake Kisale. Its discharge at Kapolowe has been measured since 1920 (Devroey 1951, 1952). It is therefore fairly accurately known. Maximum discharge (between 150 and 250 m^3/s) coincides with flooding in the second half of the rainy season (February, March, or April). The minimum (between 7 and 2.5 m^3/s) occurs toward the end of November, i.e., after the start of the rainy season. The first rains serve mainly to provide the soil with moisture equivalent to field capacity. The heavy storms of November and December cause only minor, short-lived flooding. The peaks in the diagram represent a runoff of less than 1% of the water that fell. In the basin, only steep slopes with thinner weathering mantle are likely to favor runoff or hypodermic flow. In December, the latter rises, heralding the outcropping of the aquifer in the Dembos, flared-bottomed valleys with no organized linear flow. From January to April, the centimeter-thick sheet of runoff that appears in these valleys and sometimes lasts for several days after a period of heavy rain provides a significant proportion—around 40%—of the river's flow (Alexandre 1977). The Lufira basin is a wetland of worldwide importance, as the edapho-climatic factors prevailing in the area provide good conditions for the formation of various ecosystems and the development of a varied herbaceous and shrub flora. This ensures the maintenance of biological diversity, with the presence of numerous endemic species.

Lake Tanganyika partially drains into the Lukuga River at Kalemie and further feeds the Lualaba basin. This discharge contributes to 18% of the total annual water loss of the lake, while its water balance is mainly governed by evaporation, corresponding to 82% of its total annual water loss. Similarly, Lake Bangwelu and its surrounding wetlands ultimately discharge into the Luapula River, Lake

Mai-Ndombe and its wetlands contribute to the Fimi River, and Lake Mweru with its surrounding wetlands are drained by the Luvua River.

Leketi-Mbama is a unique inland wetland with a diverse mix of habitats including lakes, marshes, and floodplains. The main hydrological function of the Leketi-Bama zone is groundwater recharge: it retains around 35% of the direct rainfall over the region. The Kouyou is the main river feeding the area, receiving water from several tributaries including the Okeli Ambori stream and flowing into the Likouala Mossaka at Loboko village.

The Tchicapika-Owando is mainly made up of the Kouyou and Alima rivers, whose tributaries are the Lavouma and Diéle, respectively. The Kouyou flows into the Likouala-Mossaka, which in turn flows into the Congo River. The Alima flows directly into the Congo River. During high-water periods, all these rivers are connected in some places to floodplains and swampy forests. Floods are regular and of fairly long duration. Variations in river discharge regulate the intensity and duration of exchanges between the various geographical elements of the river-alluvial plain system. When the water level rises, water invades part of the alluvial plain, establishing connections and enabling exchanges with the minor bed. Conversely, when water levels fall, certain areas of the alluvial plain become isolated from the riverbed. Oscillations in the hydrological regime have an impact on the amplitude, duration, and frequency of floods. Whatever the period of high or low water, they exert a greater or lesser influence on the productivity of hydro systems (Fig. 14).

Most wetlands in the Congo Basin significantly contribute to dampening the flood risks downstream through many functions (Hooijer et al. 2005; Dommain et al. 2010; Acreman and Holden 2013; Gao et al. 2016; Crump et al. 2017). The Cuvette Centrale significantly extends the travel time of water from different regions of the Congo Basin before it reaches Kinshasa and Brazzaville and partly explains the long residence times of 2 months for the flow to move from the confluence of the Lualaba and Elila Rivers to Brazzaville, 1 month from the confluence of the Kotto and Oubangui Rivers, and approximately 15 days from the confluence of the Loange and Kasai Rivers (Sridhar et al. 2022). Besides taking up water, the Cuvette Centrale acts as a natural reservoir that traps sediment from upstream rivers thus reducing the amount of suspended particles flowing downstream. Reduced uptake of sediments would lead to a rise of the riverbed and impact flooding dynamics in downstream areas.

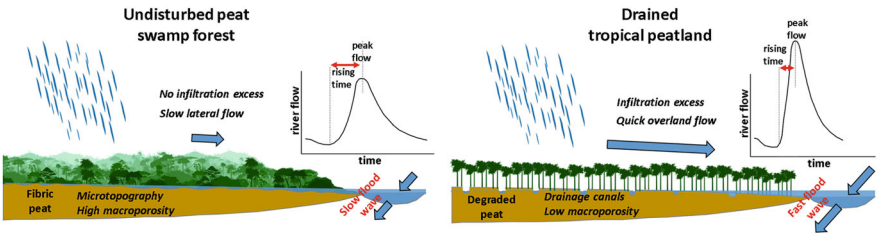

Fig. 14 Schematic illustrating the buffering role of peatlands during rainy periods and high river stages, highlighting how human disturbance amplifies downstream flood risks

In the Cuvette Centrale, peat formation began at least 19,600 calibrated years before present (cal yr BP; taken as AD 1950; Garcin et al. 2022; Hawthorne et al. 2023), but mostly from about 10,500 cal yr BP (Dargie et al. 2017), coinciding with more humid conditions at the beginning of the Holocene (Schefuß et al. 2005). Peat accumulation is a good proxy for hydrological stability, as organic material will only accumulate under relatively stable hydrology (Dargie et al. 2017). Studies of cuvette centrale peat show that shifts in the hydrology have led to periods of peat accumulation, where the hydrology has been conducive, as well as hiatuses of that growth (Garcin et al. 2022).

The heterogeneous hydrology of the Congo Basin peatlands could indicate that various processes have initiated peat development at distinct times (Biddulph et al. 2021). A drying period between 5000 and 2000 yr bp implies a regional drop in the water table, causing peat decomposition, including some of that was already accumulated. There was no evidence of human impacts on the forest in that period. After 2000 yr bp, conditions stabilized and peat accumulation resumed. The authors conclude this may show that the stability of the carbon stocks in the peatlands may be sensitive to a climatic drought threshold (Garcin et al. 2022). Whenever the self-regulating hydrology of peatlands is disturbed by external factors such as artificial drainage, land use change, and climate change, their ecosystem functions and services are often lost. Future exploration of unexposed, remote peatland areas might strongly impact the peatland hydrology in the Cuvette Centrale (Dargie et al. 2019). The Congolese rainforest is relatively dry compared to tropical forests in Southeast Asia and Central and South America, receiving approximately 35–40% less precipitation (1700 mm yr^{-1}; Samba and Nganga 2012) than its Amazonian counterpart (Guan et al. 2015; Alsdorf et al. 2016). The limited precipitation and its bimodal pattern (Longandjo et al. 2024) make the Congolese rainforest and its peatlands water-limited during dry seasons and highly vulnerable to drought intensification or changes in the rainfall pattern (Jiang et al. 2019). Drought pressure poses a major threat to the peatlands of the central Congo Basin (Loisel et al. 2021), potentially leading to carbon emissions via oxidation or fires. Ongoing climate warming will likely increase drought severity, while possible intensification of El Niño could further prolong droughts (Rifai et al. 2019). Garcin et al. (2022) used paleo records from peat cores in the Cuvette Centrale and identified a long period (between 5000 and 2000 cal yr BP) of dry conditions, i.e., the "Ghost interval." Their research showed that environmental change could lead to a regional drop in peatland water levels with decreased peat accumulation or even peat decomposition, which might be a precedent of the impact of current and future drought pressure on these peatlands.

Most of the progress in our understanding of these historical conditions before traditional measurements has therefore been made by paleoenvironmental studies. We also see evidence of these significant changes in the hydrology from studies of Congo sediment in the Atlantic. A high aridity period during the last glacial maximum, an increase in precipitation and high river discharges from 15,200 yr BP, and around 9000–8000 cal ka BP, rainforest vegetation inhibited soil erosion and therefore sediment discharge (Marret et al. 2008).

While much remains to be done in this research area, including understanding how far back peat accumulation started, what we can take away is that changes in the hydrological regime can cause significant changes in the basin, such as loss of peat, and these can last thousands of years and potentially link to important carbon climate feedback mechanisms. The point here is that there have been significant changes in the magnitude and timing of the hydrology cycle induced by climate and vegetation changes in the past, showing that it may actually change substantially in the future if we perturb the current context.

Biogeochemical Processes

Borges et al. (2019) carried out field measurements across the lowland part of the Congo River network to describe the spatial variations in fluvial dissolved carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) concentrations. Field measurements across the lowland regions of the Congo River network revealed a pronounced oversaturation of surface waters with carbon dioxide (CO_2) and methane (CH_4) relative to atmospheric equilibrium. Greenhouse gas dynamics in Congo Basin rivers showed extreme variability. CO_2 partial pressures (1087–22,899 ppm) and CH_4 concentrations (22–71,428 nmol/L) far exceeded equilibrium values (~400 ppm and ~2 nmol/L, respectively), while N_2O varied less. Spatial variability, driven by stream size, stream order, and floodplain interactions, dominated over seasonal or diurnal changes. Larger streams had lower CO_2/CH_4 and higher oxygen. Rivers draining the Cuvette Centrale exhibited highest greenhouse gas levels, linked to flooded forests and wetland inputs. Elevated DOC (1.8–67.8 mg/L) and oxygen undersaturation (0.3–122.8%) highlighted strong organic matter decomposition.

In the Congo Basin, major and trace elements and Sr isotope ratios were investigated at the Pool Malebo for the 1989 and 2010 hydrological cycles (see for details Négrel 1993; Négrel and Dupré 1995; Henchiri et al. 2016). Additionally, the main tributaries were also investigated (Oubangui, Kasaï, Sangha, Likouala, and Lefini).

Figures 15 and 16 present the fluctuations of the $^{87}Sr/^{8}6Sr$ ratios and the discharge in the dissolved load obtained for the Congo River for the 1989 and 2010 surveys. Both figures showed that the $^{87}Sr/^{86}Sr$ ratios are highest during low flow and decrease with increasing discharge. This type of relationship can be interpreted as a mixing with two signatures (Grosbois et al. 2000; Négrel et al. 2003).

The $^{87}Sr/^{86}Sr$ isotope ratios exhibited strong seasonal patterns, peaking during low-flow periods and declining with increasing discharge. This inverse relationship suggested a dual-source mixing model, where Sr inputs during low flow likely derived from rock weathering and terrestrial sources, while during high flow, dilution from precipitation or other tributary inputs dominated (Fig. 17).

Further insight was gained from the relationship between Sr and sodium (Na) concentrations. A clear positive correlation existed between Na and Sr across seasons, with lowest concentrations during low water periods. Tributaries such as the Kasaï, Oubangui, and main Congo River channel displayed higher Na-Sr contents,

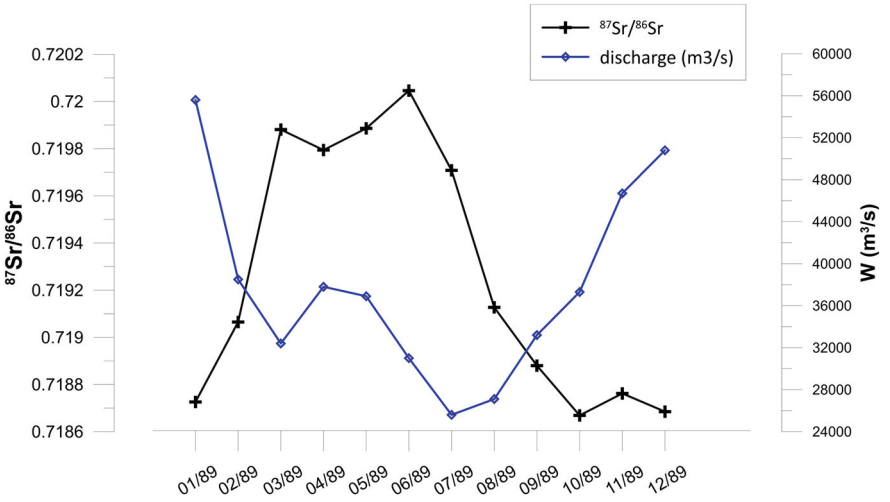

Fig. 15 Mean monthly discharge of the Congo River at the Brazzaville station (W in m^3/s) and $^{87}Sr/^{86}Sr$ values for the samples collected each month at the Brazzaville station (Négrel and Dupré 1995)

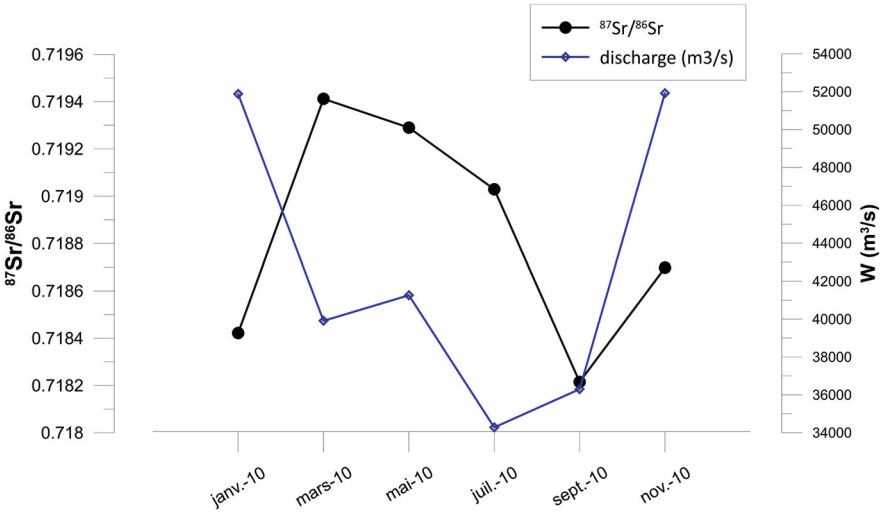

Fig. 16 Mean discharge of the Congo River at the Kinshasa station (W in m^3/s) and $^{87}Sr/^{86}Sr$ values for the samples collected every 2 months at the Kinshasa station (Henchiri et al. 2016)

while dilute, DOC-rich tributaries draining the central depression (e.g., Sangha, Likouala, Alima) exhibited much lower values. The Lefini River, draining the Batékés plateaus, also showed very low Na-Sr signatures, consistent with its geologic setting.

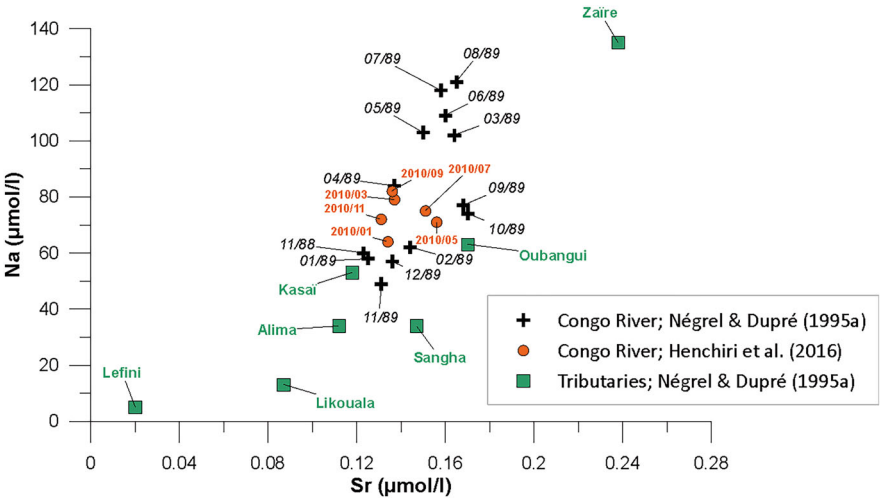

Fig. 17 Plot of Na versus Sr contents for the samples of the Congo River, collected each month at the Brazzaville station (Négrel and Dupré 1995), every 2 months at the Kinshasa station (Henchiri et al. 2016) and for the tributaries (Oubangui, Zaïre, Kasaï, Sangha, Likouala, and Lefini; Négrel 1992)

The biogeochemical processes in the Congo River Basin are controlled by a complex interplay of lateral carbon inputs, organic matter decomposition, stream size, floodplain dynamics, and geological substrate. CO_2 and CH_4 emissions are sustained primarily by allochthonous carbon sources, especially from wetlands. Meanwhile, Sr isotopes and elemental ratios offer deep insights into hydrological and geochemical mixing, helping to trace the influence of both surface water and groundwater across varying spatial and temporal scales. These findings underscore the importance of integrating biogeochemical, hydrological, and isotopic approaches to understand carbon cycling and water movement in tropical river systems like the Congo.

Supply and Demand of Water Resources

The Congo Basin's main water uses are urban/municipal supply, agriculture, hydropower, navigation, and biodiversity maintenance. The population of roughly 120 million (70% in rural areas) depends heavily on rainfed, slash-and-burn farming, a key driver of deforestation. Expanding irrigation could promote sedentary agriculture, curb forest loss, boost productivity, stabilize incomes, and mitigate rainfall variability impacts.

Hydropower potential is estimated at 100,000 MW, yet installed capacity is just 2700 MW. Electrification is low, with only 9% of the population having access. Major future projects—such as Grand Inga (40,000 MW) and Inga III (4320 MW)—could transform regional energy supply, reduce reliance on wood fuel, and cut deforestation pressure.

The basin also has around 25,000 km of navigable waterways, but navigation is hindered by infrastructure deficits. Strategic investments in ports, terminals, and dredging could lower transport costs, facilitate trade, and connect landlocked countries to global markets. Enhanced navigation would stimulate industry, attract investment, and foster political and economic integration. Additionally, improved access could support ecotourism, generating income and jobs while promoting conservation.

The Congo Basin's water resources hold transformative potential for regional development. Realizing this will require coordinated investment in water supply, irrigation, hydropower, and navigation infrastructure, alongside sustainable management to balance economic growth with environmental protection in the face of climate change.

Dynamical Evolution of the Hydrology of the Congo Basin

Like all large river basins, large-scale geological processes have shaped the Congo Basin over geological epochs. However, the changes that this basin has been exposed to have resulted in a basin like no other currently on the planet. This intracontinental sag basin has resulted in a remarkable deposit of up to one billion years of sediments (Delvaux et al. 2021). It is important to understand these shaping influences as they explain much of the core hydrological systems of what we see today, while also highlighting the long-term non-stationary aspect of the basin's dynamic hydrology. The legacy of these geological changes is evident in the basin's current hydrological systems. The interplay between tectonic stability and climate-induced fluctuations has shaped the region's deep river channels (below Malebo Pool), its vast wetlands, and rich alluvial plains, making the Congo River remarkably stable in terms of discharge.

On very short timescales of the last 100 years or so, the system does appear to be relatively stable (Laraque et al. 2020). For example, a study of the planform of the main river channel and islands conducted by Trigg et al. (2022) using a comparison of recent satellite images and historical navigation maps shows that the main river is relatively stable and only appears to change slowly over the period assessed. However, there was an indication in this study that either a recent reduction in hydrology inputs or increase in sediment inputs were driving a slow accumulation of sediment in the main channel.

While on recent human timescales there appears to be relative stability in the hydrological systems of the Congo, this can be deceptive, as large systems can change, albeit relatively slowly and are actually always changing. Studies of hydrology variables at climate and river stations across the Congo Basin reveal that, set in this stable context, we observe both gradual changes such as increases in temperature (Samba et al. 2008) and discontinuities in runoff variables during particular historical periods in the last 100 years (Laraque et al. 2020). This indicates the main flood regime is not stationary (Bola et al. 2022a) and extremes such as floods have very real impacts on the local populations (Bola et al. 2022b), as many millions live near

and rely on the Congo for their livelihood and economic transport (Trigg et al. 2022). This can be worsened in the future as climate change impact show increasing trend in flood regime. The climatic and environmental shifts over the past tens of thousands of years have also contributed to the unique hydrology of the Congo Basin, influencing everything from river discharge to biodiversity. Understanding these deeper historical changes is essential for predicting how future climatic and anthropogenic changes may impact the basin.

Given the focus on "influencing equitable resource sharing and maintaining the Congo Basin's ecological role," it is important to understand the current drivers of hydrological change in the Congo Basin. The drivers constitute interconnected demands for water, energy, and food resources, and these competing demands drive changes across the basin's hydrology. The three major drivers are hydropower and large water infrastructure development, deforestation and land use change, and mining.

These trends highlight the urgency of integrated and sustainable resource management in the CRB. While much of the current deforestation remains artisanal, experiences from other basins show that unchecked development can lead to profound hydrological consequences. Understanding ecological thresholds and enforcing land use limits will be critical to safeguarding the basin's environmental services and the livelihoods that depend on them.

Synthesis, Gaps, and Challenges

The time scale of this review spans from 1903 to the present. This is because we lack measurements prior to this year which marks the start of the hydrological monitoring in the Congo Basin. It is also unfortunate that indigenous knowledge about the hydrology in the Congo Basin is not documented prior to this period (Tshimanga 2009).

There is no doubt that there have been enormous efforts deployed during this time period to collect in situ data and use various empirical analyses and numerical models to establish an understanding of the basin's hydrologic variability and changes. The difficulty of acquiring spatial and temporal in situ data of sufficient quality prompted the use of earth observation datasets. However, quality in situ data are still required to validate data obtained from remote sensing. Many hydrology studies have been variously challenged by problems related to lack of appropriate data, as well as the lack of a thorough understanding of climate-hydrology processes. There has also been a lack of integration of this understanding in models and therefore, lack of integrated and critical model assessment. There is a lack of a quantitative understanding of the spatial heterogeneity and dynamics of different components of the hydrology of the Congo Basin, which inhibits the advancement of innovative approaches and their applications in water resources management, climate modeling, and ecosystem vulnerability studies. For example, it is currently unknown how changes to the wetland hydrology and energy balance might alter the local climate across the basin and beyond through teleconnections

(White et al. 2021). It is assumed that by stabilizing the regional hydrological cycle, wetland forests may reduce extreme variations in rainfall, which can otherwise lead to severe floods. A stronger scientific understanding of the land-atmosphere coupling over the vast wetland area of the Cuvette Centrale would give these wetlands a new value that goes beyond already known critical services such as local carbon storage and biodiversity. To advance in these fields, there is an urgent need to address the scarcity of in situ measurements of hydrological variables and to exploit the wealth of historical and newly available satellite observations.

Having looked at the past and present of the current basin hydrology dynamics, what does the future hold? Recent hydrological studies of multimodel regional climate downscaling suggest future changes in river flow ranging from −31.8% to +9.2% under RCP4.5 and −42.5% to +55.5% under RCP8.5 scenarios. In the upstream reaches, these changes are more pronounced. Discharge is also shown to decline in the basin's center and south while increasing in the southeast and northwest (Karam et al. 2023).

In the context of ongoing climate change, the CRB is geopolitically at the center of many proposed solutions due to it perceived abundance of water (Inogwabini 2020). However, across the basin, challenges such as overfishing and lack of transboundary management plans complicate this water resources management expectations. Thus, although the basin is commonly perceived as having a relatively low anthropogenic influence compared to other large river basins, this is unlikely to continue in the future as development pressures increase and humanity looks at climate change adaptation.

The future hydrology of the Congo Basin is expected to undergo significant changes due to climate change, with varying impacts across different regions of the basin. Increased temperatures and variable precipitation patterns will likely lead to changes in runoff, river flow, and the frequency of hydrological extremes such as droughts. The complexity and uncertainty in climate model projections highlight the need for comprehensive and adaptive water management strategies to mitigate the potential adverse effects on agriculture, hydropower, and water availability for human and ecological systems (Tshimanga and Hughes 2014).

While much progress has been made in the last few decades in beginning to understand the hydrological systems in the CRB and how the core of this system functions, nonetheless there is much we are still trying to explain. There are many hazards posed by changes in the future for the Congo Basin that may detrimentally affect its biodiversity and ecosystem services for humanity locally and at planetary scale. How these changes, which are inevitably coming, will affect the dynamics of the Congo Basin is still poorly understood. We urgently need to gain this understanding in order to manage as best as we can how changes manifest in the system. This will provide evidence-based decision-making to preserve and indeed, if possible, enhance the value of this unique and precious systems for local populations as well as globally. This can be exemplified by the need to improve the knowledge of surface-groundwater links. The regulating role of the aquifer is highlighted by the contrast between the low seasonal variations of the river flow rates in the Cuvette

Centrale despite the significant seasonal variability of rainfall in this part of the basin. This should be extended to other parts of the basin, in close relation with the study of wetlands.

The data scarcity problem needs to be addressed through the support of data rescue efforts, i.e., the digitization of colonial and post-colonial archives (mainly weather station and stream gauge data), as well as the expansion of the currently established monitoring network for surface waters and wetland groundwater levels as well as energy and carbon fluxes through eddy covariance towers. Together with satellite data, the new measurement data can be upscaled and combined with hydrological models to derive realistic replicates of the water cycle over the wetland in the Congo Basin that could be used in scenario modeling to present the impact of disturbance to regional and global stakeholders.

This review helps articulate a number of major challenges of hydrological research in the Congo Basin in terms of process understanding and critical information gaps, which require major scientific investment. Specifically, future work should address the following:

1. Local and external factors (atmospheric-ocean interactions and the monsoonal processes) that influence variability in rainfall
2. Influence of global warming on rainfall pattern and water storage and their seasonal distributions, and implications for rainfed agriculture-food security, hydropower, and ecosystems services
3. Forest hydrology: forest canopy interception and evapotranspiration dynamics
4. Local and regional moisture recycling and the impact of deforestation
5. The spatial distribution of permanently and seasonally inundated forests, interaction between rivers and wetland/peatland hydrology and their connectivity
6. Human disturbance in logging and oil palm concessions and local and remote impact on wetland/peatland hydrology and carbon stocks
7. Large-scale deforestation, mining and impacts of river flows, water quality, and biodiversity
8. Deforestation, evapotranspiration losses and impacts on runoff, groundwater recharge, and river base flows
9. Land cover change, land degradation, sediment yield, and changes in aquatic habitats
10. Floodplains and sediment dynamics
11. Hydro-climatic variability, trends, and environmental risks including extreme floods and droughts
12. Water pollution (plastic, industries, and mining)
13. River diversion, impoundment, and fragmentation of water resources/ecosystem services
14. Current and future water use patterns
15. Regional water stress, migrations, and conflicts

The results of such studies will not only be relevant to the Congo River Basin but will also yield important science insights that are widely applicable across other

tropical forest regions and which will transform our understanding of the role of the Congo Basin as a critical element in the global Earth System. While the challenges for hydrologic science are enormous, so are the potential rewards, and the Congo Basin is currently one of the most exciting frontiers in hydrological science.

Competing Interest Declaration The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

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6 Hydrology of the Ogooué and Sanaga Watershed Systems: Critical Case Studies in the Context of the Congo Basin Forest

Sakaros Bogning, Raphaël M. Tshimanga, Jean-Pierre Messina Ndzomo, and Jean-Jacques Braun

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Abstract

This chapter explores the hydrology of the Ogooué (Gabon) and Sanaga (Cameroon) river basins—two critical but understudied watersheds within the broader Central African hydro-ecological system. While both rivers discharge independently into the Atlantic Ocean, they are closely tied to the Congo Basin Forest through shared climatic drivers, ecological continuity, and significant contributions to regional water cycles and biodiversity. The chapter provides an in-depth analysis of their geomorphology, hydrological regimes, and socioeconomic importance, highlighting the Ogooué's largely pristine, forest-dominated catchment and the Sanaga's heavily regulated hydrosystem dominated by hydropower infrastructure. Long-term observational and satellite data reveal trends of declining rainfall and altered discharge regimes in both basins since the 1970s, driven by climate change and land use transitions. Advanced hydrological modeling—using satellite altimetry, GRACE, and distributed models like SWAT and MGB—demonstrates spatial variability in hydro-climatic responses and emphasizes the need for integrated, context-specific water resource management strategies. The chapter also stresses the ecological significance of these rivers, which host diverse fauna and flora, and underscores the role of traditional ecological knowledge in managing dynamic wetland systems. A call is made for increased scientific investment in Central Africa, where hydrological data scarcity and low international funding hinder evidence-based conservation and development planning. Recognizing the Ogooué and Sanaga as vital components of the Central African hydrological mosaic is key to enhancing resilience and sustainability in the face of rapid environmental change.

Keywords

Ogooué River · Sanaga River · Central Africa · Hydrological modeling · Climate change · Congo Basin · Remote sensing · Integrated water management

Introduction

At the very core of Central Africa lies Earth's second-largest tropical rainforest, fundamentally anchored by the Congo Basin, a hydrological and ecological marvel of global significance (White et al. 2021). This vast expanse of dense forest, often recognized as a critical "lung" for the planet, plays an indispensable role in regulating global climate through its carbon sequestration capacity (White et al. 2021; Demichelis et al. 2023). Furthermore, it intricately shapes regional water cycles by generating substantial evapotranspiration, which contributes to atmospheric moisture recycling and influences rainfall patterns far beyond its immediate boundaries, extending even to the Sahel and Ethiopian highlands (Mahe et al. 2001; White et al. 2021). While the Congo River, with its 3.7 million square kilometer catchment, is rightly celebrated as Africa's paramount fluvial system, it is crucial to recognize the importance of other major riverine networks within this hydro-ecological fabric

(Alsdorf et al. 2016). These systems, although draining independently to the Atlantic Ocean rather than into the Congo's internal network, are intrinsically linked to the broader Central African hydro-mosaic. They contribute significantly to regional water balance, support unique and often isolated ecological enclaves, and form the foundational basis for the sustenance and development of millions across the continent.

This chapter delves into two such pivotal, yet frequently less emphasized, river systems: Gabon's Ogooué River Basin (ORB) and Cameroon's Sanaga River Basin (SRB). Both these fluvial giants discharge directly into the Atlantic, distinguishing their hydrological behaviors from the Congo's interconnected interior. Nonetheless, their geographical proximity to the Congo Basin, their shared exposure to analogous climatic forces, and their deep ecological kinship firmly embed them within Central Africa's complex hydrological tableau and the expansive Congo Basin Forest biome. The ensuing exploration will unravel their particular hydrological signatures, delving into the nuances of their rainfall patterns (Bogning et al. 2025; Longandjo and Rouault 2023; Ebodé 2022), scrutinizing their seasonal flow dynamics (Mahé et al. 1990), and unveiling the deep-seated impact of their varied topographies—from ancient, high plateaus to vast, low-lying coastal plains—on flow velocity, sediment transport, and, ultimately, the perennial availability of water across their landscapes (Martin 1981; Giresse 1990).

Beyond their physical water regimes, this chapter will undertake a thorough examination of the socioeconomic leverage wielded by the Ogooué and Sanaga. These rivers function as essential arteries, serving as indispensable cornerstones for the developmental aspirations and daily existence of their respective nations, Gabon and Cameroon. Their waters are foundational to numerous critical sectors: providing potable and industrial water to expanding urban centers (Kpoumié et al. 2022), sustaining agriculture through irrigation (Zébazé Togouet et al. 2023), and, most crucially, generating energy via immense and progressively harnessed hydropower potential (Zébazé Togouet et al. 2023; Sighomnou et al. 2007). Moreover, their roles as vital transport conduits facilitate regional commerce, enable the extraction and movement of natural resources, and forge essential connections (Demichelis et al. 2023). In parallel, their irreplaceable ecological worth will be underscored, recognizing them as thriving sanctuaries of biodiversity, nurturing unique flora and fauna, and collectively contributing substantially to global terrestrial carbon storage (Moquet et al. 2020; Demichelis et al. 2023).

The overarching aim of this chapter is to firmly integrate these individual coastal basins into the grander narrative of the Congo Basin Forest. By adopting this perspective, the intent extends beyond merely delineating their unique attributes as separate drainage systems. Instead, the focus shifts to accentuating their collective susceptibility to contemporary environmental pressures and elucidating their synergistic, commanding role in shaping Central Africa's future hydrological landscape (Tsonis et al. 2008). The discussion will illuminate how large-scale atmospheric circulation patterns govern their climatic profiles (Farnsworth et al. 2011; Burnett 2005; An and Wang 2001), how their forested catchments actively modulate regional moisture budgets through intricate eco-hydrological feedbacks (Raghavendra et al. 2022),

and how they confront an escalating array of common threats. These perils stem from the triple confluence of intensifying climate disruption (manifesting as altered precipitation regimes, increased aridification, and more extreme weather events), pervasive land clearing (driven by agricultural expansion, timber extraction, and infrastructural development), and the relentless surge in human demands on finite natural resources. Through a rigorous and comparative analysis of the Ogooué and Sanaga river systems, this chapter endeavors to cultivate a more refined, holistic, and immediately applicable understanding of Central Africa's intricate and dynamically evolving hydrological tableau. This broadened and integrated knowledge is not simply academic; it is unequivocally essential for devising and rigorously implementing resilient, sustainable strategies for water resource management and effective conservation across this globally indispensable and rapidly transforming region (Abtew and Melesse 2014; Steptoe et al. 2018).

Hydrology of the Ogooué River Basin

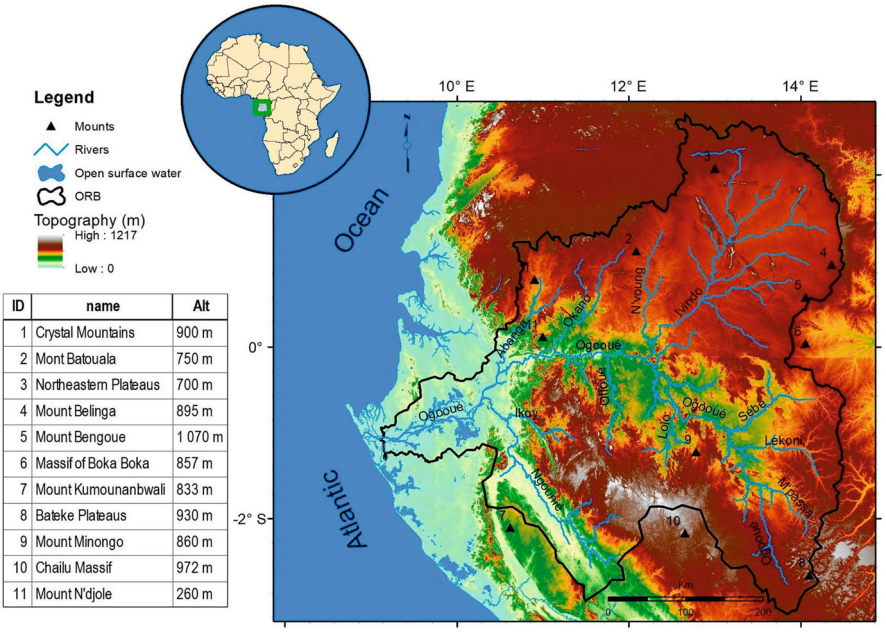
The Ogooué River, Gabon's most significant river, is also the second largest in Central Africa by discharge, with an annual average of approximately 4750 m^3/s. Its length extends to about 1200 km from its source in the Mounts Ntalé, Republic of Congo, to its mouth in the southern Atlantic coast of Gabon. The Ogooué River Basin (ORB) spans an extensive area of around 224,000 km^2, with over 80% located within Gabon, and smaller portions extending into southeastern Cameroon and the Republic of Congo. This vast catchment serves as a crucial conduit for water and sediments to the Atlantic Ocean, influencing both regional hydrology and contributing to the broader marine environment of the Gulf of Guinea (Bogning et al. 2022).

Geographical and Climatic Features

The ORB is uniquely positioned on the western Atlantic coast of Central Africa, precisely straddling the equator between latitudes 3°S and 2.5°N and longitudes 9°E and 14.5°E. This precise equatorial location profoundly dictates its climatic characteristics, leading to high humidity and consistent warmth throughout the year. The basin's topography, while predominantly mountainous, is characterized by average elevations of approximately 450 m, without exceptionally high peaks that would significantly alter regional atmospheric circulation. It is defined by three primary topographical structures that shape its hydrological response: the low coastal plain, extending inland from the river mouth, which is a complex mosaic of interconnected lakes and the expansive Ogooué delta; this hydromorphic area, typically situated below 200 m in altitude, is notable for its substantial water dominance and localized heterogeneity, deeply influenced by the underlying bedrock, thin overlying soils, and an intricate, variable drainage network (Martin et al. 1981). Further inland, extensive plateaus, often deeply dissected by the river's tributaries, cover a significant portion of the basin, stretching northward toward Ogooué-Ivindo, southeast into the

Haut-Ogooué region—including the distinctive Batéké Plateau—and southward into the Ogooué-Lolo and Ngounié regions, with elevations typically ranging from 300 to 800 m. Finally, the mountainous massifs, composed of medium-sized mountain ranges like the central Chaillu massif, feature peaks exceeding 1000 m, such as Mount Bengoué (1070 m), Mount Milondo (1020 m), and Mount Iboundji (980 m) (CBD 2004); these highlands serve as critical hydrological divides and act as essential sources for the numerous tributaries feeding the main Ogooué stem (see Fig. 1). The local landscape of the Bas-Ogooué Ramsar site, situated within the confluence zone of the Ogooué watershed, exemplifies a particularly heterogeneous mosaic of tropical rainforest, savannah, and swamps (Demichelis et al. 2023).

Owing to its position in equatorial Africa, the ORB receives substantial annual precipitation, consistently ranging from 1600 to 2200 mm/year, providing a robust input for its hydrological system (Bogning et al. 2021a). The climate is unequivocally equatorial, distinguished by a pronounced bimodal rainfall regime that features two distinct dry seasons and two rainy seasons. The "small rainy season" typically occurs between March and May (MAM), while the "large rainy season" extends from October to December (OND), both bringing significant rainfall. These wet periods are interspersed with a shorter dry season in the boreal winter (January–February) and a more prolonged, pronounced dry season during the boreal summer



ID	name	Alt
1	Crystal Mountains	900 m
2	Mont Batouala	750 m
3	Northeastern Plateaus	700 m
4	Mount Belinga	895 m
5	Mount Bengoue	1 070 m
6	Massif of Boka Boka	857 m
7	Mount Kumounanbwali	833 m
8	Bateke Plateaus	930 m
9	Mount Minongo	860 m
10	Chailu Massif	972 m
11	Mount N'djole	260 m

Fig. 1 Detailed map of the ORB, highlighting its geomorphological features, including elevation gradients (0–1217 m) and the extensive river system. Numbered triangles correspond to major mountains listed in the accompanying table with their respective altitudes (e.g., Crystal Mountains, Mont Bengoue). The inset map indicates the ORB's position along the Atlantic coast of Central Africa

(June–August), during which rainfall can drastically diminish to barely 4% of the annual total in some localized areas (Makanga and Damien 2015). This consistent and high rainfall sustains the basin's dense Central African rainforest cover, which, in turn, plays a crucial role in shaping local microclimates and regulating hydrological processes, notably evapotranspiration and soil moisture retention. Intriguingly, studies have indicated that rainfall variations in the ORB are not primarily linked to the meridian transits of the Intertropical Convergence Zone (ITCZ), a common driver in tropical regions, but rather to complex interactions with tropical Atlantic Sea Surface Temperature (SST) and other broader global oceanic influences (Nicholson 2018; Balas et al. 2007).

Hydrological Characteristics and Importance

The abundant and distinctly seasonal rainfall across the ORB directly translates into significant river discharge, which firmly establishes the Ogooué's prominence as a major river system within Central Africa. The basin's hydrology is overwhelmingly rain-fed, leading to well-defined seasonal flow patterns that closely mirror the bimodal rainfall regime observed across its catchment. Consequently, peak flows are consistently observed during and immediately following the primary rainy seasons, while considerably lower flows characterize the extended dry periods, a natural hydrological rhythm that fundamentally dictates the availability of water for various ecological and anthropogenic uses throughout the year. Historically, the Ogooué River's hydrological regime, particularly at the long-monitored Lambaréné station, was characterized by two nearly equivalent maximum floods occurring in spring and autumn, reflecting a balanced bimodal influence. However, compelling data reveal significant alterations in this pattern since the 1970s; the disparity between spring and autumn flood maxima notably increased, from 13.5% in the 1960s to 27.0% in the 1970s, reaching 38.4% in the 1980s, and remaining substantial through the 2000s and 2010s (Bogning et al. 2022). This observed shift is specifically linked to a reduction in January and February rainfall, which consequently leads to higher soil moisture deficits before the onset of the subsequent rainy season (Lienou et al. 2008). Despite these interdecadal shifts in seasonal flood dominance, overall rainfall variability on an interannual scale remains moderate within the ORB, indicated by a standard deviation of only 7.1% of the annual average precipitation (Bogning et al. 2021a).

The Ogooué River system is critical for the livelihoods and burgeoning economy of Gabon, serving as a multifaceted natural asset. Its waters directly support potable and industrial water supply for numerous communities and rapidly expanding urban centers, contributing to both direct human consumption and the vital recharge of regional water tables. The extensive and fertile floodplains, coupled with the consistent availability of water, sustain local agricultural practices, predominantly subsistence-based, which significantly contribute to regional food security and the livelihoods of rural populations. Furthermore, the river possesses substantial hydroelectric potential, with existing infrastructure like the Poubara dam already playing a

key role in supporting Gabon's energy independence and fostering economic growth, and plans for further development are underway. As a navigable waterway, particularly across its extensive lower and middle reaches, the Ogooué serves as a crucial artery for inland transportation, facilitating regional commerce, enabling the efficient movement of goods and natural resources, and providing essential connectivity that links remote interior regions to coastal hubs and international markets, notably to Lambaréné and Port-Gentil via daily boat services (Demichelis et al. 2023). Beyond its direct utility, the Ogooué Basin also contributes significantly to global carbon cycling, exporting approximately $(0.8 \pm 0.3) \times 10$–3 Pg of dissolved organic carbon (DOC) to the ocean annually, a quantity representing 3.2% of Africa's total riverine DOC export (Li et al. 2019), with dense forest cover playing a primary role in controlling the concentration and flux of this organic carbon.

Ecologically, the ORB is an invaluable global asset. It is widely considered one of the world's best-preserved ecosystems, a status largely attributable to Gabon's proactive and exceptional conservation policies (Abernethy et al. 2016, Fichet and Sannier 2014; Braun et al. 2015). The basin encompasses a remarkable array of significant national and internationally recognized protected areas, including the iconic Lopé National Park, the biodiverse Ivindo National Park, and several vital RAMSAR sites, such as the Ivindo Rapids and Falls, Mboungou Baduma, and Doumé Rapids, along with numerous other critical wetlands downstream. These designated areas function as true biodiversity hotspots, providing essential habitats for a vast array of unique flora and fauna, including numerous endemic fish species and charismatic megafauna such as African forest elephants (*Loxodonta cyclotis*), gorillas, and chimpanzees (Cutler et al. 2020; Demichelis et al. 2023). The robust preservation policies diligently implemented by Gabonese authorities have contributed significantly to the widespread regeneration of forest ecosystems throughout the basin, further enhancing its indispensable role in regional and global biodiversity conservation efforts.

Monitoring and Challenges

The ORB, despite its remarkable state of preservation, confronts a growing array of hydrological and environmental pressures, predominantly driven by changing global and regional climatic patterns alongside increasing anthropogenic activities. A persistent and significant challenge in this region has been the scarcity of comprehensive, long-term, and high-quality ground-based hydrological data, with most in situ gauging stations having ceased operation after the 1980s and completely by 1997 (Mahé et al. 1990; Maloba Makanga 2015). This profound data gap severely hinders the accurate and reliable monitoring of the basin's dynamic response to escalating environmental changes and limits the ability to develop robust predictions for future water availability.

To overcome this critical data limitation, advanced remote sensing techniques, particularly satellite altimetry, have emerged as indispensable tools. Numerous studies have successfully established multi-mission altimetry-based hydrological

networks across the ORB, utilizing data from various satellite missions including ERS-2, ENVISAT, SARAL, Jason-2 and 3, Sentinel-3A, and CryoSat-2 (see Fig. 2; Bogning et al. 2018a, 2021a). These concerted efforts have enabled the creation of continuous and extensive water level and discharge time series, offering unprecedented insight into the basin's hydrological variability. Notably, the long-term altimetry-derived monitoring of water levels in the ORB has consistently demonstrated high accuracy when compared with the limited available field-measured data, with impressive correlation coefficients (R2) frequently exceeding 0.90 and root mean square error (RMSE) values typically remaining below 0.5 m, particularly at crucial gauge stations like Lambaréné (Bogning et al. 2018b, 2021a). This robust agreement between satellite and in situ measurements unequivocally underscores the reliability and transformative potential of satellite altimetry as a powerful tool for hydrological monitoring, especially critical in data-scarce regions like the ORB.

Hydrological modeling efforts for the ORB, a historically ungauged and therefore challenging basin to characterize, have significantly leveraged this multi-mission

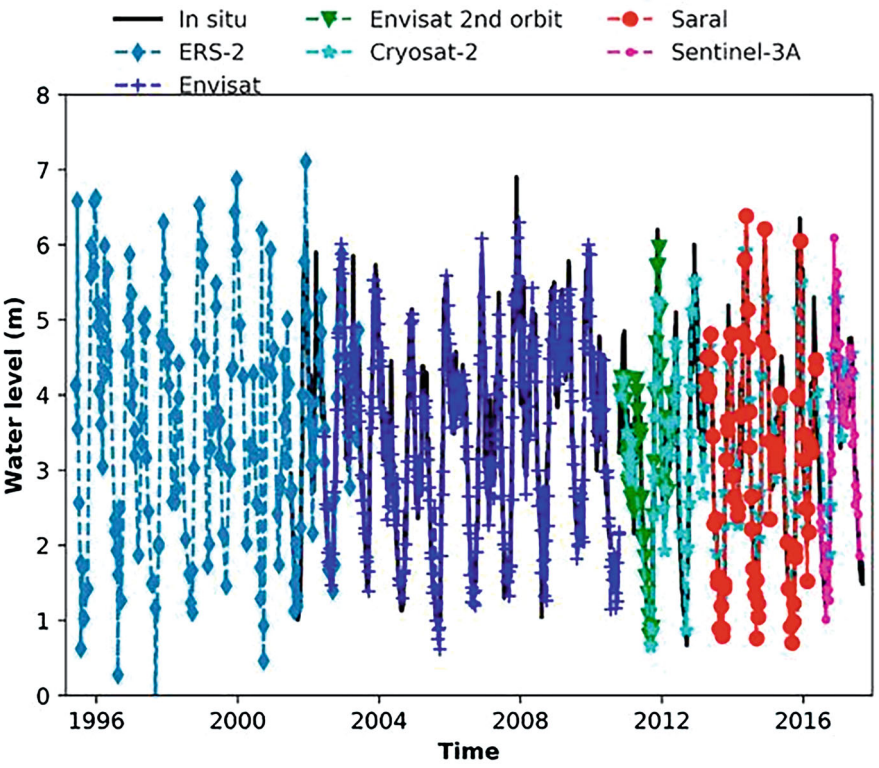


Fig. 2 Time series of water level measurements spanning two decades, from early 1995 to late 2017. This dataset is compiled from both ground-based (in situ) observations and a succession of satellite altimetry missions: ERS-2, Envisat (including a second orbital phase), CryoSat-2, Saral, and Sentinel-3A (Bogning et al. 2018b)

remote sensing data, providing crucial insights into its complex water dynamics. A lumped conceptual rainfall-runoff model, rigorously founded on the Budyko framework and effectively coupled with a Muskingum routing approach, has been applied to characterize its hydrological conditions with considerable precision (Kittel et al. 2018). This sophisticated model is primarily driven by precipitation data derived from cutting-edge satellite-based rainfall estimates, such as FEWS-RFE and TRMM 3B42 v.7, complemented by temperature data from ECMWF ERA-Interim. Calibration of the model is achieved through an aggregated objective function, strategically combining historical in situ discharge observations (dating from 1953 to 1984), a sparse but valuable record, with continuous radar altimetry measurements of river stages (from Envisat and Jason-2 at multiple virtual stations), and comprehensive GRACE (Gravity Recovery and Climate Experiment) total water storage change (TWSC) data. Validation of the model further incorporates independent CryoSat-2 observations, extracted using Sentinel-1 SAR imagery water masks to effectively overcome the persistent challenges posed by dense cloud cover that typically obscures optical satellite data in tropical regions. This innovative multi-source data integration allows for an exceptionally comprehensive characterization of the Ogooué's hydrology, even in the pervasive absence of extensive contemporary ground-based measurements. The model has consistently demonstrated good agreement between observed and simulated discharge and river stages, with RMSD values for water amplitudes at virtual stations generally remaining below 1 m, unequivocally demonstrating its robust capability to capture overall total water storage change patterns despite some minor amplitude underestimation. This combined modeling and remote sensing approach represents the most comprehensive and reliable current baseline characterization of the Ogooué's hydrological conditions, given the available observational data (Kittel et al. 2018).

Further advancements in hydrological modeling of the ORB have been achieved through the application of the MGB (Modelo de Grandes Bacias) semi-distributed process–based hydrological model (Collischonn et al. 2007), specifically tailored to simulate spatiotemporal variations in river discharges over an extensive 18-year period from 1998 to 2015 (Bogning et al. 2021a). This particular application of the MGB model utilized daily TRMM 3B42 rainfall data as its primary meteorological forcing, demonstrating the critical role of satellite precipitation products in data-sparse regions. Calibration and subsequent validation of the model were rigorously performed using a combination of both scarce in situ and abundant altimetry-based river discharges derived from missions such as Envisat, Saral Altika, and Jason-2, where satellite-derived water levels were converted to discharge using historical and, where necessary, updated rating curves in the absence of direct discharge measurements (Bogning et al. 2021a). The model's performance proved efficient in accurately identifying and reproducing the ORB's complex hydrological behavior, yielding Nash-Sutcliffe efficiency (NSE) values consistently greater than 0.66 for all calibration gauges, indicating robust reproduction of the observed hydrographs. Notably, NSElog values, all exceeding 0.51, further confirmed the model's enhanced capacity to accurately represent low-flow variations, which are inherently challenging to capture in hydrological simulations (Bogning et al. 2021a). The exceptionally

high consistency, with correlation coefficients ranging from 0.72 to 0.95, observed between rainfall and river discharge time series at both seasonal and interannual scales across various calibration and validation points, further underscores the MGB model's satisfactory replication of hydrological processes throughout the ORB, suggesting a strong spatial coherence in these hydro-climatic variations (Bogning et al. 2021a).

Beyond hydrological modeling for discharge, the intrinsic complexity and unique socio-ecological characteristics of the Ogooué's landscape, particularly evident in the Bas-Ogooué Ramsar site, demand a sophisticated socio-ecological approach that deliberately integrates remote sensing methodologies with invaluable local ecological knowledge to comprehensively grasp its intricate landscape dynamics (Demichelis et al. 2023). While conventional remote sensing methods, even those employing advanced machine learning algorithms like random forest, encounter inherent limitations in consistently monitoring tropical areas due to persistent heavy cloud cover and spectral confusion among the diverse wetland types, a synergistic combination of high-resolution Sentinel-2 satellite imagery and extensive, meticulous field surveys has proven remarkably effective. For instance, within the detailed Bas-Ogooué study site, 610 precisely georeferenced GPS points were systematically collected to enable a nuanced classification of the landscape into 11 distinct ecological classes, encompassing varied features such as perennial surface waters, seasonally inundated herbaceous swamps, transitional shrub-dominated swamps, dense forest swamps, and various upland forest and savannah types (Demichelis et al. 2023; Gallois et al. 2025). This detailed field-based classification, which demonstrated a high correlation with the corresponding satellite pixel values, facilitates the creation of high-quality land cover maps that not only accurately depict the static landscape structure but also reveal the ongoing ecological succession and the subtle, yet profound, human-induced dynamics shaping the environment. The invaluable integration of local knowledge, assiduously gathered through semi-structured interviews and collaborative participatory mapping workshops with indigenous communities, unveiled how traditional human activities, such as controlled seasonal bushfires in savannahs and precise machete fishing techniques in swamps, actively sculpt and maintain open ecosystems, thereby effectively counteracting natural forest encroachment (Demichelis et al. 2023). This robustly interdisciplinary approach provides a significantly more accurate, nuanced, and comprehensive understanding of the landscape's intricate socio-ecological system, illustrating how long-standing human practices can directly influence and modify hydrological and ecological processes at a highly localized scale, thereby emphasizing the critical imperative to integrate such profound insights for the development of truly effective and sustainable conservation and water resource management strategies within this unique, globally significant, and perpetually challenging environment (Demichelis et al. 2023).

Despite these substantial advancements in monitoring and modeling capabilities, significant and multifaceted challenges continue to persist within the ORB. Global climate change is undeniably intensifying alterations in regional rainfall distribution patterns and river discharge volumes, inevitably leading to more frequent and intense

hydrological extremes, including both prolonged, severe droughts and devastating flash floods. Concurrently, Gabon's ambitious national development plans, particularly involving large-scale projects in agriculture (e.g., palm oil, rubber plantations), extensive mining operations (e.g., iron ore, manganese extraction), and intensified forestry activities (both sustainable and conventional logging), are projected to exert considerable pressure on land use throughout the basin. Such large-scale developments carry inherent risks of accelerating deforestation, exacerbating soil erosion, increasing water pollution, and fundamentally altering natural hydrological regimes, thereby posing significant and long-term threats to the basin's invaluable ecosystems and the numerous communities that rely heavily on its natural resources. The continued reliance on remote sensing, while demonstrably vital for current monitoring, underscores the urgent need for sustained investment in integrated monitoring systems that effectively combine sophisticated satellite observations with expanded ground-based data collection to provide the robust, real-time information essential for truly sustainable water resource management in this globally important and environmentally sensitive basin. The ongoing efforts to establish an observatory of the Ogooué River Critical Zone (CZO) represent a proactive and crucial step toward comprehensively understanding and effectively mitigating these complex and escalating challenges (Braun et al. 2015).

Hydrology of the Sanaga River Basin

The Sanaga River, the largest river within Cameroon, is a pivotal artery for the nation's economic development and a critical component of Central African hydrology. Spanning a basin area of approximately 140,000 km^2 and stretching 918 km from its headwaters in the high Adamawa Plateau to its Atlantic Ocean estuary south of Douala, the Sanaga is not merely a watercourse but a fundamental resource for energy, agriculture, and human well-being in Cameroon (Zébazé Togouet et al. 2023; Kpoumié et al. 2022; Sighomnou et al. 2007). Its pronounced hydrological features and the intensive human interventions within its catchment make it a crucial case study for understanding complex riverine systems in a rapidly developing tropical region.

Geographical and Climatic Features

The Sanaga River Basin (SRB) is situated predominantly within Cameroon, extending from approximately 3°N at its mouth to 7°N in the Adamawa Plateau (Ebodé 2022; Sakpak et al. 2025). This broad latitudinal expanse results in a diverse mosaic of topography and climate, profoundly influencing its complex hydrological regime. The basin's physiography is characterized by a succession of plateaus: the northern Adamawa Plateau, with average altitudes exceeding 1100 m, serves as the primary source of the Sanaga and its tributaries (Kpoumié et al. 2022; Sakpak et al. 2025). Further south, the river traverses the South Cameroon plateau (600–900 m)

and is flanked to the west by the Cameroon volcanic line, including the Bamboutos mountains (2740 m above sea level), which profoundly influence regional rainfall distribution through orographic effects (Sigha-Nkamdjou et al. 2002; Kpoumié et al. 2022; Sakpak et al. 2025). The basin's vegetation transitions dramatically from Sudanian savanna in the higher northern reaches to dense humid forest in the central and southern parts, with riparian gallery forests specifically prevalent along the Sanaga subcatchment (Letouzey, 1985; Kpoumié et al. 2022). This dynamic forest-savanna transition zone is recognized as particularly sensitive to both long-term climatic shifts and rapid land use changes, impacting local water balances (Ebodé 2022).

The SRB experiences varied climatic conditions influenced by its extensive geographical spread. The northern, higher-altitude areas exhibit a unimodal rainfall pattern, characteristic of tropical savannas, with a single extended rainy season typically occurring from May to October, followed by a pronounced dry season (Ebodé 2022; Kpoumié et al. 2022; Sakpak et al. 2025). In sharp contrast, the southern and coastal regions are characterized by a bimodal equatorial climate, receiving two distinct rainy seasons, akin to the patterns observed in the Ogooué Basin, with peaks in March–May and September–November (Ebodé 2022; Kpoumié et al. 2022). Annual precipitation ranges significantly across the basin, varying from 1400–1600 mm in the tropical two-season climate zones to a much higher 1600–4000 mm in the four-season equatorial regions (Kpoumié et al. 2022; Sakpak et al. 2025). Interannual average temperatures across the basin typically fluctuate between 22 °C and 27 °C (Kpoumié et al. 2022). Long-term rainfall analyses have demonstrated that the Sanaga Basin, specifically at stations like Nachtigal, has experienced a statistically significant decrease in precipitation between 1950 and 2015, with a detected rupture point around 1975–1976 that led to pronounced rainfall deficits, particularly during the dry season(−35%) (Ebodé 2022; Sakpak et al. 2025). This trend aligns with broader patterns of rainfall variability and observed discontinuities across West and Central Africa since the 1970s, attributed to shifts in atmospheric circulation (Mahé et al. 2001; Ebodé 2022). Despite an overall downward trend in precipitation, particularly in the dry season, some sub-basins like Lom Pangar have shown a localized increase in dry season rainfall, a phenomenon potentially linked to localized land use changes or more complex atmospheric interactions (Ebodé 2022). The intricate spatial and temporal variability of rainfall underscores the complex interplay of large-scale atmospheric processes, localized topography, and regional climate drivers on the Sanaga's hydrological inputs (Lienou et al. 2005; Sakpak et al. 2025) (Fig. 3).

Hydrological Characteristics and Socioeconomic Importance

The Sanaga River's hydrology is characterized by its robust perennial flow and a distinctive riverbed punctuated by numerous rapids and waterfalls, features that render it exceptionally valuable for large-scale hydropower generation (Zébazé Togouet et al. 2023; Sighomnou et al. 2007). This capacity for energy production is undeniably its

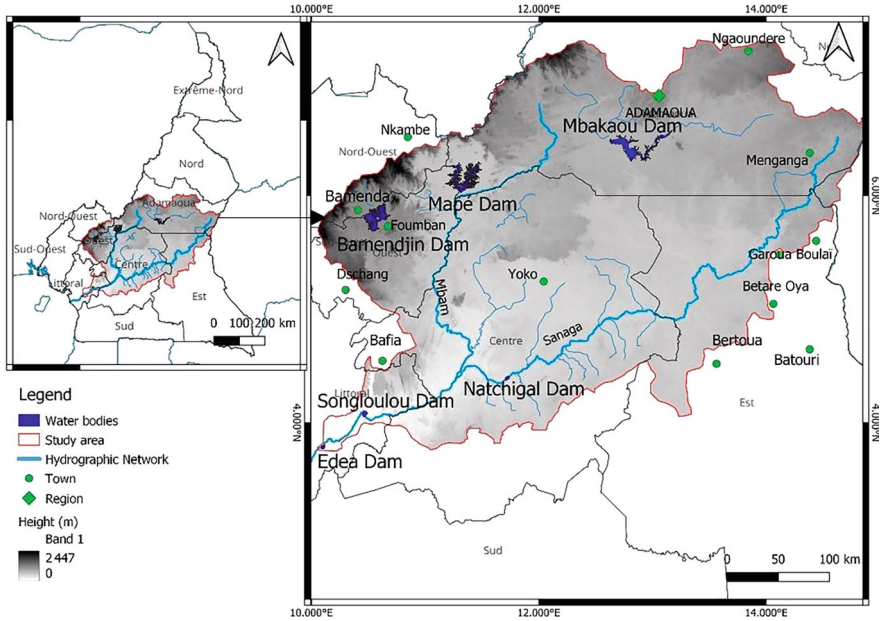


Fig. 3 Location map of the SRB using a digital elevation model (gray), its hydrographic network (light blue), and its main dams (dark blue)

most significant national role, as the Sanaga system contributes nearly 90% of Cameroon's total hydroelectric power output, primarily channeled through the Southern Interconnected Network (SIN) (Kpoumié et al. 2022; Sakpak et al. 2025). The basin hosts an impressive array of major existing dams, including Edea (operational since 1954), Song Loulou (1976), Mbakaou (1969), Bamendjing (1975), Mape (1988), and the recently completed Lom Pangar (2015), with the Nachtigal dam having been under construction since 2019, and several other significant projects remaining in the planning stages (Kpoumié et al. 2022; Zébazé Togouet et al. 2023; Sakpak et al. 2025). These large-scale hydraulic infrastructures are not solely purposed for electricity generation; they also serve a critical function in regulating the river's flow, which is crucial for ensuring a consistent power supply, particularly during prolonged dry seasons when natural flow might otherwise diminish (Ebodé 2022; Kpoumié et al. 2022). The average annual discharge recorded at the Edea Dam, a key downstream measurement point, is approximately 2070 $m^3 s-^1$ (Zébazé Togouet et al. 2023; Sakpak et al. 2025).

Beyond its pivotal role in energy production, the Sanaga River provides multifaceted support for the socioeconomic fabric of Cameroon. It sustains extensive irrigation schemes vital for cultivating diverse crops such as rice, sugarcane, tobacco, and various vegetables, thereby making a substantial contribution to national food security and bolstering rural livelihoods across its fertile plains (Jules et al.; Hoare 2007; Zébazé Togouet et al. 2023). Furthermore, it functions as

a vital source of potable and industrial water for major urban centers, including the bustling capital city of Yaoundé, which abstracts between 300,000 and 400,000 m^3 of water per day directly from the upstream Sanaga for its growing population and industries (Kpoumié et al. 2022). The river's rich fisheries are another critical sector, providing a primary source of protein and significant employment opportunities for local communities, with documented numbers exceeding 6000 fishermen actively engaged in the Lom Pangar Reservoir alone since its impoundment in 2015 (Zebaze Togouet et al. 2023). Moreover, the riverbed is extensively utilized as a source of sand for construction, an economically lucrative but largely unregulated activity that provides income for thousands of informal workers, albeit often with environmental consequences (Zebaze Togouet et al. 2023; Awoulmbang Sakpak et al. 2025).

Ecologically, the Sanaga Basin is celebrated for its exceptional biodiversity, encompassing a remarkable range of habitats including dense tropical rainforests, expansive savannas, and critical coastal mangroves (Zebaze Togouet et al. 2023). It is a vital sanctuary for numerous endemic fish species and iconic charismatic megafauna such as the West African manatee (*Trichechus senegalensis*), hippopotamuses, chimpanzees, and African forest elephants (*Loxodonta cyclotis*) (Zebaze Togouet et al. 2023). The basin notably includes globally recognized biodiversity hotspots such as the Cross-Sanaga-Bioko Coastal Forests ecoregion and the Douala-Edea Forest Reserve, underscoring its profound regional and international conservation significance (Thieme et al. 2005; Zébazé Togouet et al. 2023). However, despite legal protections, species like the West African manatee remain highly vulnerable to threats posed by unsustainable fishing practices and escalating habitat degradation resulting from pollution and alteration of riverine environments (Zébazé Togouet et al. 2023). Furthermore, the construction and operation of large dams have demonstrably impacted downstream riverine habitats, which are crucial for the survival of several threatened bird species that rely on the natural ebb and flow of the river for their ecological cycles (Zébazé Togouet et al. 2023).

Hydrological Variability, Modeling, and Contemporary Challenges

The SRB operates as a highly dynamic hydrological system, intricately responding to the dual pressures of both long-term climate variability and escalating anthropogenic interventions, thereby necessitating the application of advanced monitoring and sophisticated modeling approaches for its sustainable management. Comprehensive studies on the Sanaga's hydrological evolution indicate a statistically significant and substantial decline in mean annual flows since the late 1970s, a period broadly characterized by a widespread rainfall deficit across the greater West and Central African regions (Kpoumié et al. 2022; Servat et al. 1997; Laraque et al. 2001). This observed decrease in river flows, averaging a notable −23% across various sub-basins, is remarkably more pronounced than the corresponding reduction in precipitation, which ranged from −5% to −13.5%, strongly suggesting that factors beyond direct rainfall deficits alone, such as increasing evapotranspiration or land use changes, are significantly influencing the basin's water balance (Kpoumié et al. 2022). Intriguingly,

the early 2010s unexpectedly registered an insignificant localized increase in flows within some Sanaga sub-watersheds, including the crucial Nachtigal area, despite the overarching downward trend in regional rainfall. This counterintuitive phenomenon has been attributed, at least in part, to an expansion of impervious surfaces—resulting from urban development, road construction, and increased bare soil areas—leading to enhanced surface runoff that partially compensates for the reduced atmospheric moisture input (Ebodé 2022; Kpoumié et al. 2022). This complex interaction profoundly underscores the intricate interplay between climate change and rapid land use transformation on regional hydrological processes.

Detailed analysis of long-term hydrometeorological series from key stations such as Nachtigal (spanning 1950–2015) and Song Mbengue (1973–2019) has consistently revealed statistically significant trends and abrupt discontinuities in both rainfall and river discharge. For instance, applying the Pettitt test to rainfall data at Nachtigal identified a clear rupture point in 1975–1976, initiating a period of sustained rainfall deficits, particularly severe during the dry season(−35%) (Ebodé 2022). Correspondingly, annual and wet season flows at Nachtigal also exhibited a distinct rupture in 1970–1971, leading to notable deficits of −17% and −22.7% respectively, directly reflecting the reduced precipitation and increased evaporative demand (Ebodé 2022). These empirical findings align coherently with broader documented hydroclimatic shifts and decadal variability patterns observed throughout the West and Central African regions (Mahe et al. 2001; Ebodé 2022). Furthermore, comprehensive studies employing the nonparametric Mann-Kendall test for the 1973–2019 period discerned significant changes in both rainfall and flows across various important sub-basins, including Djerem, Lom Pangar, Mape, and Noun, although the statistical significance of these changes varied depending on the specific period and hydrological parameter examined (Ebodé 2022; Sakpak et al. 2025). The modified Mann-Kendall test, specifically tailored to account for serial correlation in hydrological time series using the "effective sample size (ESS)" approach (Yue and Wang 2004), has consistently shown negative slopes for rainfall in all three regionalized zones of the Sanaga, indicating a statistically significant decrease in precipitation across the basin (Sakpak et al. 2025).

To effectively address the systemic challenges posed by limited historical and contemporary observational data and, crucially, to provide robust forecasts for future water resource availability within the Sanaga Basin, the application of hydrological modeling techniques, particularly using semi-distributed models like SWAT (Soil and Water Assessment Tool), has proven to be an invaluable and indispensable approach (Ebodé 2022). This modeling framework integrates a diverse array of crucial spatial data, including high-resolution digital elevation models, detailed land use/land cover maps, and comprehensive soil maps, alongside essential meteorological variables such as air temperature, daily precipitation, relative humidity, wind speed, and solar radiation, to comprehensively simulate the basin's complex water balance components (Ebodé et al. 2024). These simulations encompass critical hydrological processes like surface runoff, potential evapotranspiration, groundwater recharge, and overall water yield. The SWAT model, in practical applications, has consistently demonstrated satisfactory performance in accurately simulating flows

for key sub-basins like Mbakaou and Bamendjing, yielding high coefficients of determination (R2), Nash-Sutcliffe efficiency (NSE) values, and Kling-Gupta efficiency (KGE) values that reliably exceeded 0.68 during both the calibration and independent validation phases, thereby indicating a strong capacity to reproduce observed hydrological patterns (Ebodé et al. 2024).

More recent and advanced modeling efforts have specifically focused on meticulously quantifying the separate and synergistic impacts of climate variability (CV) and land use/land cover changes (LULCCs) on the Sanaga's water resources. By systematically developing and evaluating various future climate scenarios derived from regional climate models, researchers have projected future water availability across the basin. While some models, such as REMO, project a significant decline in both precipitation and subsequent runoff, other models like HIRHAM5 and RCA4 suggest potential increases, highlighting the inherent uncertainty in climate projections for the region (Ebodé et al. 2024). Critically, these comprehensive studies consistently indicate that the impact of climate variability is projected to be the predominant forcing influencing future water resources, as the projected magnitudes of land use/land cover changes are anticipated to be relatively minimal, particularly in areas where forest cover has already experienced significant historical depletion (Ebodé et al. 2024). Furthermore, wavelet analysis, particularly cross-wavelet and wavelet coherence analysis, has been employed to investigate the relationship between precipitation time series in the Sanaga and large-scale climatic indices like El Niño 3.4, Tropical North Atlantic (TNA), Tropical Southern Atlantic (TSA), Atlantic Meridional Mode (AMM), and Dipole Mode Index (DMI) (Sakpak et al. 2025). Results indicate a significant causality between DMI, TSA, and El Niño 3.4 and rainfall variability across the Sanaga Basin, suggesting that these oceanic and atmospheric phenomena have a notable influence on the region's precipitation patterns, which can serve as a crucial decision-making tool for ongoing and future water resource projects in the SRB (Sakpak et al. 2025; Dezfuli and Nicholson 2013; Nicholson and Dezfuli 2013; Camberlin et al. 2001).

Despite these substantial advancements in monitoring and modeling, the management of the Sanaga Basin continues to present persistent and highly complex challenges. The extensive cascade of dams, while undeniably crucial for national energy security, profoundly alters the natural flow regime of the river, consequently impacting downstream ecosystems, reducing riverine biodiversity, and disrupting traditional livelihoods that are intrinsically linked to the natural flood pulses of the river (Zébazé Togouet et al. 2023; Regard et al. 2016). Sedimentation behind these dams remains a chronic issue, gradually reducing their storage capacity and operational efficiency, a problem significantly exacerbated by widespread land degradation and accelerated erosion in upstream catchment areas (Zébazé Togouet et al. 2023). Furthermore, water quality throughout the basin is under increasing threat from agricultural runoff containing pollutants, unchecked industrial discharge, and escalating urban pollution, adversely impacting aquatic life and posing significant risks to human health (Zébazé Togouet et al. 2023). Moreover, the inherent data gaps stemming from inconsistent and insufficient ground-based monitoring remain a fundamental concern, underscoring the critical necessity for continued reliance on

and seamless integration with robust satellite-derived data to ensure comprehensive oversight (Kpoumié et al. 2022). Addressing these multifaceted and interconnected challenges imperatively demands the development and rigorous implementation of integrated water resource management (IWRM) strategies that meticulously balance national development aspirations with long-term environmental sustainability. This holistic approach must be supported by sustained efforts in comprehensive monitoring, sophisticated modeling, and adaptive governance frameworks to ensure the enduring viability of this vital and indispensable river system for future generations.

Comparative Hydro-Ecological Dynamics of the Ogooué and Sanaga Basins

While both the Ogooué and Sanaga river basins are integral to the hydrological landscape of Central Africa, their distinct geomorphological settings, differing degrees of anthropogenic modification, and varying responses to regional climatic drivers present a rich tapestry for comparative analysis. This section elucidates the nuanced similarities and contrasting characteristics that define these two critical river systems.

Shared Attributes and Regional Drivers

Despite their independent drainage to the Atlantic Ocean, the Ogooué and Sanaga basins share fundamental characteristics that underscore their common ties to the broader Central African context. Both basins are profoundly shaped by the humid equatorial climate, characterized by high annual precipitation. This climatic influence typically manifests as a bimodal rainfall regime in their southern, coastal-proximal zones, driven by the seasonal migration of the Intertropical Convergence Zone (ITCZ) (Mahe et al. 2001; Ebodé 2022). This bimodal pattern, with two distinct rainy and dry seasons, directly dictates their seasonal flow dynamics, ensuring periods of high discharge interspersed with lower flows. This shared rhythm is a fundamental determinant of water availability for both natural ecosystems and human activities.

Significant portions of both basins are covered by dense Central African rainforests, which are ecologically continuous with the greater Congo Basin Forest biome. These forests serve as crucial carbon sinks, playing an indispensable role in global climate regulation. Beyond carbon sequestration, they are vital biodiversity reservoirs, harboring a rich array of endemic and iconic species, including forest elephants and various primates (Cutler et al. 2019; Zébazé Togouet et al. 2023). Hydrologically, these forested catchments are critical for regulating regional moisture budgets through significant evapotranspiration and the associated recycling of atmospheric moisture, which, in turn, influences regional precipitation patterns. The preservation of these forest covers is paramount for maintaining water quality, mitigating soil erosion, and stabilizing streamflow regimes.

Furthermore, both rivers are indispensable to the socioeconomic development and human well-being of Gabon and Cameroon, respectively. They serve as primary sources for multiple essential services, including potable and industrial water supply, agricultural irrigation, and energy generation. Their roles as navigable waterways further enhance regional commerce and facilitate the transport of natural resources (Demichelis et al. 2023; Zébazé Togouet et al. 2023; Sakpak et al. 2025). This multi-sectoral utility underscores its foundational importance to national economies and livelihoods.

Both the Ogooué and Sanaga basins also exhibit pronounced vulnerability to the impacts of global climate change. Projected alterations in rainfall seasonality, intensity, and frequency are anticipated to exacerbate hydrological extremes, leading to more frequent and severe droughts and intense flash floods. Long-term rainfall analyses have already indicated statistically significant decreases in precipitation and shifts in flow regimes across both basins since the 1970s, aligning with broader West and Central African hydroclimatic trends (Mahe et al. 2001; Ebodé 2022; Sakpak et al. 2025). Rising temperatures are also expected to increase evapotranspiration, potentially intensifying water deficits. These ongoing and projected hydrological shifts pose substantial threats to the resilience of ecosystems and the human populations dependent on these river systems. Recent studies utilizing advanced techniques like wavelet analysis have revealed that rainfall variability in both basins is significantly influenced by large-scale oceanic-atmospheric phenomena. For the Ogooué, while direct correlations with ENSO were initially weak, cross-wavelet and wavelet coherence analysis confirmed significant links (Bogning et al. 2021b). Similarly, for the Sanaga, there is a noted causality between DMI, TSA, and El Niño 3.4 and rainfall variability across the basin (Sakpak et al. 2025). These findings highlight the interconnectedness of regional hydro-climatic systems with global climate drivers, offering crucial insights for future water resource planning.

Divergent Characteristics and Management Paradigms

Despite these shared commonalities, the Ogooué and Sanaga basins exhibit critical distinctions arising from their unique geomorphological attributes and contrasting trajectories of human development.

Regarding the scale of contribution and hydrological pristineness, the Ogooué stands as the second-largest river in Central Africa by discharge, contributing approximately 4750 m^3s^{-1} of freshwater to the Atlantic Ocean (Bogning et al. 2021a; Regard et al. 2025). While it has some existing hydropower infrastructure, its upstream and midstream sections remain largely unregulated by major dams, preserving a relatively natural flow regime compared to the Sanaga (Bogning et al. 2021b). This relatively pristine state makes it an important natural laboratory for studying natural hydrological processes in a humid tropical environment. The long-term physical denudation rate of the Ogooué catchment is slow (38 $t/km^2/a$, equivalent to 15 m/Ma), which is slightly higher than the general Equatorial West Africa average, with chemical weathering contributing significantly (over 30% of total

denudation) (Regard et al. 2025). Denudation rates are spatially variable within the basin, with the southern part denuding twice as fast as the northern part, potentially due to uplift from the southern African "superswell" (Regard et al. 2025). In contrast, although Cameroon's largest river, the Sanaga's mean annual discharge (around 2070 m^3/s at Edea Dam) is considerably less than that of the Ogooué (Zébazé Togouet et al. 2023; Sakpak et al. 2025). Its basin area is also smaller (140,000 km^2) (Zébazé Togouet et al. 2023). Crucially, the Sanaga Basin is characterized by extensive anthropogenic modification, particularly through a cascade of large dams, which has significantly altered its natural hydrological regime (Zébazé Togouet et al. 2023). This high degree of regulation introduces complex management challenges distinct from the Ogooué.

Considering dominant anthropogenic pressures and management focus, while conservation policies have largely maintained the Ogooué's pristine character, pressures from conventional logging and agricultural expansion, particularly palm oil and rubber plantations, are growing (Demichelis et al. 2023). These activities, while not directly regulating river flow, can lead to localized deforestation, increased runoff, and sediment loads, impacting water quality and ecosystem health. Management efforts thus emphasize land use impact mitigation and maintaining ecological integrity through protected areas and sustainable practices (Demichelis et al. 2023). In contrast, the Sanaga Basin is heavily developed for hydropower, with numerous existing and planned dams forming a crucial part of Cameroon's energy infrastructure (Zébazé Togouet et al. 2023). This intensive regulation necessitates complex management strategies to balance energy production with environmental flows, downstream water demands (including large urban centers like Yaoundé), and sediment transport (Kpoumié et al. 2022). The challenges here revolve around optimizing dam operations, managing reservoir sedimentation, and mitigating the cumulative impacts of altered flow regimes on riverine biodiversity and traditional livelihoods (Zébazé Togouet et al. 2023).

Finally, the complexity of hydrological responses and regional variability within these basins offers distinct insights into their reactions to environmental change. Studies on the Ogooué have shown that its hydrological behavior is intricately linked to oceanic and atmospheric phenomena, with rainfall and river discharge exhibiting consistent spatiotemporal variations (Bogning et al. 2021a; Bogning et al. 2025). However, interpreting these relationships, especially over varying timescales, is complicated by the nonlinear dynamics and intermittent nature of large-scale climate influences (Bogning et al. 2021a; Bogning et al. 2025). The observed correlations between rainfall and river discharge in the ORB, ranging from 0.72 to 0.95, suggest a strong spatial coherence in hydro-climatic variations (Bogning et al. 2021a). These dynamics are further modulated by factors such as changes in river morphology or unmeasured human interventions, which can influence localized hydrological relationships. Consequently, site-specific validation of hydrological responses is crucial, underscoring that generic approaches are often insufficient for accurate hydrological assessment. Instead, tailored management strategies, sensitive to localized hydraulic complexities and human interventions (such as small-scale water abstraction or dam regulation in the Sanaga), are essential. The heavily regulated nature of the Sanaga

by dams, for instance, introduces significant nonlinearities and hysteresis in flow, potentially complicating the direct application of generalized hydrological analyses. The decline in mean annual flows in the Sanaga since the late 1970s, which is more pronounced than the precipitation reduction, further emphasizes the strong influence of anthropogenic factors and other hydrological processes beyond direct rainfall deficits (Kpoumié et al. 2022). The early 2010s even saw localized flow increases in some Sanaga sub-basins despite overall rainfall decline, attributed to increased impervious surfaces and enhanced surface runoff (Ebodé 2022). This highlights how human activities introduce unique complexities to the Sanaga's hydrological responses, requiring tailored and multifaceted assessment approaches.

Integration Within the Central African Hydro-Ecological Context and Global Significance

While the Ogooué and Sanaga basins drain independently to the Atlantic, their geographical proximity, shared climatic influences, and ecological continuity inextricably link them to the grander Central African hydrological system and the globally significant Congo Basin Forest biome. Understanding this broader integration is crucial for holistic regional water resource management and conservation efforts, particularly given the historical underrepresentation of this vital region in global scientific discourse and funding.

The forests within the Ogooué and Sanaga basins are not isolated entities but rather vital extensions of this immense biome. They share common floristic and faunal characteristics, contributing to the overall biodiversity and carbon sequestration capacity of the region. The integrity and health of these adjacent forest ecosystems are intrinsically tied to the resilience of the entire Central African rainforest. This ecological interconnectedness implies that large-scale environmental changes or significant land use alterations in one basin can have cascading effects across the broader biome, impacting regional climate, hydrology, and biodiversity (Demichelis et al. 2023). Beyond its immediate boundaries, the forest generates rainfall as far away as the Sahel and Ethiopian highlands, supporting the livelihoods of an additional 300 million rural Africans (White et al. 2021).

Both the Ogooué and Sanaga basins are situated within the broader West and Central African atmospheric circulation patterns that sustain the regional rainforests. Moisture recycling, a critical process where evapotranspiration from the dense forest cover contributes significantly to atmospheric humidity and subsequent downwind precipitation, plays a vital role in the hydro-climatic stability of the entire region (Mahe et al. 2001). Consequently, changes in rainfall patterns or river discharge within the Congo Basin itself often show correlated patterns in these adjacent basins, reflecting their shared exposure to large-scale climatic drivers such as ENSO (An and Wang 2001; Santoso et al. 2017), and Atlantic SST anomalies (Bogning et al. 2022; Sakpak et al. 2025; Izumo et al. 2020; Crespo et al. 2019; Zhang et al. 2024). This emphasizes that a comprehensive understanding of Central African hydrology necessitates considering these basins not merely as isolated systems but

as interconnected components of a larger hydro-climatic network (Stuecker 2023; Pothapakula et al. 2020).

The Ogooué and Sanaga basins, by virtue of their substantial freshwater discharge directly to the Atlantic, contribute significantly to the broader marine environment of the Gulf of Guinea. Their combined freshwater and sediment inputs influence coastal currents, nutrient cycles, and localized marine productivity (Bogning et al. 2021b; Mignard et al. 2017). From a management perspective, these basins serve as crucial case studies for developing robust, transferable strategies for water resource management and climate change adaptation across Central Africa.

Despite its global importance, Central Africa's rainforests, including the Ogooué and Sanaga basins, have historically received disproportionately less academic and public attention compared to the Amazon and Southeast Asia. Between 2008 and 2017, the Congo Basin received a mere 11.5% of international financial flows for forest protection and sustainable management in tropical areas, contrasting sharply with 55% for Southeast Asia and 34% for the Amazon (White et al. 2021). This neglect has led to significant data gaps; for instance, Central Africa was one of only two regions globally lacking sufficient data for the Intergovernmental Panel on Climate Change to assess past trends in extreme heat in its 2021 Working Group I report (White et al. 2021). Researchers even acknowledge a limited understanding of why different forest types occur where they do in the Congo Basin, and climate models for the region remain poor due to complex ocean influences and a lack of local data. Without more data and specialists, reliable predictions of these forests' responses to climate and land use changes are impossible (White et al. 2021).

Recent, albeit limited, scientific endeavors have begun to highlight the region's immense importance and understudied nature. The mapping of the world's largest tropical peatland complex in the Congo Basin (14.6 million hectares) in 2017 radically shifted understanding of regional carbon stores (White et al. 2021). Furthermore, African rainforests were shown in 2020 to annually absorb the same amount of carbon as was emitted by fossil fuel use across the continent (White et al. 2021). These findings suggest that Congo Basin tropical forests may be more carbon-dense, more efficient at slowing climate change, and more resistant than Amazonian forests, though interactions between droughts, higher temperatures, logging, and deforestation remain poorly understood (White et al. 2021). This emphasizes the critical need for a focused, well-funded scientific initiative to unlock the full potential of these ecosystems for global climate solutions and sustainable development.

Challenges and the Imperative for Integrated Management and Scientific Investment

The management of the Ogooué and Sanaga basins and indeed the wider Central African hydro-ecological system are confronted by a confluence of persistent challenges that underscore the urgent need for a paradigm shift toward integrated management and substantial scientific investment.

A pervasive challenge across Central Africa, explicitly including the Ogooué and Sanaga basins, is the chronic scarcity of comprehensive, long-term, and high-quality ground-based hydrological data. This deficiency severely hampers the ability to accurately monitor dynamic responses to environmental changes and to formulate robust predictions for future water availability (Kpoumié et al. 2022; Maloba Makanga 2015). This data void has even led to Central Africa being identified as one of only two global regions without sufficient data for key climate assessments by the IPCC (White et al. 2021). To counter this, there has been a crucial reliance on remote sensing techniques, such as satellite altimetry, which has proven effective for monitoring water levels and estimating discharge in regions like the Ogooué (Bogning et al. 2018b). Nevertheless, the imperative remains for sustained investment in truly integrated monitoring networks that seamlessly combine sophisticated satellite observations with expanded and consistently maintained ground-based data collection.

Given the multifaceted utility of these rivers for hydropower, agriculture, domestic supply, and ecological services, the principles of integrated water resourcemanagement (IWRM) are paramount. This entails a delicate balancing act of competing demands, a thorough consideration of environmental impacts, and the active promotion of participatory governance across various sectors and, where applicable, transboundary areas (Ebodé et al. 2024). The intricate lessons derived from studies on hydrological index reliability within the Ogooué Basin, demonstrating varying correlations between river stage and streamflow depending on spatial context and timescale, powerfully highlight that generic approaches are insufficient (Bogning et al. 2021b). Instead, tailored management strategies, sensitive to localized hydraulic complexities and human interventions (such as small-scale water abstraction or dam regulation in the Sanaga), are essential.

The environmental and socioeconomic pressures in these basins are escalating due to climate change and ongoing development. The Ogooué faces increasing impacts from extensive logging and expanding agricultural plantations (Demichelis et al. 2023), while the Sanaga grapples with the profound cumulative effects of its numerous large-scale hydropower dams, including altered flow regimes, reservoir sedimentation, and impacts on downstream biodiversity and livelihoods (Zébazé Togouet et al. 2023). These challenges are compounded by the broader vulnerability of Central African forests to climate change, including potential reduced rainfall in critical distant regions like the Sahel (White et al. 2021).

Addressing these complex and interconnected challenges demands a concerted scientific effort. The proposed "Congo Basin Climate Science Initiative" outlines a decade-long, $100 million research program complemented by a $50 million fund to train 200 PhD-level Central African scientists (White et al. 2021). Such an investment is crucial to (White et al. 2021)

- Transform understanding of how the Congo Basin operates as an integrated system and how land use and climate change affect its function.
- Provide essential data for policymakers to enact effective environmental policies, including accurate carbon storage assessments (currently relying on potentially inaccurate default values).

- Expand existing, but sparse, research infrastructure, such as the AfriTRON and ForestGEO permanent sample plots, which currently cover a minuscule fraction of the forest.
- Develop economic models that demonstrate the value of standing forests over converted landscapes, supporting policy decisions to maintain forest cover.
- Assess improved forest management approaches that empower local populations and promote sustainable resource utilization.

This initiative represents a strategic investment that would pay for itself many times over, not only in terms of climate change mitigation and environmental protection but also in reducing risks like zoonotic disease outbreaks and bolstering the scientific capacity of the region (White et al. 2021). The argument that development aid is more urgent than science is increasingly obsolete, as the interconnectedness of poverty eradication and environmental protection becomes undeniable, particularly for African populations disproportionately affected by climate change (White et al. 2021). Sustained efforts in comprehensive monitoring, sophisticated modeling, and adaptive governance frameworks, underpinned by robust scientific capacity building, are indispensable for ensuring the enduring viability of the Ogooué and Sanaga river systems and the entire Central African rainforest for future generations.

Conclusion

The Ogooué and Sanaga watershed systems stand as vital, yet historically understudied, hydrological cornerstones within the larger Central African landscape. While geographically distinct in their direct oceanic drainage, their intrinsic links to the vast Congo Basin Forest biome underscore a profound ecological and climatic interconnectedness. This chapter has revealed nuanced hydrological dynamics shaped by shared equatorial climate patterns, differing geomorphological controls, and varying degrees of human influence. The Ogooué, largely pristine but facing emerging pressures, offers insights into natural hydrological responses and the complex spatial reliability of assessment indices. In stark contrast, the heavily regulated Sanaga highlights the intricate challenges of balancing national development imperatives, particularly hydropower generation, with environmental sustainability and the preservation of crucial ecosystem services. Both basins, alongside the broader Congo, are profoundly vulnerable to escalating climate change impacts and burgeoning anthropogenic demands. The persistent data gaps across the region necessitate a continued, multifaceted approach to monitoring, heavily leveraging advanced remote sensing while urgently reinvesting in comprehensive ground-based networks. Ultimately, safeguarding the long-term water security, ecological integrity, and socioeconomic resilience of Central Africa hinges upon a transformative increase in dedicated scientific research and capacity building, coupled with adaptive, integrated water resource management strategies. Such concerted global and regional efforts are indispensable for unlocking the full potential of these critical river systems and ensuring the enduring vitality of Earth's second "great green lung" for future generations.

Competing Interest Declaration The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

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Central African Rainforest Archaeology

7

Richard Oslisly, Pascal Nlend Nlend, Louis Champion, Alexandre Livingstone Smith, and Geoffroy de Saulieu

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Abstract

Although it remains largely unknown to the general public, archaeological research in Central Africa has uncovered an extraordinarily rich heritage. Lack of awareness is probably due in part to the lack of recent synthesis work, but it is also true that the absence of political support, the lack of media coverage, logistical difficulties, and the dependence of African research units on foreign research funding are all obstacles to the advancement of our knowledge. However, the gradual integration of rescue archaeology into land use planning projects represents an opportunity to update existing local and regional datasets, even if the transformation of a simple consultancy into genuine scientific research issues remains a major challenge.

Central Africa's forests have long been perceived as having no history. This denial, linked to the justification of the slave trade of the sixteenth to nineteenth centuries by the colonization of the nineteenth and twentieth centuries, was undoubtedly reinforced by a lack of written sources. The development of archaeological research as part of multidisciplinary projects integrating oral tradition, art history, and linguistics has helped change mindsets and develop richer, more

nuanced historical narratives. In this contribution, we will first present a very general overview of the evolution of our knowledge and the methods that have enabled us to achieve this; we will then examine the major phases in the history of human societies and their ability to adapt to the tropical environment over the long term.

Keywords

Central Africa · Methods · Stone Ages · Iron Ages · Kingdoms · Emergence of agriculture

Introduction

The Central African forest block is dominated by the Congo and Ubangi river basins, but it is important not to overlook other major basins such as the Sanaga, the Ogooué, and up to the Cross River and the Nyanga.

Research carried out to date shows an extraordinary richness of archaeological heritage in the Congo Basin, but it has to be said that major challenges still have to be overcome before it can take its rightful place in the history of mankind.

No comprehensive work on the archaeology of Central Africa, such as *The Archaeology of Central Africa* (Van Noten 1982), *Paysages Quaternaires* (Schwartz and Lanfranchi 1990), or *Aux Origines de l'Afrique Centrale* (Lanfranchi and Clist 1991), has been published for over 30 years.

The development of archaeology in this part of Africa is hampered by a lack of political support, a lack of media coverage, logistical difficulties, and the dependence of African research units on foreign research funding. Despite these difficulties, it should be noted that international academic research projects and preventive and salvage archaeology initiatives carried out on large-scale projects have nevertheless made a significant contribution to improving our knowledge of Central Africa's past (Oslisly 2014).

The major summaries published in the past on the archaeology of Central Africa, as well as the numerous scientific publications in international journals, have tended to emphasize environmental history to the detriment of social and cultural history; to convey outdated evolutionary concepts, particularly with regard to the relationship between material culture and identity; or to focus on linguistic phenomena such as the Bantu expansion, where numerous problems of circular reasoning between archaeology and linguistics have arisen (Fig. 1).

State of the Art

For a long time, the perception of tropical forests was dominated by the idea of primary, static forests. Today, we suppose that the Central African forest block is subject to a variety of dynamics: Successive expansions and regressions have given

Fig. 1 Map of excavated and dated archaeological sites in the forests of Central Africa and neighboring areas based on Cornelissen and Livingstone-Smith (2015) and Garcin et al. (2018)

way to the development of savannahs with varying degrees of shrub cover over several centuries.

The same applies to the history of human societies. Intertropical Africa has long been perceived as having "no history." This denial is probably linked to the justification of the slave trade of the sixteenth and nineteenth centuries and the colonization of the nineteenth and twentieth centuries, but this simplistic prejudice has undoubtedly been reinforced by the lack of textual documents, long considered to be the fundamental source of history. The development of archaeological research, including within multidisciplinary projects integrating oral history, art history, and linguistics, has greatly enriched our vision of African history (Vansina 1990; Livingstone Smith et al. 2023).

In its early days, the archaeology of the region was essentially centered on prehistory, with little openness to interdisciplinary approaches. However, from the 1960s onwards, a series of methodological advances strengthened the discipline, enabling richer and more nuanced scenarios to be developed. The introduction of absolute dating techniques, such as radiocarbon and thermoluminescence, helped to establish solid chronology. At the same time, the rise of related disciplines such as archaeozoology and archaeobotany has enriched our understanding of past environments and ancient ways of life. More recently, isotope analyses, particularly of oxygen, are providing climate indicators that are independent of the study of vegetation alone. Other advances, such as beryllium/aluminum dating, optically stimulated luminescence, accelerator mass spectrometry, and soil carbon analysis, have opened up new perspectives. Finally, the development of computer tools and genetic studies has considerably expanded the possibilities for analysis and interpretation (Patin et al. 2014). For the first time, these different methodologies are

enabling archaeologists to write the complex history of a region that is critical to the evolution of our species.

In this contribution, we will quickly outline the methods allowing for this endeavor, before examining the most salient points of the very long history of Central Africa. To do so, we will consider in turn the main chronological eras: the Stone Ages (between 650,000 and 10,000 yrs BP); the end of the Late Stone Age (10,000–3000 yrs BP); the Beginnings of Sedentarization (3000–1400 yrs BP); Break-ups, Resilience, and Innovations (1400–800 yrs BP); and Emergence and Development of Large Political Entities (800–120 yrs BP). In each case, we will summarize the main aspects of past societies and consider their impact on past ecosystems.

Methods

In Central Africa, as elsewhere, reconstructing the past requires multidisciplinary work and the use of a variety of analytical methods.

The results of the archaeological excavations consist mainly of remains of material culture, mainly because of the conditions in which they were preserved. These include flakes of chipped stone, pottery, iron, and copper objects. Techniques have also been developed to collect ecofacts, organic remains such as charred seeds or fruit, bones, microscopic and geochemical traces, etc., making it possible to reconstruct lifestyles in the environmental context of the time (Livingstone Smith et al. 2017b).

Lithics

Lithic analysis enables us to reconstruct the lifestyles of ancient populations, their techniques, and their cultural exchanges. Studying stone tools reveals invaluable information about social organization, the economy, and adaptation to the environment. This analysis is essential if we are to fill in the gaps in our knowledge of human evolution in Central Africa. It sheds light on the interactions between human groups and their exploitation of local resources while enriching our understanding of the region's cultural, geographical, and geological heritage.

The study of chipped stone tools reveals the appearance of heavy, archaic, macrolithic stone tools, such as pebble tools, in the Congo Basin at least 650,000 years ago. Over time, these tools became more refined and took on new forms, such as handaxes, leading to armatures, finely carved foliate points, and microlithic stone tools such as blades, scrapers, and trenchers. Hunter-gatherers had a very good knowledge of rocks, preferring siliceous rocks such as quartz, jasper, and flint.

Pottery

Pottery was first introduced into the Congo Basin from the Luani Early Phase around *ca.* 4000 yrs BP (Coutros et al. 2025). Pottery fragments are the predominant

remains found in archaeological sites dating back to at least 2500 years or less in the Congo Basin. The analysis of ceramic remains is therefore an important aspect of archaeological research. Reconstructing vessels from shards makes it possible to identify styles of manufacture, finishing, and decoration and to put forward hypotheses about their use. All of this makes it possible to address aspects relating to the identity of ancient populations and their dietary practices. The study and comparison of decorative styles on pots also suggest ancient regional or continental cultural interconnections and, in some cases, allows us to track people's movements in time and space.

Metals

The archaeometry study of iron and copper metallurgy in Africa enables us to understand metal manufacturing techniques, the evolution of skills, and their impact on ancient societies, in terms of daily life, rituals, and trade. These analyses also shed light on regional and transcontinental trade networks, the specialization of craftsmen, and social organization. Iron metallurgy was first introduced into the Congo Basin region around 2600 BP. Iron is extracted from ore in low furnaces that produce iron burls. The burl is purified by hammering by the blacksmith, who then takes fragments that are gradually shaped into an artifact. This produces objects or tools, such as hoes, knives, axes, spear points, and jewelry. In many parts of Central Africa, metal objects were used as currency in certain exchanges.

Copper metallurgy appeared later, around the twelfth and thirteenth centuries, in the southwestern part of the Congo Basin. This rare, yellow, shiny material was considered a prestige metal used mainly to make jewelry (bracelets, necklaces, money clips, bracelets, etc.).

Archaeobotany

Although archaeobotanical analysis is booming in the Congo Basin, published studies are still limited, and even fewer have employed statistical and systematic sampling methods. However, the research that does exist offers an initial insight into the evolution of agriculture and food practices in the region. This evolution reflects a shift from the collection of wild plants to more complex agricultural systems, including the cultivation of plants from the New World and the management of forest plots. It also reflects the adoption of African dryland crops such as millet, cowpea, and sorghum, as well as Asian crops such as taro and banana.

Archaeozoology

Archaeozoology, which studies the faunal remains, provides information about the dietary practices of ancient populations. It complements archaeobotany by providing

clues about the types of animals consumed, hunting and rearing methods, and eating habits. In Central Africa, however, archaeozoological studies remain limited due to soil taphonomy and the lack of rigorous methods, such as fine dry or wet sieving in archaeological digs. These techniques, often neglected, limit the collection of relevant data. However, in more favorable preservation conditions, such as in caves, bone remains are better preserved, permitting more comprehensive analyses of ancient fauna communities harvested by people.

Oceanic and Continental Palaeoenvironmental Issues

The study of marine and continental cores makes it possible to reconstruct the climatic and ecological history of the Earth over long periods. By analyzing the sediments, fossils, and pollen in these cores, researchers can trace past climatic variations, such as glacial and interglacial periods, and understand the evolution of landscapes. These cores also provide information about changes in vegetation, fauna, and environments. They are crucial for understanding better the impacts of climate change and for predicting the future.

The results of the analysis of marine and continental cores (Maley and Brennac 1998), as well as the work carried out in Cameroon (Garcin et al. 2018), Gabon (Ngomanda et al. 2007, 2009), including in the marshes of the Lopé National Park (Bremond et al. 2021), provide essential elements for understanding climate change and the evolution of landscapes inhabited by hominids and humans over time. The issues addressed in a continental context also include stone-line and alluvial terraces, stony formations that often amalgamate chipped stone tools.

Dating

The dating of archaeological sites is based on three families of methods: radiocarbon (AMS), measurement of exposure to solar radiation (OSL), and cosmogenic dating (Beryllium). In this way, we can establish a more precise chronology of the history of the sites (Livingstone Smith et al. 2017b).

- Radiocarbon dating: It is based on measuring the quantity of 14 carbon, a radioactive isotope present in all living organisms.
- Optically stimulated luminescence: OSL is used to date minerals, such as quartz or feldspar, present in ceramics, sediments, or heated stones back 400,000 years. This method is particularly useful for dating ceramic objects and sediments, complementing ^{14}C dating.
- Cosmogenic dating: It is based on the accumulation of energy in siliceous artifacts linked to extraterrestrial radiation.

Using these methods, the past of the Central African forest block can be divided into major chronological phases characterized by significant societal changes.

The Stone Ages (650,000–10,000 Yrs BP)

In Africa, the Stone Age began 3.3 million years ago at the Lomekwi 3 site in the north of Kenya (Harmand et al. 2015). In forest-dwelling Central Africa, a few sites have revealed large-sized pebble tools that have recently been dated at over 650,000 years old (Braucher et al. 2022).

Material Culture

Earlier Stone Age (ESA) 650,000–320,000 Yrs BP

Geoarchaeological studies of Early Stone Age sites in the Congo Forest Basin are rare in the vast expanse of forest that stretches from the Atlantic coast to the great lakes of the African Rift. This region combines open environments of the Sudano-Zambezian type with more closed areas of the Guineo-Congolian type. The main challenge for prehistoric research lies in characterizing the chronological and techno-cultural framework of the Pleistocene, which is still poorly defined today. This paucity of knowledge is due to a lack of specific research on this period and to taphonomic conditions, where tropical vegetation and/or climate disturb or conceal traces of ancient human occupation.

Nevertheless, we know that the first lithic industries, represented by choppers and chopping tools, appeared in both open and forested contexts. The Elarmekora site (Gabon, 650,000 yrs) illustrates this technological adaptation to the forest block of Central Africa, often considered hostile to human settlement (Braucher et al. 2022). These technologies are also observed at Dungo 4 (Angola, 650,000 yrs), where the patterns suggest a certain continuity in the production of pebble tools (Lebatard et al. 2019). These pebble tools are undoubtedly evidence of adaptation to a variety of environments.

Middle Stone Age (MSA) 320,000–50,000 Yrs BP

This period saw the development of Middle Stone Age industries, of which the Lupembian, a lithic industry characterized by bifaces (Lanceolate points) and tools on prepared cores, appears to be a local variant.

In recent decades, the Middle Stone Age has received renewed interest as the archaeological context for the appearance of *Homo sapiens*, around 320,000 yrs ago (Hublin et al. 2017). Research has focused on the rare examples of technological diversity and material culture circumscribed in time and space, which are generally found in open regions, particularly shrub savannahs. Examples include Still Bay, Howiesons Poort (South Africa), and Lupemban (DRC), all of which can be considered as specific variants.

On the other hand, archaeological assemblages apparently devoid of distinctive features have received little attention in their own right. Such assemblages can be grouped together under the informal term of the Middle Stone Age, which is more generic. The apparent continuity and commonality of generic Middle Stone Age elements over large spatial and temporal scales raise many questions about the early

evolution of our species. It could be seen as the common technological and material substrate for the behavior and culture of the first *Homo sapiens*. However, it must be stressed that we lack the quantitative studies that would justify grouping nearly 300,000 years of material culture under a single category.

While the Lupemban industry is presented by some as the only representative of the Middle Stone Age in the region, it must be stressed that the details of its chronostratigraphic relationship with previous industries are still unclear. The Lupembian has mainly been conceptualized as part of the Early Stone Age/Middle Stone Age transition and as an early Middle Stone Age entity at the end of the Middle Pleistocene. It was subsequently superseded or passed into an "undifferentiated" MSA or into a "Lupembo-Tshitolian" subregional industry. In contrast, the shorter records from the lowlands of Atlantic Central Africa mean that archaeologists have instead reported the Lupemban as a persistent Late Pleistocene industry that temporally adjoins the Late Stone Age without any "generic MSA" (Will and Scerri 2024).

Among the regional assemblages best contextualized to document the Late Pleistocene period in the Atlantic Congo Basin, we find a good example of the difficulties of classifying Central African industries according to one or other regional techno-cultural facies, during the Late Pleistocene, and even in terms of the broader continental framework of the MSA and LSA. However, we can now state that at Maboué 5 in central Gabon (Mesfin et al. 2021), in an environment marked by the onset of savannah expansion, hunter-gatherer lithic technology is composed of both MSA-type technological features, such as the high variability of production methods and the use of prepared core technology, but also includes LSA-type features, such as a microlithic component and the dominance of quartz raw material.

Considering the chronology of Maboué 5, we cannot say whether the co-occurrence of the MSA and LSA technical models depicts a continuity of MSA-type technical behavior during the Last Glacial Maximum (LGM) or the emergence of LSA-type technical behavior before the LGM.

Later Stone Age (LSA) 50,000–10,000 Yrs BP

The lithic assemblages became more complex and showed an increasingly assertive choice of raw materials (flint, jasper, quartz). Archaeologists point to the existence of various trends. The first, known as Tshitolian, seems to be an extension of earlier practices characterized by symmetrical tools with bifacial core-axe retouching (Fig. 2), particularly in the southwestern Congo Basin. Elsewhere, we find traditions whose cutting practices are more diversified. There is little standardization in production, with a relatively wide range of nuclei and cutting methods, from microliths to medium-sized blades.

At Maboué 5, quartz tools and microliths coexist with production techniques that are also still linked to the MSA, indicating a gradual technological transition. At the Shum Laka site, a trend toward microlithization, a reduction in the size of armatures to less than 2 cm, suggests tools and weapons dominated by the insertion of flakes and lamellae into bone or wood supports (Cornelissen 2003). It is thought that this type of material made it easier to adapt to different types of hunting in a changing

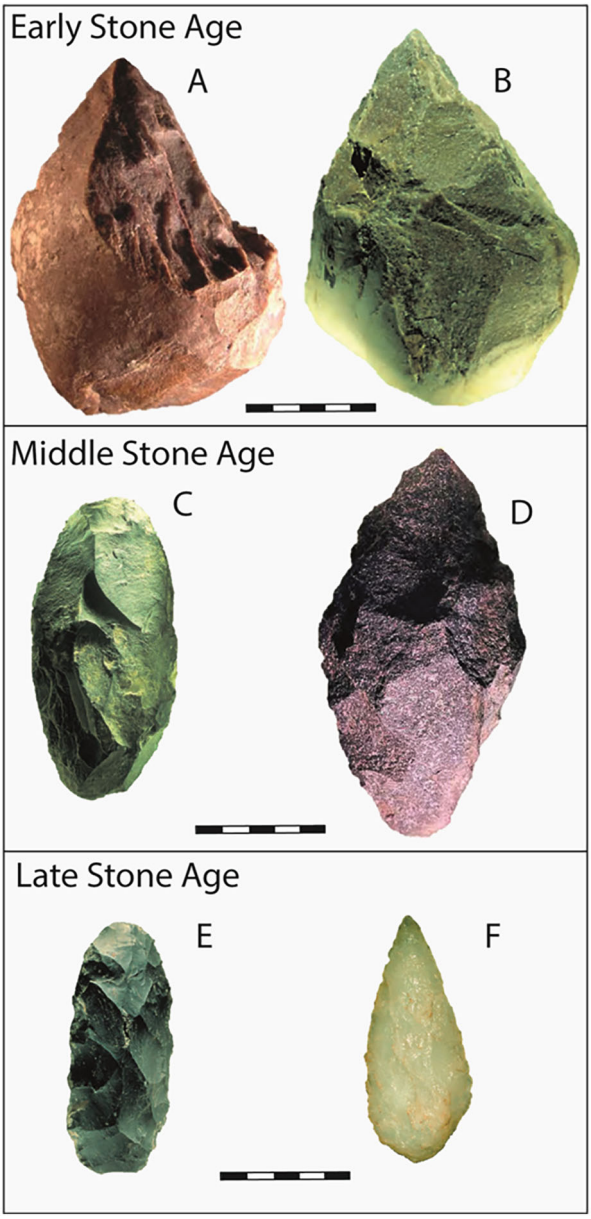

Fig. 2 Stone tool characteristic of the Stone Ages of the Congo Basin forests. (**a** and **b**) Pebble tools, (**c**) handaxe, (**d**) double-pointed peak, (**e**) core-axe, and (**f**) arrowhead. (© Duboze R (B, C, D, E, F), © Oslisly R (A))

landscape. This approach continued during the reconquest of the forests and the drastic retreat of the savannahs in Central Africa at the end of the LGM, after 10,000 yrs BP.

Food Sources

Most of the information on the food sources of Stone Age peoples comes from indirect evidence or comparisons with better-documented regions. There is no direct evidence of plant use before 10,000 yrs BP. Archaeobotanical studies have mainly been devoted to recent Holocene periods, and virtually nothing is known about plant use in earlier periods. The timing and location of transitions in human-plant interactions, such as the shift from foraging to plant management or cultivation, remain unknown. It is assumed that the populations of the Congo Basin depended on gathering and hunting, with gradual changes toward the management of certain species, such as *Canarium*. We should bear in mind that over such long periods of time, human societies also had to adapt to climatic variations and their consequences for the environment.

Social Organization

Absolutely nothing is known about social organization during this period. Mobility was a key factor in enabling human groups to adapt to varied ecosystems and to respond to changes brought about by climatic variations. The absence of permanent structures in archaeological sites from this period supports this idea. Analyzing the mobility of hunter-gatherers is a field of research.

Changes and Transitions

During the Late Glacial Maximum (LGM, 26,000–19,000 yrs BP), it is assumed that savannahs expanded and forests retreated, influencing subsistence and land use patterns. Marine cores show climatic changes, but continental data are limited, with the oldest dating back 90,000 years (Lézine et al. 2019). However, it is likely that some changes were regional, with drier periods favoring the expansion of savannah and wetter periods leading to an increase in forests. It is assumed that, at LGM, the forests were fragmented, although some areas, particularly in the center of the Congolese basin, may have always been forested due to the density of the hydrographic network. Studies also suggest a decoupling of environmental variations between the coastal region and the basin of the Congo Basin.

Key Sites

Gabon: Elarmékora (ESA). This site is an alluvial terrace 175 m above the Ogooué River containing 650,000-year-old pebble tools (Braucher et al. 2022).

Angola: Dungo 4 (ESA) is a full site with pebble tools dating from 600 to 650,000 years ago (Lebatard et al. 2019).

Gabon: Maboué 5 (MSA/LSA). This open-air site, located on a hilltop, shows seven levels of occupation, including a level of 280 cm dated at 45,000 years, and reveals a microlithic industry on quartz (Mesfin et al. 2021).

Cameroon: Shum Laka (LSA). This rock shelter was occupied as early as 30,000 BP and shows microlithic industries associated with diversified exploitation of forest resources (Lavachery 2001).

Conclusion

The period between 650,000 and 10,000 BP in Central Africa corresponds to a key phase in human evolution. Marked by climatic variations, it saw alternating arid and humid phases that shaped the forest and savannah landscape. The first traces of human settlement appear in the form of early lithic industries, followed by the more sophisticated tools of the Middle Stone Age. However, archaeological data remains fragmentary, particularly for densely forested areas, limiting our understanding of the dynamics of settlement and technical innovation in this vast region. Few well-preserved sites dating back to this period are known, and they are very far apart. It is, in fact, too early to be able to propose a synthesis. Everything remains to be done.

End of the Late Stone Age (10,000–3000 Yrs BP)

This period, which follows the Last Glacial Maximum, corresponds to the deglaciation of the Holocene and is marked in its first half by the African wet period, a humid climate that favored the expansion of forests and the development of new ecological systems. At the same time, the emergence of specialized practices, notably the processing of plant resources, was reflected in the evolution of tools. Lithic assemblages diversified, reflecting adaptation to a variety of environments and more specific uses. Palaeoenvironmental studies, using core samples from lakes Barombi Mbo (Maley and Brennac 1998; Garcin et al. 2018) and Bambili (Lézine et al. 2019) in Cameroon, provide detailed climatic chronosequences dating back more than 25,000 years BP, revealing the impact of climate change on regional ecosystems.

Material Cultures

The small number of well-contextualized sites excavated to date, and the conditions in which they are preserved in a humid tropical environment, limit our understanding of life at this time. The two main types of artifacts are lithic (stone tools and manufacturing waste) and a few ceramic shards from 7000 BP onwards (Lavachery 2001).

Lithic

Lithic assemblages vary from region to region. At Shum Laka, LSA microliths appear to be a continuation of an earlier trend (Cornelissen 2003). These tools, often made of quartz, reflect an adaptation to varied environments and more specific uses. At other sites, not necessarily marked by microlithism or by the predominance of quartz, we note the presence of tools that are not standardized or retouched. The emergence of new specialized practices concerning plants is perhaps indicated by the appearance of macrolithic tools during the Holocene: Tools resembling hoes were discovered around 7000 years BP at Shum Laka, while partially polished stone axes are beginning to appear sporadically in Cameroon (Lavachery 2001) and in sites currently being studied in Cameroon and Gabon. In addition, regional industries such as the Tshitolian show local variations, but their classification remains a source of debate in the absence of well-contextualized sites.

Ceramics

Ceramics appeared in the northwestern part of the forest block, on the border between Nigeria and Cameroon ca. 7000 BP in Shum Laka and Mbi Crater rock shelters (Asombang 1988; Lavachery 2001). Ceramics dating back 4000 years may also have been discovered in the Democratic Republic of the Congo (Coutros et al. 2025), but the data is too sparse to be able to confirm the fact.

Food Sources

The emergence of agroforestry practices at Shum Laka can be traced back to 8250–6200 BP, marking the gradual shift toward management of wild plants. The increasing use of *Canarium schweinfurthii* (Lavachery 2001), probably as a pre-tree crop, is an early example, while dietary diversification is seen with the appearance of species such as *Elaeis guineensis* (oil palm) and *Ensete gilletii* (a plant from the same family as banana). Despite a few interruptions, the stratigraphy of the cave extends into modern times. The period between 4500 and 4000 BP saw a significant expansion in the exploitation of *Canarium*, moving toward formal arboriculture. The appearance of new taxa of plants, such as *Ensete gilletii* and *Canarium*, suggests that forest cover is changing, perhaps because of arboricultural practices. Evidence of *Canarium* arboriculture would persist until at least 2100 yrs BP. The remains of *Elaeis guineensis* also appear currently. However, pastoralism and cereal farming (millet and sorghum) did not reach the region before 1000 BP, or even later.

Preliminary analyses of the Youmbidi cave show similar use of *Canarium* and other tree fruits, but sampling and analysis are ongoing.

In short, the archaeobotanical evidence suggests a transition to arboricultural and agroforestry practices well before the introduction of cereal-based agriculture. The use of *Canarium* at Shum Laka is evidence of selective collection leading gradually to the probable domestication of plant resources, illustrating a key stage in the evolution of food systems and anthropized landscapes.

Social Organization

We have no data on the organization of societies during this period. Some groups developed semisedentary strategies, particularly in favorable environments where resources were abundant. The regular reoccupation of rock shelters such as Shum Laka and Mbi Crater in Cameroon and Youmbidi in Gabon suggests cycles of exploitation and abandonment of sites, but there is nothing to suggest that there was a filiation between the groups of humans that used the site.

Developments and Transitions

This period marks a significant transition: The gradual changes of the forests and the expansion of the savannahs coincided with a shift from opportunistic collection to active management of plant resources. This change, which is reflected in the early emergence of agroforestry practices (notably through the management of *Canarium schweinfurthii*) and the appearance of species such as *Elaeis guineensis* and *Ensete gilletii*, probably led to a diversification of feeding practices.

Impact on Ecosystems

We lack data for a detailed appraisal of human impact on ecosystems during the Early Stone Age. Indeed, there were even doubts that early hominins could have adapted to tropical rainforests. Data available elsewhere indicate that Earlier Stone Age population made use of fire (Hlubik et al. 2019), but there is little evidence about their mastery.

The Middle Stone Age (MSA) is better represented in Central Africa, and we can speculate that the impact of humankind is increasing. MSA-type assemblages have been found from Cameroon and Gabon to Angola and Eastern DRC, suggesting adaptation to a variety of environments. Fire is mastered and used for stone working (Brown et al. 2009), including forest edges. The question of penetration of dense forest by MSA populations remains a matter of debate, but there is increasing evidence of adaptation to forested environments (Roberts et al. 2021), and there are some stone implements designed for woodworking. Fire is also used elsewhere for cooking, thus extending the reach of humans in their environment (Wadley et al. 2020).

In short, while we can attest to the increasing foothold of mankind in the environments of Central Africa, it is difficult to have a clear picture as the data is few and far between.

Key Sites

*Shum Laka and Mbi Crater (Cameroon): This site reveals a major technological transition, with the gradual introduction of macroliths (polished axes, typical hoe

shapes suggesting the beginnings of horticultural management) from 7000 yrs BP onwards. This new set of tools seems to have coexisted with microliths from the earlier period. The appearance of pottery is attributed to 7000 yrs BP onwards, but according to Asombang 1988, pottery found at Mbi crater could have appeared earlier, around 9000 yrs BP.

*Caves in the Lastoursville area (Gabon): Youmbidi and Pahon. The Youmbidi site, which is currently being excavated, shows stable lithic industries that are not very standardized or retouched (Angue Zogo et al. 2023). Traces of *Canarium* and *Elaeis* have been found here since at least the Middle Holocene. A fragment of a partially polished axe was discovered in the Pahon cave in a well-dated stratigraphic situation.

Conclusion

This pivotal period, marked by the end of the LGM, is still poorly understood. It was marked by the appearance of polished stone tools, characteristic of new activities, and the first pottery. Increased management of plant resources, with evidence of early manipulation of the landscape, was evident in the specialized use of fruits such as *Canarium* and the emergence of agroforestry practices. The diet, diversified and adapted to local environments, was based on a combination of hunting, specialized gathering, and fishing, making full use of the forest resources.

The Beginnings of Sedentarization (3000–1400 Yrs BP)

This period is clearly distinguished by major sociocultural transformations. Whereas the previous period was marked by subsistence practices based mainly on hunting, gathering, and management of forest resources, this period saw the introduction of domesticated plants from the Sahelian and Sudanese regions. This spread of agriculture and arboriculture, adapted to humid tropical environments, marked a turning point. It was accompanied by significant changes in all aspects of society, including what appears to have been a village lifestyle, the emergence of iron metallurgy, the spread of ceramics throughout Central Africa, and indications of trade. Not only was there a diversification of foodstuffs, but also a radically different social structure, reflecting the emergence of societies in the throes of change.

Material Culture

Stone to Metal Age

Lithic industries are rare, marking a transition toward the use of metals. Iron metallurgy emerged between 2600 and 2500 yrs BP with even earlier evidence in eastern Cameroon, although this is not universally accepted (Zangato 2008).

Ceramics

The early phases (3000–2000 yrs BP) reveal similar ceramic assemblages, forming stylistic horizons of sorts, such as those at the Obobogo, Bwambé, and Bissiang (Cameroon) and Okala and Epona (Gabon) sites. Related styles quickly appeared along the Atlantic coast as far as the mouth of the Congo River, then as far as the interior basin of the Congo River (Wotzka 1993), and as far as Bakebena to the southeast of Kisangani (Nieblas Ramirez et al. 2024). In the beginning, there is striking similitude in the repertoire of shapes and decoration styles evolved progressively in the different regions without any major break until around 1500 yrs BP (Fig. 3).

Refuse Pits

Pits are structures dug and used as dumps (Livingstone Smith et al. 2017a), and they are typical of many sites from this period. They were dug in or around village sites and are filled with the refuse of everyday life (charcoal, burnt fruit, shards, ashes, etc.). Some of the pits may have been used for a variety of purposes: septic tanks, pits for rotting clay, traps, etc. Whatever the case, they

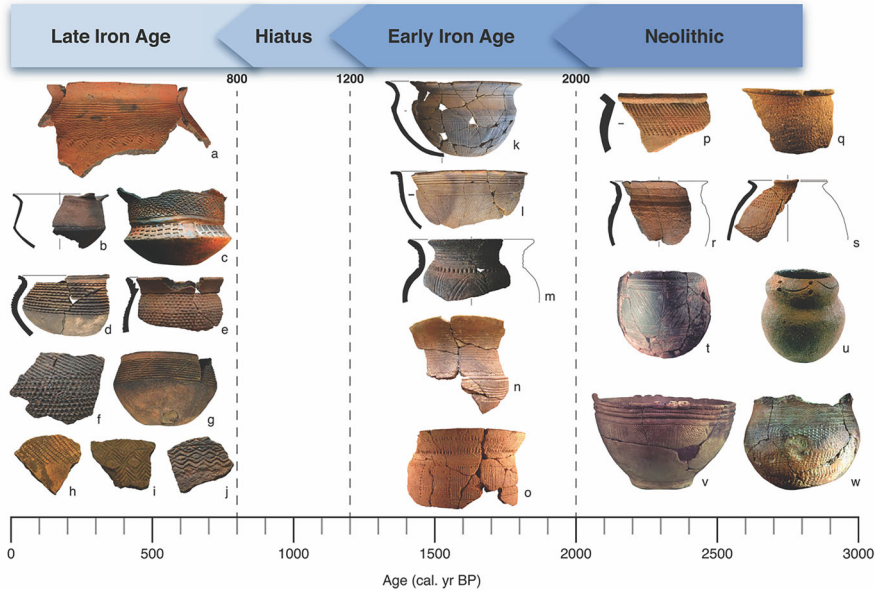

Fig. 3 Chronology of Western Central Africa with pottery traditions over the past 3000 years from de Saulieu et al. (2021). Late Iron Age: (**a** and **b**) Dibamba A—Cameroon; (**c**) Lopé region from eleventh to eighteenth centuries—Gabon; (**d** and **e**) Dibamba B—Cameroon; (**f**) Oku—Cameroon; (**g**) Dibamba C—Cameroon; (**h** and **i**) Lobéké—Cameroon; (**j**) Kovifem—Cameroon. Early Iron Age: (**k** and **l**) Campo—Cameroon; (**m**) Akom—Cameroon; (**n**) Lalara—Gabon; (**o**) Otoumbi—Gabon. Neolithic: (**p**) Dibamba E—Cameroon; (**q**) Mpolongwé—Cameroon; (**r** and **s**) Nya Zanga—Cameroon; (**t** and **u**) Epona—Gabon; (**v**) Imbonga—DRC; (**w**) Madingo-Kayes—Republic of Congo. (© Denbow J (**w**), © Oslisly R (**c, q, o, n, t, u**), © Saulieu G de (**a, b, d–m, p, r, s**), and ©Wotzka HP (**v**))

all bear witness to rigorous domestic organization. In addition, some of the pits undoubtedly had a symbolic and ritual dimension, as suggested by the deposit of a few complete vessels (Wotzka 1993; Nlend Nlend 2013; Livingstone Smith et al. 2017a).

Food Sources

The dietary transition was marked by the domestication and cultivation of plants such as millet (*Pennisetum glaucum*) and oil palm (*Elaeis guineensis*). Archaeobotanical and archaeozoological analyses indicate a combination of food crops, hunting, and fishing. This dietary diversity reflects adaptation to local environments.

Introduction of Domesticated Cereals and Agricultural Diffusion

Millet was introduced from the West African savannahs. Pearl millet appeared in several archaeological sites in Cameroon and DRC around 2400 BP (Eggert et al. 2006). Initial archaeobotanical analyses showed limited quantities of grain, suggesting ritual or occasional use, perhaps in connection with social events or symbolic practices. Thanks to new sampling methods, thousands of grains have recently been detected in field excavations, suggesting that they were an integral part of everyday life, both as food and potentially in the manufacture of beer. The adaptability of millet, now grown in humid climates, testifies to its resilience and makes it a key element for food security in the face of climate change. Cowpeas (*Vigna unguiculata*) were grown alongside millet, reflecting the gradual introduction of legumes, improving dietary diversity and contributing to protein-rich diets (Kahlheber et al. 2014a, 2014b; Neumann et al. 2022) and perhaps soil management.

Other plants also appeared 3000 BP onwards, including sorghum, plantain, and taro. Sorghum (*Sorghum bicolor*) was probably introduced from Sudan around the beginning of our era, although its exact spread remains uncertain. As for plantain, taro, and yams, these tubers and fruits would have been adopted from adjacent forest regions, encouraging mixed farming practices combining cereals and arboriculture.

Transformation of Arboricultural Practices

Despite being a key resource in earlier periods, the *Canarium schweinfurthii* appears to have declined after 3000 BP, to the benefit of *Elaeis guineensis*—whose fruit is used primarily to produce palm oil. The appearance of large quantities of palm nuts in archaeological pits suggests an intensification of their management and their central role in food and socioeconomic exchanges.

Social Organization

Thanks to the discovery of villages and necropolises, we have more information on the organization of societies. Villages, located on hilltops or on the banks of rivers,

are identified by a series of refuse pits, testifying to a structured community organization (de Saulieu et al. 2015). The similarity between ceramic styles suggests regional and supra-regional cultural interconnections. The funerary sites of Akonetyé and Campo in Cameroon and on the island of Corisco in Equatorial Guinea reveal the existence of high-ranking individuals, buried with elaborate pottery, weapons, and ornaments, indicating social stratification.

Evolution and Transition

This period is the setting for a series of major transitions, including the almost simultaneous appearance of metallurgy, agricultural practices, and new ceramic styles (~2500 BP). These changes indicate significant cultural transformations on the scale of the entire forest block. Sites showing long-term occupations and reoccupations (Dibamba, Nachtigal in Cameroon, and Otoumbi, Lopé in Gabon) contrast with sites showing shorter occupations, often limited to one or two phases.

These changes are thought to be related to the Bantu language expansion phenomenon (Vansina 1990), marking a key stage in the structuring of forest societies. The origin of the expansion is thought to have started as early as 6000 yrs BP around the Cross River plain in Nigeria. The existence of a population movement was confirmed by genetic studies (Pakendorf and de Filippo 2015), but the processes of the expansion and its correlation with the archaeological record are still debated.

The spread of Sahelian agriculture is probably linked to population movements. The integration of these new resources favored the development of permanent villages, often located on hilltops not far from a permanent watercourse (Oslisly 2001) with typical dumping pits, evidence of stable domestic and agricultural organization. The cultural sequence shows relative continuity up to 1500 yrs BP, followed by a marked transition after 1400 yrs BP, when interruptions appear in the chronologies of many sites.

Impact on Ecosystems

During this period, the impact of human societies in the Congo Basin changed dramatically. The construction of villages means openings in the forests and the development of agriculture induced extensive clearing of forest patches (Morin-Rivat et al. 2014; de Saulieu et al. 2018). While we have no direct evidence for agricultural techniques, the recurrent occupation of sites at different periods of time may indicate a degree of mobility related, among other things, to slash and burn agriculture. One should also keep in mind that once opened, the forest may have been subject to other processes—it seems that animals, like elephants, play a role in the husbanding of forest clearing (Baï). Archaeozoological results also indicate that domesticated ovicaprids were probably herded and that forest hunting and fishing still provide an important part of the diet. While the use of wood for cooking was probably of a marginal impact, new technologies such as iron smelting and iron

smithing to produce tools and weapons must have had significant consequences (Eichhorn et al. 2019).

Key Sites

- Cameroon: Obobogo, Nkometou, Oliga, Okolo, Nkang, Ndindan, Nachtigal, (Yaoundé area), Malongo, Bwambé, Bissiang, Mpolongwé (Kribi coastal region), and Dibamba (Douala), which present the first homogeneous cultural sequences showing a transition toward complex ceramic assemblages and early metallurgy as early as 2700–2500 yrs BP (Mbida Mindzie 1996; Nlend Nlend 2013; de Saulieu et al. 2017, 2024).
- Gabon: Epona, Lopé, Okanda, and Okala with long cultural sequences (Oslisly 1998; Clist 2005). These sites show long occupations spanning up to 2700 years, revealing dump pits, metal tools, and ceramic production as village markers.
- Democratic Republic of the Congo: Dimba, Ngovo, Sakuzi, Imbonga (Wotzka 1993), Bomane Yangwa, and Yamontonga (Livingstone Smith et al. 2017a; Nieblas Ramirez et al. 2024; Vutseme Sokoni et al. 2024). Overall, these were early food-producing villages, with pits filled with ash and plant remains (millet, palm nuts). The ceramics are mostly ovoid with flat bottoms and everted necks. Pits containing specific assemblages of vessels bear witness to ritual activities and inter-regional contacts.
- Exceptional sites: Akonetyé and Campo in Cameroon (Eggert and Seidensticker 2016) and Corisco Island in Equatorial Guinea (González-Ruibal et al. 2011) for their burial wealth.

Conclusion

During the period from 3000 to 1400 yrs BP, the archaeology of Central Africa reveals a radical change in material culture and lifestyles. Ceramics, which are characterized by styles specific to each region, also display common features indicating a kinship of origin or strong social interactions. This period also saw the emergence and spread of iron metallurgy—although the details of this process are still poorly understood.

Funerary deposits of metal attest to one or more forms of social stratification, with some tombs clearly more richly endowed than others. The almost systematic presence of dumping pits is also characteristic. Diversified dietary practices, the emergence of organized villages, and evidence of social stratification all point to a new complexity.

The arrival of Sahelian plants (millet, cowpea) and Sudanese plants (sorghum) marked a decisive stage in the spread of agriculture in forested Central Africa. These agricultural innovations, combined with the spread of iron metallurgy and the diversification of tree resources (*Elaeis g.*), led to an increase in population and the structuring of communities into stable villages (de Saulieu et al. 2021).

The successful integration of these cultures highlights the flexibility of ancient societies and offers lessons for adapting to contemporary environmental change. The recent Holocene saw the emergence of societies that would give rise to the great states that would mark the history of Africa during the second millennium AD.

Break-Ups, Resilience, and Innovations (1400–800 Yrs BP)

The period from 1400–800 yrs BP is marked by a notable break in the archaeological sequences in the Atlantic Congo Basin and could be described (Fig. 4), as in Europe, as the "Dark Age." It is important to remain cautious, however, as this break is marked by a lack of data; in fact, virtually no sites have been dated to this period in the forest block of southern Cameroon, central-eastern Gabon, and northern Congo (Oslisly et al. 2013). What is striking is that we see this decrease at the regional level as well as the local level, with sites with a long chronology presenting interruption of occupation (de Saulieu et al. 2017; de Saulieu et al. 2024).

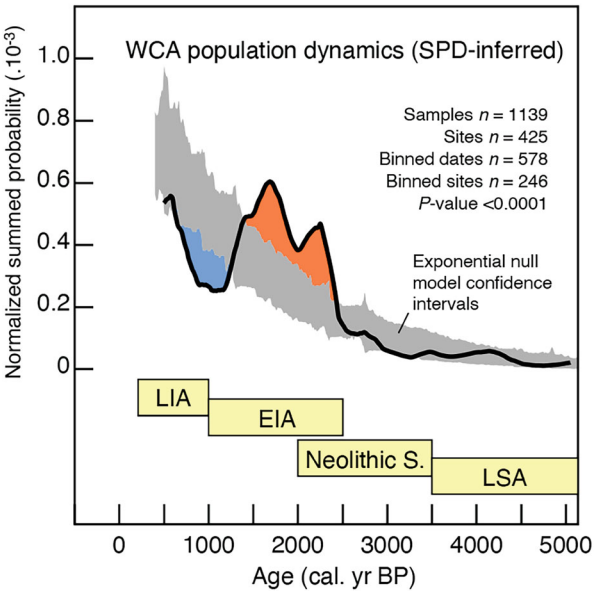

Fig. 4 Archaeological synthesis of Western Central Africa during the past 5000 years. All archaeological data presented rely on the SPDs of calibrated 14C dates. Summed probability density is a statistical method to reduce geographical and chronological bias, allowing for inferring population dynamics of the past: SPD of 14C dates (thick line) was compared against an exponential model used as a conservative null hypothesis. In other words, only the difference with the model is significant. The dark grey area represents the 95% confidence interval for the null model. Red and blue areas represent intervals with significant positive and negative deviations from the exponential model. A positive deviation may be interpreted as a demographic increase and a negative one as a decrease. (Regional cultural timeline shown at the bottom: *LSA* Late Stone Age, *Neolithic S* Neolithic stage, *EIA* Early Iron Age, *LIA* Late Iron Age. (From de Saulieu et al. (2021))

There are many possible explanations for this: a decline in population—perhaps linked to an epidemic crisis—major social upheavals, the relocation of settlements to areas that are still unexplored from an archaeological point of view, or selective soil erosion and loss of fertility during this period. The regions bordering the forest block bear witness to complex social and environmental dynamics, which perhaps explain this situation. In Katanga, there seems to be a relative disconnect with what is described above. Indeed, in the Upemba Depression, this period marks the beginning of a flourishing cultural phase, with a hierarchical society engaged in various forms of trade (De Maret 1999; Nikis and Livingstone Smith 2017). In any case, in the absence of data, it is difficult to propose serious global hypotheses, whether in terms of settlement, material culture, diet, or social organization.

Key Sites

- Cameroon: Bwambé-Beach, Eboundja 3, and Mpolongwé, most of which have low levels of occupation (Nlend Nlend 2013).
- DRC (Katanga): Sanga and Katoto, necropolises rich in ceramics, copper jewelry, and prestigious iron objects (bells, parade axes). The funerary material suggests, among other things, the probable existence of a political and/or ethnolinguistic demarcation, a marked social stratification, and a trade network operating over medium to long distances (De Maret 1999).
- DRC (Tshopo): Yangambi and Basoko. The appearance of ceramic techniques typical of the Sahel attests to new interactions with populations north of the Congo River (Livingstone Smith et al. 2017a).
- No sites dating from this period have been discovered in the forests of Gabon. The period 1400–800 yrs BP in Central Africa marks a major break in demographic and cultural dynamics. The causes of this transformation remain to be elucidated, although we believe that an epidemiological phenomenon may have had an impact on Central African forests (Oslisly et al. 2013).

Emergence and Development of Large Political Entities (800–120 Yrs BP)

This period was a turning point for humanity and particularly for Central Africa. Today, thanks to a variety of sources—archaeological, oral, written, artistic, and genetic—we can better understand its history in terms of politics, trade, and intercontinental exchanges. Analyzing this period requires a multidisciplinary approach.

From an environmental point of view, we know that this period corresponds, for the northern hemisphere, to the medieval optimum (1100–750 yrs BP) followed by the Little Ice Age (750–350 yrs BP) (Ngomanda et al. 2007), but the environmental dynamics and their impact on societies remain little explored for Central Africa. At the time of the arrival of European travelers, there were large political groups, sometimes controlling considerable territories like the Kongo Kingdom, engaged

in short-, medium-, and long-distance trade. Certain trade goods had probably existed before, such as iron, copper, and salt, but we also see the arrival of manufactured objects from Europe (as well as local copies) and the start of international trade in goods such as ivory and human beings (Arazi et al. 2024).

Material Culture

Ceramics

The ceramic traditions that emerged at the end of the previous period sometimes showed elements of continuity with earlier traditions, but above all mark an abrupt change in relation to everything that had gone before. In some regions, flat-bottomed ovoid shapes were abandoned in favor of round-bottomed hemispherical shapes; in others, square shapes, previously nonexistent, made their appearance. The previous decorative techniques were still used, but new techniques were emerging, notably *roulette* decorations using woven plant fibers or engraved on a wooden core. There was great stylistic diversity in terms of decorative schemes. These changes probably reflect major societal changes and medium- and long-distance interactions, as well as the emergence of new social spaces within which stylistic norms were established. These social spaces can often be linked to political formations (Livingstone Smith 2016).

Metallurgy

Iron continued to be produced and traded. Tools and weapons were produced with great skill. They were both utilitarian objects and currencies, the shapes and calibers of which varied from region to region.

Copper production began at Boko Songho-Mindouli (Republic of Congo) in the Pool Malebo region. This copper was used to make jewelry and coins for inter-regional trade. This is also the case at the southern edge of the forest block, on the Katanga side, where copper production continues. However, there have been changes in the style of ingots (shapes and sizes), the famous "croisettes." These changes indicate a regionalization of production, which could be linked to the emergence of new political entities (De Maret 1995; Nikis and Livingstone Smith 2017).

European Dishes, Guns, Pearls, and Cowries

Beads appear around 200 yrs BP in the forest block, from the northern coastal region of Cameroon (Douala) in the Upemba Depression west to Katanga (De Maret 1977). Similarly, European earthenware, stoneware, and glass vessels appear scattered in archaeological contexts from 200 yrs BP onwards. Produced outside Central Africa, they quickly became the imported objects of choice, competing with certain local crafts. In addition to their value as ornaments, they were used in a whole series of transactions, some of them of great prestige, as can be seen from the descriptions of bride prices in ethnographic sources from the nineteenth and twentieth centuries.

Food Sources

Colonization introduced plant species of American origin that profoundly altered local agricultural and food practices.

Crops such as maize, cassava, sweet potatoes, and groundnuts, which originated in America, as well as new varieties of yams, bananas, and taro from Asia, have been adopted by local populations. These new species have diversified diets and changed farming practices, contributing to a transformation of production systems and eating habits in the region. In arboriculture, the introduction of exotic fruit species has enriched cultivated biodiversity but has also led to changes in the management of orchards and local ecosystems.

Although the range of new plants and farming practices introduced during this period is more in line with today's food situation, unfortunately, few studies have been carried out on the subject. Everything remains to be done to gain a better understanding of the new agricultural dynamics introduced during this period.

Social Organization

Central Africa presented a mosaic of social and political systems, ranging from powerful centralized states, such as the Kongo Kingdom, the Mwat Yav, and the Luba, to small lineage-based societies, and even acephalous societies, particularly among hunter-gatherers. It is undeniable that, except for the so-called "pygmy" populations, wealth plays an important role everywhere, particularly in terms of marriageability. Chiefs were able to accumulate wives at the expense of their communities, while external slavery (as a result of war) and internal slavery (enslavement of relatives) are well documented in ethnohistorical sources (Vansina 1990), helping to concentrate power along river routes, along the coast, and in strategic areas.

Evolution and Transition

This period was marked by migrations, cultural changes, and outside influences, such as the introduction of Sahelian ceramic traditions into the Congo Basin and of American fruits and plants. The dramatic increase in human trafficking to Muslim markets and to the American colonies had a lasting effect on social structures and demographics.

Key Sites

- Littoral (Cameroon): Dibamba presents five ceramic traditions that succeed one another over 2500 years BP, some of which show an interconnection with those of other regions (de Saulieu et al. 2017).

Fig. 5 Beautifully crafted twisted copper bracelet from the burial cave Iroungou (Gabon, fourteenth to fifteenth century CE). (© Tigoe N)

- Southern Gabon: The Iroungou cave is a necropolis revealing a massive burial and prestige goods, including more than 500 iron and copper objects. Thirty skeletons, including many skulls, show antemortem dental avulsions (Villotte et al. 2021) (Fig. 5).
- West (Kongo Kingdom): Mbanza Kongo and Kindoki are major centers documented by historical and cartographic sources (Balandier 1965).
- Pool Malebo (DRC): Sites such as Gombe and Kingabwa, linked to the Teke Kingdom, show traces of important economic activities, particularly metallurgy (Van Noten 1982).
- Central (Congo-DRC Basin): Lisala and Ubundu have Sahelian influences and cultural dynamics that have been little explored (Livingstone Smith et al. 2017a; Nieblas Ramirez et al. 2024; Vutseme Sokoni et al. 2024).
- Southeastern DRC (Upemba): The burial sites of Sanga, Kabamba, and Katoto show a complex social organization with well-defined chronological sequences such as the Kisalian and Kabambian (De Maret 1977, 1999).
- Eastern DRC (Kindu, Kasongo): Little data, but historical sources mention the presence of Zanzibarite merchants in the nineteenth century (Arazi et al. 2020).
- Mbanza Nsundi (DRC): This is a major site for understanding the formation of the Kongo Kingdom (Bostoen and Brinkman 2018).
- Kingabwa (DRC): The remains around Pool Malebo are rich in evidence of commercial and craft practices (Van Noten 1982) (Fig. 6).

Conclusion

The period from 800 to 120 BP reflects a profound transformation of Central Africa, marked by the history of major political entities, major cultural changes, and the development of international trade networks. The material remains, and external

Fig. 6 Aerial view of the center of the ancient Swahili City of Kasongo-Tongoni (Maniéma, DRC), with the stone foundations of some buildings. (© Arazi and Livingstone Smith MRAC-KMMMA)

influences bear witness to a resilience in the face of upheaval and a capacity for innovation that shaped pre-colonial societies.

Making Archaeological Heritage Part of Our Heritage

Showcasing our archaeological heritage remains a major undertaking. The remains of excavations are rarely exhibited in museums or officially restored. However, there have been some successes. An exhibition on the Iroungou site is still running at the National Museum in Libreville since September 2022. Some institutions in Central Africa, such as the Museum of Civilization in Dschang, Cameroon, the Lopé Ecomuseum in Gabon, the National Museum of the Congo in Kinshasa, and the National Museum of Lubumbashi in the DRC, have archaeological collections.

General Conclusion

The history of Central Africa over the last 650,000 years has been marked by major environmental and sociocultural transformations. The first human societies adapted to climatic cycles using rudimentary lithic tools, as attested by a few archaeological sites. The Last Glacial Maximum and the African Wet Period profoundly altered the environment, encouraging the expansion of forests and influencing lifestyles.

Around 7000 yrs BP, a more specialized management of plant resources appeared, accompanied by the combined use of macrolithic and microlithic tools. This period marked the beginning of a gradual transformation toward agriculture, with the early domestication of certain plants and the manipulation of the landscape.

Between 3000 and 1400 yrs BP, the introduction of Sahelian plants such as millet and cowpea led to the development of an agricultural and arboricultural economy in the rainforests. The growing exploitation of oil palm and other species reflects the ingenuity of local populations in the face of environmental constraints, marking a significant diversification of the food supply.

Between 1400 and 800 yrs BP, a phase of social reorganization led to a reduction in archaeological occupation. However, by 800 BP, new kingdoms were emerging, such as those of Mbanza Kongo and Kingabwa, illustrating a revival of political and economic dynamism (Clist et al. 2018). Inter-regional trade intensified, thanks to the production of copper goods in the southern Congo Basin, soon to be rivaled by the first European objects from the sixteenth century onwards.

With colonization, the introduction of American crops (cassava, maize, tomatoes, chillies, and potatoes) and Asian crops (rice and taro) profoundly transformed diets and agricultural landscapes, redefining production systems and trade. Central African societies have adapted to climatic, cultural, and economic challenges, laying the foundations for modern social and economic structures.

Research carried out to date has revealed the extraordinary wealth of Central Africa's archaeological heritage. However, major challenges remain if this heritage is to find its rightful place in the history of humanity. Nevertheless, international research projects and archaeological safeguarding initiatives have made a significant contribution to enriching our knowledge of Central Africa's past. We need to continue in this direction by encouraging preventive archaeology programs during major works (dams, roads, pipelines, mines…).

For a long time, the perception of tropical forests was dominated by the idea of a primary, static forest hostile to human development. Today, it is recognized that the Central African forest is subject to a variety of dynamics: Successive expansions and regressions have given way to the development of more or less shrubby savannahs over several centuries.

The protection of archaeological heritage is essential to preserve and enhance these remains, but it requires a collaborative approach. Involving local political players and civil society, particularly at the local level, is crucial to ensuring that this heritage is managed sustainably and with respect. Archaeology, in dialogue with local populations, can offer insights into the adaptability of past societies to environmental and social change, providing valuable lessons for tackling contemporary challenges. By promoting an interdisciplinary and participatory approach, archaeology in the Congo Basin contributes not only to understanding the past but also to building a sustainable future for local communities.

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Human Occupation of the Congo Basin

8

Birgit Ricquier, Benoît Henriet, Olivier Hymas, Paulin Kialo, Hines Mabika Ognandzi, Caroline Michellier, Stephanie Rupp, Gretchen Walters, and Catherina Wilson

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Abstract

The Congo Basin has an impressive cultural diversity resulting from millennia of contact, networking, intermarriage, and other types of interethnic mingling and pairing. The region has been inhabited for at least 650,000 years. Hunter-gatherer communities probably preceded the others, but Bantu, Ubangi, and Central Sudanic–speaking communities arrived over the last 4 to 5 millennia. Until the colonial period, mobility was the norm; small, local movements and large, regional shifts were frequent. Climatic changes, the search for natural resources and economic opportunities, conflict avoidance, flight from disease, and social traditional beliefs triggered mobility. During the colonial era (c. 1880–c.1960), traditional patterns of mobility were interrupted. To extract timber, oil, and minerals; to produce palm oil and kernels, cocoa, and cotton; and to secure export markets for metropolitan companies, villages were frequently forcibly relocated to sites where displaced people worked on plantations, logging concessions, mining sites, or infrastructural projects.

After World War II, colonial settlements evolved into large urban centers. Urbanization is one of the recent changes in the Congo Basin. From 1960 to 1968, the Congo Basin countries gained independence; one-party regimes were installed, and repression and economic deterioration followed. Since the 1990s, political regimes have been challenged, and conflicts have broken out in many parts of the Congo Basin, leading to regional and cross-border migrations. Current challenges include high population growth, a youthful demographic, gender disparities, and the marginalization of minority groups. Urbanization, urban expansion, the urban need for natural resources, conflict-induced migrations, and forestry and mining concessions threaten the high cultural and biological diversities.

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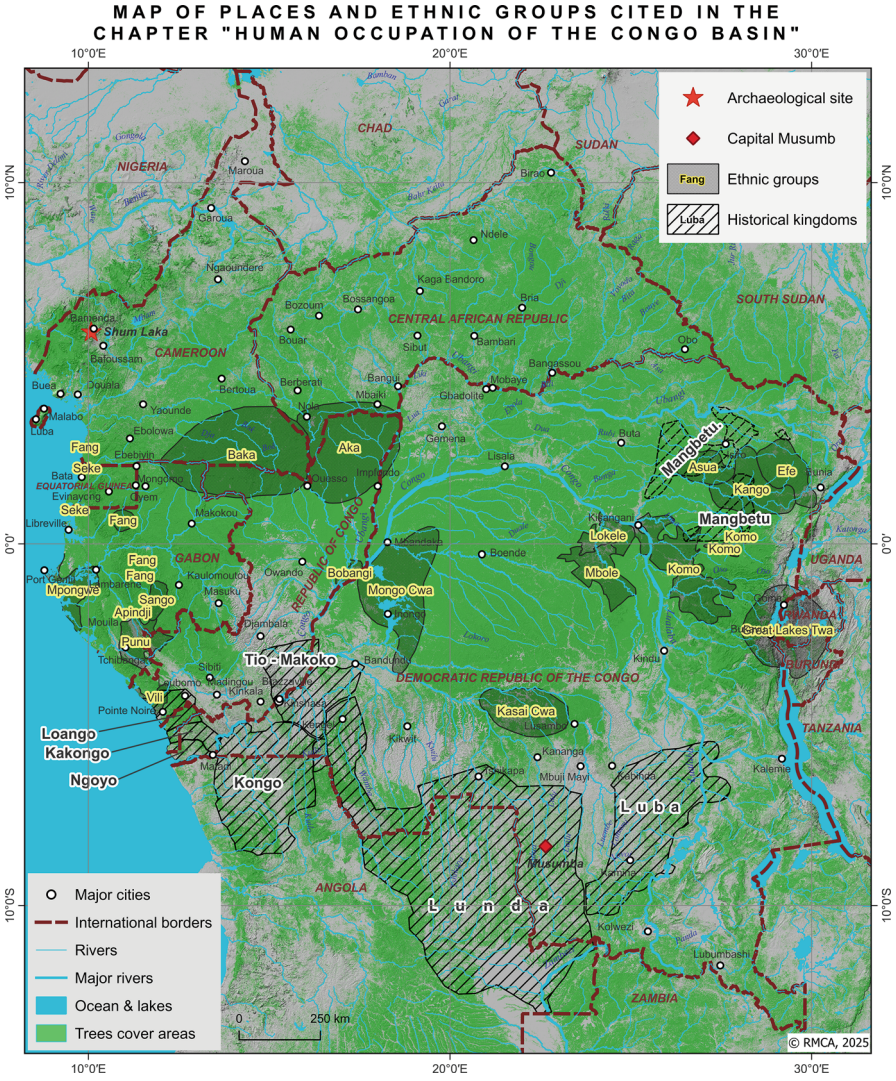
Keywords

High cultural diversity · Traditional mobility · Forced relocation · Indigenous people · Urbanization · Migrations



Introduction

The high degree of biodiversity in the Congo Basin is equaled by an impressive cultural diversity. To number all communities present in the six countries of the region is difficult, but a language count forms a good proxy. The website Ethnologue lists a total of 605 languages, which constitute 8.5% of all languages spoken in the world (Eberhard et al. 2025).[1] This estimation does not represent the actual number of different communities, as one community can speak various languages and vice versa, but clearly the Congo Basin is highly diverse culturally. The current cultural diversity is not the result of developments occurring in isolation but, on the contrary, of millennia of contact, networking, intermarriage, and other types of interethnic mingling and pairing across the Congo Basin. The region has always been a crossroads, attracting communities from different directions, at different epochs, and with different objectives (subsistence, long-distance trade, colonization). Triggers for the human occupation of the Congo Basin include climate and natural resources, but since the early days, people have also interacted with the rainforest ecosystem, e.g., through practices of small-scale agriculture, hunting and gathering, or fishing – and often through multiple, integrated subsistence approaches. The present chapter offers a history of human dynamics in the Congo Basin: migrations and settlement, demographic rise, economic activities, and more.

Congo Basin Communities

Cultural and political identities of forest communities throughout the Congo River Basin are complex, varied, and often fraught. The ways that any given person self-identifies are plural, layered, and contextual. Forest communities form multiethnic, multilingual clusters, in which local identities are shaped by relationships that traverse and entangle many different social boundaries of similarity and difference, and are shaped by complex dynamics of mutuality as well as tension. Moreover, the ways that people identify themselves and the ways that they are identified by others, particularly by institutions, do not always align.

Since early colonial times, outside observers have used contrasting categories to distinguish the tremendous cultural, economic, and political diversity of the region: pygmies vs. villagers, hunter-gatherers vs. farmers vs. fisher people, and indigenous people vs. those who (are presumed to) have migrated into the forest. These etic (outside) categories offer conceptual handles for making sense of and creating policies for diverse forest communities that live throughout the basin (Bahuchet 1993a). At the same time, forest people identify themselves in a variety of layered, culturally and contextually specific ways; such emic (inside) identities may reflect language, clan, historical heritage, contemporary alliances, and other meaningful,

[1] Own calculations: sum of languages per country minus doubles.

dynamic, and shifting ways of expressing the self and relations to others. Importantly, these emic identities may also include etic, outside identities such as "pygmy"—perhaps in alignment with the institutional, political, or outside expectations of the qualities, but in other cases with meanings that diverge, complicate, or even contradict and fill the category with cultural meanings that are specific to a local context in time and place. Whether a forest dweller or an entire forest community is classified as a "pygmy" or a "villager" in scholarly literature or policy papers, such terms flatten out a universe of salient features of ancestry, ecological connection, ritual participation, economic pursuit, marriage and alliance, and many other features of sociality that shape identities (Rupp 2011).

Reliance on static, homogenizing categories of social and political identities leaves outside observers with the impression that the people of the Congo River Basin and the forest itself can be reduced to archetypes and, furthermore, that these distilled simplifications of identity are sufficient, even appropriate, to use as categories to designate political and economic policies that impact and regulate the complex realities of forest peoples today. Because the identity politics of forest communities throughout the Congo River Basin region are complex, dynamic, and varied, this chapter uses reductive categories of identity sparingly and only where they offer value in synthesizing information that pertains across communities. Otherwise, we refer to Congo Basin communities simply as "forest communities," "communities," or simply "people," to avoid layering in distilled categories of identity that can have administrative and political implications for the people of this vast forest region.

Today, the politics of identifying who counts as an "indigenous person" is similarly fraught, particularly when conventions on "indigenous people" offer rights of access to protected areas of the forest or rights to hunt in particular ways, to some forest peoples and not all. The diverse and dynamic human history in the Congo River Basin renders such simplistic demarcations of "indigenous" and "non-indigenous" both impossible and foolish. While linguistic and genetic research demonstrates that certain language communities that have been identified as "pygmy" groups since the mid-nineteenth century were the first human inhabitants of the Congo River Basin, such ancient origins do not preclude movement within the basin over time. Furthermore, being identified as a "pygmy" group does not necessarily mean that the community is an autochthonous or indigenous person in the particular region where they live today. "Pygmy" communities, for example, the Baka and Aka, also have histories of displacement, migration, arrival, and contact with pre-existing forest communities (Bahuchet 1992, 1993b). Furthermore, the deep histories of Bantu language–speaking forest communities (a linguistic group that also includes numerous "pygmy" communities) span a few thousand years (see below), long enough to also be considered indigenous. Identifying who counts as "indigenous" is a contrived and politically motivated exercise, which has more to do with the politics of resource allocation than with accurate understandings of Congo River Basin history.

Human Occupation of the Congo Basin in Precolonial Times

The Congo Basin has been inhabited by modern humans and *Homo* ancestors for at least 650,000 years (Braucher et al. 2022). Little is known about the earliest inhabitants. Data stem mostly from archaeology (see ▶ Chap. 7, "Central African Rainforest Archaeology") and genetics. Such multidisciplinary evidence in combination with oral traditions of Congo Basin communities indicates that the ancestors of the present-day hunter-gatherers preceded the other people currently living in the Congo Basin (Klieman 2003). The mentioned hunter-gatherers include the Aka or Bayaka (Congo, DRC, CAR), Baka (Cameroun, Gabon, Congo), Babongo (Gabon), Mbuti and Efe (eastern DRC), and the Cwa and Twa communities (DRC and the Great Lakes countries). Genetic studies demonstrate that these communities separated 70,000 years ago from the ancestors of communities whose subsistence practices emphasize forest horticulture, including but not limited to Bantu-speaking peoples, and that the population size of Western hunter-gatherers decreased in the period that Bantu communities are thought to have settled the Congo Basin, i.e., between 4000 and 650 years ago (Batini et al. 2011). Oral traditions mention that hunter-gatherers were guides into the rainforest for the newcomers of that time (Klieman 2003; Metegue N'nah 2006). They continue to be considered as "forest specialists" and have long been in symbiotic relationships with farming communities (e.g., Terashima 1986), to such an extent that they exclusively speak languages closely related to, sometimes even dialects of, the languages of the corresponding farming community.[2]

The "newcomers" are communities speaking Bantu, Ubangi, and Central Sudanic languages. Parts of their history can be traced by comparative historical linguistics, for instance, the location of their homeland and subsequent expansions (see Ricquier 2020). Efforts are made to couple the resulting insights with archaeological data. While this is met with skepticism by certain scholars, it allows for the formulation of hypotheses about past mobility and networks in the Congo Basin. The best studied case is "the Bantu Expansion." Linguistic criteria such as high linguistic diversity and the presence of closely affiliated languages ("Bantoid," "Grassfields Bantu") indicate that the first Bantu speech communities must have lived in the Grassfields area bordering Nigeria and Cameroon. The archaeological site of Shum Laka was for some time linked to the earliest Bantu speech communities, thus offering a date: 4000 to 5000 years ago. Recent research on ancient DNA proves that the human remains are not genetically related to current Bantu-speaking communities (Lipson et al. 2020). Still, recent genetic research confirms the original linguistic theory that the settlement of the current Bantu-speaking region started in southern Cameroon and spread south and southeastwards (Fortes-Lima et al. 2024). The following large-scale migrations of Bantu-speaking communities tend to be linked to a drier climatic

[2] These relations might shift, and language then may become an indicator of past networks (e.g., Duke 2021). Scholars are still on a quest to trace the original language of the hunter-gatherer communities, but thus far results are only promising on more recent epochs (e.g., Bahuchet 2012).

period (see below) and to the progressive settlement of the Congo Basin by peoples sharing a similar pottery culture. Archaeological dates set the expansion of the latter as early as the mid-first millennium BC for the Pool region, progressing into the inner Congo Basin and arriving at the Lualaba (eastern DRC), no later than 2010 BP.[3]

The northern part of the Congo Basin is home to Ubangi-speaking communities. Based on historical-comparative linguistics, Bouquiaux and Thomas (1980) and Saxon (1982) proposed an eastward expansion north of the rainforest 3500 to 4000 years ago. Recent developments in comparative linguistics question the unity and affiliation of Ubangi languages, meaning that the settlement history of Ubangi-speaking communities should also be reconsidered (see Güldemann 2018: 216). The third language group in the Congo Basin is Central Sudanic, largely present in the northeast of the DRC, plus two communities, Furu and Bagiro, on the western part of the CAR-DRC border (Boyeldieu 1990). Relatives of the Congo Basin Central Sudanic languages can be found to the North, on the CAR-Chad border, and in South Sudan. Research on the history of Central Sudanic communities is scant. Based on linguistic arguments, McMaster (1988) assumes that Central Sudanic communities predate Bantu presence in the northeastern DRC.[4]

The static idea of communities being linked to a specific geographic location is a construct of colonial rule (see below). Up to the early colonial period, large population movements were frequent. The Fang, for instance, only settled a few centuries ago in Equatorial Guinea and Gabon, in response to the invasion of other peoples and in search of economic opportunities on the Atlantic Coast (Sitna 2023). This set up a chain of events where the Fang displaced people throughout Gabon (Gray 2002). Another example is the Komo expansion in the northeastern DRC, again triggered by the movement of other peoples, possibly Arab slave traders, and the search for economic opportunities. This expansion, still ongoing at the start of the twentieth century, was considered problematic and halted by early Belgian colonial administrators (Ricquier et al. 2023). Accounts of migrations in the last few centuries are attested by oral traditions, also known as "vernacular history" (see Schoenbrun 2017; Ricquier et al. 2023). Certain colonial administrators, missionaries, and learned local people assembled oral traditions to provide insights into their territories' precolonial population history, e.g., Gabonese Abbot Raponda-Walker (1960) for communities in Gabon and Governor Moeller (1936) for the Orientale Province of the DRC.

The high mobility in the precolonial era contrasts with the preconceived image of isolated communities in the rainforest. In the Congo Basin, contact has been the norm, not just because of the cited migrations, but also because of trade networks

[3] See ▶ Chap. 7, "Central African Rainforest Archaeology" on archaeology and Bostoen (2018) for a recent overview of the Bantu Expansion.

[4] Central and North Cameroon is also home to other language groups and families, such as Bantoid (Niger-Congo) and Chadic (Afro-Asiatic). From this, we can infer that the precolonial history of this region differs from the remainder of the Congo Basin. It will not be further discussed here.

and alliances between different communities, for instance, to co-organize initiation rituals (see Allovio 2000). As a result, the cultural practices and techniques of the peoples encountered and of the regions crossed were adopted and disseminated. Thus, cults such as Bwiti were adopted by the Fang and Punu peoples from the Apindji and Sango peoples of southeastern and central Gabon (Raponda-Walker and Sillans 2011; Mabika Ognandzi 2017). The languages spoken in the Congo Basin bear witness to this cultural admixture. Sounds and morphological and syntactic elements have been exchanged across language family boundaries (cf. the "Macro-Sudan belt": Güldemann 2008), and some languages were readily exchanged for alternatives that were more advantageous in the networks at play, such as for hunter-gatherer communities.

Drivers of Movement in the Precolonial Era

Climate and Natural Resources

Scholars tend to explain the settlement of the Congo Basin by rather sedentary communities in terms of subsistence needs and the link with climatic changes. The Bantu Expansion is often cited as a prototypical example of a language/farming dispersal: farmers practicing slash-and-burn agriculture and slowly advancing while clearing new land (Phillipson 2002). The drier period approximately 2500 years ago is believed to have accelerated the process. Openings in the rainforest, especially the Sangha River corridor, would have attracted Bantu speech communities and led them to the savannahs south of the rainforest from where they spread further south and east (Maley and Willis 2010; Bostoen et al. 2015; Grollemund et al. 2015). The adoption of plantains and iron has been considered to have facilitated farming in the rainforest (Vansina 1990). In recent years, the assumption that the earliest Bantu speakers were farmers has been regularly challenged (Bostoen and Koni Muluwa 2017; Bostoen 2018). However, new insights into the antiquity of pearl millet cultivation in the Congo Basin may reaffirm the importance of agriculture for early Bantu speakers (Neumann et al. 2022). Less is known about the link between the expansion of the Ubangi and Central Sudanic communities and natural resources.

After their initial expansions and settlement of specific parts of the Congo Basin, precolonial communities remained mobile as a function of natural resources. Hunter-gatherer communities are known to have preferred a mobile lifestyle, but horticultural communities also relocated, especially to open new fields for cultivation, in search of drinking water supplies, or to avoid conflict. Apart from villages, people also seasonally occupied camps for fishing or hunting as horticulturalists, thus complementing their produce with wild meat or fish.

Human occupation had a profound impact on the composition of the rainforest (Morin-Rivat et al. 2016; Garcin et al. 2018; see ▶ Chap. 4, "The Evolution of Congo Basin Ecosystem Diversity," for more details). Former village areas leave a mark on the vegetation, from creating short-lived, sun-loving mono-dominant forests in former agricultural fields (which over time transition to shade-tolerant forests)

to leaving distinct species assemblages related to cultural practices in former village centers (Yasuoka 2013). Large expanses of former agricultural fields, now abandoned, have become the primary sources of Okoumé trees, a key forestry export (Engone Obiang et al. 2014), thus demonstrating the large extent to which previous settlement has impacted forest composition (Walters et al. 2025).

Precolonial Politics

In the precolonial era, the Congo Basin was mostly home to smaller political entities. In the precolonial matrilineal belt of Gabon, small villages of approximately 100 people tended to form around matrilineal groups. These populations often relocated village sites within their territories. Some villages are principally located along rivers such as those along the Mpassa River corridor (Deschamps 1962: 61) or Ogowe (Schweitzer 1995: 38–45). In the Batéké Plateaux, numerous copses (small village forests) are a visible testimony to historic settlement and migration patterns (Guillot 1980), present in the form of former village sites throughout today's savanna. In forest areas, villages were established with regular migration, documented from the 1880s to the 1960s (Walters et al. 2025). Past village displacement was the result of villages dividing in response to limited resources, sorcery accusations (Vansina 1973), death, or the overcrowding by shade trees in the case of savanna villages. The villages customary institutions often managed extensive territories (Walters et al. 2015). These territories contained natural resources targeted by colonial governments, and so territorial governance became a crucial question during colonization.

On the edges of the Congo Basin, namely, the south and the northeast, kingdoms arose as early as the fourteenth century, for instance, the Kongo Kingdom and its neighbors Loango, Kakongo, Ngoyo, and Tio at the Atlantic Coast and savannah states such as the Lunda and Luba empires in the south, and some centuries later, the end of the eighteenth century, the Mangbetu Kingdom in the northeast of present-day DRC. With the centralization of power, capital cities emerged, e.g., the Lunda capital Musumb (see Mwangal Mpalang'a-Maruv 2023). With the advent of intercontinental trade around 1500 and the slave trade, larger, commercial settlements grew, for example, at the Loango Coast and along the Congo River (Vansina 1990).

Economic Activities

When European merchants arrived at the African coast at the end of the fifteenth century, they found existing long-distance trade routes. Linguistic and botanical evidence together suggest that the Congo River Basin region has been integrated into networks of trade that extended over long distances, even reaching as far as the Indian Ocean region, as is exemplified by the distribution of bananas throughout the basin (Vansina 1990). The peoples of the Atlantic coast (Mpongwè, Sèkè, Vili, etc.) became commercial intermediaries between the Europeans on the coast and the hinterland trading populations (Chamberlin 1977). From the Malebo Pool (area of

present-day Brazzaville and Kinshasa), the Bobangi took merchandise further east along the Congo River (Harms 1981). Precolonial merchandise included copper, iron, and pottery. Central African Rainforest Archaeology in copper-producing areas as early as the tenth century, e.g., the Copperbelt in the Upemba region (southern DRC) and the Niari valley (southern Congo), bear witness to economic and cultural exchanges, for example, in the form of imported ceramics (Nikis and Livingstone Smith 2017; Nikis 2018). Other trade goods probably included salt, raffia cloth, deep red powder made from camwood used for cosmetics and ritual decoration, palm oil, canoes, and food (Vansina 1990: 94). In some areas, an exchange of products between forest specialists, fishermen, and farmers was common. At the end of the nineteenth century, for instance, Lokele (fishermen on the Lomami and Congo River) and Bambole (forest specialists and farmers living in the hinterland) exchanged fish, bushmeat, and agricultural produce, salt, pottery, canoes, drums, and other items (Hunt 1999: 17, 36). Recent anthropological research demonstrates that traders walk distances of 200 km through the forest to trade at markets on the river banks (Takamura 2015). Considering the long-distance trade routes mentioned, this market system may also have a precolonial history.

Demography

Successful agricultural practices may lead to population growth. Indeed, this was the case after the arrival of sedentary communities in the Congo Basin, as is inferred from the accumulation of palm oil and pearl millet remains in archaeological sites, alongside evidence of metallurgy. Two important phases of demographic growth can be cited: the first between 2500 and 1500 BP and the second between 800 and 400 BP (Oslisly et al. 2013; de Saulieu et al. 2021; Seidensticker et al. 2021). In between the two, from 1500 to 1200 BP, a demographic crisis may have occurred, with the population again stabilizing between 1200 and 800 BP. The idea of a "hiatus" or "population collapse" is inferred from a reduction in archaeological sites and is hypothetically attributed to the outbreak of epidemic disease. This hypothesis has not yet been corroborated. Criticism suggests that the idea of a population collapse is rather due to sampling methods (Clist et al. 2021). Still, the epidemic hypothesis should not be completely overlooked since the history of medicine and health portrayed the Congo Basin in general and territories such as Gabon in particular as highly unhealthy through time (Mabika Ognandzi 2017).

Mobility in the Colonial Era

Historical Context

From the end of the fifteenth century onwards, European presence in the Congo Basin remained limited to the coast and had essentially two goals: aggregating and sending enslaved people across the Atlantic Ocean toward the New World

plantations and, in a more limited extent, to spread the Catholic faith among the elites and populations of the Kongo Kingdom. Along with these expansionist activities, European traders and missionaries began to aggregate and export resources such as ivory and ebony, sowing the avaricious extraction of natural resources to come. Colonization in the Congo Basin started in earnest around the 1880s. It had one main driver: the need to secure natural resources for the ever-expanding industries of the West, especially after the demand for enslaved people in the Atlantic world progressively came to a halt in the second half of the nineteenth century (Reid 2020). Technological improvements, such as the steamboat, the machine gun, and the use of quinine as a treatment against malaria, allowed Europeans to move around, map, and eventually take over regions that previously remained out of their reach.

The colonial era (c.1880–c.1960) brought new power structures, modes of governance, and economic practices in the Congo Basin, which heavily impacted human mobility, activities, and spatial dissemination. Colonialism, both as an ideology and as tangible practices of rule, trade, and extraction, has three main characteristics. First, it is a form of racist violence, where rights and duties are unevenly distributed according to the alleged "race" and "ethnicity" of individuals and communities. "Colonizers" saw themselves as biologically and culturally superior to the "colonized" and believed they were endowed with the legitimacy to preside over the political and economic future of the "overseas" territories they aspired to control. Second, the colonial economy was by essence extractive and bent on fostering scalability, that is, simplifying and standardizing modes of production. The main goals of colonial economies were to extract primary resources (oil, minerals, logs), to produce cash crops (palm oil and kernels, cocoa, cotton, …) as efficiently as possible, and to secure export markets for metropolitan companies. Third, colonial systems resorted to protean forms of violence to reach their goals. They segregated spaces and social hierarchies and routinely resorted to violence and intimidation, to forced labor, and to ensure that the "colonized" would not overstep the subaltern positions to which they were confined.

Although these main characteristics run through the entire colonial time, the end of World War II marked a significant change in the policies and practices in the Congo Basin. Until 1945, violence remained essential to mobilize the African workforce on infrastructure projects, plantations, and rubber harvesting, the enforcement of schemes of population displacement, the assessment and collection of taxes, and the incorporation of local communities in colonial biomedical schemes, such as vaccination campaigns. Colonial governance, wage labor, and Western "hygiene" were considered an integral part of the "civilizing mission," allegedly undertaken by Europeans in the field, no matter how much constraint their implementation required. In the postwar era, *a.k.a.* the "second colonial occupation" (Ukelina 2017), colonial actors devoted more means and attention to initiatives contributing to "development" and "native welfare." This period, marked in both French and Belgian colonies by the implementation of ambitious ten-year plans, led to increased urbanization, industrialization, and access to the wage economy by new segments of the Central African population (Cooper 2019).

Colonial Politics and Land Occupation

In the advent of colonization, Europeans established relations and signed treaties with local dignitaries to secure property and sovereignty rights that could be recognized by their imperial competitors. In the future French Equatorial Africa (AEF), some of the first acts of colonial territorialization are the numerous treaties signed between agents of the French government and customary authorities between 1787 and 1899 in present-day Cameroon, Equatorial Guinea, Central African Republic and Tchad, Gabon, and the Republic of the Congo (Maurin et al. 2016). Numerous exploratory missions were conducted to map lands, identify customary authorities, and document resources for exploitation (e.g. Guiral 1889) and later to create concessions (Coquery-Vidrovitch 1972). In the territories of the future Congo Free State (1885–1908) and Belgian Congo (1908–1960), several "geographic associations" set up by King Leopold II of the Belgians signed treaties with local authorities settled on the banks of the Congo River and its tributaries. These treaties, devolving either sovereignty or property rights to Europeans, would serve as the legal foundation for the allocation of a significant portion of the Congo Basin as a personal colony to Leopold II during the Berlin Conference of 1884–1885 (Henriet 2015).

Following these "agreements," colonization became the driving force behind population movements in the Congo Basin in the nineteenth and twentieth centuries. In the AEF, the colonial policy of *regroupement* forced villages to "regroup" in larger settlements near roads to ensure health and education, as well as to create a controllable workforce for the colonial state and its concessions (Legault and Cochrane 2021). *Regroupement* resulted in villages being involuntarily displaced, sometimes over long distances, and was often heavily resisted by local populations (Sautter 1966). During this time, voluntary movement of villages by communities largely stopped, and the colonial *regroupement* policy tended to fix them in their present-day location. Many hunter-gatherer groups also abandoned their mobile lifestyle and settled along roads, near the settlement of farmers or forestry operations (Walters et al. 2025). Certain hunter-gatherers adopted agriculture. However, hunting and collecting food often remained the main subsistence strategy, cultivated foods being mostly obtained through exchange (Joiris and Bahuchet 1993).

The application of *regroupement* policy was highly uneven in space and time. In Gabon, the policy was enacted from 1910 to the 1970s; in the 1950s, 4111 villages were reduced to 770. *Regroupement* policy resulted in large areas of forest and savanna that appeared to be "uninhabited" and which seemed clear for the establishment of colonial concessions for the extraction of natural resources and later for the creation of national parks (Cinnamon 2003; Walters and Wardell 2024). *Regroupement* and the rural exodus also contributed to the emptying of the countryside in Congo of its youth (Vansina 1973), estranging people from their traditional lands and weakening their natural resource governance. The policy and the associated change from customary to colonial rule are remembered by local people for causing intervillage disputes, misunderstandings with colonial administrators, imprisonment, revolts, and bloodshed (Metegue-N'Nah 1981).

In colonial Congo, from 1885 onwards, legal dispositions sanctuarized so-called "native lands"—which comprised recognized villages and their immediate vicinity.

In principle, it was impossible for the colonial administration or for private companies to forcibly displace these settlements and their inhabitants in zones where their workforce could effectively be mobilized and better monitored, such as in and around mines, plantations, or agglomerations. However, in practice, public servants deployed in the field effectively used the pretext of sanitary emergencies to actively displace hard-to-reach populations to spots where they could be easily reached by private recruiters and tax collectors. If a zone was classified as infested by the tsetse fly, villages were forcibly removed to stop the spread of sleeping sickness. In several instances, these laws were effectively used to aggregate populations closer to the enclaves and nodes deemed strategic by colonial actors (Henriet 2021).

Colonial Economic Activities

Colonial economies in the Congo Basin were characterized by infrastructural scarcity and extractive priorities. Furthermore, the presence of colonial actors in the field, public or private, has always been limited (Ndaywel 2021). Neither the Belgian Congo nor the AEF were ever meant to become a settler colony. Instead, they were designed as hubs of mineral extraction and cash crop production based on forced labor. They were intended to be economically self-sufficient, so as not to financially burden their respective metropoles. This created a fragmented spatial order, driving coerced economic migration as local populations left their villages to work in precarious conditions in forestry and mining sites.

During colonization, many of the local people were thus called upon to serve the colonial economy in strategic enclaves. Therefore, taking up a job in the colonial economic system generally meant (constrained) economic migration, leaving one's village or region to work in forestry or mining sites in precarious conditions and far from one's family (Rich 2007).

In the Congo Basin, the concessionary model dominated the first phase of colonial capitalism, until World War II (Vellut 1982).[5] From the early 1910s onwards, many companies involved in both extractive and plantation activities implemented paternalistic policies, which included the formal education, religious conversion, medical supervision, housing, and food provision of their indigenous workers and their families. This practice entailed many shortcomings and did not automatically generate an improvement in the general well-being of the labor force. Life in labor camps was often unsanitary, recruits remained regularly constrained to work, epidemic outbreaks were frequent, and food rations were often insufficient (Seibert 2011).

After World War II, the ten-year plans led to an expansion of the GNP of 7 percent per year between 1950 and 1957, although colonial actors failed to achieve their wider objectives in terms of welfare and economic efficiency (Vanthemsche 1994). The combination of private paternalism and increased investment in infrastructure

[5] Concessionary model: The state delegates sovereign prerogatives to a private actor in exchange for the exclusive right on natural resources produced and/or extracted from extensive territories.

stimulated the ongoing urbanization of the Congo Basin. Already in the 1950s, rural exodus was one of the main anxieties for colonial actors, who feared the lack of control they could exert on urban dwellers.

Demography

Colonization triggered a massive demographic crisis in the Congo Basin. It was visible from the late nineteenth century onwards and remained a key driver of imperial biopolitics until the ultimate demise of the Belgian Congo and the AEF. Its causes were multiple yet intimately linked.

First and foremost, the early colonial expansion generated massive population displacements. Inhabitants of the Congo Basin were forcibly mobilized in the accumulation of primary resources that could turn the private colony of King Leopold II into a profitable venture. Hunting elephants and collecting wild rubber—Congo Free State's (CFS) main sources of income—required entire communities to remain on the move or to settle in unsanitary regions, where sleeping sickness was prevalent. New clearings and settlements also transformed existing ecosystems and supported the spread of species that carried deadly illnesses, e.g., the tsetse fly or mosquitoes (Spinage 2012). Furthermore, communities also attempted to escape the grasp of colonial agents and relocated to more remote regions, with limited access to food resources, where they were more vulnerable to illnesses and prone to falling short of foodstuffs. These collective stresses, combined with the introduction of new diseases such as smallpox, influenza, and venereal disease, were linked to a surge in mortality and a dramatic fall in fertility rates (Ndaywel 2021).

The spread of diseases during the colonial era resulted in empty areas on population density maps as entire villages disappeared, which were then claimed by forest (Sautter 1966: 969). Multiple outbreaks of diseases and famine occurred in colonial Gabon from 1910 to the 1930s. During this period, European traders appropriated local trade networks while also aiding the spread of disease (Chamberlin 1977: 6–7; Hymas et al. 2021), bringing people in remote areas into contact with novel coastal diseases (Hartwig and Patterson 1978, pp. 9–10; Headrick 1990, p. 42). Colonial administrators described seeing bodies and skeletons along well-established trade routes (Sautter 1966, pp. 860–861; Coquery-Vidrobitch 1985, pp. 54–56; Gray 2002, p. 158). The best known of the outbreaks was the 1918 Influenza pandemic, when it is estimated that half the population died (Patterson 1975, 1981; Debusman 1993; Rich 2007). The road building, carried out through *regroupement* policy, exacerbated the spread of various diseases, as did bringing porters and workers from greater distances. In some cases, areas were completely depopulated, becoming a "dead zone" which people feared was cursed (Choubert 1954, p. 37; Gray 2002; Hymas 2015). Such areas could remain uninhabited for decades, during which the forest returns, and new settlement later occurs, creating a cycle of disease/depopulation/forest regeneration (Hymas et al. 2021).

Furthermore, dehumanization at the heart of colonial processes also took an important toll on the populations of the CFS. Enquiries performed in 1904–1905 readily confirmed multiple large-scale exactions purported by soldiers, mercenaries,

and representatives of the state and of private companies (Burroughs 2018). They include rape, incarceration, fustigation, amputations, and shooting on sight. However, historians and demographers agree that no genocide effectively took place in the CFS, as it was, for instance, the case in German West Africa in the same period. This consensus is based on the postulate that all definitions of genocide entail the intent to eliminate a specific group and to implement specific strategies of annihilation to achieve this goal. Officials of the Congo Free State and representatives of private companies did not have the intent to massively dispose of the population or to eradicate specific communities. They effectively needed the local labor force to make the colony profitable (Verbeeck 2024). Nevertheless, the massive exactions perpetrated in the CFS are no less abhorrent. They were crimes against humanity, whose extent, scope, and systematic character provoked a widespread public outrage in the Global North, even though most people largely accepted and shared the racist ideology that supported colonial imperialism.

After World War I, colonial actors endeavored to tackle this ongoing demographic crisis. Some administrative reports from the 1930s even alarmingly delve into a potential, impending "wipeout" of the colony's human population (Sanderson 2018). Christian missions, private companies, and public servants thus massively invested in the development of biopolitical strategies aimed at improving birth rates and curbing death rates. It led to the emergence of sub-Saharan Africa's largest network of nurseries, dispensaries, and hospitals (Hunt 1988). Significant efforts were made in monitoring and medicalizing childbirth, but also in containing epidemics of sleeping sickness, malaria, and leprosy, among many others. European actors developed massive screening and treatment campaigns, whose preventive and compulsory nature also entailed a fair amount of violence and constraint (Webel 2019). After World War II, the "Second Colonial Occupation" generated significant investments in infrastructure, housing, and urbanization, which stimulated the ongoing Central African demographic growth.

Recent Changes

From the 1960s to the present, Central Africa has undergone profound political, social, and economic transformations marked by independence struggles, authoritarian consolidation, violent conflicts, migration waves, rapid urbanization, and shifting livelihoods. Migration and urbanization continue to reshape societies, while ecological pressures, conservation policies, and climate change intensify challenges for local communities.

The early 1960s saw the independence of Cameroon, the Republic of the Congo, the DRC, the CAR, and Gabon, followed by Equatorial Guinea, which gained independence from Spain in 1968. Initial optimism was quickly replaced by turbulence, with coups, civil wars, and the Congo Crisis. Economic mismanagement and reliance on structural adjustment programs, combined with oil shocks and copper price collapse, fueled economic decline. A system of patronage and state privatization enriched elites but impoverished the majority, reducing ordinary people to survival strategies.

Repression, economic decay, and lack of opportunities pushed many people from the Congo Basin to envisage and look for a future elsewhere. During the different waves of conflict in the late 1990s and early 2000s, (the 1994 Rwanda genocide, Kabila's coup d'état in Kinshasa, wars in Congo-Brazzaville and the CAR), people migrated in large numbers with their families and remained abroad for long periods. Diasporas in neighboring countries became a springboard for a journey to further horizons, both in Africa and elsewhere. But these diasporas in neighboring countries can also serve as a short-time away, and many people end up returning to their country of origin, repatriating voluntarily, after spending some years away (Wilson 2019). Moreover, while the diasporas increase during conflict times, they do not disappear when the situation calms down. Many end up playing an important economic role in terms of commerce and remittances for those who stay behind in the country of origin, such as the CAR diaspora in Douala, Cameroon, or the Congolese diaspora in Luanda, Angola, and Dar es Salaam, Tanzania.

Despite hardening borders, Europe and North America remain an important pole of attraction. In the 1990s, the ancient metropoles, in particular Paris and Brussels, received many immigrants from the Congo, Cameroon, and, to a lesser extent, CAR (MacGaffey and Bazenguissa-Ganga 2000; Alpes 2016). Latin America has become, in the last decade, a new route to the North, yet many do not make it and get stuck along the way (Echeverri Zuluaga and Acevedo Sáenz 2018). Even if almost negligible in numbers, programs of resettlement also feed into the diasporas of the Global North.

Since the 1980s, subsistence-driven mobility has led to more conflict in the northern and northeastern DRC. Mbororo pastoralists from the CAR, Chad, and Sudan seek pasture and drinking water for their cattle. Some link their recent incursions into the DRC to climate change and drought in the Sahel (Nagabhatla et al. 2021). The tensions between the immigrant pastoralists and local farmers over land use frequently result in violent conflict.

Current Status

The Congo Basin is one of the most ecologically diverse and resource-rich regions globally (Trefon 2016). However, the region also faces significant human challenges, including demographic pressures, shifting age structures, gender dynamics, marginalized populations, and the growing issue of refugees. Analyzing the human occupation of the Congo Basin is challenging, as the area is rarely treated as a whole. Examining sub-Saharan Africa's demographic trends provides insights into the Congo Basin's situation. Understanding this demographic landscape is key to addressing sustainable development, conservation, and governance issues.

Demographics and Population Trends

Sub-Saharan Africa is undergoing a demographic transition characterized by a decrease in mortality, particularly infant mortality, and a slower decline in fertility.

This transition is slower than in other regions, leading to rapid population growth and a very young population (May and Guengant 2020; UNDSA 2021). The Congo Basin mirrors this demographic momentum: its young age structure will ensure continued population increase for several decades despite declining fertility (May and Guengant 2020).

This demographic dynamic is further shaped by natural increase and migration, with varying trends across the six countries (Tabutin and Schoumaker 2020). The combined population of these countries exceeds 140 million. The DRC, the most populous country in the region, counts nearly 100 million inhabitants, with one of the highest population growth rates globally (about 3.2% annually). This rapid growth is largely driven by high fertility (around six children per woman) and declining child mortality, resulting in a predominantly youthful population. Cameroon, with 28 million people, faces demographic challenges driven by rapid urbanization, particularly in cities like Yaoundé and Douala, where growing populations are putting increasing pressure on essential services such as water supply, sanitation, healthcare, and education. Despite rapid urban growth, Cameroon faces substantial rural population pressures. The Republic of the Congo (approximately 5 million) and Gabon (about 2.5 million) are also growing, though at slower rates. Gabon's growth is linked to immigration and oil industry development, while the Republic of the Congo's growth is mostly rural (United Nations 2024).

Gabon is the most urbanized country in the region, but population densities vary greatly within the other countries, with urban areas like Kinshasa, Brazzaville, and Yaoundé hosting millions, while vast interior areas are sparsely populated. In rural areas, subsistence farming remains the dominant livelihood, limiting population mobility and economic development (Trefon 2016; May and Guengant 2020; Tabutin and Schoumaker 2020). Consequently, the region is marked by a contrast between rapid urbanization and rural depopulation due to economic challenges, limited infrastructure, and insecurity, particularly in the DRC and the CAR (Trefon 2016).

Age Structure

Like the rest of sub-Saharan Africa, the Congo Basin has a predominantly young population, with a high proportion under the age of 30. This youthfulness results from high fertility rates and relatively low life expectancies, especially in rural areas (May and Guengant 2020; Tabutin and Schoumaker 2020). In the DRC and Cameroon, more than 60% of the population is under 25, while Gabon and the Republic of the Congo show slightly lower youth proportions. However, the region faces increasing life expectancies, which, coupled with higher birth rates, result in growing infrastructure needs to cater to both young and aging populations (UNDESA 2012; United Nations 2024).

In the DRC, nearly half of the population is under 15, creating challenges in education and healthcare, while offering opportunities because it is a dynamic workforce that can drive economic development (World Population Prospects 2024). This demographic also results in high dependency ratios, where a large portion of the population relies on

working-age adults (Tabutin and Schoumaker 2020). Sub-Saharan Africa has the potential to benefit from a "demographic dividend" if the working-age population increases relative to dependents (May and Guengant 2020). However, for the region to reap the full benefits of this demographic dividend, fertility must decline, and investments in health, education, and employment are essential. Without these measures, rapid population growth may worsen poverty and inequality (Canning et al. 2015; May and Guengant 2020). In Gabon, for example, there are currently an estimated 200,000 public and private sector jobs but 800,000 people in full-time education. This is a potentially explosive recipe over the coming decade. The Congo Basin, particularly the DRC, faces significant challenges in poverty reduction, governance, and healthcare, which could hinder its ability to benefit from the demographic dividend.

Gender Dynamics and Marginalized Groups

As elsewhere in sub-Saharan Africa, gender relations in the Congo Basin are influenced by traditional, cultural, and modern factors. While gender dynamics are shifting in urban centers, where more women are accessing education and engaging in small-scale trade and entrepreneurship, in rural areas, women face challenges in accessing education, healthcare, and economic opportunities (UN Women 2024). In this environment, gender roles are traditionally focused on agriculture, household tasks, and caregiving. However, NGOs and government programs are working to increase women's participation in decision-making, especially in conservation and development (UN Women 2024).

Gender-based violence, particularly sexual violence, is a significant issue, especially in the DRC, which has one of the highest rates globally, often linked to ongoing conflict, political instability, and entrenched gender inequalities (Kelly et al. 2024). While international and some national efforts are addressing this challenge to developing women's equality and opportunity, progress remains slow.

Besides these gender dynamics, several marginalized groups in the Congo Basin face economic, social, and political exclusion. These include ethnic minorities and people living in remote or conflict-affected areas. Hunter-gatherer groups are marginalized both economically and politically. Their rights to land, culture, and traditional knowledge are often overlooked, and they face discrimination, especially in accessing healthcare, education, and legal protections (Minority Rights Group International 2004; Quattrini 2019).

Refugees and Displacement

As mentioned above, the Congo Basin is heavily impacted by conflict-driven displacement. Political instability, armed conflict, and environmental challenges have led to large numbers of refugees and internally displaced people in all directions (Flahaux and De Haas 2016; UNHCR 2022; Van Praag et al. 2022). The DRC has dealt with internal displacement for decades, particularly due to the ongoing

conflict in the eastern part of the country. Currently, around 5.5 million people are displaced within the DRC, and over 500,000 refugees have fled to neighboring countries, like Uganda and Rwanda (UNHCR 2022). Similarly, the CAR has experienced political instability and armed conflict, leading to significant displacement, with over 600,000 people displaced internally, and many seeking refuge in neighboring countries (UNHCR 2022).

Refugees from the Congo Basin often face difficult conditions in host countries, where access to resources and services is limited. The refugee crisis exacerbates socioeconomic pressures in already-strained countries like Uganda and Cameroon, which host large numbers of displaced persons (UNHCR 2022). Addressing the refugee crisis in the Congo Basin requires not just humanitarian support but also long-term solutions focused on peacebuilding, economic integration, and infrastructure development.

Looking to the Future?

The Congo Basin faces complex demographic, social, and political challenges, deeply intertwined with its environmental and economic conditions. High population growth, a youthful demographic, gender disparities, marginalized groups, and refugee flux necessitate inclusive development strategies. To ensure long-term social cohesion and sustainable development, comprehensive policies must address demographic shifts while focusing on empowering marginalized groups, achieving gender equality, and integrating displaced populations. As May and Guengant (2020) highlight, the long-term stability and development of sub-Saharan Africa in general, and the Congo Basin in particular, will depend on balancing population growth with expanding employment opportunities and investing in education, healthcare, and infrastructure, while ensuring the inclusion of all groups in the development process.

Impact of Colonial and Recent Changes in Mobility on Cultural Identity, Loss of Language, Customary Governance Systems, and Biodiversity

Considering that mobility and contact between different communities are an inherent element of the history of the Congo Basin, cultural elements such as crafts, rites, and languages have been in constant flux. Today, there is increased awareness of the loss of cultural elements. UNESCO dedicated the decade 2022–2032 to the "preservation, revitalization and support of indigenous languages worldwide."[6] Language shift occurs at a high pace today. Minority languages are exchanged for majority languages, mostly official, national, and/or vehicular languages, or sometimes simply a larger language (e.g., case of Bokala: Lofemba Boningoli Batita 2018). This is not only an

[6] https://www.unesco.org/en/decades/indigenous-languages

urban phenomenon, but ease of contact with urban centers surely has an impact. The rich linguistic diversity can be preserved for future generations in the form of recordings. In the Congo Basin, language documentation is urgent: The number of endangered languages is much higher than the official counts by UNESCO or on the Ethnologue website, and too many of the languages concerned have never been studied (see Ricquier et al. 2022).

There are similar issues for other cultural elements. While contact caused past cultural changes, the current availability of cheap imported commodities accelerates the abandonment of specific crafts. Pottery is a craft currently under pressure and in some places has totally disappeared because of the availability of plastic containers and aluminum pots; traditional palm oil soap is replaced by imports, hunting nets by wire snares and shotguns, fishing nets made of local fibers by nylon nets, etc.

The preservation of traditional knowledge is also important in view of wildlife conservation efforts and even climatic challenges. In a collective volume, Gabonese scholars show that biodiversity preservation is not a new idea for local people in Gabon and the wider Congo Basin. Indeed, traditional knowledge has always been key to the preservation of nature in its diversity. The real issue has been the formulation and transmission of such culturally rooted knowledge (Mouguiama Daouda and Moussirou-Mouyama 2023).

Colonization resulted in many cases in the loss of community lands and the associated governance of natural resources, including lineage-based systems that once governed large parts of the savannas (Vansina 1966). Such losses reduced the power of customary authorities to govern hunting, fire use, and other activities (Walters et al. 2015). Furthermore, the current movement of populations impacts the social fabric and traditional economic systems, resulting in loss of economic autonomy and impoverishment (Ratanga-Atoz 1985: 70–80). The sociocultural transformations that have taken place are proving to be more destructive of the identity of the peoples of the Congo Basin than elsewhere in Africa (Naipul 2010).

It must be observed that the lifestyle of Congo Basin communities, already altered by forced settlement, is currently further endangered by intensive logging operations. Some trees rich in fruit and bark are felled, others knocked down by bulldozers, traps set for game are crushed, nets dragged away, and the animals take refuge deeper and deeper in the forest. The same is true for water, as construction and logging machinery turn streams into ponds, dry them up, or pollute them. There are also cultural consequences, such as the desecration of sacred areas, but some communities also resist logging incursions with varying success (Evine-Binet 2023; Ibola dja bana ba Massaha et al. in press). Wildlife reservations further restrict the access of these communities to forest resources. On the other hand, bushmeat demand from cities is very high, and hunter-gatherer communities gain cash by engaging in this commerce. Unfortunately, this leads to the impoverishment of biodiversity and eventually affects their own hunting activities.

Urbanization, finally, tends to have negative impacts on biodiversity (Gutu Sakketa 2023) and is predicted to have increasing negative impacts in Africa and worldwide (Ayeni et al. 2023). Protected areas, as a result of urbanization, may decrease in size, as is the case for a protected area near Libreville, Gabon, which, despite the area

decreasing, permitted multiple usages for urban populations while also conserving endangered species (Walters et al. 2016). One of the main drivers of the reduction of protected areas near cities is industrial-scale resource extraction and development (Mascia et al. 2014), often linked to the presence or development of urban areas. For these impacts to be better understood, urban ecology requires further development from a Global South perspective (Shackleton et al. 2021), which, currently, in Africa is largely dominated by studies in South Africa (Awoyemi and Ibáñez-Álamo 2023).

With the inevitable and unending cascades of changes across centuries and throughout the region, communities of the Congo River Basin continue to rely on deep traditions of innovation and resilience. Forest communities continually and actively adapt to new contexts, technologies, and opportunities of the twenty-first century, as they have in centuries past. It is imperative that we work to understand their lived realities today, and work alongside forest communities to ensure the sustainability of people, families, and communities—as well as the forest itself.

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Critical Interconnections Between Cultural and Biological Diversity in the Congo Basin

9

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Abstract

In this chapter, we explore the interconnections between biological and cultural diversity in the Congo Basin. This chapter focuses on the worldviews, human-nature relationships, knowledge systems, livelihood strategies, and governance regimes of people living and working in the basin: farmers, pastoralists, fishermen, and hunter-gatherers, documented from a range of disciplinary perspectives. The peoples of the Congo Basin can be broadly grouped into hunter-gatherer groups of "Pygmy" ancestry, farmers of Bantu origin, and pastoralists of Nilotic origin. Worldviews and human-nature relationships differ considerably between and within these three groups, with hunter-gatherers' worldviews being more egalitarian and emphasizing unconditional sharing, which the other groups do not do. The languages spoken in the Congo Basin, which are over 400, convey detailed vocabulary and traditional ecological knowledge (TEK) systems, intricately linked to different habitats, biodiversity, and their uses and management. In many parts of the Congo Basin, though, changing social aspirations and traditions have meant that younger generations acquire less traditional ecological knowledge than older generations possessed. Traditional farming, fishing, hunting, and gathering practices are changing, driven by increased market demand for some products and globalization. These occur alongside changes in techniques used, the erosion of

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traditional governance systems, and weakened enforcement of customary rules, which have led to biodiversity loss, negatively impacting the food security, health, and livelihoods of the peoples depending on them. A diversity of governance arrangements and policies regulates access not only to land and natural resources, but also markets, differing in their socio-ecological impacts. In general, though, local communities have little power and agency in most arrangements, making recognizing their needs, voice, rights, and well-being imperative.

Keywords

Cultural diversity · Congo Basin · Hunter-gatherers · Bantu farmers · Indigenous and local knowledge (ILK) · Local cosmologies and epistemologies · Livelihoods · Governance of natural resources

Introduction

There are approximately 157 million people living in the six countries of the Congo Basin: 111.5 million in the DRC, 29.5 million in Cameroon, 6.5 million in the Republic of the Congo, 5.5 million in the Central African Republic, 2.5 million in Gabon, and 1.5 million in Equatorial Guinea.[1] Among these 157 million people, there is a huge cultural diversity. If we consider language as an indicator of cultural diversity, there are 273 living indigenous languages in Cameroon, 208 in the DRC, 66 in the CAR, 55 in Congo, 40 in Gabon, and 12 in Equatorial Guinea.[2] Broadly, the people speaking all these languages can be clustered into Bantu sedentary farmers (the majority), Fulani pastoralists of Nilotic origin, and "Pygmy" hunter-gatherers. In the Congo Basin, "indigenous peoples" (or "peuples autochtones" in French) mostly refer to hunter-gatherer groups, which are estimated to be 1 million (Olivero et al. 2016). These groups were historically categorized by Western explorers and scientists under the term "Pygmies" which derives from ancient Greek and refers to their short stature (Bahuchet 1993a). Actually, the term assembles several ethnic groups who speak different languages (e.g., Baka, Bayaka, Bezan, Efe, Batwa, Bambuti) and have different cultural and morphological characteristics (Verdu 2016) (Fig. 1). Formerly, most "Pygmy" ethnic groups were nomadic hunter-gatherers living in the forest, who exchanged wild meat and other wild products for crops and other goods with the neighboring Bantu farmer communities (Bahuchet and Guillaume 1979). In the past three to five decades, however, several "Pygmy" ethnic groups have become increasingly sedentarized and involved in farming—with important implications for their diets, health, cultures, and general well-being (Dounias and Froment 2006). As the word "Pygmy" is sometimes used derogatorily—to indicate "backwardness" or being less than human—by

[1] https://www.worldometers.info/

[2] https://www.ethnologue.com

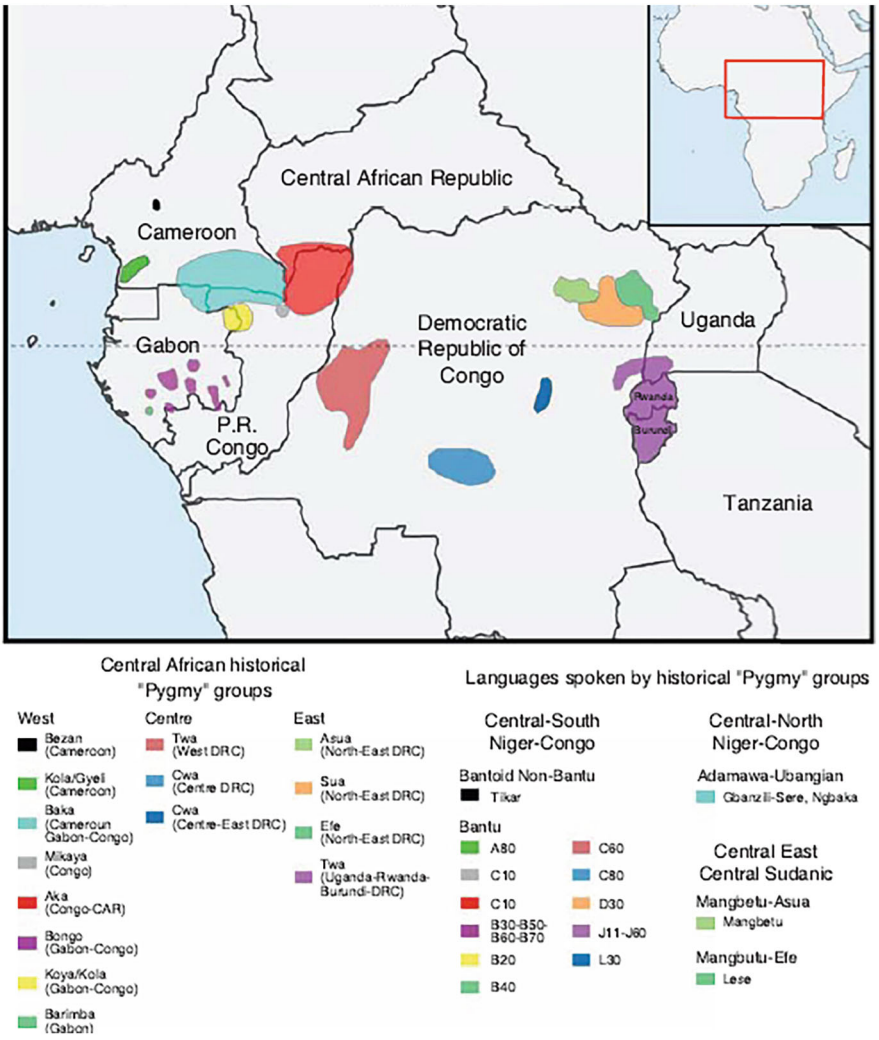

Fig. 1 Geographical location of historical "Pygmy" groups and their languages. (Source: Verdu 2016)

non-Pygmies, in this chapter, we will use "hunter-gatherer" to refer to all these ethnic groups of "Pygmy ancestry."

The downside of grouping them under a common term is that it hides the differences that exist between these groups (Bahuchet 2017). Depending on the region and local history, there are major differences within these groups in terms of mobility, social organization, and subsistence. Today, however, most hunter-gatherer populations in the Congo Basin depend on agriculture for their livelihoods, either through their own production or through day labor in the fields of their farming

neighbors in return for cassava tubers. It is the case for the Bakoya of Gabon, who have been sedentarized since the 1930s, and the Baka of Cameroon from the 1950s (Soengas 2009; Leclerc 2012). These latter also increasingly take up cash crop cultivation like cocoa, although it is at odds with their way of life and value system (Oishi 2012). Farming and living in bigger settlements involve more individualism compared to their collective and egalitarian approach to living (Soengas 2009). Differences also exist among different hunter-gatherer groups of any one region. In the Ituri forest of eastern DRC, for example, while Mbuti have been trading wild meat with nearby Bantu farmer communities since the 1950s, up to the early 2000s, the Efe rarely traded wild meat with nearby farmer communities (Terashima and Ichikawa 2003).

Several pastoralist groups can also be found in the Congo Basin, including the Fulani people (also called Fula or Fulbe) in Cameroon or the Banyamulenge in the DRC. Historically, the Fulani did not own land but had rights to graze their animals on the communal lands of their "host" farming communities (Mbih et al. 2018). Over the past few decades, though, the Fulani have also become increasingly sedentarized, and many have started farming (Ayodele et al. 2014). Compared to their "host" farmer communities, they tend to have no identity attachment to forests and do not perform ceremonies in them (Cuni-Sanchez et al. 2019a). The Banyamulenge, of the Fizi region of eastern DRC, are a Tutsi group speaking a variety of Kinyarwanda (Verweijen and Brabant 2017). Since the 1980s, this pastoralist group has also become increasingly sedentarized and has increased its farming activities (Katunga and Muhigwa 2014). Pastoralist groups, like Bantu farmer groups, are generally not considered "indigenous peoples" in the Congo Basin region.

Contrary to the Amazon, indigenous lands and territories have not been legally recognized in the Congo Basin countries; therefore, no "hunter-gatherer" group owns the forest where they live. There are, however, moves by COMIFAC to recognize indigenous peoples (Eba'a Atyi et al. 2022). Several groups were evicted from their ancestral lands in the name of forest conservation when national parks were created, e.g., the Twa of Kahuzi-Biega National Park in the DRC (Barume 2000). Nowadays, legal access to their ancestral lands varies between countries and regions, but overall, more remains to be done to ensure the recognition of their rights in social and environmental policies.

Cosmologies, Worldviews, and Knowledge Systems

In the Congo Basin, hunter-gatherers and farmers show both differences and similarities in terms of ways of living, cosmologies, and knowledge, all being intimately related to each other (Bahuchet and Guillaume 1979; Joiris 2003). First, differences in worldviews become evident when looking at the relation with the landscape. Farmers lay claims over areas of forest, villages, and water bodies; these claims are supported by an ideology of ownership of land, whereby traditional rights are generally passed down from father to son (Pemunta 2017). Contrary to this, hunter-gatherers' understanding of land is centered on a philosophy of guardianship

and care: The forest does not belong to anyone in particular, but it is rather considered as a caring and giving mother, providing equally for all her children.

In Baka and Bayaka cosmologies, Komba created the forest for everyone to share in its abundance. This origin has repercussions on subsistence practices and resource management. In immediate-return societies, resources are acquired when needed and not accumulated (associated with hunting, fishing, and gathering activities), whereas in delayed-return societies, investment is put into future harvest (associated with agriculture; Woodburn 1982). These approaches support specific worldviews and social structures. The former, held largely by hunter-gatherers, rejects private ownership, maximizing the sharing rather than exchange of resources and avoiding accumulation as the way to achieve abundance and holistic joy—for both forest and people (Lewis 2019; Hoyte and Mangombe 2024). This sharing ethos supports egalitarian social structures and resists the emergence of inequalities in terms of age, gender, and status. The latter approach, held primarily by farming groups, places more emphasis on ownership rights and on the accumulation and exchange of resources, leading to more hierarchical social systems and fewer reciprocal relations with the forest (MacGaffey 1983). However, some farmer groups also have strong cultural connections with the forests they inhabit and perform different ceremonies in such forests to maintain "the order" in their everyday lives, such as the Oku people of Cameroon (Cuni-Sanchez et al. 2019a) or the Kuti, Kusu, and Ngengele of the DRC (Batumike et al. 2021). In some cases, these ceremonies and cultural attachment to the forest by these farmer communities have contributed to the conservation of such forests (e.g., Mt. Oku in Cameroon).

Traditional rules and taboos often guide the behaviors of both hunter-gatherer and farmer groups (Rupp 2011). These are often encoded in storytelling, which is an integral part of the culture of many Congo Basin groups. Tales most often reflect on the other-than-human world—the sun, moon, plants, and animals, through stories that give them the status of persons (Brisson 2010). Among both farmer (e.g., Fang, Bateké) and hunter-gatherer groups (e.g., Baka, Bayaka), these stories bear an important moral component, linked to sharing and social cohesion and allowing for the transmission of a wealth of ecological knowledge, cultural values, and oral history (Ondo 2013). The vast zoological and botanical knowledge across the Congo Basin is therefore inherently socio-ecological and cannot be divorced from the unique cultures from which it arose.

Many farmers and hunter-gatherer groups hold that the forest is inhabited by spirits. Far from being separate from humans, these spirits interact closely with their human counterparts, through divine healers (generally known as "ngangas"), but also in dreams and encounters during forest walks. Ancestral spirits, for example, are widely considered to inhabit forests; known for their invisibility and shape-shifting abilities, they continue interacting with the living, sharing knowledge and influencing the luck of their descendants (Ma 2021; Vittoria 2024; Hoyte 2024). Many groups, like the Baka and Bayaka hunter-gatherers, also recognize another class of spirits: forest beings that are socialized in the human sphere through singing, dancing, and play. Interacting with the invisible is intimately tied to health and well-being. These groups tie individual and collective health to ceremonies with

forest spirits; farming groups, such as the Mpangu of the DRC, may directly address ancestral spirits to ensure protection and healing (Kitewo 1998).

Health and well-being are also often associated with the notion of balance in food and social life, supported by a respect for a certain number of prohibitions (dietary or behavioral; Motte-Florac et al. 1996). Nonobservance of avoidances, as well as attacks by malevolent spirits and sorcerers, might be considered as causes for certain illnesses, leading people to turn to traditional pharmacopoeia, with which they feel confident. Across the whole basin, an astounding array of medicinal knowledge is evident, not only for healing physical illnesses but also psychological troubles, restoring luck, and providing extraordinary abilities (Pathy et al. 2021; Gallois et al. 2024).

Languages and Biocultural Conservation

The Congo Basin is known to be a biolinguistic hotspot, like the Amazon Basin and Indo-Malaysia/Micronesia (Maffi 2001; Loh and Harmon 2005, 2014). Although the number of languages spoken in this region might seem high (over 400), this is all that remains of a much larger number of languages, after centuries of European colonization, formal schooling in French, globalization, mobility, and other driving forces (Bromham et al. 2022).

Nowadays, all hunter-gatherer groups of the Congo Basin speak languages adopted—in a more or less recent past—from neighboring farmer groups—so they lack a common language or language family (Bahuchet 2012). In contrast, words for naming tools used in gathering are less frequently exchanged and may result from adaptation to different ecological contexts. However, among western hunter-gatherer groups, there is a common lexicon for terms such as wild yam, honey, hunting, or elephant, which supports both the existence in the past of a common ancestry language and the important role of forest knowledge for their cultural identity (Bahuchet 1993b). Local languages may convey traditional ecological knowledge intricately linked to biodiversity, the habitat where it can be found, and its uses. Ethnoecological studies among several groups have revealed a detailed vocabulary on habitats, plants, and animals, but also on ecological interactions among them. For example, Mbuti and Efe hunter-gatherers in the Ituri Forest of eastern DRC use over 300 (Efe) and 350 (Mbuti) plant species for food, medicine, and material culture (tools, baskets, dye, etc.) (Terashima and Ichikawa 2003). Notably, differences in plant use can be found between villages of the same ethnic group, with only about 30% shared use of species (Terashima and Ichikawa 2003). Hunter-gatherer groups also use numerous plant species for hunting and fishing. The Baka of southeastern Cameroon report uses of 176 plant species in various hunting and fishing practices, most frequently as hunting luck, psychoactive stimulus for improving the dog's scent and capacity for hunting, materials for traps, and remedies for attracting animals and for making the hunter courageous (Fongnzossie et al. 2023). The Baka also show great knowledge of wildlife: They have at least ten terms for specific types of gorillas, depending on sex, age, and companionship status, and most of the knowledge is consistent with modern primatologists' findings (Oishi 2013).

While ethnobotanical knowledge of hunter-gatherers has been widely acknowledged, remarkable knowledge on plant uses has also been documented for Bantu-speaking farmers. For example, the Lega farmers of eastern DRC reported 287 plant species as useful, including 178 species for medicine, 38 for food, 139 for material culture, and 29 for ritual and magic (Terashima et al. 1991). The Nyindu farmers (living near the Lega) use 412 plant species, including 227 species for medicine, 45 for food, 196 for material culture, and 46 for ritual and magic (Yamada 1999). Some Bantu farmers also hold great ethnoecological knowledge about fish. For example, the Bakwelé of southeastern Cameroon collect 97 species of fishes and have elaborated a great variety of fishing techniques that mediatize their extensive knowledge regarding fish ecology, diet, and behavior, in relation to diversified aquatic microhabitats (Oishi 2016). The fishing techniques they use include bail fishing, poison fishing (using, e.g., *Millettia sanagana* or *Turraeanthus africanus*), net fishing, barrier fishing, traps, hook and lines, longline fishing, and harpoon. Among these fishes, 46 species are subject to taboos and consumption restrictions, and some fish species also have medicinal uses (Oishi 2016).

As reported in other regions of Africa, though, knowledge of plant use among younger generations is decreasing: for example, among the Bayaka hunter-gatherers of northern Congo who are born in towns instead of forest camps (Salali et al. 2020). Intra-regional rural migration is also increasing, as people follow economic opportunities (e.g., logging, mining, or cash crops), which affects the acquisition of traditional ecological knowledge by both long-term residents and immigrant communities. Near Mt. Cameroon, long-term residents have a much wider breadth and depth of knowledge of plant species in comparison to migrant households (Laird et al. 2011). Recent work in the Lac Télé Community Reserve and Ndoubale-Ndoki (Republic of the Congo) and Okapi Reserve (DRC) has also shown that recent migrants are less likely to engage in forest-harvest-based livelihoods and harvest several types of forest foods (L'Roe et al. 2023). Each language represents an irreplaceable cultural heritage of specialized knowledge, management systems, and worldviews that are preserved and transmitted by its linguistic categories and structures, so the consequences of language loss are severe not just for sociocultural entities but also for ecological ones.

Biocultural Diversity, Lands, and Livelihoods

Agriculture and Agroforestry

Traditional agricultural systems of the Congo Basin are generally based on slash-and-burn practices and contain a mix of cultivated and managed food, medicinal, and ritual species. Useful wild tree species are often saved during land clearing for farming, and sometimes, seedlings of such useful trees are transplanted from forests to enrich farms. Cassava or manioc (*Manihot esculenta*) is the primary staple crop for most contemporary communities in the region, although plantain (*Musa* spp.)

and maize (*Zea mays*) are also often cultivated together. Because of the trees left or planted during land clearing, some of these farms can be considered agroforestry systems, especially those where oil palm, cacao (*Theobroma cacao*), coffee (*Coffea canephora* var. *robusta*), or the semidomesticated bush mango (*Irvingia gabonensis*), the African plum (*Dacryodes edulis*), and kola nuts (*Cola* spp.) are abundant (Sonwa et al. 2007; Lescuyer et al. 2024, Chap. 10).

Due to increasing populations and land scarcity, fallow periods in slash-and-burn farming systems are being reduced, as well as the number of trees on farms, which negatively affects soil fertility and crop yields. In most of the Congo Basin, agriculture is not mechanized, and no animals are used to plough or provide compost to enrich the land—although mechanization is increasing in flat regions of, e.g., southern Cameroon. Currently, most small-scale cash crop plantations operate under land tenure insecurity, meaning they are cultivated on land that farmers customarily "own," but to which they have no legal title. New initiatives to secure land tenure, such as legalizing customary tenure and "household agroforests," could be further encouraged, as well as new forms of social forestry designed to protect land used for shifting cultivation and cash crop production (Vermeulen and Julve 2022).

For many Bantu farmer groups, a "nice farm" or a "nice cocoa plantation" is source of pride and their heritage, related to wealth and prestige, and it is an asset to pass to descendants (e.g., for the Bakossi in Cameroon, Cuni-Sanchez et al. 2025). Several Bantu communities place a high value on the microclimate regulation forests provide, as they "bring good rains for our crops" (e.g., Oku in Cameroon, Tembo and Shi in the DRC, Cuni-Sanchez et al. 2019a, b). They also acknowledge the importance of forests and fallows for soil formation and control of soil erosion and, therefore, good crop yields.

The Congo Basin is a center of genetic diversity for crops such as palm oil (*Elaeis guineensis*), the Robusta coffee variety (*Coffea canephora* var. *robusta*, first discovered in the late nineteenth century in the DRC), and some yam species, although the two most cultivated yam species—the white Guinea yam (*Dioscorea rotundata*) and the yellow yam (*D. cayenensis*)—originated in West Africa. With regard to wild yams (*Dioscorea* spp.), these remain primordial sources of carbohydrates for many hunter-gatherer groups in the region. Wild yams also play a key role in their symbolic perception of the forest. The Baka of southern Cameroon accurately distinguish and name the 14 wild yam taxa found in their area, which they classify distinctively into edible from inedible species (Fig. 2, Dounias 2011). The Baka practice "paracultivation" of some of these wild yam species, by not just "unplanned" dispersal of *Dioscorea* spp. tubers discarded during cooking, but also their para-cultivation by reburying tuber parts with the intention of promoting their regeneration (Dounias 2011). Conscious and unconscious dispersal of oil palm (*Elaeis guineensis*) seeds by both farmers and hunter-gatherer groups is also thought to have influenced the distribution and abundance of this species in the wild. Such examples show how local communities of the Congo Basin have been modifying forest ecosystems, not just negatively (deforestation, degradation) but also positively, co-creating them (sensu services to ecosystems, Comberti et al. 2015).

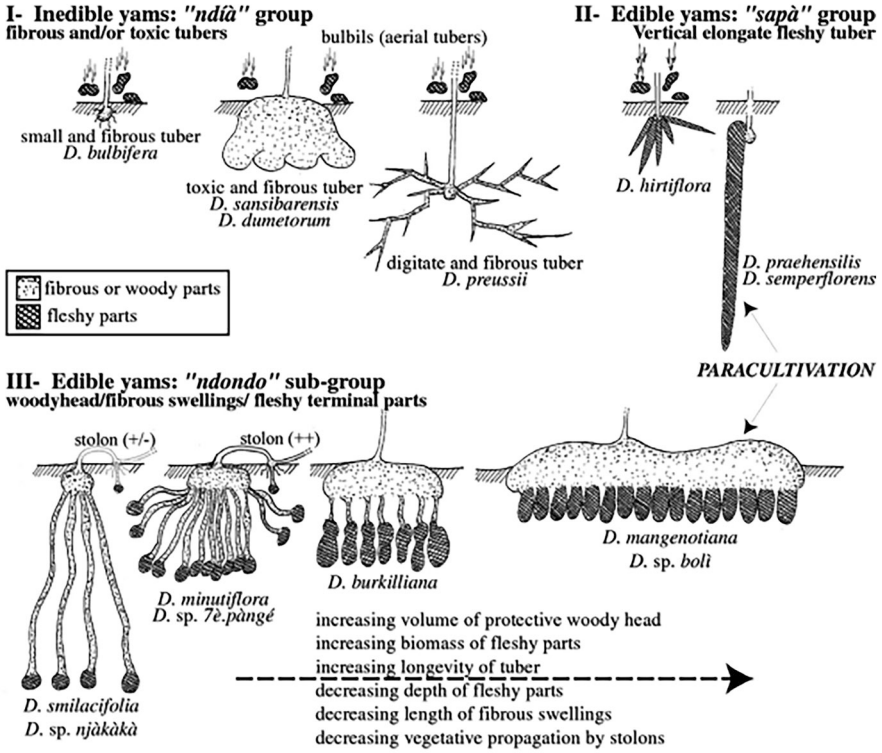

Fig. 6. Tuber morphology.

Fig. 2 Wild yams (*Dioscorea* spp.) species identified by the Baka hunter-gatherers of southeastern Cameroon. (Source: Dounias 2011)

Hunting

For many rural communities in the Congo Basin, wild meat (commonly referred to as bushmeat) is the primary source of protein (Fa et al. 2003). Often the sole provider of essential nutrients such as iron and fat (Siren and Machoa 2008; Golden et al. 2011), it plays a critical role in food and nutrition security, directly influencing health and well-being (Fa et al. 2003). Beyond its nutritional value, wild meat consumption also contributes to psychological well-being. Periods of "meat hunger," where access to wild meat is limited, can lead to psychological distress, manifesting as anxiety, fatigue, or even depression (Pagezy 1982; Garine and Pagezy 1990). In southeastern Cameroon, distinct ethnic groups have unique terms to describe this condition: "kbokaku" among the Bangando (Kimura et al. 2012), "zoo" among the Bakwelé (Oishi 2014), and "pene" among the Baka and Bayaka hunter-gatherers (Bahuchet 1992; Brisson 2010).

Wild meat also holds profound cultural and social significance, shaping personal and relational well-being. Hunting skills and experience symbolize prestige, while spiritual and cultural connections to wildlife influence traditions and beliefs. Additionally, social norms surrounding the sharing of wild meat reinforce communal ties both in rural and urban contexts (Van Vliet and Mbazza 2011; Dounias and Ichikawa 2017; Duda et al. 2018). Cultural drivers play an important role in the increasing demand for wild meat in urban areas, as it is perceived by urban people and elites as a sign of prestige and as more tasty, healthy, and nutritious compared to domesticated animals (Van Vliet and Mbazza 2011).

Historically, hunting techniques vary widely among ethnic groups, even within the same region (Fa et al. 2021). In the Ituri Forest of eastern DRC, the Mbuti hunter-gatherers primarily use nets, though they occasionally employ bows for arboreal monkeys and spears for large animals like bush pigs. In contrast, Efe hunter-gatherers rely solely on bows and spears, never using nets (Terashima and Ichikawa 2003). Similarly, Pouvi farmers in central Gabon favor bows with poison arrows, while the nearby Bateké farmers rely on fire and extensive netting (Walters et al. 2015). Traditional hunting is often governed by strict cosmologies, rituals, and taboos, with certain species protected due to spiritual beliefs. For example, the Baka of southeastern Cameroon avoid hunting gorillas, believing them to be reincarnated people. In contrast, Bakwelé farmers refrain from hunting the yellow-backed duiker (*Cephalophus silvicultor*), considering them reincarnated Baka (Oishi 2013).

Enforcement of these rules remains deeply embedded in spiritual beliefs, with sorcery believed to cause illness, bad luck, or even death to violators. Direct punishments, including slavery or death, may also be imposed by the owners of hunting territories (Walters et al. 2015). These traditional practices and specific hunting techniques continue to contribute to sustainable wildlife management in some communities. In urban areas of the Congo Basin, wild meat consumption persists for various reasons, including affordability, taste preference, and social status. Among wealthier urban dwellers, consuming wild meat is often seen as a symbol of prestige and a way to maintain a symbolic connection to the forest (Van Vliet et al. 2015; Ichikawa et al. 2016). However, increasing urban demand, combined with a shift toward more efficient hunting methods such as metallic cable traps and shotgun hunting (e.g., among the Baka in Cameroon, Duda et al. 2018), has fueled unsustainable harvest rates. The erosion of traditional governance systems and weakened enforcement of customary hunting rules (Walters et al. 2015) have further exacerbated this trend, leading to what is now referred to as the "bushmeat crisis" (Nasi et al. 2008; Ichikawa et al. 2016).

This crisis extends beyond biodiversity loss, threatening the food security and livelihoods of those who depend on wild meat for survival (Fa et al. 2015; Duda et al. 2018). Addressing these challenges requires a balanced approach, considering conservation and local communities' food and income needs, ensuring that wild meat remains a viable and sustainable resource for future generations.

Fisheries and Aquatic Management

Freshwater fish is also an important source of protein, micronutrients, and income for many rural and urban households across the Congo Basin. While some fishing methods are passive, opportunistic, and can be carried out by one person, many others require active collective management of habitats and deep knowledge of hydrological patterns and of fish behavior (Comptour et al. 2016). Examples of habitat management to attract fish include constructing artificial floating prairies and shelters, dams or fish weirs, or digging ponds to trap fish in the dry season (Dounias 2011; Toko et al. 2007; Comptour et al. 2016).

Historically, fishing techniques also varied widely among ethnic groups and locations. In the DRC, for example, the Songola of the Lualaba River used 22 different fishing methods, while the Bwari of northern Lake Tanganyika used 17 different ones (Ankei 1989). Considering collective fishing methods only, the Ntombe of Lake Tumba (also in the DRC) practiced nine different types of these, including some specific to flooded forests, small rivers, larger rivers, lakes, and backwaters of the main river (Pagezy 2006). The Bomitamba of the Lac Télé Community Reserve in the Republic of the Congo still use a wide range of fishing methods, including "kokopa" (the manual drainage of ponds to capture fish historically performed using large raffia baskets held by several men), "mbilo" fishing (the strategic removal of vegetation during the dry season to facilitate the redirection of fish into designated catchment zones during rainy season), "okala" (traps targeting fish, snakes, and crocodiles), "motresse" (large nets), "ndobo" (individual hook-and-line fishing), and "eyika" baskets to trap small-sized fish along shallow banks and small ponds (only used by women) (Beekmann et al. in prep).

Fishing is not just a material practice, it is often rooted in a complex social, symbolic, and ritual construction. In many fishermen societies, waters are inhabited by supernatural forces such as water spirits, and fishermen must deal with these. Water spirits, often human-like, but also shaped like crocodile (*Crocodylus niloticus*) or large snakes, can be good and generous, providing food, good health, and protection to the human beings living around their waters, but they can also be bad and bring misfortune and take pleasure in killing people (Comptour et al. 2016; Pagezy 2006). Traditional fishing is often governed by norms, rituals, and taboos, with certain species being protected due to spiritual beliefs. Taboo fish species may never be consumed among a segment of the population (e.g., pregnant females) or by all people, and some are used as medicine or in rituals (Ankei 1989). Enforcement of these traditional rules remains deeply embedded in spiritual beliefs, with sorcery believed to cause illness, bad luck, or even death to violators (Comptour et al. 2016; Pagezy 2006). In general, though, there has been a decrease in the practice of collective fishing strategies, driven by increased attractiveness of individual fishing methods with faster and greater economic returns on investment, difficulty of mobilizing lineage members to do collective tasks in sometimes remote locations, pond deterioration, and even fear of engaging with water spirits (Comptour et al. 2016; Pagezy 2006).

As for wild meat, increasing market demand, combined with a shift toward more efficient fishing methods such as small mesh gear (including mosquito nets), has

fueled unsustainable harvest rates. The annual economic losses of increased use of small mesh gear (and related harvesting of juvenile individuals) have been estimated at USD 2.1 million for the Lake Tanganyika sardine *Limnothrissa miodon* alone (Mulimbwa et al. 2018). Although historical data on inland fish stocks is limited, it seems that there is an increasing widespread overexploitation of fish resources. A severe decline (65–85%) in multispecies catch and a homogenization (due to some species becoming rare) have been reported by local fishermen in the Kadey River (Cameroon) and the Congo River (DRC) (Castello et al. 2023). Apart from increased use of small mesh gear and poison, destruction of littoral fish habitats by sand and gravel mining, and climatic changes (declining water levels), water pollution related to artisanal mining is also known to reduce fish abundance and diversity in rivers (e.g., in South Kivu province in the DRC, Wasso et al. 2025). The erosion of traditional governance systems and weakened enforcement of customary fishing rules have most likely further exacerbated overfishing and habitat destruction.

Timber and Firewood

Timber, firewood, and charcoal are also important resources for many communities across the Congo Basin, both for household consumption and as a source of cash income. Wood fuel remains the main source of energy for cooking for households, particularly in rural areas. However, this is changing in some urban areas where gas and electricity are available (Schure et al. 2012). Local preferences for timber species vary among ethnic groups, even among those living within the same area. In Mt. Oku in Cameroon, differences in species used for construction between farmers and Fulani pastoralists are driven by the type of houses they build, with the former preferring hard-wood species and the latter *Raphia* spp. (palms) fronds, as these are easier to bend when constructing Fulani's small huts and fences for their animals. For the Fulani, their cattle hold such high cultural value that they do not separate human and livestock plant use (Cuni-Sanchez et al. 2019a). In general, greater cultural differences for timber species than firewood species have been reported (Lhoest et al. 2020; Cuni-Sanchez et al. 2019b). Preferences for wood fuel species are associated with factors such as species distribution, local knowledge, and resource availability. For example, in urban areas with large populations, such as Kinshasa, a wide variety of species, including fruit trees, are used to meet demand from the hinterland supplying the metropolis (Schure et al. 2011). Wood fuel collection and trade are generally highly gendered, with women and children mainly responsible for collection and retail and men largely involved in charcoal production and wholesale (Ingram et al. 2014).

Several timber species with international commercial value have cultural importance for local communities. Examples include *Erythrophleum suaveolens* in parts of the DRC or *Milicia excelsa* in parts of Cameroon (de Meyer 2023). Sometimes the cultural importance of the species is so high that it prevents the species from being logged (e.g., *Dacryodes edulis*, whose fruits are edible and widely traded, Blaser et al. 2021, see below). However, this is not often the case, and instead, the high

timber value overrides other uses, negatively affecting local communities' access to wild foods, medicines, or income opportunities (Blaser et al. 2021). An example of where conflicts occur between multipurpose trees, timber, food, medicinal use, and income is *Baillonella toxisperma* (moabi), prized for its timber as well as its kernel oil.

Non-wood Forest Products

Non-wood forest products are extremely important for many rural communities in the Congo Basin and increasingly important for consumers of these products in urban areas and as income sources for the many, largely unquantified numbers of people engaged in their value chains. They contribute to food security, nutrition, and health and can be an important source of cash income. Some are traded to major urban centers within and among countries, and some are exported regionally and even globally. While most species are harvested from the wild, some species have been semidomesticated by some ethnic groups, including bush mango (*Irvingia gabonensis*), the African plum or "safou" (*Dacryodes edulis*), and kola nuts (*Cola* spp.) (Leakey et al. 2004; Adebola and Morakinyo 2006).

The bush mango produces mango-like fruits, which can be eaten fresh like mangos. However, this species is mostly appreciated for its oil-rich kernels, which are roasted, pounded, and used in several traditional dishes across Central Africa. Pounded paste or cake from bush mango kernels can be stored for over 1 year without spoiling (Gallois et al. 2020). The annual harvest of bush mango nuts in Cameroon is estimated at 4000–6000 t, valued at over 8 million USD, part of which is traded to Nigeria, Gabon, and even the USA and Europe (Ingram and Schure 2010; Ingram et al. 2017). Locally, the kernels of related species are also consumed and traded: While three other *Irvingia* species are used by the Bayaka of the CAR, four more *Irvingia* species and two related genera are also used by the Baka of Cameroon (Bahuchet 1978; Gallois et al. 2020, Fig. 3). Bush mango is also the product that hunter-gatherers exchange the most with nearby farmer groups and is a marker of seasonal calendars (Gallois et al. 2020). It is so important that it is considered a "cultural" keystone species.

The African plum or Safou (*Dacryodes edulis*) produces a fatty, butter-like tasting fruit, which is eaten fresh, boiled, or roasted. In Cameroon, the annual trade of 11,000 tons of Safou is worth over USD 7.5 million annually, and over 100 tons are exported to Europe (Tabuna 1999; Awono et al. 2002). Some of its sister species are also widely consumed and traded in some parts of the Congo Basin: ozigo (*D. buettneri*) in Makoukou in Gabon (Yobo et al. 2020) or *D. osika* in Kisangani in the DRC (Termote et al. 2012).

Caffeine-rich kola nuts (*Cola nitida, C. acuminata*) when chewed dispel sleep, thirst, hunger, and fatigue and are very popular among hunters on long hunting trips and drivers, laborers, and students cramming for exams, as well as among Muslims in the drier regions of West Africa during the Ramadan (Adebola and Morakinyo 2006). The seeds are pounded to make energetic drinks, and in many ethnic groups,

Fig. 3 Biocultural interactions by Baka hunter-gatherers expressed through knowledge and use of bush mangoes (Irvingia spp., including at least *I. gabonensis*, *I. excelsa*, *I. wombulu*, *I. robur*). (Source: Gallois et al. 2020)

they are offered to guests as a symbol of hospitality. Bitter kola (*Garcinia kola*) seeds, used as a stimulant, aphrodisiac, and digestive aid, are also culturally important for some ethnic groups, which use them as gifts to receive visitors, and in traditional weddings and ritual naming (Adebisi 2004). The annual production of *G. kola* nuts in Cameroon is estimated at 50 tons or about USD 660,000 (Awono et al. 2016; Maňourová et al. 2019). In this country, while ethnic groups from the savanna zone mainly harvest its nuts, ethnic groups from the forest zone mainly collect bark and roots, and the uses differ between farmers (Fang and Bassa) and hunter-gatherers (Baka) (Yogom et al. 2020).

Beyond wild fruits and nuts, wild leafy vegetables, wild species, medicinal plants, mushrooms, and edible caterpillars are also of key economic importance. The bark of the African Cherry (*Prunus africana*)—which has multiple medicinal uses, including treating benign prostatic hypertrophy—has a long history of international trade. Over 3000 tones were exported annually from Cameroon alone in the past, with a retail value of over USD 18 million (Cunningham et al. 2016). The leaves of *Gnetum africanum*, a vine consumed as a vegetable, are also widely traded in the Congo Basin, with over 2500 people working in the value chain in Cameroon and Nigeria (Ingram et al. 2012).

Many of these highly valued non-wood forest products providing species have multiple uses, and some also have timber value. In Gabon, a 2009 Forestry Decree

banned the logging of five of such species (bush mango or *Irvingia gabonensis*, ozigo or *Dacryodes buettneri*, *Poga olesosa*, *Tieghemella africana*, and moabi or *Baillonella toxisperma*), to ensure local communities' access to such resources in logging concessions (Iponga et al. 2018). Some authors, though, argue that other important species with high timber value should have been included, such as the Gabon hazelnut (*Coula edulis*). The importance of considering the impacts of logging caterpillar-hosting species such as sapelli (*Entandrophragma cylindricum*) and tali (*Erythrophleum ivorense*) has also been highlighted (Muvatsi et al. 2018). Indeed, for the Bayaka hunter-gatherers, harvesting caterpillars is so important that it has its own season called "*Kongo*" in their annual seasonal calendars, even for sedentarized groups (Boyette et al. 2022).

The increasing demand for both timber and non-wood forest products, like bush mango kernels, in urban centers in and outside Africa, leads to unsustainable gathering methods, such as felling trees laden with ripe fruit (Ingram et al. 2017). As for hunting and fishing, market demand, low levels of law enforcement, and a lack of other income generating alternatives may drive local communities to overexploit their non-timber forest resources, while simultaneously impoverishing their diets and negatively affecting their livelihoods (Ingram et al. 2017; Gallois et al. 2020).

Governance and Policymaking

Reflecting the ecological and cultural diversity of these ecosystems, there is a diversity of governance arrangements and policies that regulate access not only to land and natural resources, but also the markets for products and services. Laws and regulations govern many of the ecosystems and their most well-known products (such as timber), on paper, but the capacity, ability, and willingness of governments to implement and enforce laws on resource exploitation have been shown to be often ineffective. This is particularly the case for non-timber products, charcoal, and wild meat and recently created ecosystem service markets such as carbon and intellectual property (Brandt 2014; Piabuo et al. 2021; Schure et al. 2015; Mavah et al. 2022). Unevenly applied and top-down, unilaterally international agreements such as FLEGT (Tegegne et al. 2022; Trefon, 2017; Nago and Ongolo 2021) and the EU Deforestation Regulation (McDermott et al. 2024) have also been difficult to apply in the Congo Basin.

In many rural areas of the Congo Basin, traditional (or customary) authorities still have significant influence over land tenure and govern access to ecosystem products, for example, by who, when, and where specific resources can be harvested (Ingram 2017; Majambu et al. 2019). Cultural norms such as taboos and prohibitions also play a major role in limiting access, although these are changing, especially for resources which have high economic values (such as wild meat) and near urban markets (Tegegne et al. 2022; Ingram 2017; Assembe-Mvondo 2009). In the past decades, new institutions have been created to govern particular ecosystems or resources, led by project-related civil society organizations and enterprises. These increasingly take on roles traditionally reserved for governments. Projects and

programs have created short- and longer-term rules, standards, and practices governing landscapes, resources, and products (Ingram 2017). They are generally conceived and implemented by nongovernment organizations and donor organizations, sometimes in partnership with the private sector, and often alongside market-based institutions using value chain approaches such as Forest Stewardship Council and Rainforest Alliance certification (Cerutti et al. 2017; Ingram 2017) and payments for ecosystem services, such as REDD+ and carbon credits (Reyniers 2021; Molua 2023). Project and market-based governance arrangements generally create multiple, layered, plural governance arrangements that intersect with statutory forest, agriculture, land use, and trade regulations, with both positive and negative social, economic, and ecological impacts.

Corruption is persistent and prevalent and forms a parallel, shadow arrangement alongside statutory laws and market-based arrangements in the timber (Gan et al. 2016; Assembe-Mvondo and Kan 2022; Trefon 2010; Piabuo et al. 2021), non-timber, and charcoal value chains (Tieghouong et al. 2015; Ingram 2017; Schure et al. 2015). It should be noted that often actors with little voice in formal governance arrangements (such as communities, informal, and small businesses) create their own messy, "bricolaged" governance arrangements, such as for timber and charcoal (Ingram 2017; Schure et al. 2015; Karsenty 2019). Governance based on "exclusiveness" (i.e., where other actors are excluded from accessing resources and markets—such as in kola nut and *Raffia* spp. value chains) can lead to sustainable forest value chains and livelihoods in the long term (Ingram 2017) but exclusivity is often perceived as contrary to development rhetorics about inclusion (Mavah et al. 2022; Ingram 2015).

The different governance arrangements and combinations affect the livelihoods of those involved in the market value chains, from harvesters to consumers, as well as the ecosystems where products are harvested and their sustainability, in different ways, both positively and negatively (Ingram 2017; Cerutti et al., 2017). Governing ecosystems—increasingly seen from an economic perspective and termed "bioeconomy"—is also challenged by actor fragmentation, limited organization among value chain actors, and the absence or overlap of responsibilities, policies, and institutions.

Conclusions and Recommendations

The many interconnections between cultural and biological diversity, with ethnic groups' and individuals' worldviews and identities being strongly bound to land and natural resources, indicate that the legal recognition of their rights to access and govern land and resources and their voice in social and environmental policies is essential. Despite the legal frameworks outlined in ▶ Chap. 33, "Spatial Dimensions of Existing Conservation Areas and Other Land Uses in the Congo Basin," more statutory acknowledgement of customary rights to land and resources could be transformative in promoting local governance—particularly for specific ethnic groups, whose traditions, views, and practices, such as nomadism and forest dwelling, are not considered in current legal frameworks.

The strong links between language and biodiversity are important but threatened by the erosion of traditional knowledge and use of languages, suggesting that policies and practices documenting and promoting the use of local languages to allow their associated rich meanings regarding biodiversity to be more widely understood are needed.

The multifaceted ways that biodiversity diversity supports agriculture, agroforestry, fishing, hunting, timber, and non-wood product–based livelihoods indicate that documenting, preserving, disseminating, and celebrating these links are critical, alongside stronger good governance through statutory, customary, and voluntary market-based arrangements. As ethnic groups and languages traverse administrative borders, as do trade and knowledge flows, regional policies are recommended, particularly when they are well embedded and effectively implemented nationally.

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The Ecological Functions of Congo Basin Ecosystems and Basin-Wide Carbon Cycle

10

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Abstract

The Congo Basin, spanning over 3.7 million km^2 across Central Africa, plays a critical role in regulating global climate, sustaining biodiversity, and supporting regional livelihoods. We explore the ecological functions of the Congo Basin ecosystems, emphasizing their role in the carbon cycle. We synthesize current knowledge on biogeochemical processes, carbon stocks, species interactions, and biodiversity patterns, while highlighting key data gaps and research needs. The region's forests, soils, wetlands, and aquatic systems together form one of the world's most significant carbon sinks, with unique characteristics, including high megafaunal density, extensive peatlands, and relatively low deforestation rates, shaping its contributions to carbon sequestration and climate regulation. We detail carbon cycle dynamics across lowland, montane, flooded, and savanna ecosystems and underscore the vast belowground carbon storage in

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the Cuvette Centrale peatlands. Patterns of alpha and beta tree species diversity affect ecosystem function and resilience, with plant functional traits playing a key role in nutrient cycling and productivity. Species such as forest elephants influence forest structure and carbon storage through seed dispersal and disturbance. Moreover, strong land-atmosphere feedbacks mean that evapotranspiration from the Congo Basin's tropical forests plays a key role in shaping regional rainfall patterns. Land use and climate change pose growing threats to these functions, potentially triggering regime shifts and biodiversity loss. Ultimately, the Congo Basin remains underrepresented in ecological research and monitoring despite its global importance. Enhanced field-based and remote sensing efforts are urgently needed to inform integrated conservation and climate change mitigation strategies that account for both carbon dynamics and biodiversity.

Keywords

Central Africa · Peatlands · Evapotranspiration · Biodiversity · Land use change · Nutrient cycling

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Introduction

The Congo Basin plays a critical role in global climate regulation; biodiversity conservation; climate change mitigation via carbon sequestration in trees, mineral soils, and peatlands; regional water cycling; local energy production (e.g., hydropower); and staple and cash crops and medicine provisioning. Spanning over 3.7 million km^2 across six countries in Central Africa, Congo Basin ecosystems, illustrated broadly in Fig. 1, act as a major carbon sink, absorbing vast amounts of atmospheric carbon dioxide and mitigating climate change. The region's extensive river network, including the Congo River, supports hydrological cycles and land-atmosphere interactions that influence local, regional, and global climate systems. The Congo Basin is also home to an extraordinary array of flora and fauna, including endemic and endangered species such as forest elephants (*Loxodonta cyclotis*), bonobos (*Pan paniscus*), and okapis (*Okapia johnstoni*), making it one of the most biodiverse regions on Earth. Interactions between the Congo Basin's forests, biodiversity, and biogeochemical and hydrological cycles yield emergent ecosystem functions that underpin many services on which people depend. The Congo Basin provides resources directly to over 75 million people in local communities, including Baka, Bayaka, Bagyele, and Bantu communities, who rely on Congo Basin forests and rivers for food, medicine, and cultural practices. Billions of people worldwide depend on the

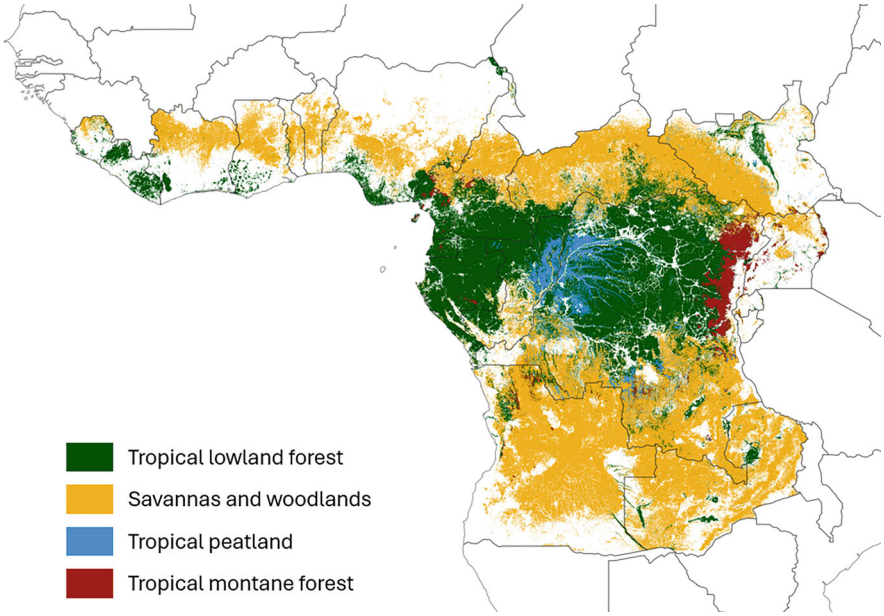

Fig. 1 Map of ecosystem types across the Congo Basin. Map created based on a reclassification of land cover CCI maps by ESA. Tropical moist forest below 800 masl was considered tropical lowland forest, while tropical moist forest above 800 masl was considered tropical montane forest (consistent with Cuni-Sanchez et al. 2021)

region's multifold services indirectly. Understanding the many interconnected functions of the Congo Basin ecosystem—its carbon sequestration, water regulation, biodiversity support, and socioeconomic contributions—is essential for developing strategies that ensure its stability and resilience for future generations. In this chapter, we focus on these interactions through the lens of the Congo Basin carbon cycle.

Congo Basin Ecosystem Functions

Interconnections Between Forests, the Atmosphere, Soil, Freshwater, and Biogeochemical Cycles in the Congo Basin

Congo Basin ecosystem functions, including carbon cycling, result from complex interactions between soils, vegetation and wildlife, the atmosphere, and the cycling of water and nutrients. While these dynamics play out in all tropical forest regions, several unique aspects of the Congo Basin contribute to the region's ecosystem functions (Atyi 2022; Malhi et al. 2013; White et al. 2013; White 2021). Compared to other tropical forest regions, the Congo Basin has a higher average elevation, lower annual precipitation, a sweeping range of mixed deciduous-evergreen vegetation, and historically lower rates of land cover change (Parmentier et al. 2007; Ernst et al. 2013). In addition, the abundance of megafauna in Africa is suggested to be one of the major drivers of intercontinental differences in forest structure between the Congo Basin and the Amazon (Blake et al. 2009).

Terrestrial Biogeochemical Fluxes

The African continent contributes to about 70% of global burned area and about half of global fire carbon emissions, with most biomass burning occurring within savannah regions (Chen et al. 2010; Ramo et al. 2021). These fires release nitrogen (N) and phosphorus (P) into the atmosphere that is subsequently transported by winds to the Congo Basin, contributing significantly to nutrient translocation within the region (Bauters et al. 2018, 2021a). In total, the Congo Basin forests receive approximately 18.2 kg N ha^{-1} yr^{-1} as wet deposition, with additional dry deposition via canopy interception (Bauters et al. 2018), while secondary forests have been shown to receive up to 3.1 ± 1.4 kg P ha^{-1} yr^{-1} from wet and dry deposition (Bauters et al. 2021a). Model simulations indicate that phosphorus deposition has significantly influenced aboveground carbon sequestration within the Congo Basin, which is more phosphorus-limited than nitrogen-limited (Du et al. 2020; Goll et al. 2023). However, land cover and land use changes also alter nutrient cycling in the region. Repeated clearing can lead to declines in plant-available N and P in the topsoil, but it mainly reduces soil cation stocks (Bauters et al. 2017, 2021b). This is due to the mobility of cations in the soil, as well as the high fraction of cations locked up in the aboveground woody biomass (Bauters et al. 2022a). Regrowing secondary forests cycle an increasing amount of N and P deposition through a more efficient dry deposition filtering

(Bauters et al. 2021a; Makelele et al. 2022). Therefore, along succession, forests in the region are potentially increasingly cation-limited (e.g., calcium) (Bauters et al. 2022b). In combination with the vulnerability of these cations in the fate of land use change, further research is needed to determine the role of cations in sustaining forest productivity in both old-growth as well as secondary forests.

Aquatic Biogeochemical Fluxes

The Congo River exports the second largest amount of terrestrial carbon to the ocean after the Amazon, mostly sourced from the region's humid lowland forests (Coynel et al. 2005; Spencer et al. 2016; Drake et al. 2023). In total, the Congo River exports 2 MtC yr^{-1} of particulate organic carbon (POC), 12 MtC yr^{-1} of dissolved organic carbon (DOC), and 4 MtC yr^{-1} of dissolved inorganic carbon (DIC), while outgassing between 133 and 177 MtC yr^{-1} of carbon to the atmosphere, although there remain large uncertainties in this particular carbon flux (Seyler et al. 2005; Coynel et al. 2005; Drake et al. 2018; Komba et al. 2024; Moustapha et al. 2022; Spencer et al. 2016; Wang et al. 2013; Aufdenkampe et al. 2011; Raymond et al. 2013). Seasonal variations in POC and DOC exports are largely hydrologically driven (Coynel et al. 2005; Drake et al. 2023; Hemingway et al. 2017). While many studies have focused on assessing sediment and carbon fluxes from the main stem of the Congo River at Kinshasa-Brazzaville (Coynel et al. 2005; Seyler et al. 2005; Wang et al. 2013; Lambert et al. 2016; Spencer et al. 2016; Hemingway et al. 2017; Kurek et al. 2022), studies investigating fluxes at smaller tributaries and sub-basins reveal contrasting within-watershed biogeochemical characteristics (Lambert et al. 2016; Borges et al. 2019; Bouillon et al. 2012, 2014; Coynel et al. 2005; Mann et al. 2014; Upstill-Goddard et al. 2017; Drake et al. 2019, 2020, 2023; Spencer et al. 2010; Baumgartner et al. 2022), largely driven by terrestrial ecosystem structure and to some extent hydrology (Mann et al. 2014). The Cuvette Centrale peatland complex additionally plays an important role in changing the composition of sediments and flow, storing large amounts of sediment from upstream while likely altering the amount of organic material from C3 vegetation passing through the Congo River headwaters (Datok 2021; Hemingway et al. 2017; Molliex et al. 2019; Laraque et al. 2009).

Climate and land use changes are impacting aquatic biogeochemical fluxes in several ways. Land use changes from deforestation are altering the sources of dissolved organic matter and concentrations of DOC, POC, and DIC (Battin et al. 2023; Drake et al. 2019, 2024), with increases in flooding frequency and duration associated with land use changes increasing carbon exports (Bradshaw et al. 2007). Carbon and nutrient balances are also affected by changing storm severity and frequency. Storm events in the region have increased in extent and intensity since the 1980s (Raghavendra et al. 2018; Alber et al. 2021) and are projected to continue on this track (Fotso-Nguemo et al. 2018), which has the potential to increase suspended sediment exports, as well as dissolved nutrients (Baumgartner et al. 2022, 2023).

Land-Atmosphere Interactions

The contribution of evapotranspiration to precipitation over land affects both local and regional climate, as evaporated moisture can travel thousands of kilometers in the atmosphere (Theeuwen et al. 2023; van der Ent and Savenije 2011). Recent studies suggest that the Congo Basin relies heavily on evapotranspiration to provide atmospheric moisture for rainfall via moisture recycling (Worden et al. 2021; Baker and Spracklen 2022; Sorí et al. 2022), while also providing moisture for areas downwind, including nearby agricultural regions that are primarily rainfed (Nyasulu et al. 2024; van der Ent et al. 2010; Te Wierik et al. 2024). Deforestation and degradation can significantly disrupt this key ecosystem process by decreasing evapotranspiration. For example, deforestation from 2003 to 2017 was observed to have an impact on moisture recycling and ultimately result in lower precipitation in the Congo Basin (Smith et al. 2023). However, these impacts have been more extensively studied in Amazonian tropical forests compared to the Congo and would benefit from further research in the region (Zemp et al. 2017; Xu et al. 2022; Staal et al. 2018, 2020; Flores et al. 2024).

Species Interactions

Animals, especially large herbivores and frugivores, can impact tree growth and forest structure via seed dispersal, forest disturbance, nutrient cycling enhancement, and other animal-mediated ecosystem processes in the Congo Basin (e.g., Malhi et al. 2022). A unique example of the region lies in the interaction between African forest elephants and large-seeded tree species. African forest elephants disperse the most intact large seeds across the longest distances (tens of kilometers) and from the highest diversity of plants (Blake et al. 2009; Poulsen et al. 2021). In addition to their seed dispersal impact, elephant trampling and herbivory decrease forest stem density, which can alter light and water availability as well as the spatial partitioning of resources, resulting in forests with fewer trees that tend to be larger-statured and higher wood density species (Berzaghi et al. 2019, 2023; Deblauwe et al. 2025). Vegetation demographic modeling suggests that forest elephant disturbances—typical around 0.5–1 elephants km^{-2}—increase AGB by 26–60 tons (t) C ha^{-1} (Berzaghi et al. 2019). However, this can simultaneously decrease forest net primary productivity (NPP) as larger and slower-growing trees dominate. Critically, the African forest elephant population is declining rapidly due to overhunting and habitat fragmentation (Blake et al. 2009; Poulsen et al. 2013; Maisels et al. 2013). Increasing the population to ~201,000 elephants over the next 30 years could create a carbon sink of 109 tC (Berzaghi et al. 2022). Much work is needed on this topic to understand the many ways that animal species interact with trees and forest ecosystems more broadly to influence the carbon cycle. For example, areas with higher gorilla abundances have been shown to correspond to forests with 27.5 tC ha^{-1} higher carbon stocks, while this relationship was not observed for chimpanzees, although the generalizability of this result and its underpinning mechanisms require improved understanding (Vale et al. 2024).

Congo Basin Carbon Stocks and Productivity

Recent work suggests that C dynamics in old-growth forests in the Congo Basin diverge from those in the more extensively studied and better characterized Amazonian tropical forests (Hubau et al. 2020). Although the mechanisms underpinning these divergent patterns have yet to be conclusively determined, there is strong evidence that the two largest tropical forests differ in forest structure (Banin et al. 2012; Lewis et al. 2013) and species composition (Slik et al. 2018). Additionally, the African tropics experience a drier average climate compared to the Amazon, with bimodal seasonality along the equator (Guan et al. 2015; Nicholson 2022), and substantially higher atmospheric nutrient deposition resulting from biomass burning on the continent (Bauters et al. 2018, 2021a).

Recent bottom-up work based on forest inventory plot data demonstrated that C uptake and emissions from African forests amount to some of the largest fluxes globally (Pan et al. 2024). Top-down findings from the Orbiting Carbon Observatory-2 model intercomparison project (OCO-2 MIP) showed net carbon sinks over the Congo Basin, which contrasted with net carbon sources over northern tropical Africa (Byrne et al. 2023). Signals of the Congo Basin's net biosphere exchange (NBE) from 2009 onwards also indicate a persistent carbon sink that contrasts with large sources of emissions in the western and eastern parts of tropical Africa (Palmer et al. 2019), although net CO_2 emissions were temporarily observed by OCO-2 (a contrast from the typical sink) over the region following the 2015/2016 El Niño, possibly owing to increased respiration resulting from heightened temperatures (Liu et al. 2017). In contrast, repeated forest census observations in the Congo Basin showed a persistent carbon sink during that same El Niño event, with no significant reduction in carbon gains from tree growth or increase in carbon losses from tree mortality (Bennett et al. 2021).

Large uncertainties remain related to the individual effects of the above drivers on the Congo Basin C sink (Ciais et al. 2011). Despite the role of tropical forests as the highest contributors to gross primary productivity, carbon sequestration, and natural methane emissions, tropical forest regions have the fewest research plots and flux towers (Baldocchi 2020; Schimel et al. 2015), and only limited efforts currently focus on the monitoring of GHG fluxes in the region. Very few comprehensive datasets exist that have reasonable spatiotemporal resolution for forest floor GHG fluxes (Barthel et al. 2022; Daelman et al. 2024). Additionally, only one flux tower exists in the entire Central African humid tropical forest biome (Sibret et al. 2022).

Below, we review what is currently known about carbon stocks and fluxes across the lowland, flooded, and montane forests, as well as savannas, woodlands, peatlands, and freshwater systems in the Congo Basin (Fig. 2).

Lowland Forests

The carbon sink in live aboveground biomass in intact African tropical forests has been stable for the past three decades. As such, intact forests in the region act as a net C sink, sequestering approximately 0.66 tC ha^{-1} $yr.^{-1}$ (Hubau et al. 2020). Forest inventory data and long-term carbon studies had previously estimated a stock change

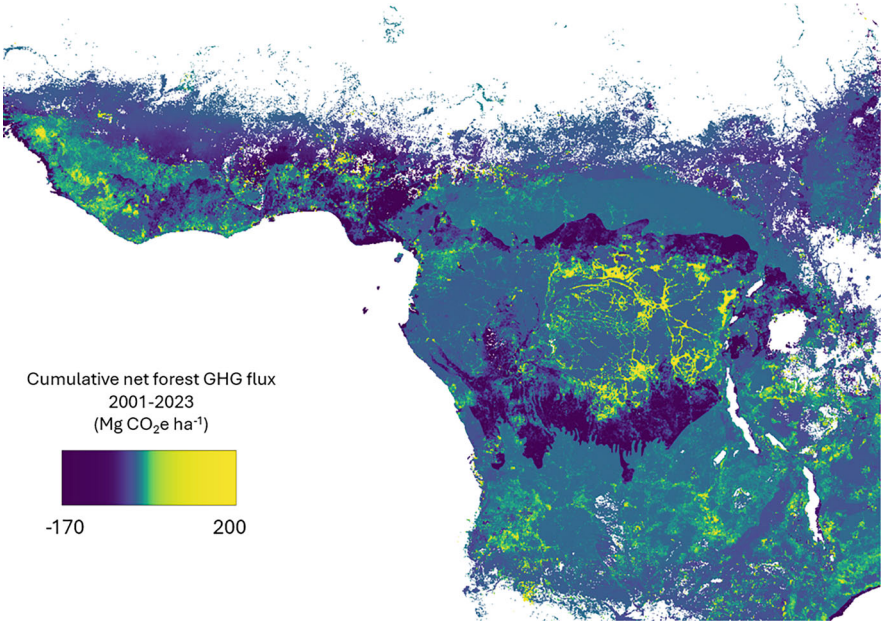

Fig. 2 Net annual forest-related GHG fluxes across the Congo Basin, summing per-pixel emissions over 2001–2023 from forest disturbance and removals associated with forest regrowth or with undisturbed forests. Positive fluxes represent emissions from the ecosystem to the atmosphere; negative fluxes represent removal from the atmosphere to the ecosystem. (Data source: Harris et al. (2021))

of 0.94 tC ha^{-1} $yr.^{-1}$ in intact African tropical forests from 2000 to 2007, totaling 482 MtC yr^{-1} (Pan et al. 2024). Field studies suggest that Central African forests may be more resilient to changing climatic conditions and may offer a longer-term carbon sink compared to other tropical forests (Hubau et al. 2020; Bennett et al. 2021). From 2001 to 2019, the Amazon region (5.14 million km^2) was a weak net carbon sink (-0.03 GtC yr^{-1}), with gross uptake (-0.4 GtC yr^{-1}) and gross emissions (0.3 GtC yr^{-1}). In contrast, the smaller African Congo Basin (2.98 million km^2) was a considerably stronger carbon sink (-0.17 GtC yr^{-1}), despite having similar gross uptake rates(-0.3 GtC yr^{-1}). The magnitude of gross emissions in the Congo Basin (0.14 GtC yr^{-1}) was approximately half of the emissions in the Amazon (Harris et al. 2021). However, satellite remote sensing studies that encompass not only forests, but also agricultural, urban, and aquatic systems, indicate that Central African forests are just as sensitive to climate anomalies as the Amazon (Liu et al. 2017; Palmer et al. 2019). In addition, future projections for the region from Earth system models remain highly uncertain, largely due to the lack of historic climate data and resultant low confidence projections of future climate (Brando et al. 2019).

On average, African tropical forests store roughly 180–195 tC ha^{-1} in above-ground biomass, which is notably higher than East or West African forests and comparable to Bornean forests (Lewis et al. 2013). A relatively small percentage of

species, around 1.5%, accounts for half of the regional aboveground carbon storage, exhibiting a pattern of "biomass hyperdominance" similar to the Amazon (Bastin et al. 2015; Cooper et al. 2024). Although uncertainty and variation between regional estimates of aboveground carbon stocks exist (e.g., Mitchard 2018), general patterns have emerged in recent years (Fig. 3).

Spatial variation in carbon stocks within the Congo Basin is driven by a complex interplay of environmental, geographical, biological, and historical factors. Climate plays a significant role, with the maximum temperature showing a negative effect on aboveground carbon (AGC; Sullivan et al. 2020). Rainfall seasonality also exhibits a negative relationship, with more carbon stored in less seasonal forests. Relatedly, light conditions play an important role, particularly in western Central Africa, where extensive low-level cloud cover during the dry season leads to a light-deficient climate but enhances the quality of light via increased diffuse irradiance, enabling evergreen forests to thrive, despite low mean annual rainfall (Philippon et al. 2019). Nutrient availability and soil properties like topsoil organic carbon and soil potassium can also influence above- and belowground carbon allocation, further adding to the complexity of spatial carbon stock variation (Bauters et al. 2019a; Bukombe et al. 2022; Doetterl et al. 2015; Gourlet-Fleury et al. 2011; Philippon et al. 2019).

Finally, C fluxes from deforestation, degradation, and regrowth are becoming increasingly important in the region's overall C balance (Noon et al. 2021). Over the past three decades (1990–2019), tropical deforestation offset approximately two-thirds of the gains provided by the global forest carbon sink (2.2 ± 0.5 GtC yr^{-1};

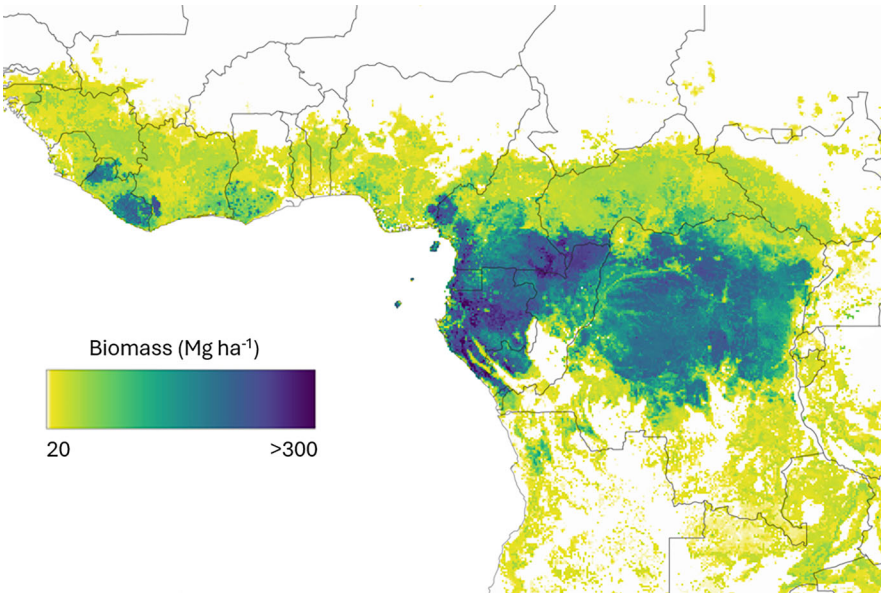

Fig. 3 Biomass distribution across the region. Values lower than 20 t ha^{-1} were masked. (Data source: Xu et al. (2022))

Pan et al. 2024). Unlike South America and Southeast Asia, shifting cultivation is the main driver of land use change in Central Africa (Gillet et al. 2016; Tyukavina et al. 2018; Van Vliet et al. 2012; Curtis et al. 2018). The Congo Basin is projected to experience a fourfold increase in human population by the end of this century before stabilizing (Gerland et al. 2014), which, in combination with the prevailing shifting and subsistence cultivation system, is already accelerating deforestation (Tyukavina et al. 2018; Kleinschroth et al. 2019) and has the potential to make Central Africa the future land use change hotspot. Importantly, however, different countries in the region are undergoing distinct trends. In the DRC and Cameroon, for example, deforestation has been accelerating over the past several decades, shifting their trajectories increasingly away from high forest, low deforestation countries to deforestation frontiers (Tyukavina et al. 2018; Shapiro et al. 2021; Biswas et al. 2025). In contrast, Gabon and the Republic of Gabon remain high forest, low deforestation countries, with distinct regrowth dynamics associated more with logging disturbances (Heinrich et al. 2023; Biswas et al. 2025). Understanding the regrowth trajectories of secondary forests following disturbance is essential to project future land cover changes, regional forest productivity, tree species distributions, and C cycle-climate feedbacks (Anderson-Teixeira et al. 2021). Widely varying post-disturbance forest regrowth trajectories that span 60 to 200 years have been reported in the Congo Basin (Makelele et al. 2021) and West Africa (Amani et al. 2022), underscored by the large variation in global C sink estimates in regrowing forests (Pugh et al. 2019). For example, estimates from 1990 to 2000 vary from 1.2 to 1.6 GtC yr^{-1} using bookkeeping methods (Pan et al. 2024; Houghton et al. 2012) and 0.4 to 0.6 GtC yr^{-1} based on global vegetation models (Shevliakova et al. 2009; Kondo et al. 2018).

Montane Forests

African tropical montane forests, defined as forests located ≥800 m above sea level (a.s.l.), have a mean AGC stock of 149 tC ha^{-1}, which is significantly higher than previously thought (Cuni-Sanchez et al. 2021). The mean AGC stock in these forests is comparable to lowland forests in Africa (Lewis et al. 2013) but about 70% and 32% higher than averages from plot networks in Neotropical montane (Spracklen and Righelato 2014; Vilanova et al. 2018; Álvarez-Dávila et al. 2017) and lowland (Sullivan et al. 2020) forests, respectively. African montane forests are characterized by low stem density but a high abundance of large trees (Lewis et al. 2013; Cuni-Sanchez et al. 2021), trees >70 cm diameter contributing substantially to AGC stocks.

The high AGC stock of African montane forests is a pervasive, albeit unexpected, phenomenon across a wide environmental gradient (Cuni-Sanchez et al. 2021), with montane forests generally assumed to have lower AGC stocks than lowland forests due to decreased temperature, cloud immersion, soil waterlogging, and nutrient-limited soils, which reduce productivity. However, AGC, stem density, and the density of large stems are not significantly related to elevation but rather increase with annual precipitation and decrease with soil fertility (Cuni-Sanchez et al. 2021). Montane forests with elephants were found to have lower AGC stocks (Cuni-Sanchez et al. 2021).

Since 2000, approximately 8000 km^2 of old-growth African montane forest have been lost, critically threatening this carbon stock (Cuni-Sanchez et al. 2021). The Democratic Republic of the Congo, Uganda, and Ethiopia have experienced the highest losses. Studying carbon dynamics in montane regions is crucial for enhancing our understanding of the factors affecting carbon storage, which requires establishing permanent plots in both disturbed and undisturbed forests to gain deeper insights into tree biomass dynamics (Imani et al. 2021).

Savannas and Woodlands

Forest-savanna woodlands in sub-Saharan Africa play a pivotal role in carbon dynamics and sustain the livelihoods of approximately 150 million people (Demol et al. 2024; Dewees et al. 2010; Frost 1996). The most well-studied savanna woodland systems in the Congo Basin are the Miombo woodlands, spanning ~2.5 million km^2. In the Congo Basin, Miombo woodlands occur primarily in the southern DRC, forming a transitional zone between the dense humid tropical forests and more open savanna ecosystems, characterized by distinct wet and dry seasons, nutrient-poor soils, and a dominance of *Brachystegia*, *Julbernardia*, and *Isoberlinia* species (Ryan et al. 2016). Despite their ecological significance, they face increasing pressures from agricultural expansion, logging, and changing fire regimes (Demol et al. 2024; Pelletier et al. 2018; Ryan et al. 2016).

Carbon stocks in Miombo woodlands vary widely, influenced by land use history, fire frequency, climatic conditions, and conservation approach (Bulusu et al. 2021; Gumbo et al. 2018; Shelukindo et al. 2014; Walker and Desanker 2004). AGC stock estimates across the biome for undisturbed Miombo range from 28 to 63 tC ha^{-1} (Bulusu et al. 2021) and 1 to 95 tC ha^{-1} (Gumbo et al. 2018). In contrast, recovering Miombo shows lower AGC stocks, with estimates averaging 19 ± 16.8 tC ha^{-1} (Bulusu et al. 2021). Recent estimates using lidar for total aboveground carbon storage across Africa's Miombo woodlands are estimated at approximately 3.7 GtC and suggest that conventional methods may underestimate carbon sequestration potential (Soka and Nzunda 2014; Demol et al. 2024).

A defining characteristic of Miombo woodlands is their capacity for rapid regeneration after disturbances and thus rapid AGC recovery, primarily through coppicing (Syampungani et al. 2015). AGC recovery rates range between 0.98 and 1.42 tC ha^{-1} yr^{-1} for agriculture and charcoal fallows, respectively, and vary with recovery age and disturbance type (Chidumayo 2013; Kalaba et al. 2012, 2013). Chronosequence studies find that C stocks between old-growth Miombo and 20–30-year-old fallows do not significantly differ, suggesting that these woodlands can recover aboveground carbon storage in as little as 20 years (Kalaba 2013; Williams et al. 2008). There is also increasing evidence that African tropical forests and savannas can exist as alternative stable states, with transitions influenced by climate, fire regimes, and historical land use (Aleman et al. 2020; Hirota et al. 2011). While precipitation plays a role, fire seems to be a key driver—frequent burning maintains savannas by limiting tree recruitment, while fire suppression allows forests to expand (Staver et al. 2011). Paleoecological and floristic data suggest these biomes have remained distinct over long timescales, with minimal species overlap (Aleman et al. 2020).

As climate change and human activities intensify, understanding these dynamics is crucial for predicting biome shifts and guiding conservation efforts (Hirota et al. 2011).

Peatlands and Flooded Forests

Seasonally and permanently flooded forests are extensive within the Congo Basin (Verhegghen et al. 2012; Dargie et al. 2017; Sonwa et al. 2022), storing ~103–191 tC ha^{-1} of AGC (Ifo et al. 2019; Djuikouo et al. 2010). Some studies report similar AGC in flooded forests to *terra firme* (Ifo et al. 2019; Djuikouo et al. 2010), while Lewis et al. (2013) reported relatively lower AGC in flooded forests. The central depression of the Congo Basin, known as the Cuvette Centrale, contains seasonally flooded and swamp forests that have an average AGC of 104 tC ha^{-1} (Xu et al. 2022). However, the Cuvette Centrale peatlands contain a substantial amount of belowground carbon, with a median estimate of 29 GtC (Crezee et al. 2022). This represents approximately 28% of the world's tropical peat carbon, which is a significant increase in the estimate from an earlier study, now revised to between 26 and 32 GtC (Dargie et al. 2017). Peat depths average 2.4 ± 1.6 m, with a maximum of 6.4 m.

The Cuvette Centrale peatland complex is the largest in the tropics, covering an area of 167,600 km^2. The peatland carbon is not evenly distributed and is found in different geomorphological settings, including rainfed interfluvial basins and river-influenced areas with low nutrient status, where peat has accumulated over thousands of years, beginning around 10,600 years ago (Dargie et al. 2017). The DRC holds ~20 GtC, and the Republic of the Congo stores ~9 GtC (Crezee et al. 2022). These belowground peat carbon stocks are enormous when compared to aboveground forest carbon, with the peat carbon equivalent to approximately 82% and 238% of each country's aboveground forest carbon stock, respectively. The mean carbon density within these peatlands is estimated at 1712 ± 634 tC ha^{-1}, with some areas reaching a maximum of 3970 tC ha^{-1} (Crezee et al. 2022), which is about nine times the mean carbon stored in the aboveground live tree biomass of African tropical moist forests (Crezee et al. 2022). Despite the vast quantity of carbon stored in these peatlands, only 8% (2.4 GtC) is within nationally protected areas. Logging, mining, and palm oil concessions overlie 26% of the total carbon stocks or 7.4 GtC, and hydrocarbon concessions cover almost the entire peatland complex, highlighting their vulnerability to land use change.

Biodiversity and Ecosystem Functions

Below, we discuss diversity patterns of tree species as they relate to ecosystem function. See ▶ Chaps. 4, "The Evolution of Congo Basin Ecosystem Diversity," ▶ 22, "Human Influence on Current Status of Biodiversity of the Congo Basin," and ▶ 23, "Opportunities and Potential for Sustainable Development in the Congo Basin from an Environmental Sustainability Perspective," for more detailed reporting on other aspects of floral and faunal diversity.

α-Diversity for Critical Areas of the Congo Basin

Alpha diversity, i.e., site-specific species diversity, in Congo Basin forests is a result of complex ecological interactions, historical biogeography, and anthropogenic influences (Couvreur et al. 2021). While tropical forests worldwide share a common physiognomy, African tropical forests stand out in cross-continental comparisons (Richards 1973). The "odd man out" hypothesis was developed to explain this phenomenon and describes three features: (1) the relative paucity of the African flora, (2) the wide distribution of African species, and (3) the sparseness of certain plant groups in Africa. Evidence now abounds to support the relative paucity of African tropical flora, including plot-level comparisons of alpha diversity between the Neotropics and Afrotropics (Parmentier et al. 2007) and across all three tropical regions (Slik et al. 2015). Tropical Africa is home to an estimated 4500–6000 tree species, substantially less than the Amazonian or Indo-Pacific regions, yet still significant in terms of endemism and functional diversity (Slik et al. 2015). While flora are approximately four times less diverse in tropical Africa than the Neotropics, the same families are the most species-rich (notably, Fabaceae) (Silva de Miranda et al. 2022). The wide distribution of African species is confirmed by low species turnover, evidenced by the relatively rapid accumulation and saturation of species along accumulation curves (Slik et al. 2018), with many tree species occurring across the entire Guineo-Congolian region (White 1983). The seminal work of Frank White on African vegetation and its spatial organization has since been confirmed by numerous empirical analyses (e.g., Küper et al. 2004; Linder et al. 2001, 2012; Droissart et al. 2018). Finally, several plant groups are sparse in Africa, with a notable example being palms. For example, tree-like palms are ubiquitous in the Neotropics but rare in the African tropics, which is dominated more by tree-climbing palms (Muscarella et al. 2020).

In relative terms, Africa hosts around 15% of the number of tree species that exist globally (Gatti et al. 2022). This diversity is not evenly distributed, with local hotspots of richness and endemism occurring, such as the Albertine Rift (Orme et al. 2005), recognized early on by White (1983) as the regional mosaic of Lake Victoria. Lower Guinea is especially rich in tree species diversity, with wet evergreen forests in Gabon hosting enormous plant diversity (Texier et al. 2022). In contrast, the inner Congo Basin, in the Sangha River interval between the two subcenters of endemism, is depauperate (White 1983) and is thought to be a former savanna corridor (Maley 2001, 2002).

A key characteristic of tree diversity in the Congo Basin is the presence of monodominant stands, particularly those dominated by *Gilbertiodendron dewevrei*, described by Gerard (1960) in northern Congo and observed across the Sangha River interval (Fayolle et al. 2014b) and eastward to Ituri (Hart et al. 1989; Hart 1995). Monodominance is generally recognized as occurring when a single tree species dominates >50% of the stems in a forest stand (ter Steege et al. 2019; Makana et al. 2011). The mechanism leading to this dominance has long eluded researchers (Hart et al. 1989; Torti et al. 2001; Peh et al. 2011; Bauters et al. 2019a). Recent work suggests that ectomycorrhizal association might enable *Gilbertiodendron* trees to

access nutrients directly from the soil organic matter, subsequently promoting nutrient limitation for co-occurring species (Hall et al. 2020). These forests, while structurally complex, exhibit lower alpha diversity due to the competitive exclusion of other tree species.

Anthropogenic disturbances, including selective logging, agriculture, and shifting cultivation, have profound effects on alpha diversity. Secondary forests recovering from these disturbances exhibit rapid increases in species richness and functional trait diversity, often reaching near-old-growth levels within six decades (Makelele et al. 2021). However, full recovery of floristic composition is much slower, with old-growth forests continuing to harbor unique assemblages of species that do not easily re-establish in disturbed areas (Makelele et al. 2021; Bauters et al. 2019b). Alpha diversity in the Congo Basin forests reflects both ecological and evolutionary processes, shaped by natural environmental gradients and increasingly modified by human activities. Maintaining this diversity requires an integrated conservation approach that considers species richness, functional traits, and the ecological roles of common and rare species.

β-Diversity Across Critical Areas of the Congo Basin

Beta diversity, which measures species turnover across different sites or communities, is a key determinant of Congo Basin forest biodiversity patterns. It reflects the degree of species differentiation between habitats and is shaped by historical biogeography, environmental gradients, and anthropogenic pressures (Duivenvoorden et al. 2002). Strong floristic discontinuities exist across the region, with species composition varying significantly along climatic and edaphic gradients (Réjou-Méchain et al. 2021; Picard et al. 2024). One of the most pronounced biogeographic divides is located at the Albertine rift that separates the dry, moist, and wet forests of West and Central Africa (the entire Guineo-Congolian region) from the upland and coastal forests of East Africa (Fayolle et al. 2014b). This major floristic discontinuity has also been characterized for savannas (Fayolle et al. 2019). Described decades ago by White (1983), this discontinuity has subsequently been challenged and reconfirmed by multiple studies (Küper et al. 2004; Linder et al. 2005, 2012; Droissart et al. 2018).

On average, African tropical forests are exposed to drier and more seasonal climates compared to tropical forests on other continents (Guan et al. 2015). Across tropical Africa, climate (e.g., seasonal drought) shows strong spatial variations (White 1983), with many species having evolved toward specialized climatic niches (Gorel et al. 2022). Recent analyses indicate that climate is a primary driver of beta diversity in the region (Fayolle et al. 2014a, b; Réjou-Méchain et al. 2021), distinguishing the Congo Basin from other tropical forests where soil properties exert a stronger influence on species turnover (Réjou-Méchain et al. 2021; Fayolle et al. 2012; Vleminckx et al. 2020). Strong variation between function and floristic turnover exists, for example, from equatorial areas with a low water deficit to areas with a high-water deficit toward the limits of the tropics (Réjou-Méchain et al. 2021), areas with high evapotranspiration rates (e.g., the northern limit of Central African

forests), and areas with a cool and light-deficient dry season (e.g., coastal Gabon). In general, rainfall seasonality, maximum temperature, and evapotranspiration rates seem to be particularly important in structuring tree communities in the Congo Basin, with drier regions supporting different species assemblages than wetter areas. Functional beta diversity (i.e., variation in species traits between sites) further underscores the complexity of forest composition in the region. While floristically distinct forest types exist, they often exhibit functional convergence, meaning that different species may occupy similar ecological niches in response to comparable environmental conditions. This redundancy in functional traits can buffer ecosystems against disturbances but also highlights the need to preserve both taxonomic and functional diversity to ensure long-term ecosystem stability (Réjou-Méchain et al. 2021).

Functional Properties of Biodiversity

Functional diversity, i.e., the value and range of the functional traits of the organisms in a given ecosystem, in African tropical forests, is a critical aspect of their resilience, productivity, and capacity to provide ecosystem services. Based on pan-tropical modeled estimates of functional richness and divergence, these forests exhibit functional trait variation driven by environmental gradients, disturbance regimes, and long-term evolutionary processes (Aguirre-Gutiérrez et al. 2022). Functional diversity appears to play a key role in ecosystem stability, influencing carbon storage, nutrient cycling, and the ability of forests to withstand climatic fluctuations (Day et al. 2014; Aguirre-Gutiérrez et al. 2019). The functional contribution of large, rare tree species, with a unique combination of functional traits, is particularly significant, as they likely affect ecosystem functioning more than smaller trees (Kearsley et al. 2019).

An additional key feature of African tropical flora is deciduousness (Loubota Panzou et al. 2018). The proportion of deciduous stems varies across the Congo Basin (Réjou-Méchain et al. 2021), and its response to climate was found to be mediated by the geological substrate in the Sangha River Interval. Recent work shows that phylogenetic constraints and climate shape drought-related traits in African tropical trees, with leaf habit responses to climate mediated by tree height and wood density (Gorel et al. in press JEcol).

Integrating functional diversity with carbon storage in conservation and restoration is critical (Achieng et al. 2023). In the Congo Basin, secondary forests recover functional diversity within six decades of shifting cultivation, yet carbon stocks and species composition rebound more slowly, with specialist species often missing (Makelele et al. 2021). Successional studies also show shifts from acquisitive to conservative traits, especially in nitrogen-related leaf traits that affect nutrient cycling and productivity (Bauters et al. 2019b). Frequent disturbances further deplete soil nutrients and alter functional composition (Bauters et al. 2021b). Maintaining functional diversity is thus crucial for ecological integrity and adaptation, with future work needed linking field traits with remote sensing and models to assess long-term impacts of climate change and land use.

Changing Biodiversity and Ecosystem Function: Dynamics and Drivers

Climate change and land use changes are significantly impacting ecosystem function and biodiversity in the Congo Basin. Both interpolated gridded climate datasets (Tsalefac et al. 2015; Dezfuli 2017; Nicholson et al. 2018, 2019; Mabrouk et al. 2022) and satellite products (Diem et al. 2014; Zhou et al. 2014) report a lengthening of the dry season in Central Africa over the last few decades, starting between 1990 and 2000 (Malhi and Wright 2004; Saatchi et al. 2013; Zhou et al. 2014; Nicholson et al. 2018). Multiple independent precipitation and satellite-derived vegetation datasets show that the dry season length increased by 6–10 days per decade from 1988 to 2013 due to an earlier dry season onset and a delayed dry season end (Kasongo et al. 2023; Jiang et al. 2019). Coincidentally, wet and dry extreme events are expected to become more frequent and more severe in the region (Fotso-Nguemo et al. 2018; Kendon et al. 2019; Karam et al. 2022).

A hotter and more seasonal climate may have important consequences for Congo Basin forest composition, carbon sequestration, and ecosystem functioning more broadly. Such shifts have led to species composition turnover in West Africa (Fauset et al. 2012; Aguirre-Gutiérrez et al. 2020) and in the drier parts of the Amazon (Esquivel-Muelbert et al. 2019), with drought-tolerant (deciduous) species replacing trees adapted to wetter conditions. Although no field studies exist for Central Africa, satellite data show a long-term decline in Congo Basin forest greenness, likely from a canopy shift toward more deciduous species (Zhou et al. 2014). Long-term and systematic monitoring of both forest species composition and climate across the Congo Basin is necessary to develop early warning systems for ecosystem degradation and regime shifts.

Synthesis

The Congo Basin plays a vital role in global climate regulation and biodiversity conservation and acts as a major carbon sink by sequestering carbon through its forests, soils, and peatlands. Unique characteristics, such as high megafauna density, unique vegetation types, and low deforestation rates compared to other tropical continents, shape the region's emergent ecosystem functions. Soil properties, biogeochemical cycles, and aquatic fluxes interact with the Congo River, exporting carbon, while peatlands store immense belowground carbon reserves. Biodiversity drives ecosystem processes, with elephants enhancing seed dispersal and carbon sequestration. Climate change and land use shifts threaten these functions, with deforestation reducing carbon stocks and altering water cycles. As climate pressures intensify, further research into ecosystem dynamics will be crucial for maintaining the region's resilience. Forthcoming advances in remote sensing technologies offer a powerful means to map forest composition, estimate biomass, and detect degradation at fine scales, helping to address gaps in carbon cycle dynamics in the region, although doing so depends on continued and expanded large-scale in situ monitoring (Bossy et al. 2025). Safeguarding its stability requires integrated conservation strategies that address these interconnected dynamics, including, for example, both carbon sequestration and functional biodiversity.

Competing Interest Declaration The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

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Section II

The Impact of Global, Regional, and Local Human Activity on the Ecosystems of the Congo Basin

Global, Regional, and National Economic Drivers of Deforestation and Forest Degradation in the Congo Basin

11

Danae Maniatis, Emmanuel Nuesiri, Florence Palla, and Charles Perrings

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Abstract

Between 1990 and 2020, 352,642 km^2 of the Congo Basin's dense forest, equivalent to 8.5% of the total land area, were lost. If current deforestation rates are not reduced, more than 25% of the tropical forest is expected to disappear by 2050. This chapter reviews the proximate and underlying drivers of deforestation and forest degradation in the Congo Basin: the activities directly responsible for forest loss and the underlying conditions that support those activities. The main proximate drivers are land clearance for subsistence shifting agriculture and small-scale plantations of cacao and oil palm; large-scale industrial agriculture; illegal illegal within mining concessions, areas of dispersed artisanal mining, and unclassified dense forests; artisanal forestry aimed at the production of fuelwood and charcoal; and large-scale export-oriented forestry in timber concessions. Underlying drivers include rural population growth, the lack of secure property rights, and weak systems of governance at local, national, and international scales. In all countries except Gabon, the rural population has continued to grow since 1990. The highest rates of rural population growth and the highest rates of deforestation in unclassified forests occur in Cameroon, CAR, and DRC. Widespread insecurity of land tenure, the absence of defined land rights, and an ineffective regulatory regime discourage investment in productivity improvements and encourage the persistence of shifting agriculture.

Keywords

Deforestation · Forest degradation · Shifting agriculture · Illegal logging · Artisanal forestry · Governance · Regulatory failure · Population growth

The Problem of Deforestation

The Congo Basin harbors one of the largest tropical rainforests in the world, offering significant environmental, social, and economic net benefits at many spatial and temporal scales. The forest is one of the most biodiverse systems on the planet, and the species within it provide people with a range of provisioning, regulatory, and cultural services. Individual species provide the foods, fuels, and fibers sought in agriculture, horticulture, aquaculture, forestry, foraging, medicine, and recreation. The community of species supports regulatory functions that include carbon sequestration, hydrological and temperature control, the filtration of atmospheric and water pollutants, and disease and pest control (Brondízio et al. 2019). There are, however, trade-offs between services.

Forest clearance to support agriculture, transport, energy, mining, commerce, industry, and housing compromises other services, including the regulation of the world's climate or the control of infectious zoonotic diseases. The costs involved are substantial. The forests and peatlands of the Congo Basin store over 60 billion metric tons of carbon (Dargie et al. 2017) and sequester 0.6 billion metric tons of carbon dioxide a year more than they emit (Harris et al. 2021b), yielding an annual benefit to

the global community of approximately $55 billion (Mitchell and Pleeck 2022). Every hectare cleared reduces the benefit to the global community. Similarly, depletion of intact forests exposes users to novel pests and pathogens with effects that may be transmitted more widely through trade and travel (Jones et al. 2008). Just one of the many infectious zoonotic diseases to emerge from the Congo Basin, HIV/AIDS, involves annual direct costs of $48 billion (Kavanagh and Gostin 2018). Every hectare cleared increases disease risk to the global community.

The six countries that span the tropical rainforest in the Congo Basin—Cameroon, the Central African Republic (CAR), the Democratic Republic of the Congo (DRC), the Republic of the Congo (RoC), Equatorial Guinea, and Gabon[1] — collectively lost 352,642 km^2 of dense forest between 1990 and 2020 (equivalent to 8.5% of the total land area). The deforestation rate varied over both space and time (Figs. 1 and 2). In 1990–2000, 215,938 km^2 was lost. The rate declined between 2000 and 2010, before increasing again in 2010–2020 when 86,658 km^2 of forest

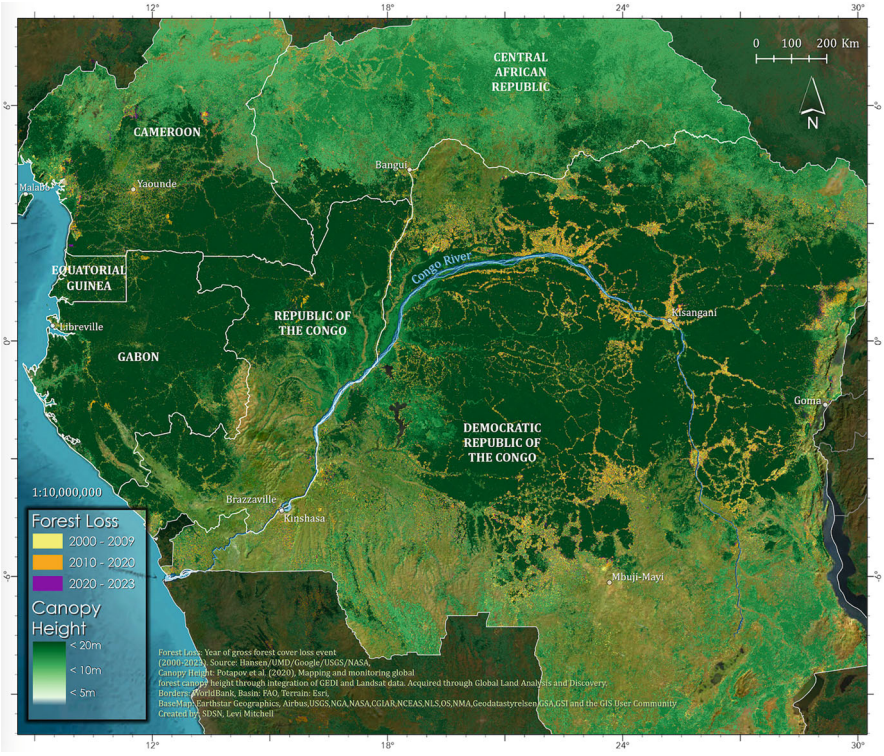

Fig. 1 The Congo Basin forest showing deforestation between 2000 and 2023. (Data sources: See map)

[1] The first four countries lie wholly or partly within the Congo catchment itself. The last two lie in the adjacent Ogooué and Muni River catchments.

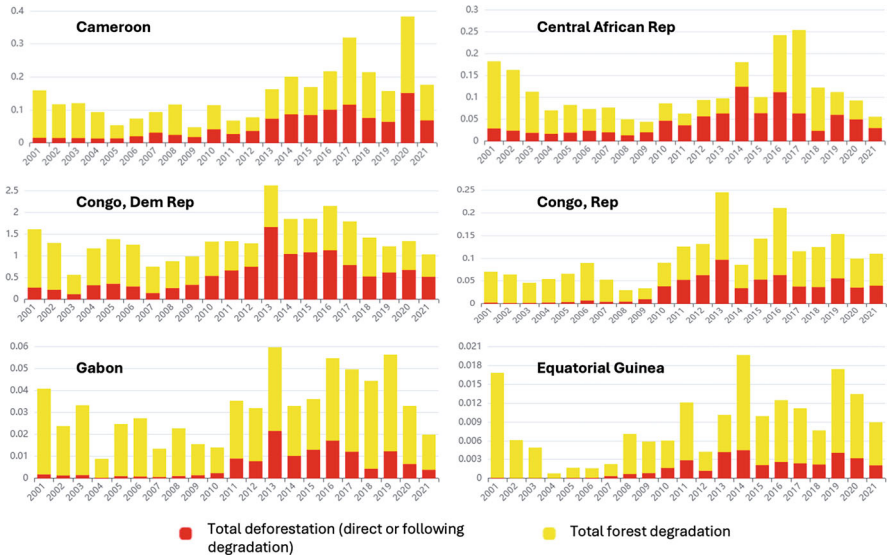

Fig. 2 Annual deforestation and forest degradation in the Congo Basin, in million hectares (Mha), between 2001 and 2021. (Data source: Observatoire des forêts d'Afrique centrale. (2025) Evolution de forêts, OFAC, Yaoundé. https://www.observatoire-comifac.net/analytical_platform)

was lost (Yuh et al. 2024). At current loss rates, 27% of intact forest, equivalent to 4% of total land area, would be lost by 2050 (Eba'a Atyi et al. 2022).

Change on this scale threatens the UN Sustainable Development Goal 15: to "Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss." This chapter offers an overview of the economic drivers behind deforestation and forest degradation. It identifies the activities involved and the way they are influenced by national economic policies, environmental regulations, and the system of forest governance.

Economic and Demographic Characteristics of the Congo Basin Countries

The Congo Basin countries all depend on natural resources. In CAR, DRC, and Cameroon, forests are the principal natural resource exploited. Minerals are secondary to forest resources. In RoC, Equatorial Guinea, and Gabon, oil is more important. CAR and DRC are both low income by the World Bank's classification.[2] Cameroon

[2]The current World Bank classification is as follows: low income, < $1135 GNI per capita; lower-middle income, $1136–$4465; upper-middle income, $4466–$13,845; and high income, > $13,845.

and RoC are lower-middle income, and Equatorial Guinea and Gabon are upper-middle income (Table 1).

Figure 3 reports natural resource rents[3] associated with forest, mineral, and oil resources in the region, expressed as a percentage of GDP during 1990–2020. Resource rents represent the payoff to depletion in natural capital stocks. A conventional test for the sustainability of natural resource–based economies is whether resource rents are invested in alternative reproducible assets of equivalent value (Hartwick 1977). This requires that "adjusted net savings" (ANS)(net national savings plus education expenditure minus depletion of energy, minerals, forests, and CO_2) be positive. ANS have been positive in Gabon since 2005 but have mostly been negative for other Congo Basin countries.[4]

Investment and employment generation have been concentrated in high-growth, natural resource–based sectors, while other sectors have languished. In the oil-rich countries, this has resulted in rural migration to the capital cities, where the mineral and oil rents are invested (Rudel 2013), and economic stagnation and political instability away from the capital (Fofak 2022). Figure 4 shows the population in RoC and Gabon to be concentrated around the capital cities and sparse elsewhere (Fig. 4). In Cameroon, CAR, and DRC, by contrast, the population is distributed more widely, is more dependent on forest resources, is more impoverished, and is more likely to experience politically unstable conditions. In the DRC, for example, the eastern provinces of Ituri, North Kivu, and South Kivu have been significantly impacted by a long-standing insurgency that has, to date, cost around six million lives and displaced more than seven million people.

Natural Resource–Based Activities Driving Deforestation and Forest Degradation in the Congo Basin

Deforestation has had relatively little impact on the core intact forest in the Congo Basin, but a very significant impact on the patch and corridor forests that account for 27% of total forest area. There is a tight association between deforestation and the

[3] Natural resource rents are the difference between the price of the commodity or commodities produced from natural resources and the average cost of their production including a normal profit. They arise because the resources occur naturally and so are in relatively fixed supply. They are not produced.

[4] The World Bank Development Indicators do not include estimates of adjusted net savings for Equatorial Guinea and CAR. Estimates for other countries (%GNI) follow.

	2005	2010	2015	2020
Cameroon	2.20	−2.24	−1.51	−0.31
DRC	−22.99	−7.39	−12.40	5.16
RoC	−32.49	−2.38	4.65	−32.37
Gabon	3.58	0.39	14.13	..

Table 1 Characteristics of Congo Basin countries, 2020

	Cameroon	CAR	DRC	RoC	Gabon	Equatorial Guinea
GDP						
GDP per capita (const 2015 US$)	1419.33	375.22	487.43	1740.83	6619.69	5995.91
GDP per capita, PPP (const 2021 int $)	4711.11	1069.27	1320.79	6406.88	19,678.04	18,378.50
GDP per capita growth (annual %)	−2.42	−1.62	−1.49	−8.43	−3.97	−7.36
Agric, forestry, fishing (% of GDP)	17.50	29.50	20.88	10.69	6.63	3.15
Population						
Population, total	26,491,087	5,343,020	92,853,164	5,702,174	2,292,573	1,596,049
Net migration	−9889	−24,803	−1643	−4465	1514	0
Population density (per sq. km)	56.04	8.58	40.96	16.70	8.90	56.90
Rural population (% total population)	42.44	57.80	54.36	32.17	9.91	26.90
Rural population growth (annual %)	1.33	1.80	2.14	0.92	−1.29	0.99
Urban population (% total population)	57.56	42.20	45.64	67.83	90.09	73.10
Urban population growth (annual %)	3.75	3.55	4.53	3.01	2.59	3.38
Life expectancy at birth, total (years)	60.83	54.60	59.74	63.79	66.53	60.71
Fertility rate, total (births per woman)	4.54	5.99	6.21	4.23	3.55	4.35
Land area						
Land area (sq. km)	472,710	622,980	2,267,050	341,500	257,670	28,050
Forest area (% of land area)	43.03	35.80	55.65	64.26	91.32	87.29
Agricultural land (% of land area)	20.63	7.88	14.95	31.15	8.36	3.74
Protected areas (% land area)	10.95	18.06	13.83	36.79	22.44	19.27
Annual forest loss 2010–2020 (%)	0.27	0.13	0.83	0.06	0.05	0.34

Data sources: World Bank (2024); Food and Agriculture Organization (2020)

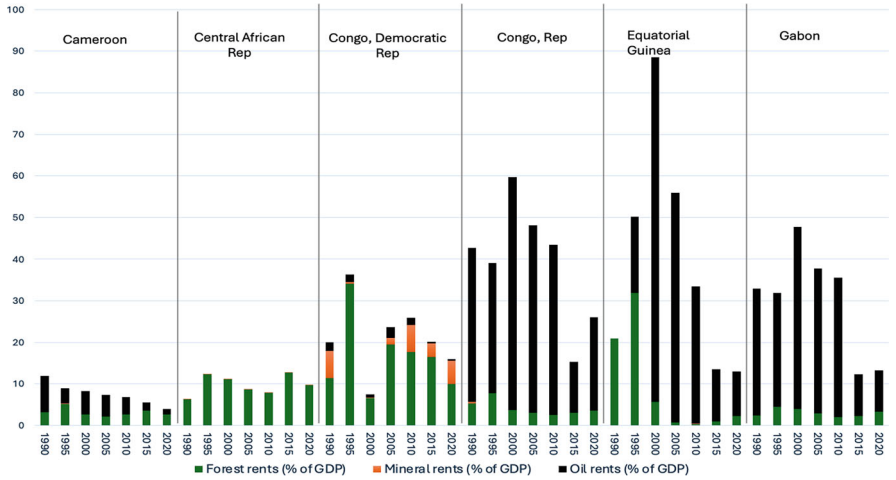

Fig. 3 Principal natural resource rents as a percentage of GDP, 1990–2020. (Data source: World Bank (2024))

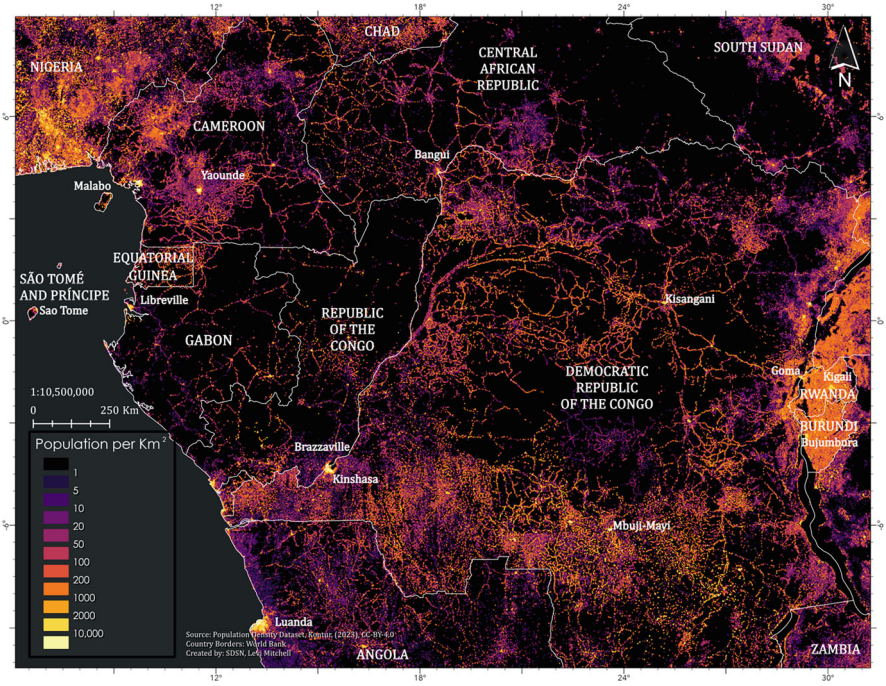

Fig. 4 Population distribution in the Congo Basin countries. (Data source: Kontor (2023))

growth of human settlements and transport routes: 80% of all deforestation occurs within 4 km of settlements or roads (seen in Figs. 2 and 8). Industrial forestry and large-scale agriculture have both led to forest loss, but the main proximate causes of deforestation in the Congo Basin are subsistence shifting agriculture, illegal logging in protected and unclassified forests and around settlements and along transport routes, and artisanal and industrial mining (Eba'a Atyi et al. 2022). Forest degradation implies a more general deterioration in forest structure and function, along with the loss of forest biodiversity. The activities behind both processes are described below.

Agriculture

Agriculture accounts for the greatest share of the labor force in all Congo Basin countries (above 50% in CAR, DRC, and Equatorial Guinea) (Fig. 5). Agriculture generally involves small-scale shifting production, where forest patches are cleared to create small fields to produce subsistence crops. The result is a mosaic of fields, both active and fallow, together with secondary forest regrowth, found along the network of roads and rivers. This is referred to as the rural complex (Devaux et al. 2019).

Although the agricultural share of the labor force has declined, the rural population has increased in all countries except Gabon. In Cameroon and DRC, rural population growth is currently above 1% and 2%, respectively. Rural population growth increases the rate at which new fields are cleared from primary forest, yielding a pattern of deforestation known as "perforation": the clearance of land in core primary forest away from the existing rural complex (Molinario et al. 2017).

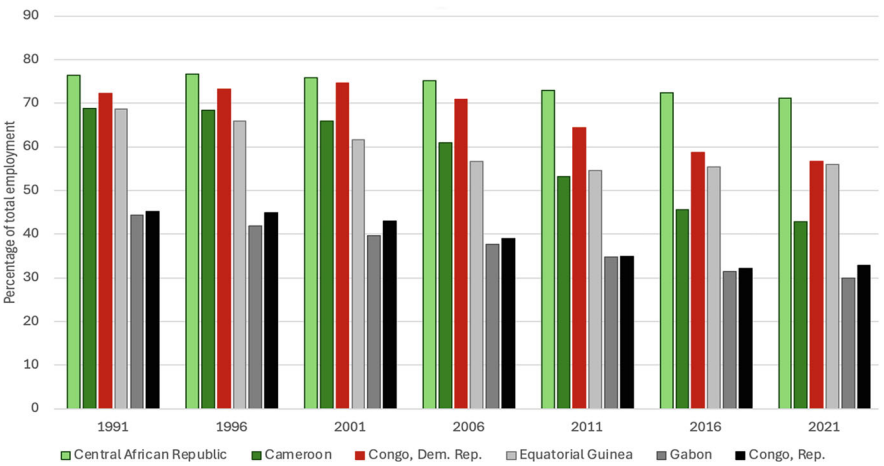

Fig. 5 Agriculture share of employment (modeled ILO estimates) 1991–2021. (Data source: World Bank (2024))

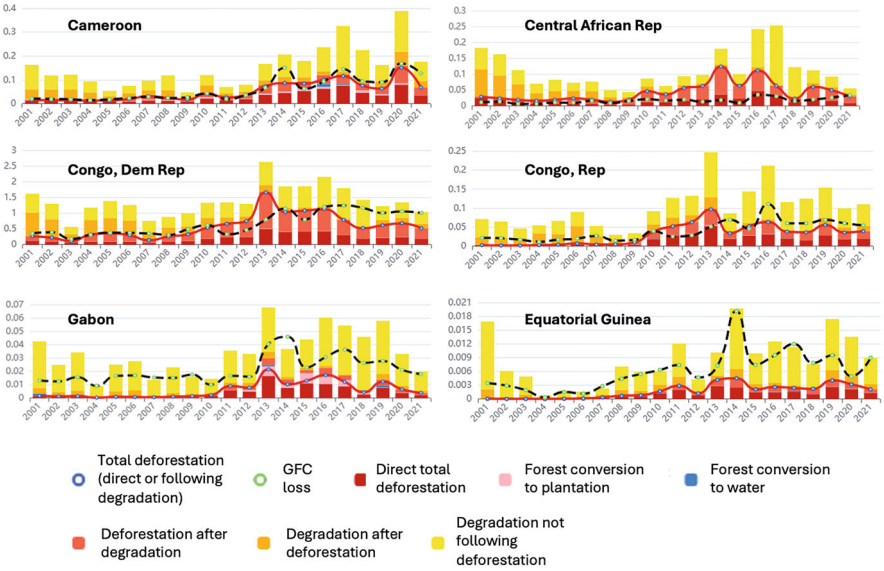

Fig. 6 Annual deforestation and forest degradation transitions in the Congo Basin, in million hectares, between 2001 and 2021. (Data source: Observatoire des forêts d'Afrique centrale, 2025)

The persistence of shifting agriculture reflects several factors. Insecure land rights deter investment in productivity improvements and encourage the clearance of new fields in primary forest (Shittu et al. 2018). Lack of access to capital markets and weak agricultural extension services inhibit the adoption of productivity-improving technology (Karume et al. 2022). Inadequate transport infrastructure limits access to markets (Ulimwengu et al. 2009).

Aside from shifting agriculture, there has been forest clearance for export-oriented cash crops such as palm oil, coffee, cacao, and rubber by both industrial-scale and small-scale producers. Oil palm, for example, is largely cultivated in smallholder plantations in CAR, Equatorial Guinea, RoC, and DRC. In Gabon and Cameroon, by contrast, production is still dominated by large estates originally created as parastatals during the period 1960–1990. Coffee and cocoa are everywhere produced on small plantations of 3 ha or less. In 2008, the land area under plantations, large and small, was 11% of the total land area committed to agriculture—then around 12 million ha (Hourticq et al. 2013) (Fig. 6).

Forestry

Congo Basin forests are formally divided into production, conservation, and unclassified or rural domain forests. Production forests, 33% of the forest area, are

managed through private concessions to produce timber.[5] Conservation forests, 14%, are not exploited in principle. The balance, around 100 million hectares, is unclassified state-owned lands (Fig. 7).

In practice, logging occurs in all areas. It is regulated in production forests, where concession holders are required to produce management plans that specify logging rules. Industrial forest concessions account for a small proportion of total logging. In DRC, for example, industrial forest concessions account for approximately 7% of the forested area and 10% of logging. Across the Congo Basin, the relative importance of industrial logging varies, but it is generally a less important driver of deforestation than agriculture or infrastructure development.

Most logging is small-scale, illegal, or informal. In DRC, for example, such activities account for 90% of logging and are concentrated in mining concessions and in unclassified and conservation forests (Table 2). Actors include logging

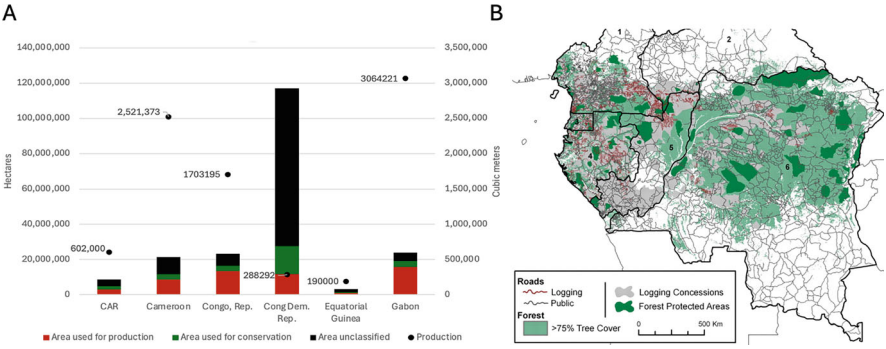

Fig. 7 (**a**) Congo Basin tropical moist forest categories (columns, left axis) and production of roundwood and sawnwood (dots, right axis), 2020. (**b**) Spatial distribution of forest categories. (Data sources: (**a**) Eba'a Atyi et al. (2022), (**b**) Laporte et al. (2007))

Table 2 Deforestation rate (%) in different forest categories 2010–2020

	Forestry concessions	Protected dense forests	Mining concessions	Unclassified dense forest
Cameroon	0.04	0.04	0.19	0.53
CAR	0.27	0.28	0.32	0.65
Congo, Dem. Rep.	0.46	0.18	0.70	0.61
Congo, Rep.	0.13	0.08	0.19	0.35
Equatorial Guinea	0.06	0.03	0.14	0.16
Gabon	0.02	0.01	0.03	0.12

Data source: Eba'a Atyi et al. (2022)

[5] From seven main tree species: mahogany, sapele, ebony, wenge, limba, okoumé, and agba.

companies operating illegally and small-scale artisanal foresters producing roundwood, fuelwood, and charcoal.

The main producers of timber for export are Cameroon, Gabon, and RoC. Exports comprise both processed timber and whole logs. Gabon has banned the export of whole logs since 2009. Pressure on other countries to do the same has been increasing, and in 2022, all agreed to impose a general ban on raw timber exports. Cameroon, which currently processes around 70% of exports, will enforce the ban by 2026, but CAR, DRC, and RoC have yet to commit to a date for enforcement, and their exports are still dominated by whole logs.

While logging is a major driver of deforestation, legal logging for export from forestry concessions has a much lower impact than illegal logging. In fact, there is a strong negative correlation between legal timber exports and deforestation rates. Between 2010 and 2020, the national deforestation rate was lowest in the countries with the highest value of legal exports and the highest rates of processing, Gabon (0.02%) and Cameroon (0.04%), and highest in the countries with the lowest value of legal exports and the lowest rates of processing, DRC (0.46) and CAR (0.27) (Eba'a Atyi et al. 2022). This is because land clearance for agriculture, illegal logging, and artisanal wood fuel and charcoal production are more important drivers of deforestation than export-oriented logging within timber concessions. Where export-oriented timber production does have a significant impact is in forest disturbance. Selective logging accounts for around 10% of forest disturbance across the region, but 60% of forest disturbance in Gabon (Tyukavina et al. 2018).

Transport

Historically, the transport network in the Congo Basin has been based on the Congo River and its tributaries, which, together, provide some 15,000 km of navigable waterways. This is supplemented by a sparse network of road and rail routes. Not all road and rail routes are operational, however, and only a small proportion of road routes are paved. In parts of the region, specifically in eastern DRC, maintenance has been compromised by the effects of armed conflict, making overland movement of goods expensive and unreliable. The road system is nevertheless a major factor in deforestation and forest degradation. Figure 8 illustrates the pattern around the city of Kisangani in DRC.

Not all road construction has the same impact. A World Bank study of the relation between the economic benefits and forest losses of a road project linking major urban centers in DRC, for example, identified areas where forest losses were high or low relative to the local GDP impact of road construction. The study found areas where the economic benefits of road improvement would be high while the deforestation risks would be low (marked green in Fig. 9) and areas where the opposite would be true (marked red).

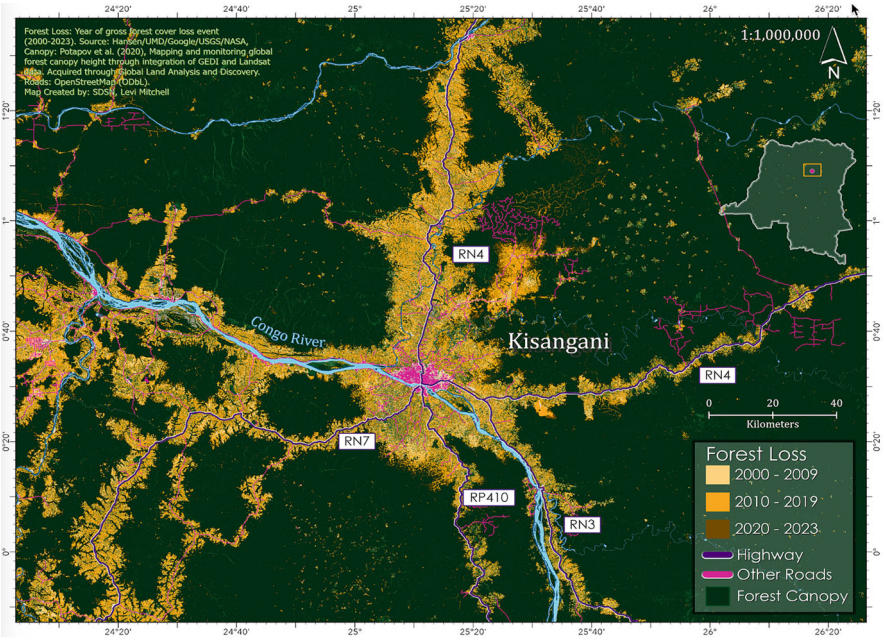

Fig. 8 Deforestation along national and provincial roads around Kisangani, Democratic Republic of the Congo. (Data source: Hansen et al. (2024))

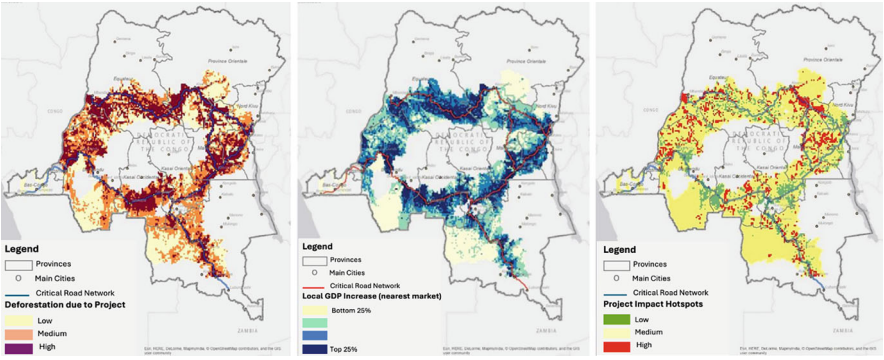

Fig. 9 GDP change and forest cover loss from the Major Urban Center Road Project. The left panel indicates the spatial distribution of forest loss. The center panel indicates the spatial distribution of the impacts of GDP. The right panel indicates the spatial distribution of the combination of deforestation risk and GDP impact. (Source: Figs. 7.2a, 7.2b, and 7.3 in Damania et al. (2018))

Minerals and Oil Extraction

Mining is a less important driver of deforestation than agriculture and forestry but still has a considerable impact (Abernethy et al. 2016). Deforestation rates in mining concessions are significantly higher than in both forestry concessions and protected

dense forests (José-Zobel et al. 2023). Mining activity is concentrated in five mineral provinces: the copper (and cobalt) belt in DRC's Katanga, gold in the DRC's North and South Kivu and Ituri, the bauxite province in central north Cameroon, iron in the Tridom (Tri-national Dja-Odzala-Minkébé—the land between Cameroon, Gabon, and the Republic of the Congo), and a nickel and cobalt province in southeastern Cameroon. In addition, manganese mining occurs in the DRC and Gabon. Only the Katanga copper belt and the bauxite deposits in Cameroon lie outside the tropical moist forest. All other mineral deposits lie wholly or partly within the forest.

Some deposits are exploited on an industrial scale. Specifically, copper, cobalt, and tin are mined by the DRC parastatal Générale des Carrières et des Mines (Gécamines), manganese in Gabon is mined by Compagnie Minière de l'Ogooué (COMILOG), and the Tridom iron ore deposits are mined by several international companies, as are bauxite and cobalt deposits in Cameroon. However, most mineral deposits in Gabon, Cameroon, RoC, CAR, and DRC are exploited by artisanal and small-scale miners (ASMs) using rudimentary techniques to process relatively small quantities of ore a year. The scale of ASM activity differs substantially across these countries: fewer than 10,000 in Gabon and RoC, just under 500,000 in CAR, and around 2,000,000 in DRC. Minerals extracted include copper, cobalt, diamonds, gold, cassiterite, wolfram, and coltan (International Peace Information Service 2023).

The environmental impacts of mining follow from the establishment of roads and secondary activities around the mine site, principally agriculture, and from the pollution of air, water, and soils (wa Mutombo et al. 2022). A study of the forest loss around ASM sites in eastern DRC found that, over the ten years following the establishment of a mine, forest loss from settlement development and agriculture was 25 times the loss from the mine site itself and extended 5 m from the site (Ladewig et al. 2024).

Several governments in the region aim to develop mineral and oil resources within the tropical moist forest on a large scale. Of 840,000 km^2 of intact forest landscapes in the Congo Basin, 221,000 km^2 are subject to oil and gas contracts (most in DRC and RoC), and 139,000 km^2 are subject to mining claims (most in DRC) (Fig. 10). The development of oil fields that threaten the tropical peatlands of the Cuvette Centrale is of concern, given the potential impacts of the infrastructure required to support oil production and the potential pollution from oil and produced water (Lawson et al. 2022).

Forest Governance in the Congo Basin

Forest governance in the region has seen a gradual shift toward more sustainable practices in response both to international pressures and to local needs but still suffers from several weaknesses described below. Major challenges include the need for better law enforcement, the integration of local knowledge into governance processes (Dkamela et al. 2014), and respect for traditional land rights on state lands (Karsenty and Ferron 2017).

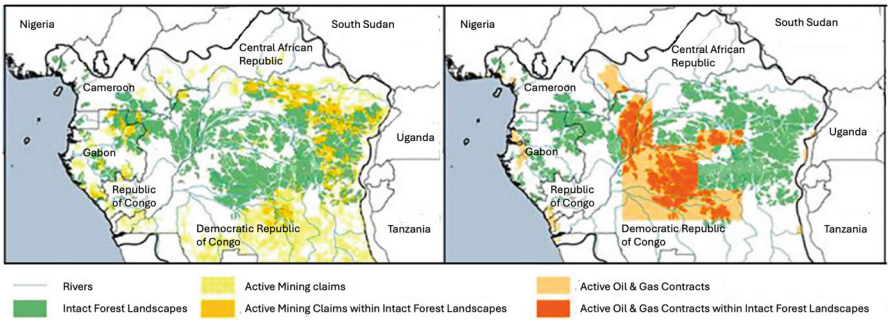

Fig. 10 Intact forest landscapes affected by oil and gas contracts and mining claims in the Congo Basin. (Source: Adapted from Fig. 1 in Grantham et al. (2021))

There are three main aspects of the system of forest governance in the region: a set of legal frameworks and policies, a set of regional cooperative institutions, and a set of international agreements on natural resource use. The legal frameworks governing forest management in the Congo Basin are shaped by global conventions like the UN Convention on Biological Diversity (CBD), regional agreements, national laws, and customary norms. Most Congo Basin countries have established forest management codes. Gabon has also instituted a log export ban and a requirement for forest certification of all forest concessions in the country (Karsenty 2019). However, enforcement of the codes remains weak in some areas due to civil conflict, lack of resources, corruption, and the ineffectiveness of regulatory bodies.

Among regional initiatives, the Central African Forests Commission (COMIFAC), established in 2005, plays a central role in promoting regional cooperation on forest governance. COMIFAC brings together ten Central African countries to foster harmonized policies, exchange best practices, and work on joint initiatives to monitor deforestation and illegal logging. COMIFAC aims to integrate sustainable forest management across the region, but progress is limited by the generic nature of the plan objectives and the fact that not all partners are aware of their obligations under the plan (Verhaeghe and Vanheukelom 2017).

At the international level, several initiatives influence regional forest governance. The Forest Law Enforcement, Governance and Trade (FLEGT) Action Plan by the European Union, seeks to combat illegal logging and promote good forest governance. It includes Voluntary Partnership Agreements (VPAs) with Cameroon, RoC, and Gabon. VPAs aim to enhance governance structures and improve transparency—issues that have historically plagued forest management in the region (Mbzibain and Tchoudjen 2021). However, monitoring and enforcement of VPAs are weak (Mbzibain and Ongolo 2019), and FLEGT has yet to achieve its stated goals (Karsenty 2019).

The voluntary REDD+ (Reducing Emissions from Deforestation and Forest Degradation, plus the sustainable management of forests and the conservation and enhancement of forest carbon stocks) initiative aims to mitigate climate change by providing financial incentives to countries to implement core activities. However, coordination

with sectors that are key drivers of deforestation—agriculture, mining, and energy—remains weak. Countries have yet to harmonize carbon monitoring tools and bring them in alignment with the carbon accounting framework under the Paris Climate Agreement Enhanced Transparency Framework. Funding of REDD+ in the region has also been slow (Karsenty 2020; Eba'a Atyi et al. 2022).

At the national level, forest governance spans community-based management, commercial logging in concessions, and forest conservation in national parks. Commercial logging companies are required to produce Forest Management Plans (FMPs) and may be required to adopt sustainable forestry practices and to secure certification from the Forest Stewardship Council (FSC) (Tritsch et al. 2020). Community-Based Forest Management (CBFM) is well established in Cameroon and DRC, where it has empowered local communities to participate in ways that reduce conflict and promote equitable benefit sharing and sustainable forest management (Lucungu et al. 2021).

Forest conservation focuses on protected areas, including national parks that exclude subsistence activities, community reserves that allow some subsistence activities, and wetlands that fulfill national commitments under the Ramsar Convention on Wetlands (Doumenge et al. 2021). Effectiveness depends on the commitment of national governments to enforce regulations, engage local communities in conservation efforts, and balance conservation with human development needs. The rights of Indigenous peoples and local communities, who rely on the forest for their livelihoods, are often sidelined in both large-scale forest exploitation and forest conservation projects (Assembe-Mvondo 2013).

Challenges include the weakness of national governance structures, corruption, and the lack of enforcement mechanisms (Karsenty 2020). Ineffective monitoring and enforcement of environmental safeguards lead to environmental degradation. Corruption compromises efforts to reduce deforestation driven by agriculture (particularly oil palm, cocoa, and rubber plantations), mining, and infrastructure development (Eba'a Atyi et al. 2022).

Efforts to improve forest governance focus on the capacity of forest management institutions, transparency in concession allocation, and strengthening monitoring systems. They involve institutions such as the Centre for International Forestry Research (CIFOR), the International Union for Conservation of Nature (IUCN), the German Agency for International Development (GIZ), USAID's Central Africa Regional Program for the Environment (CARPE), and the Central African Forest Initiative (CAFI). In addition, networks of civil society organizations such as the Network of Indigenous and Local Populations for the Sustainable Management of Forest Ecosystems in Central Africa (REPALEAC) are involved in strengthening local participation and advocacy efforts.

Actors and Institutions

Forest governance in the Congo Basin includes both governmental and nongovernmental actors. Governmental actors include both national agencies and international cooperative institutions. Nongovernmental actors include local and

international nongovernmental organizations (NGOs), international research institutions, and international certification bodies.

Governmental Actors

Intergovernmental institutions include COMIFAC, which aims to enhance forest governance and support international initiatives such as REDD+ (Nago and Ongolo 2021), and the Congo Basin Forest Partnership (CBFP), established in 2002 to protect and sustainably manage the Congo Basin's tropical forests. Collaborative programs, such as CARPE, have been instrumental in addressing environmental challenges while fostering sustainable development (Tyukavina et al. 2018).

Several international development agencies have significant influence on forest governance in the Congo Basin. The major actors include the World Bank, the European Union (EU), America's USAID, France's AfD, Britain's DFID, Germany's GIZ and KfW, and the United Nations (UN) agencies—such as the UNDP, UNEP, and FAO. CAFI, referred to earlier, is a regional multi-donor initiative aiming to reduce deforestation and forest degradation. Recent developments in the USA suggest that at least one of these, USAID, may no longer be involved.

At the national level, the main actors are the relevant ministries and agencies in the Congo Basin countries.[6] Traditional authorities also play a role in governance by bridging the gap between state institutions and local communities, thereby fostering more inclusive decision-making (Majambu et al. 2019). The interplay between local needs and external pressures, such as logging and agricultural expansion, necessitates working with traditional authorities to balance conservation, development, and local needs (Boyette et al. 2022). The effectiveness of national institutions is often undermined by the weakness of political systems and insufficient technical capacity, which have historically led to the failure of forest policies in the region discussed in more detail in section "Country Level Challenges and Prospects."

Nongovernmental Actors

NGOs play a critical role in conservation, sustainable management, and policy advocacy, thereby facilitating the inclusion of local perspectives in policy-making processes (Brown et al. 2014) and ensuring that conservation efforts do not compromise local livelihoods (Mbatu 2011). NGOs and community-based organizations (CBOs) also advocate for the rights of local populations and marginalized groups (Brown et al. 2011) and facilitate the implementation of sustainable practices at the local level.

The World Wildlife Fund (WWF) and the Wildlife Conservation Society (WCS) have both been actively involved in increasing protected areas and promoting sustainable forest management practices. Along with the IUCN, they have

[6] Cameroon: Ministry of Agriculture, Livestock, Fisheries and Food Security, Ministry of Environment, Forestry and Water Resources. Gabon: Ministry of Water and Forests, Sea, and Environment. Democratic Republic of Congo (DRC): Ministry of Environment and Sustainable Development. Republic of Congo: Ministry of Forest Economy. Central African Republic: Ministry of Water, Forests, Hunting and Fishing. Equatorial Guinea: Ministry of Agriculture and Forestry.

contributed to the establishment of twelve priority landscapes that encompass approximately 38% of the forested area in the region, in which biodiversity conservation is integrated with sustainable development (Ordway et al. 2019).

CIFOR has shown how interactions among timber companies, governments, NGOs, and local communities affect the sustainability of practices (Delahais and Toulemonde 2017). Their work emphasizes the importance of integrating local community needs into forest management strategies, particularly in the context of climate change adaptation and mitigation efforts (Brown et al. 2014). In addition, FSC certification aims to improve timber traceability and stakeholder participation. However, while FSC has had some positive impacts, corruption and ineffective governance signal the need for continued NGO involvement to enhance transparency and accountability in forest management (Lescuyer et al. 2021).

Other influential international NGOs include the Rights and Resources Initiative (RRI), the International Land and Forest Tenure Facility, African Wildlife Foundation (AWF), the Territories and Areas Conserved by Indigenous Peoples and Local Communities (ICCA) consortium, and, more recently, the Bezos Earth Fund. Local NGOs recognized for making significant contributions to forest governance in Central Africa include the Center for Environment and Development (CED) Cameroon, Ajemalebu Self Help (AJESH) Cameroon, Nsombou Abalghe-Dzal Association (NADA) Gabon, and the Alliance Nationale d'Appui et de Promotion des Aires et Territoires du Patrimoine Autochone et Communautaire en République Démocratique du Congo (ANAPAC RDC).

Country-Level Challenges and Prospects

Cameroon: Forest governance in Cameroon has evolved significantly since the introduction of the 1994 Forestry Law, which aimed to decentralize forest management and empower local communities. However, it is limited by poor governance practices, corruption, and inadequate law enforcement. Community forestry has certainly contributed to the local well-being (Enukwa et al. 2022) but has largely failed to meet its management and conservation objectives due to governance issues (Ewane 2022; Nuesiri 2022).

The REDD+ program aims to provide financial incentives for developing countries to reduce deforestation and promote sustainable land use practices, but in Cameroon, it is hindered by underfunded state institutions and the lack of clear property rights for local communities (Ngendakumana et al. 2014).

Independent forest monitoring (IFM) networks have emerged as a critical factor in enhancing forest governance in Cameroon. IFMs can improve accountability and transparency by facilitating better compliance with management plans (Mbzibain and Ongolo 2019). Their effectiveness has, however, been constrained by weaknesses in the forest administration (Ofoulhast-Othamot 2015) and powerful vested interests (Dkamela et al. 2014).

Central African Republic: Forest governance in CAR faces multiple challenges, including illegal logging, poaching, and land use conflicts (Malhi et al. 2013). In

protected areas, such as Dzanga-Sangha (DSPA), human activities are controlled to preserve biodiversity (Sak et al. 2013). However, their effectiveness is often undermined by external pressures, including poaching and illegal resource extraction. The decline of forest elephant populations due to poaching has consequences for forest structure and biodiversity (Maisels et al. 2013; Poulsen et al. 2018). Since recovery from poaching will require decades, conservation measures are urgent (Turkalo et al. 2017).

The sociopolitical status of CAR compromises forest governance. Political instability has weakened governance institutions and increased corruption (Huggins 2022). There is inadequate oversight of resource exploitation, further exacerbating environmental degradation. The interplay between local communities and governance structures is critical; empowering local populations through participatory governance can enhance conservation efforts and ensure that the benefits of forest resources are equitably distributed (Eba'a Atyi et al. 2022).

Democratic Republic of Congo: The DRC is home to approximately 60% of the Congo Basin's forests. Governance of these forests has been marred by a history of political rivalries, ineffective policy implementation, and ongoing conflict, leading to significant challenges in sustainable forest management and conservation efforts (Majambu et al. 2021). Governance weaknesses are amplified by ongoing armed conflicts, especially in eastern DRC, which create an environment where illegal logging and other unsustainable practices flourish (Mpoyi et al. 2013).

REDD+ was intended to address these governance issues by providing financial incentives for forest conservation (Majambu et al. 2024). The governance framework for REDD+ remains underdeveloped, however, and while there have been some institutional changes, the impact on forest conservation has been minimal (Aquino and Guay 2013). The state's role in forest governance has diminished, leading to increased reliance on markets and reduced protection for local communities (Reyniers 2021).

While rural people rely on forest resources for their livelihood, they lack formal land rights (Majambu et al. 2019). This has led to conflicts over land use and resource extraction, further complicating governance efforts. The lack of a national consensus on the drivers of deforestation and forest degradation partly reflects the fragmented nature of governance in the DRC (Achille et al. 2021). The result is a governance vacuum that undermines conservation efforts.

Republic of Congo: The requirement for forest management plans for timber concessions, which began in neighboring Cameroon, has been adopted in the RoC. This helps regulate logging and so mitigates deforestation (Mayaux et al. 2013). Extraction rates are currently estimated to be less than 2.5 trees per hectare, which is within the sustainable range (Harris et al. 2021a). Community forest management initiatives are also being promoted to empower local populations and ensure that they benefit from forest resources (Fuller et al. 2019). Such approaches help conserve biodiversity and improve the livelihoods. The integration of traditional authority in forest governance has been proposed as a means to address issues of illegal logging (Majambu et al. 2019). By recognizing customary rights and involving local stakeholders in decision-making processes, governance can be more effective and equitable.

Forest governance in RoC is influenced by commitments under REDD+ (Aquino and Guay 2013), to address deforestation and promote biodiversity conservation and sustainable land use (Nasi et al. 2012). Remaining challenges include pressure from agricultural expansion, illegal logging and infrastructure development, lax law enforcement, the absence of alternative livelihoods for those dependent on forest resources (Tyukavina et al. 2018), and ineffective management and monitoring (Stokes et al. 2010).

Equatorial Guinea: Forest governance in Equatorial Guinea is complicated by the sociopolitical context. The country has experienced single-party rule since independence, which has implications for environmental policy and governance (Fielding and Barrientos 2021). The lack of democratic accountability often leads to inadequate enforcement of environmental regulations, resulting in unsustainable exploitation of forest resources. This situation is exacerbated by policies that prioritize short-term economic gains over long-term environmental sustainability (Obiri and Bjeirmi 2019).

Local communities near forests are increasingly aware of the impacts of climate change and deforestation and have adapted their practices accordingly (Gross-Camp et al. 2015). However, they are hindered by limited access to resources and support from the government. The interplay between local perceptions and governance structures is essential for developing effective conservation strategies that align with community needs and ecological realities.

Gabon: Gabon is one of the most forested countries globally, with forest covering approximately 88% of its land area (Austin et al. 2017). The primary challenge in Gabon's forest governance is balancing economic growth with environmental protection. Implementation of mandatory forestry certification and sustainable concessions has enabled Gabon to promote responsible forest management practices (Legault and Cochrane 2021). However, Gabon also aims to become a leading producer of palm oil in Africa, with plans to increase production to 280,000 t per year by 2025 (Burton et al. 2017). This raises concerns about the deforestation and degradation of high-carbon stock areas, as agricultural expansion often encroaches upon forested lands with negative impacts on biodiversity and carbon sequestration (Legault and Cochrane 2021). Effective forest governance frameworks must therefore integrate sustainable practices that mitigate these risks while promoting economic opportunities.

The role of community forestry is increasingly recognized as a vital component of sustainable forest management, ensuring that the rights of forest-dependent communities are respected (Minang et al. 2019) and leading to more equitable and effective outcomes, particularly in areas surrounding national parks where local populations rely heavily on forest resources (Yobo and Ito 2015).

Regional Integration and Deforestation

Natural resource management in the Congo Basin is affected by initiatives at both continental and regional scales. At the continental scale, three initiatives are especially relevant to the issue of deforestation and forest degradation in the Congo

Basin: the African Continental Free Trade Area (AfCFTA), the Program for Infrastructure Development in Africa (PIDA), and the African Union Biodiversity Strategy and Action Plan (ABSAP). At the regional scale, two economic initiatives, the Communauté Economique et Monétaire de l'Afrique Centrale (CEMAC) and the Economic Community of Central African States (ECCAS), and one natural resource management initiative, COMIFAC (Sonwa et al. 2020), promote coordination in the management of the economic activities most responsible for forest loss.

Against the global trend, AfCFTA came into force in 2019 with a remit to

- Progressively eliminate tariffs and nontariff barriers to trade in goods
- Progressively liberalize trade in services
- Cooperate on investment, intellectual property rights, and competition policy
- Cooperate on all trade-related areas
- Cooperate on customs matters and the implementation of trade facilitation measures and establish a mechanism for the settlement of disputes concerning their rights and obligations (World Bank 2020)

By creating a continent-wide market, AfCFTA is designed to allow African countries to diversify exports, attract foreign direct investment, and achieve higher rates of growth.

PIDA allows cross-border cooperation in infrastructure projects in four areas: energy production and transmission, including high-capacity oil and gas pipelines; cross-border hydraulic infrastructures; road, rail, sea, and air transport networks; and access to reliable and affordable information networks.

ABSAP has five main objectives:

- To strengthen biodiversity governance and practice
- To promote the sustainable use and benefit sharing from biological and genetic resources
- To encourage member countries to adopt ecosystem-based approaches to all sectors that significantly affect biodiversity
- To increase financial resources for biodiversity conservation from all sources
- To build capacity and ensure equity in the implementation of the strategy (African Union 2023)

These objectives map directly into the Kunming-Montreal Global Biodiversity Framework, adopted at the 15th Conference of the Parties of the Convention on Biological Diversity (CBD).

CEMAC and ECCAS have similar development objectives to AfCFTA. CEMAC aims explicitly to promote integration through a monetary union based on the Central African Franc (CFA) used by Gabon, Cameroon, CAR, Chad, RoC, and Equatorial Guinea. CEMAC countries share the same financial, regulatory, and legal structure and apply the same external tariff on imports from non-CEMAC countries (Communauté Economique et Monétaire de l'Afrique Centrale 2024). The broader ECCAS aims to establish a common market and the free movement of goods,

services, capital, and people between countries, to eliminate tariffs and nontariff barriers to internal trade, and to establish an ECCAS/CEMAC common external tariff, along with a common agricultural policy, a common commercial policy, harmonization of economic policies, and standardization of exceptional exemptions allowed in mining, forestry, and oil production (Economic Community of Central African States 2024). These goals are consistent with both AfCFTA and PIDA.

The closer integration of African countries facilitates adoption of a common approach to deforestation and forest degradation. COMIFAC is responsible for coordinating the conservation and sustainable management of Congo Basin forests. It promotes harmonization of forest policy and taxation, biodiversity conservation, the sustainable use of natural resources, ecosystem management, the monitoring of flora and fauna, capacity-building, community participation, research, and the development of biodiversity financing mechanisms (Commission des Forêts d'Afrique Centrale 2024).

Economic Measures to Mitigate the Environmental Effects of Natural Resource Use in the Congo Basin

There are several economic measures aimed at encouraging the adoption of forestry policies that mitigate both the climate and biodiversity consequences of deforestation and forest degradation in the Congo Basin.

Global Environment Facility Climate Change and Biodiversity Programs

The Global Environment Facility (GEF) is the financial mechanism for the United Nations conventions on biological diversity, climate change, and desertification. It makes grants to nations for projects aimed at meeting the terms of the conventions. In principle, the GEF covers the incremental costs of local projects that offer global benefits, where incremental cost means the additional cost warranted by the global benefits delivered by a national project. In the eighth replenishment, STAR GEF 8, 2022–2026, total funding stood at $5.33 billion. Biodiversity accounts for the largest proportion of GEF funding in each replenishment period since 2010 (Fig. 11).

The GEF Program aims to address both the proximate and underlying drivers of deforestation and forest degradation in the region, to improve forest governance, to strengthen the management and financing of protected areas, and to mitigate the damage done by private resource users (Global Environment Facility 2024). The main weakness of the program is the mismatch between the resources committed by national governments to the program and the social benefits it secures. Taking the impact on carbon sequestration alone, a conservative estimate of the annual benefit conferred on the global community—the value of net carbon sequestration of 0.6 billion metric tons—is $55 billion. The annual commitment for climate change to all six countries of the Congo Basin under STAR GEF 8 is $2 million, a serious

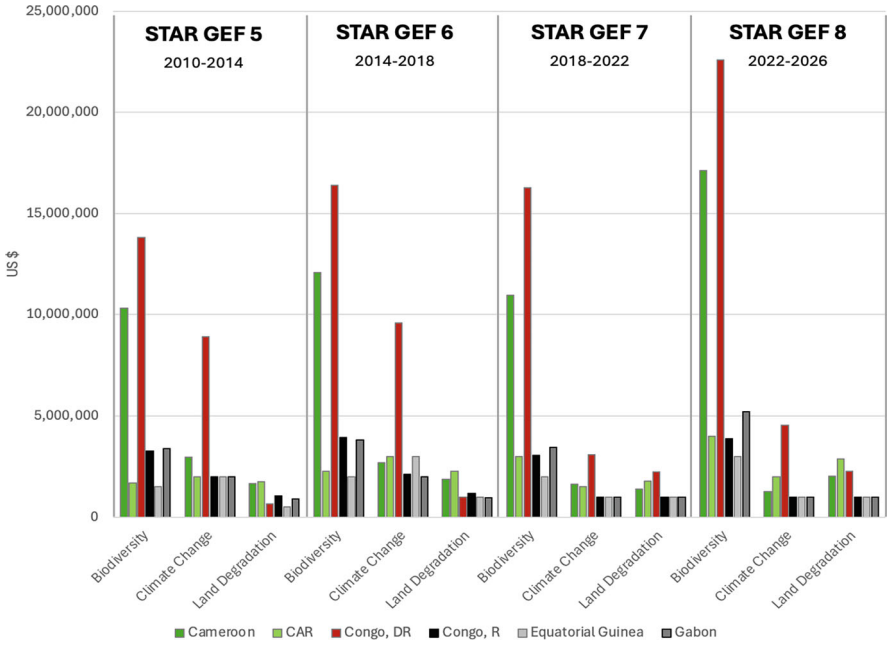

Fig. 11 Global Environment Facility funding for biodiversity, climate, and land degradation projects, 2010–2026. (Data source: Global Environment Facility (2024))

underinvestment in the macroclimatic climate regulation services it provides to the rest of the world.

The Central African Forest Initiative

CAFI was established in 2015 by a coalition of donors and partner countries to reduce forest loss and poverty. CAFI is both a trust fund that invests on the ground and a platform for high-level political dialogue. CAFI funds measures that effectively address both direct drivers of deforestation (agriculture, wood energy, forestry, and mining) and underlying drivers (lack of land use planning and insecure land tenure, poor governance, and rapid population growth). CAFI is the largest UN Climate Fund with $897 million in capitalization.

Other multilateral agencies committing resources to the region, often in partnership with the GEF, include the Food and Agriculture Organization (FAO), the International Fund for Agricultural Development (IFAD), the United Nations Development Programme (UNDP), the United Nations Environment Programme (UNEP), and the African Development Bank (AfDB). As with the GEF, many programs address the root causes of deforestation. For example, the FAO and the Green Climate Fund (GCF), through PREFOREST CONGO, have committed $46.6

million for initiatives to move subsistence farmers away from shifting agriculture and the use of fuelwood toward an agroforestry model that combines trees and crops. The model involves fuelwood plantations with productive agroforestry, agricultural finance, market access, and the restoration of degraded forests (Food and Agriculture Organization 2024). As with GEF, too, the funds committed in such multilateral programs fall well short of the funds that would be warranted by the incremental cost principle.

Development Assistance

An important source of funds to address deforestation and forest degradation in the Congo Basin is official (bilateral and multilateral) development assistance (ODA). Both the magnitude and direction of ODA have changed over time. Figure 12 reports ODA as a proportion of gross national income (GNI) in each of the Congo Basin countries between 1990 and 2020. The figure shows the declining importance of ODA in the oil-rich countries and its increasing importance in other countries, especially CAR. The major reduction in bilateral development assistance by several key donor countries, especially by the USA, is likely to have severe repercussions in the region.

Not all ODA addresses the causes and consequences of deforestation and forest degradation, but some programs have been especially important. USAID's long-standing CARPE has been the largest land management program in sub-Saharan Africa. It aimed to promote the development and implementation of sustainable management plans for the tropical moist forest, focusing on protected areas as

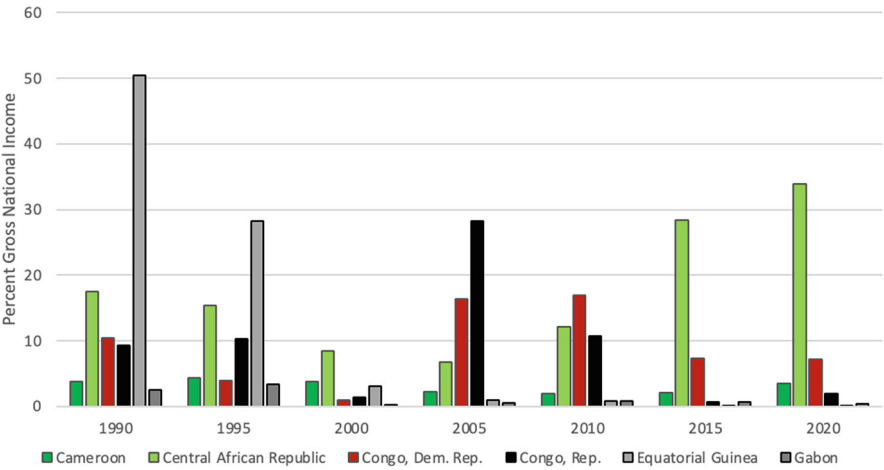

Fig. 12 Official development assistance as a percentage of GNI. (Data Source: World Bank (2024))

anchors for sustainable development (USAID 2022). It is not clear if the program will continue in any form in the future.

Bilateral development assistance for forest projects was boosted by the 26th Conference of the Parties to the UN Framework Convention on Climate Change (UNFCCC) in 2021, when a group of countries (Belgium, France, Germany, Japan, Netherlands, Norway, Republic of Korea, Sweden, UK, and USA, plus the Bezos Earth Fund and the European Union) pledged $1.5 billion for the protection and sustainable management of the Congo Basin forest.[7] The 2022 Congo Basin Pledge Report indicates that around 70% of the pledged funds had been expended by the end of that year, whether through bilateral projects or through the Central African Forest Initiative (CAFI) (Congo Basin Forest Partnership 2023). Projects focus both on strengthening protected area management, on assuring sustainable land use, and on reforesting deforested areas. It is also not clear that bilateral funding for climate programs on this scale will be maintained into the future.

REDD+

The financial element in REDD+ has already been identified as one of the challenges to be addressed. The valuation of carbon sequestration services provided by the Congo Basin forest, currently estimated at $55 billion annually, is needed to develop the results-based payments (RBPs) embodied in REDD+ (Maniatis et al. 2019). Although several programs exist to support preparation for REDD+ (known as REDD+ readiness), very few REDD+ payments have been obtained by countries in the region. Despite 15 years of effort and millions of dollars in funding for REDD+ readiness across Africa, as of September 2024, Gabon and Uganda were the only African countries to have fully gone through the UNFCCC REDD+ process and to have demonstrated results.

The CAFI RBPs paid to Gabon comprise USD 17 million for emissions reductions of 3,382,204 tCO_2 (at $5 per tCO_2) made in 2016 and 2017, compared to annual emission levels from 2006 to 2015 (Norway's International Climate and Forest Initiative 2021). The Forest Carbon Partnership Facility (FCPF) Carbon Fund is advancing in the DRC (Mai-Ndombe Province) and RoC (Sangha and Likouala Departments). More recently, DRC received a first payment of $19.47 million in June 2025 for reducing 3.89 million tons of carbon emissions through efforts to protect and restore forests in the Mai-Ndombe province (World Bank 2025).[8]

It is not entirely surprising that RPBs have taken time to appear in the Congo Basin countries. This is mainly due to weak governance and corruption, a

[7] An overlapping group of countries (Canada, Germany, France, Japan, Belgium, Denmark, Netherlands, Norway, Korea, UK, and USA plus the European Union) pledged an additional $12 billion in climate finance to forest programs.

[8] It is important to note though that the first FCPF CF payment was made to Ghana in 2020 and to Mozambique in 2021, so there is not such a huge time gap compared to the Congo Basin region, showing that these things also take time.

challenging business environment, a failure to create and manage institutions, and human capacity. The same challenges also affect the volume and value of the voluntary carbon market (VCM) forest projects (REDD+, afforestation/reforestation, reduced impact logging, etc.) in the region.

Although not yet fully operational, Article 6 of the Paris Agreement on voluntary cooperative implementation of nationally determined contributions (NDCs) might provide more climate finance and carbon finance opportunities in the future for Congo Basin countries to mitigate climate change, either through government-to-government agreements using Internationally Transferred Mitigation Outcomes (ITMOs) (Article 6.2) or through the Paris Agreement Crediting Mechanism (PACM, Article 6.4). Under the PACM, which aims to mobilize private sector investment in climate mitigation projects, a company operating in one country can achieve emission reductions locally and receive credits for those reductions. These credits can then be sold to a company in another country, which may use them to fulfill its own emission reduction commitments or to progress toward its net-zero goals.

Furthermore, the Congo Basin Climate Commission (CBCC) has embarked on a move to develop a carbon registry, paving the way for an African carbon market (United Nations Economic Commission for Africa 2023). The objective is that the CCBC carbon registry will function as a transparent and credible carbon platform to attract investments in low-carbon projects across Africa. This should bolster forest conservation and restoration efforts and promote progress in renewable energy sources and sustainable infrastructure.

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Agriculture, Ecosystem Functions, and Services in the Congo Basin

12

Lucie Félicité Temgoua, Nyong Princely Awazi, Denis Jean Sonwa, Etienne Yusufu Kachaka, Salomon Mampeta Wabasa, and Emmanuel Abwe

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Abstract

Agriculture in the Congo Basin is essential for food security and economic development, but it faces major challenges such as deforestation, biodiversity loss, and climate change. Agricultural systems, ranging from industrial agriculture to subsistence practices, are transforming the landscape and damaging ecosystems and their ability to provide ecosystem services. While industrial agriculture drives significant land conversion, especially for oil palm and rubber, smallholder and subsistence farming (often through shifting cultivation) remain the dominant cause of deforestation. Agricultural policies often favor multinational companies, leading to land leases over communities' rights and environmental protection. Moreover, policies such as the European Union Deforestation Regulation pose new challenges and opportunities for local farmers. To safeguard ecosystems and livelihoods, the path forward must prioritize sustainable land management practices such as agroforestry and conservation agriculture that balance productivity with environmental protection.

Keywords

Subsistence agriculture · Industrial farming · Ecosystem services · Deforestation · Biodiversity loss · Land leases · Agroforestry

Introduction

Agriculture is the cornerstone of global food security and economic stability, supporting billions of livelihoods through diverse practices that range from industrial monocultures to small-scale subsistence farming. Across many regions, particularly in developing countries, small-scale or subsistence agriculture remains the backbone of rural livelihoods. However, these farming systems are under threat from unsustainable practices and climate change, leading to a decline in yields, thus impacting on food security in the context of growing food demand and population

growth. In the Congo Basin, small-scale farming and, to a lesser extent, industrial farming have transformed the landscape, leading to significant environmental challenges. The legal framework governing land use often favors multinational companies, resulting in extensive land leases that disrupt local ecosystems. As both industrial and subsistence agriculture expand, they contribute to deforestation, biodiversity loss, and ecosystem degradation. However, sustainable practices such as agroforestry offer promising solutions, allowing for enhanced productivity while preserving the region's vital ecological functions. Understanding these dynamics is essential for fostering a balanced approach to agriculture in the Congo Basin.

Agriculture Throughout the World

Worldwide, the agricultural sector plays a strategic role in improving the availability of food and achieving food security (Smutka et al. 2009). Agriculture is the largest employment sector globally. In agriculture-based countries, including most of Sub-Saharan Africa, on average, agriculture generates 29% of the gross domestic product (GDP) and employs 65% of the labor force (World Bank 2008). However, the greatest problems with ensuring food security are observed in developing countries with a high percentage of agriculture in their GDP, where adverse conditions, climate change, and deficient infrastructure hinder production (Pawlak and Kołodziejczak 2020). Global food demand in 2050 is projected to increase by at least 60% above 2006 levels, driven by population and income growth, as well as rapid urbanization (FAO 2016). Growth in agricultural production is constrained by increased scarcity and diminished quality of land and water resources. In many countries, the expansion of agricultural land for subsistence and commodity crops is among the main causes of land-use change and deforestation (Ordway et al. 2017, 2019a; Tyukavina et al. 2018; Branthomme et al. 2023). These not only contribute to the loss or fragmentation of natural habitats but also result in carbon stock reduction and global greenhouse gas emissions.

History and Geographic Extent of Agriculture in the Congo Basin

In the Congo Basin rainforest, agriculture did not emerge locally; it was introduced from elsewhere after the third millennium BCE (Neumann 2005). Archaeological evidence suggests that agriculture was introduced into the Central African rainforest from the drier West African savanna, coinciding with a major climatic change that amplified seasonality just after 2500 BCE (Neumann et al. 2012). One of the most significant events in the agricultural history of Central Africa was the Bantu migration (Phillipson 2003). As they migrated, the Bantu people introduced crops, including bananas, millet, and yams, in new areas. They also introduced iron tools and helped people in the new areas to change from using stone tools. This shift led to an increase in food production and had significant impacts on the Congo Basin forest ecosystem (White and Oates 1999; Oslisly et al. 2013).

Agriculture is by far the largest employer in the Congo Basin region. Except in Gabon, in other countries, more than half of the economically active population is

engaged in agricultural activities. Agriculture is characterized by traditional subsistence systems with low input and low production levels, and the gap between potential and actual yields is huge (Magevand 2013). The dominant type of agricultural practice is slash-and-burn shifting cultivation with fallow periods of varying lengths. The most common form of agriculture is family farming, dominated by food crops. However, there is also a form of market-oriented family farming, involving food crops (cassava, maize, potatoes) and cash crops such as cocoa, coffee, and palm oil (de Wasseige et al. 2015).

With colonization, agriculture underwent transformations with the introduction of cash crops. Originally grown on colonial plantations, these crops were gradually adopted by local farmers. In Cameroon, cocoa and coffee have rapidly become the main source of income for farmers. Coffee and cocoa are produced in agroforestry systems where many woody species are introduced or maintained to provide shade for cash crops and diversify production and income sources. These systems not only help farmers achieve their livelihood goals but also provide important ecological services, including biodiversity conservation and carbon sequestration. Cocoa-based agroforestry systems have been extensively described in literature, particularly in terms of their structure and diversity (Abada Mbolo et al. 2016; Saj et al. 2017; Sonwa et al. 2017), and their carbon sequestration potential, up to 138 $tC.ha^{-1}$, demonstrating their importance in the fight against climate change (Madountsap et al. 2019).

Oil palm is the most widespread commodity in Central Africa (Feintrenie 2014). From 1990 to 2017, the land area allocated to oil palm plantations increased by 40% (Ordway et al. 2019b). Oil palm is cultivated in both smallholder plantations and industrial plantations operated by multinational companies (Magevand 2013; Ozigis et al. 2024). Agricultural policies in the Congo Basin have evolved over time, adapting to development strategies. From the 1960s to the 1990s, a policy of agricultural transformation, known as the Green Revolution, was pursued in developing countries, with the aim of achieving a rate of growth in food production higher than population growth, thus ensuring food self-sufficiency. In Central Africa, as in other regions of the African continent, the objectives of this Green Revolution have not been fully achieved (Griffon 2002). In the 1990s, all Congo Basin countries went through a structural adjustment process with associated dramatic cuts in public expenditures to reduce the substantial external and internal deficits of their economies. The agricultural sector was one of the most impacted by budgetary restrictions: fertilizer and pesticide subsidies were removed, extension services drastically reduced, and the sector was liberalized (Magevand 2013). In recent years, the development strategy plans of Congo Basin countries have included agriculture as one of the economic pillars for development and growth. Therefore, policies aimed at attracting foreign investors and allocating land have led to an increase in the number of agro-industrial concessions.

Legal Industrial Agriculture Framework in the Congo Basin

Agricultural practices in the Congo Basin, particularly industrial agriculture, are shaped by a complex legal framework that varies across the different countries. Each country has developed its legal frameworks to manage agricultural activities,

mostly influenced by international agreements and local priorities. Cameroon has implemented the 1994 Forestry Law (recently updated with the 2024 Forestry Law) and the Agricultural Investment Code, which encourage investment in agricultural projects. In addition, one of the government's targets in its development strategy is to boost production of the main cash crops, including cocoa, coffee, and palm oil. For cocoa, the target is to triple national production by 2030 (MINEPAT 2020).

Gabon has made strides with its 2014 Agricultural Orientation Law, promoting sustainable practices and the development of agroecological techniques. However, the implementation remains uneven, often favoring large-scale agribusiness at the expense of smallholder farmers (Ruysschaert et al. 2023). Equatorial Guinea has seen less focus on agriculture compared to its oil sector, resulting in limited legal frameworks specifically for industrial agriculture. The country's Law No. 4/2009 and Forestry Law No. 1/1997 remain outdated and do not adequately address modern agricultural practices or sustainability (Aghalarli 2022). The Republic of Congo's Land Code seeks to enhance land tenure security but often struggles with enforcement, especially concerning industrial agriculture projects that encroach on community lands (DeValue et al. 2022). The Central African Republic (CAR) faces challenges due to ongoing political instability, which hampers the development of a coherent agricultural policy. The agricultural policy outlines goals for increasing productivity but lacks clarity in legal provisions for industrial agriculture (DeValue et al. 2022).

The industrial agriculture frameworks in the Congo Basin have significant environmental implications, often prioritizing economic gains over ecological stability. The regulatory framework often fails to impose adequate environmental impact assessments, allowing agribusinesses to operate with minimal oversight. In the Democratic Republic of the Congo (DRC), the lack of comprehensive land-use planning has resulted in uncontrolled land clearing for agriculture, impacting critical habitats (Sikuzani et al. 2023). A draft Law on land-use planning was adopted in 2023 but its promulgation is pending. The government's reliance on foreign investments often overlooks local environmental concerns, which can lead to long-term ecological degradation. Gabon's approach to promoting sustainable agriculture is commendable. For example, for palm oil, beyond guaranteeing a robust identification of sites, the government wishes to develop the sector by aligning with international best practices. For environmental, social, and societal protections, Gabon requires, at a minimum, compliance with the national interpretation of Roundtable for Sustainable Palm Oil (RSPO) principles and criteria for certification (Gabon's National Directive 2020). However, actual practices reveal a disconnect between policy and implementation, highlighting the need for stronger enforcement of existing laws (Hetemäki et al. 2023).

Equatorial Guinea's focus on oil has resulted in a neglect of agricultural policy, leading to unsustainable practices when industrial agriculture is employed, often without proper environmental oversight (Aghalarli 2022).

In a study conducted by Sartoretto et al. (2017), the authors examined how existing legal frameworks influence the conversion of forests to agricultural land. They found that legal mechanisms facilitating conversion primarily involve the granting of concessions and licenses for land clearing, which are often accompanied by subsidies. This practice creates an environment conducive to deforestation in parts of the Congo Basin. Furthermore, the application of these legal tools, which

extend beyond environmental considerations, often undermines community-based rights and livelihoods. While there is a push for private sector investment in agriculture, it is crucial to establish robust legal frameworks that protect forests and their associated communities. Strengthening law enforcement is essential to ensure that agricultural development contributes positively to sustainable practices in the Congo Basin.

Thus, the legal frameworks governing industrial agriculture in the Congo Basin present a mixed picture, with each country facing unique challenges and opportunities. While there is a growing recognition of the need for sustainable practices, implementation remains inconsistent.

A Regional Overview of the Land Lease to Multinational Companies for Industrial Agriculture

The Congo Basin has increasingly become a focal point for multinational corporations seeking to expand their agricultural operations. Large-scale land leases are not new in the Congo Basin, but the global food and financial crises of 2007–2009 prompted investors to outsource and secure their food production on a global scale by acquiring vast tracts of agricultural land on long leases (Nguiffo and Sonkoue 2015). There have been several periods of large-scale investment, beginning with the development of large-scale agro-industrial plantations or crops in the colonial era, followed by nationalization in the postcolonial period after independence, and privatization in the 1980s and 1990s (Feintrenie 2014). In Central Africa, at the end of 2013, more than 1.5 M ha had been acquired for agricultural production or plantations (Feintrenie 2014). In the literature, figures on surface areas and the number of deals concluded between investors and the State vary widely from one author to another, making it difficult to obtain precise information. According to Nguiffo and Sonkoue (2015), more than 1.3 M ha of land had been sought by investors for agro-industrial purposes between 2005 and 2013 in Cameroon, mainly for oil palm, rubber, sugar cane, and banana. Hamann and Sneyd (2020) reported 12 agricultural deals concluded in Cameroon between 2000 and 2019 for about 316,887 ha, oil palm plantations representing almost 50% of the surface area, followed by rubber (38%). In Gabon, 356,291 ha of agricultural concessions, the majority for palm oil and rubber, was reported by Legault and Cochrane (2021). In the agricultural sector, the Land Matrix database consulted in October 2024 gave the number of concluded deals and surface areas for the four countries listed in Table 1.

Table 1 Number of land deals and size in the Congo Basin

Countries	Number of deals	Size number (ha)	Number of investors
Cameroon	11	233,643	21
DRC	13	545,032	49
Congo	06	333,000	18
Gabon	08	1,060,131	13

Data source: Land Matrix (2024)

The lease of land for industrial agriculture poses significant socioeconomic and environmental challenges, as various countries within the region adopt differing policies and frameworks. Cameroon has experienced a surge in land leases to multinational companies, particularly for palm oil, rubber, and banana plantations. The Cameroonian government has actively promoted foreign investment in agriculture, often simplifying the leasing process to attract international players (Nguiffo and Sonkoue 2015). However, this has led to land conflicts and displacement of local communities. Moreover, the lack of transparency in the leasing process often exacerbates tensions between companies and local communities. A notable case is the leasing of land to companies like Herakles Farms, which was granted an area of 73,000 ha for palm oil plantations by the State in 2009. The company's operations faced a backlash from local communities and environmental activists, who highlighted the adverse effects on biodiversity and local livelihoods. Further to these accusations, in 2013, the government reduced the area granted from 73,000 ha to 19,000 ha (Feintrenie et al. 2016).

While many companies insist on strict compliance with national regulations, including the implementation of official requirements in terms of social and environmental accountability, some like Olam in Gabon and Blattner Elwyn group in the DRC have voluntarily adhered to sustainable criteria due or not to their commitment to an international sustainability certification process (Feintrenie 2014; Feintrenie et al. 2016). These criteria include the signature of Free Prior and Informed Consent, social impact assessment, and exclusion of high conservation value zones and Ramsar sites from the concession. Indeed, OLAM Palm in Gabon is the only example of a greenfield investment in palm oil that is 100% RSPO certified.

Leasing land for industrial agricultural production in Africa is evolving, influenced by government initiatives aimed at addressing the shortcomings of smallholder agriculture, which has struggled to benefit from the Green Revolution. The leasing process is increasingly shaped by global geopolitics, with actors from new countries and continents, particularly Asia, becoming more prominent in agricultural investments. This trend may sometimes come at the expense of forests in the Congo Basin. These land leases encompass not only the agricultural sector but also intersect with international cooperation and diplomacy between the countries of the Congo Basin and countries outside the continent. In the context of inadequate land-use planning, such developments raise concerns about environmental protection and the rights of local communities. Local and international nongovernmental organizations (NGOs) are actively advocating for environmental safeguards, including the protection of forests, as well as social protections for vulnerable farmers. These civil society organizations have the potential to leverage the legal and regulatory frameworks of both the Congo Basin countries and the countries of origin of foreign investors to promote sustainable practices and protect local rights.

While the Congo Basin presents significant opportunities for industrial agriculture, the implications of land leasing practices must be carefully managed. In the context of emerging international trade regulations on deforestation-free commodities, there is the necessity for sustainable, equitable governance that prioritizes both economic growth and environmental stewardship. The EU's deforestation regulation aims to curb global forest loss by banning imports of products like cocoa, coffee, palm oil, and

timber unless they are proven to be deforestation-free. While promoting global climate goals, it poses serious challenges in the Congo Basin. Lyons-White et al. (2022) highlight that zero deforestation represents an international perspective that marginalizes issues from a national perspective. This may produce unintended consequences that undermine the legitimacy of zero deforestation, including conversion of ecosystems like savannas and disincentives for sustainable business. Also from a local perspective, zero deforestation is embedded in an agro-industrial vision that may marginalize value judgments concerning forests and traditional livelihoods. Only through equitable implementation can the policy both protect forests and support the livelihoods of those living closest to them. A just transition is essential for achieving conservation goals without sacrificing rural well-being in the Congo Basin.

Current Categories and Levels of Agriculture in the Congo Basin

Two forms of agriculture coexist in the Congo Basin. Industrial agriculture, characterized by large-scale operations and monocultures, contrasts sharply with subsistence agriculture, which involves smallholder farms relying on diverse crops for local consumption. The impact of these practices varies significantly by country due to factors such as governance, economic conditions, and agricultural policies.

Industrial Agriculture: Features, Geographic Extent, and Impact on Forest Habitats

Industrial agriculture in the Congo Basin is primarily focused on cash crops such as palm oil, rubber, and cocoa. Palm oil plantations have proliferated due to investment from foreign companies, leading to significant land conversions (Ordway et al. 2019b). Figure 1 shows the evolution of area harvested for the major cash crop in the Congo Basin from 2010 to 2022.

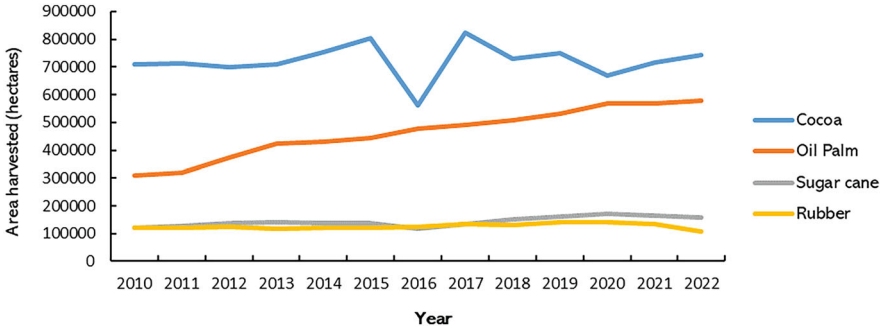

Fig. 1 Area harvested from 2010 to 2022 for the major commodity crops in the Congo Basin (FAOSTAT 2024)

As Fig. 1 shows, even if the area under cocoa cultivation is the highest, oil palm is the fastest-growing commodity in the Congo Basin. For cocoa plantations, Cameroon alone accounts for 84% of cultivated area, while for oil palm, the DRC and Cameroon have the largest areas, with 60% and 35%, respectively, of cultivated area in 2022 (FAOSTAT 2024). However, a study by Ozigis et al. (2024) using Sentinel-1 and Sentinel-2 data for the year 2021 showed that oil palm plantations in the Congo Basin covered an area of 3740 km^2, Cameroon having the highest area and Equatorial Guinea the least. Oil palm plantations include a mixture of both industrial (59%) and smallholder plantations (41% of the area) (Table 2).

The geographic extent of industrial agriculture varies greatly among Congo Basin countries. The DRC stands out due to its vast land area and relative underexploration for agriculture. According to the World Bank (2022), about 21 million hectares have been earmarked for agricultural development in the DRC. In Cameroon, industrial agriculture has rapidly expanded in the Littoral and South regions, where palm oil and rubber plantations are predominant. Forest conversion to monoculture systems (oil palm, rubber, and banana) in Southwest Cameroon has increased significantly since 2000 and accounted for 47% of total deforestation in 2000–2015 (Ordway et al. 2017). Gabon has experienced the most strictly defined landgrab for commodities post-2007/08, with agriculture concessions increasing by 370% since 2008, the majority for palm oil, rubber, and cattle (Legault and Cochrane 2021).

Several countries in the Congo Basin are oil-producing nations, and the development of the oil sector has significantly influenced the relationship between agriculture and forests. In Cameroon, oil revenues have been managed by a government that aims to maintain the country's agricultural identity. This has led to the establishment of large agro-industries in forest landscapes of the Littoral and Southwest regions. These agro-industries have been strategically positioned to facilitate the rapid transport of agricultural products to the nearest ports, primarily Douala.

In contrast, countries like Gabon are experiencing the detrimental effects of "Dutch disease," where increasing oil revenues come at the expense of agricultural development and inadvertently lead to forest protection (Wunder 2003). This dynamic illustrates the challenges faced by these nations. As oil revenues decline,

Table 2 Total area coverage of smallholder and industrial oil palm in the six Congo Basin countries

Countries	Estimated area (km^2)	Industrial oil palm (km^2)	Smallholder oil palm (km^2)
Cameroon	1900	1260	590
Central African Republic	30	20	10
Republic of Congo	60	10	50
DRC	1390	890	500
Equatorial Guinea	10		10
Gabon	410	270	130
Total	3740	2450	1290

Source: Adapted from Ozigis et al. (2024)

there is a pressing need to invest in agriculture, often at the cost of forest conservation.

Utilizing oil or mineral revenues to develop and enhance the agro-industrial sector presents a significant challenge for countries in the Congo Basin. In the Democratic Republic of the Congo (DRC), the government has expressed a commitment to using mining revenues for agricultural modernization. Overall, it seems that there is a gradual effort to move away from the dynamics of Dutch disease and promote sustainable agricultural practices, including agro-industries.

Industrial agriculture therefore poses a significant threat to forest habitats in the Congo Basin, with varying impacts depending on the country-specific context. As the demand for agricultural products continues to grow, the challenge lies in finding sustainable pathways that reconcile agricultural expansion with the urgent need to protect one of the world's most vital ecological treasures that serve as a major carbon sink and biodiversity hotspot. Gabon's Oil Palm Policy, formally adopted by its Land Use Planning Commission and Government, which only allows for oil palm and other industrial agriculture in highly degraded forests and savannas, minimizing carbon emissions and biodiversity impacts, could serve as a model for other countries to follow.

Artisanal and Subsistence Agriculture: Features, Geographic Extent, and Impact on Forest Habitats

Artisanal and subsistence agriculture are critical components of rural economies in the Congo Basin, influencing both livelihoods and environmental sustainability (Kotto-Same et al. 2000; Sonwa and Hanna 2017). Artisanal agriculture is typically characterized by small-scale farming that emphasizes traditional techniques and local resources. Farmers engage in diverse cropping systems, often cultivating cash crops such as cocoa, coffee, or palm oil alongside food crops. Artisanal agriculture can be seen as a bridge between subsistence and commercial farming, as it allows farmers to sell surplus produce in local or regional markets. A study by Shapiro et al. (2023) notes that this system can enhance farmers' incomes and provide access to better markets, but it may also lead to increased environmental pressures if not managed sustainably. Subsistence agriculture, on the other hand, primarily focuses on producing enough food for the farmer's family, with little surplus for sale. This system relies heavily on traditional practices and local knowledge, often involving shifting cultivation and agroforestry methods. Subsistence farmers may grow a variety of crops, but their primary goal is food security rather than profit. According to FAO (2020), approximately 70% of the food consumed in the Congo Basin comes from subsistence agriculture, highlighting its importance in ensuring food security for rural populations.

In the DRC, subsistence agriculture dominates rural landscapes, with over 90% of farmers relying on this method for their livelihoods (Shapiro et al. 2023). Rapid population growth and land pressure have led to deforestation as farmers clear land for cultivation. Artisanal agriculture is also present, particularly in the eastern

regions, where cash crops are increasingly promoted. Cameroon and Gabon exhibit a blend of both agricultural types. In Cameroon, artisanal agriculture is significant in areas like the Southwest, where cash crops are cultivated alongside subsistence farming. Gabon, while primarily forested, is experiencing encroachment of both types of agriculture, driven by logging activities and land conversions for cultivation.

Forest and Land Degradation Rates Due to Industrial and Subsistence Agriculture

In the Congo Basin, small-scale forest clearing for agriculture is the largest direct driver of forest disturbance (Tyukavina et al. 2018; Shapiro et al. 2023). Tyukavina et al. (2018) found that between 2000 and 2014, 84% of forest disturbance in the region was due to small-scale, nonmechanized forest clearing for agriculture, while large-scale clearing for agriculture constitutes only about 1% of the overall forest area loss. Annual rates of small-scale clearing for agriculture in primary forests and woodlands doubled between 2000 and 2014, mirroring increasing population growth. Smallholder clearing in the Democratic Republic of the Congo alone accounted for over 90% of total deforestation. In both DRC and CAR, more than 90% of forest loss is due to small-scale clearing for rotational agriculture.

In Southwest Cameroon, forest conversion to agriculture increased by 10%, from 0.08% in 1986–2000 to 0.09% in 2000–2015 (Ordway et al. 2017), with industrial agriculture contributing only 17% of deforestation, while 83% of agricultural expansion into forest areas was driven by nonindustrial actors. During the same period, two-thirds of oil palm expansion occurred at the expense of forest, and over two-thirds of all expansion was carried out by nonindustrial producers, near small-scale, low-efficiency, informal mills (Ordway et al. 2019a).

In a global effort to address slash-and-burn agriculture in the tropics, led by CGIAR centers, a benchmark representing the rural characteristics of the Congo Basin was established in southern Cameroon, through a process facilitated by the International Institute of Tropical Agriculture (IITA). This research provided insights into the general characteristics of farming systems in the forest fringe of the Congo Basin and their impacts on the forest (Kotto-Same et al. 2000). The benchmark outlines various pathways related to the conversion of land cover, primarily forests, to different land uses, particularly smallholder agriculture. It also includes environmental metrics, such as biodiversity and carbon stock, associated with various land conversions toward agricultural practices. This work was recently complemented by a study conducted by Mangaza et al. (2022) in the Yangambi Landscape (DRC).

Among smallholder agricultural practices, the conversion to food cropping systems generally has a more detrimental effect on the original forest species composition and carbon stock compared to certain agroforestry practices, such as cocoa agroforestry. The latter may preserve some forest species and thus maintain a noneligible biomass, as well as products and ecosystem function at a lower magnitude.

Forest and land degradation in the Congo Basin due to agricultural practices presents a complex and varied landscape across different countries in the subregion. Generally, contrary to what one would expect, compared to industrial agriculture, small-scale and subsistence agriculture, though less damaging per unit area, can lead to significant cumulative effects when practices are unsustainable.

Agriculture and Ecosystem Health and Functional Degradation

The encroachment of agricultural activities in this biodiverse region provokes a decline in wildlife species populations. Additionally, the burgeoning bush-meat trade, fueled by agricultural demands, further exacerbates the decline of wildlife populations, as local communities rely on hunting to supplement their diet and livelihoods. The establishment of road networks to facilitate agricultural access not only fragments habitats but also accelerates illegal logging and poaching, intensifying the pressure on already vulnerable species. Agricultural practices are equally altering freshwater ecosystems, leading to soil degradation and loss of aquatic biodiversity.

Agriculture-Driven Decreases in Abundance and Species Extirpation

Agricultural encroachment into this biodiversity-rich region has led to a loss in the population of wildlife and plant species. The loss of the forest not only reduces habitat availability but also disrupts ecological networks. In an agricultural system, the diversity of interactions between species decreases, or even collapses, depending on the intensity of agricultural treatments (physical, chemical, and biological) imposed (Teyssedre 2025). A study by Wich et al. (2014) shows that in most Central African countries where great ape species predominantly inhabit rainforests, a large proportion of land (49%) containing sustainable environmental conditions for these species overlaps with suitable oil palm area. This is, however, not the case in Gabon (RSPO 2016). Ozigis et al. (2024) report that the transition from tropical moist forest cover to oil palm within most of the six Congo Basin countries suggests the conversion of over 1000 km^2 of forest within great ape ranges to oil palm between 2000 and 2021. This led to a decline in great ape subspecies' ranges, especially *Gorilla gorilla gorilla, Pan troglodytes troglodytes, Pan troglodytes schweinfurthi,* and *Pan paniscus*. That said, this is much less than in SE Asia where oil palm has replaced an estimated 60–80,000 and 20–30,000 km^2 in Indonesia and Malaysia, respectively (Gunarso et al. 2013). However, oil palm development in Gabon is only allowed in low ape density forests and strong environmental and social impact assessment (ESIA) laws require in-depth studies to be validated before starting an oil palm plantation (RSPO 2016; Gabon's National Directive 2020).

In Cameroon, Mahmoud et al. (2020) and Whytock et al. (2021) report that the conversion of forest to agriculture has led to the decline of species such as the Western lowland gorilla (*Gorilla gorilla gorilla*) and the forest elephant (*Loxodonta*

cyclotis). The fragmentation of habitats isolates populations, reducing genetic diversity and increasing the risk of local extirpation. Most countries have implemented some conservation measures, including the establishment of protected areas. Gabon established a network of 13 national parks in 2002, protecting 11% of its national territory. Although the enforcement of these measures often falters due to economic pressures and corruption, Gabon has put in place adequate mechanisms to ensure that conservation measures are effectively implemented (Laguardia et al. 2021).

Agricultural land is generally known to have a negative impact on wildlife (see details in Weinbaum et al. 2007). Consolee et al. (2024) indicate that agricultural expansion is a primary driver of habitat loss, pushing wildlife closer to human settlements and facilitating hunting. On a global scale, Gaston et al. (2003) estimated the reduction in global terrestrial avifauna (excluding seabirds) due to the expansion and intensification of agriculture from the Neolithic period to 1990 to be about 30 billion birds, or 20–25% pre-agricultural numbers.

Concerning flora diversity, a study by Mangaza et al. (2022) in the forest landscape of the Yangambi (DRC) shows that forests have higher tree richness and densities compared with agricultural lands. The conversion of forests into agricultural land also affects the function of ecosystems, particularly in terms of carbon storage. Studies carried out in Cameroon (Njomgang et al. 2011; Temgoua et al. 2018) and DRC (Mangaza et al. 2022) have shown a decrease in carbon stocks from primary forest to mixed crops, with this decrease being up to 97% of the total carbon in the above-ground biomass.

The introduction of non-native plants for agricultural purposes is another concern linked to agricultural practices in the Congo Basin. Some of these species have become invasive species. One example is *Chromolaena odorata*. Native to tropical America, *C. odorata* was introduced to the Congo Basin from West Africa in the early 1960s as a cover crop for cocoa (Ngobo et al. 2004). Nowadays, the plant is an aggressive competitor with food crops. *C. odorata* forms dense stands, preventing the establishment of other species, both due to competition and allelopathic effects and, when dry, it becomes a fuel that may promote wild bushfires (GISD 2025). In freshwater ecosystems, Numbere and Moudingo (2023) highlight the displacement of native flora and fauna due to the introduction of *Nypa fruticans*. Invasive species can alter nutrient dynamics and disrupt food webs, ultimately reducing biodiversity. The interplay between agriculture and invasive species underscores the need for careful management practices to prevent ecological imbalance.

It is also important to notice that persistent pests and diseases significantly reduce crop productivity. The most damaging are cassava mosaic disease (CMD), cassava brown streak disease (CBSD), bacterial blight (*Xanthomonas axonopodis*), and root rot caused by fungi such as *Phytophthora* spp. (Chikoti and Tembo 2022). Cassava, the region's most important food crop, is especially vulnerable to CMD and CBSD, which are transmitted by the whitefly vector *Bemisia tabaci* and can cause yield losses of up to 90% in susceptible varieties. Insect pests such as cassava green mites (*Mononychellus tanajoa*), mealybugs (*Phenacoccus manihoti*), and the root scale insect *Stictococcus vayssierei* are also prevalent, particularly in humid forest zones (Doumtsop et al. 2020). These pests stunt plant growth, reduce root size, and open

pathways for secondary infections. Traditional methods of pest control are often ineffective or unaffordable for smallholders, making genetic resistance a critical strategy.

Agriculture-Driven Road Networks

Road infrastructure is crucial for linking rural agricultural producers to urban markets. According to a study by Badibanga and Ulimwengu (2020), inadequate transportation infrastructure significantly hampers agricultural productivity by increasing the cost of inputs and limiting access to markets. In DRC, the National Strategic Plan for Agricultural Sector Development emphasizes the need for investment in road networks to improve food distribution and stimulate local economies. Sadiki et al. (2020) highlight that road improvements in this country have led to increased agricultural output, as farmers gain better access to markets. However, many rural areas remain inaccessible, particularly during the rainy season.

The development of agriculture-driven road networks raises significant environmental concerns across the Congo Basin. The expansion of roads often leads to deforestation and habitat fragmentation. A study by Mahmoud et al. (2020) notes that in Cameroon, road construction has led to increased agricultural encroachment into previously protected areas, jeopardizing biodiversity. In contrast, Gabon's approach to road network development includes provisions for environmental impact assessments and the establishment of wildlife corridors, as outlined in the study by Vanthomme et al. (2019). This proactive strategy aims to balance agricultural expansion with conservation efforts, demonstrating a model that other countries in the region could emulate. A World Bank annual report (2017) found that investments in rural roads primarily benefited wealthier farmers with access to better resources, leaving smallholders behind. Cameroon has implemented community-based road construction projects, which involve local farmers in the planning and execution stages. This participatory approach not only improves road quality but also ensures that the benefits of road access are more equitably shared (Ngwa and Wanie 2022).

Impact of Agriculture on Freshwater Ecosystems and Biodiversity

The Congo Basin, with its network of rivers, lakes, and wetlands, plays a vital role in supporting both ecological integrity and human livelihoods. Very rich in biodiversity, the Congo River Basin has over 1200 fish species, 400 mammal species, 1000 bird species, and over 10,000 vascular plant species (Harrison et al. 2016). Agricultural practices can influence freshwater ecosystems and overall biodiversity. On the scale of the Congo Basin, agricultural activities represent the second cause of soil erosion and sedimentation in rivers after deforestation (Mushi et al. 2019).

In Cameroon, studies have documented the effects of shifting cultivation and the use of agrochemicals on local waterways. The introduction of fertilizers has led to

nutrient loading in rivers, resulting in eutrophication—a condition detrimental to aquatic life (Jokam Nenkam et al. 2022). Ayompe et al. (2021) highlight that the establishment of oil palm plantations next to water bodies causes eutrophication and siltation, impacting local water purification and supply services. Eutrophication decreases oxygen levels, harming fish populations and altering the natural balance of freshwater ecosystems. In the DRC, the conversion of wetlands for agriculture has had similar consequences. Agricultural runoff contributes to increased sedimentation in rivers, which affects water clarity and disrupts habitats for various fish species (Niba et al. 2022). In the Congo River, Inogwabini and Lingopa (2013) found that fish morphotype richness decreased with increasing field sizes. The destruction of wetlands, which act as natural filters, exacerbates the issue, leading to a decline in water quality and overall biodiversity.

While agricultural expansion contributes to habitat destruction, water quality degradation, and biodiversity loss in the Congo Basin, there are opportunities for sustainable practices like conservation agriculture and agroforestry that can mitigate these effects. It is imperative that stakeholders across the Congo Basin collaborate on sustainable agricultural practices, implement effective policies, and engage local communities in conservation efforts.

Human–Elephant Conflicts in the Congo Basin

Human–elephant conflict (HEC) in the Congo Basin has intensified in recent decades, primarily due to the increasing overlap between agricultural expansion and forest elephant (*Loxodonta cyclotis*) habitats (Maurice et al. 2023). Forest elephants, which roam vast tracts of tropical rainforest in countries like Cameroon, Gabon, and the Republic of Congo, are drawn to farmlands due to the availability of nutrient-rich crops such as cassava, bananas, and maize (Blake and Maisels 2023). In southern parts of Cameroon, studies have shown that elephants often target farms located near forest edges, particularly during the night, making it difficult for farmers to deter them without risking their safety (Maurice et al. 2023). Matsuura et al. (2024) observed that in Gabonese villages surrounding Moukalaba-Doudou National Park, elephant raids have led to farmers abandoning their fields, constructing makeshift shelters in farmlands, and in some cases, relocating entirely. In the Democratic Republic of Congo, villages have experienced fatal elephant encounters, leading some women to abandon agriculture entirely (Trogisch 2023). These conflicts are not only economic but also psychological, with many communities reporting increased fear, food insecurity, and a breakdown in traditional farming practices. Efforts to reduce HEC have included electric fencing, chili-based deterrents, and beehive fences, the latter of which have been effective in other parts of Africa. However, long-term solutions must integrate landscape-level land-use planning with community involvement and sustainable livelihoods to ensure both elephant conservation and human well-being.

Impact of Farming on Carbon Balance in the Congo Basin

Agriculture in the Congo Basin significantly influences the regional carbon balance, primarily through deforestation and forest degradation associated with small-scale farming. Slash-and-burn agriculture, a dominant land-use practice in the region, is the leading cause of forest loss and carbon emissions. Shifting cultivation involves clearing forested areas for temporary crop production, followed by fallow periods. Although this system traditionally allowed some forest regeneration, increasing population pressure has shortened fallow cycles, leading to net carbon losses (Tanzito et al. 2020). Moreover, degraded forests, even after fallow, do not recover their original carbon storage potential. Michel et al. (2022) noted that most disturbed forest areas remain in a degraded state rather than regrowing fully, which contributes to long-term reductions in above-ground carbon stocks. Soil carbon is also impacted, as frequent burning depletes soil organic matter and microbial activity (Drake et al. 2020). Burton et al. (2017) predict that the conversion of 11,500 ha of logged forest to a palm plantation in Gabon will release 1.50 Tg C. These emissions could be completely offset over 25 years through sequestration in planned forest set-asides given a ratio of 2.6 conserved hectares to each hectare of logged to converted forest (Burton et al. 2017).

Climate-smart agricultural approaches, particularly agroforestry and conservation agriculture, show promise in restoring carbon balance. Agroforestry systems that integrate nitrogen-fixing species such as *Acacia* and crop cultivation have been shown to enhance both soil fertility and carbon sequestration. Drake et al. (2020) demonstrated that such systems significantly increase organic soil carbon and maintain higher biomass compared to conventional cropping systems. Conservation agriculture (characterized by minimal soil disturbance, permanent soil cover, and crop rotation) further improves soil structure, water retention, and carbon sequestration (Molua et al. 2023). Fixing farmers on a single plot reduces the incentive to slash and burn new forest, cutting emissions and preserving biodiversity. Simultaneously, increased productivity per hectare means that food needs can be met without expanding agricultural frontiers.

Agroforestry Systems and Sustainable Agriculture Practices

Agroforestry systems in the Congo Basin present a promising solution to the myriad challenges facing the agricultural sector, particularly in the context of sustainable agriculture. With increasing pressures from deforestation, soil degradation, and climate change, integrating trees with crops and livestock can enhance biodiversity, improve soil health, and boost resilience against environmental fluctuations. One notable example is the cocoa-based agroforestry system, which combines cocoa cultivation with shade trees, optimizing land use while promoting ecological balance (Abada Mbolo et al. 2016; Sonwa et al. 2018; Temgoua et al. 2018). This system not only enhances cocoa yields but also supports local ecosystems and provides additional income through the sale of timber and nontimber forest products. Similarly,

agroforestry fallows (periods during which land is allowed to regenerate with natural vegetation) play a crucial role in restoring soil fertility and biodiversity. By adopting these agroforestry practices, communities in the Congo Basin create sustainable livelihoods while conserving their rich natural resources, paving the way for a more resilient agricultural future.

Agroforestry as a Solution to the Many Challenges Facing the Agricultural Sector

The countries of the Congo Basin face many challenges, including climate change, food insecurity, land degradation, and high levels of poverty. In such a context, it is crucial to identify agricultural practices that would meet these challenges while promoting sustainable agriculture. One solution would be to resort to diversified agriculture involving cropping systems based on agroforestry. Agroforestry is a generic term referring to land-use systems in which trees are deliberately associated with agriculture (agricultural crops and/or livestock) for a variety of benefits and services (Atangana et al. 2014). Because of the presence of trees, agroforestry has different ecological, economic, and sociological implications than conventional agriculture (Atangana et al. 2014; Muthee et al. 2022). In the Congo Basin, many studies have demonstrated the benefits of agroforestry practices in terms of improving soil fertility (Koutika et al. 2021; Kachaka et al. 2023) contribution to (Sonwa et al. 2018) improving farmers' incomes and reducing farmers' vulnerability to climate change (Awazi et al. 2019). The different types of agroforestry systems are complex and diverse. Their characteristics differ greatly according to system design, objectives, and the species involved. Among the most common agroforestry systems are annual and perennial crops under shade, multi-strata systems (such as family gardens and successive farming systems), silvopastoral systems, hedgerows, and windbreaks (Montagnini and Metzel 2024).

The Cocoa-Based Agroforestry System

The cocoa-based agroforestry systems (CAS) are mainly composed of cocoa (*Theobroma cacao* L.) grown under the shade of other trees. Most of the woody species present in the system are those that were spared during land clearing, but according to the context, farmers can also introduce trees in their farms. These forest trees, intentionally maintained, are those that provide shade to cocoa trees in addition to other goods and services (Atangana et al. 2014). The complexity of these systems should optimize the use of the resources available in the system. Thus, when installing cocoa trees, farmers choose to maintain or introduce trees that play one or more roles, notably shade, food, medicine, and wood (Saj et al. 2017; Michel et al. 2024).

The complex structure of CAS contributes to the conservation of biodiversity. A study by Abada Mbolo et al. (2016) reveals that in the central region of Cameroon, CAS appear to conserve 46% of forest tree species found in nearby forests. CAS also

have a high potential for carbon storage compared to other agricultural systems, depending on the managing systems adopted by farmers. Madountsap et al. (2019) reported an above-ground carbon stock of 125.3 tC ha^{-1} in traditional CAS in Central Cameroon, while in Yangambi in DRC, Batsi et al. (2021) found an amount of 44.48 tC ha^{-1}. It should be noted, however, that the quantity of carbon stored by CAS remains lower than that of forests in most cases. A study by Temgoua et al. (2018) in East Cameroon reports that CAS appear to store 57% of the amount of carbon stored by nearby forests. Cocoa-based agroforestry systems can, under certain conditions, provide satisfying yields. Jagoret et al. (2014) reported that in Cameroon, the yield of agroforestry cocoa farms in which cocoa trees were planted at a density of 1000 plants per hectare in association with a hundred trees (70% fruit and 30% forest) could exceed 900 kg/ha after about 20 years. This annual yield was similar to or even higher than that of some cocoa farms managed in monoculture.

However, despite its assets, cocoa cultivation is not without risk in the Congo Basin. Ngouhouo-Poufoun et al. (2024) show that as currently produced in the Tridom landscape, cocoa is an agricultural commodity entailing a high risk of deforestation if the income from cocoa production increases. Kamath et al. (2024) highlight the Congo Basin's central belt as an area where biodiversity would be put at high risk from cocoa expansion. Policies for expanding this crop should therefore take account of these high-risk areas to limit the impact on biodiversity and other ecosystem services. Cocoa is one of the commodities concerned by the deforestation-free regulations from the European Union that ban imports of cocoa linked to recent forest clearance. While this policy aims to reduce global deforestation, it creates complex challenges for smallholder farmers in the region. Cocoa farming requires long-term investment. Trees typically take 3–5 years to mature and produce commercially viable yields. For farmers with limited resources, this delay in return makes cocoa a high-risk crop, especially in contexts where there is little financial support, market stability, or infrastructure. With the EU's new regulation, cocoa producers must also meet strict traceability and land-use standards, which many smallholders are ill-equipped to fulfill without external assistance. This raises the risk of exclusion from EU markets, threatening livelihoods and potentially pushing farmers toward unsustainable practices or illegal markets. To support compliance and ensure cocoa contributes to sustainable development, investments are needed in farmer training, agroforestry systems, cooperative organizations, and financial incentives during the establishment phase. Without such support, the regulation could undermine smallholder resilience rather than promote forest conservation. Balancing economic viability and environmental goals is essential to making deforestation-free cocoa a reality in the Congo Basin.

Agroforestry Fallows

Agroforestry fallows consist of planting trees during the fallow period (a period of rest between harvesting and recultivation), rather than allowing native species to germinate spontaneously (Torquebiau 2007). This agroforestry concept is essentially

based on the ability of trees to restore soil fertility more rapidly by removing nutrients from the lower layers of the soil and returning them through the litter, as well as through nitrogen fixation, in the case of legumes (Kachaka et al. 2023).

In these agroforestry fallows, improving trees are chosen for their ecological function (e.g., trees with mycorrhizal and nitrogen-fixing symbiosis) or economic function (e.g., trees for fodder or likely to produce charcoal), or better still, for both (Torquebiau 2007; Atangana et al. 2014). Agroforestry fallows are likely to improve soil physicochemical properties, maintain satisfying levels of organic matter, and allow better nutrient recycling (Atangana et al. 2014). In Cameroon, Harmand et al. (2017) reported that the N_2-fixing species, *Acacia polyacantha,* increased the nitrogen budget of the system through N_2 fixation and nitrogen recycling and showed a significant increase in soil carbon and nitrogen content (layer 0–20 cm) after 6 years of age. In DRC, Kachaka et al. (2023) reported that *Acacia auriculiformis* fallows stored 1.5 times more carbon than traditional fallow soils. As well as providing farmers with wood, improved fallows reduce fallow time, enabling farmers to return to the plot more quickly, thus reducing pressure on the forest. However, despite the benefits or agroforestry fallow, farmers will only adopt this practice if they are convinced of its profitability. The future of agroforestry fallow diffusion will therefore rely on the implementation of proven, solid techniques, and approaches that can be applied in real-world field conditions. More generally, the success of agroforestry will depend on how its institutionalization in national and local contexts occurs (Ndlovu and Borrass 2021).

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Pastoralism: Access to Land and Ecosystem Functions and Services in the Congo Basin

13

Roger-Louis-Paul Kabelong Banoho, Moses B. Libalah, and Bonaventure Sonké

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Abstract

Pastoralism is a cornerstone of livelihoods and subsistence for millions in sub-Saharan Africa, particularly in arid and semi-arid regions, where rainfall variability limits other agricultural activities. It supports over 20 million people and underpins livestock economies in several African countries, contributing significantly to global agricultural production and food security. Beyond its economic importance, pastoralism plays cultural and ecological roles, reinforcing social bonds, maintaining biodiversity, and promoting ecosystem health through natural grazing patterns. In recent years, climatic conditions, coupled with insecurity in the Sudano-Sahelian zone, have led herders to move increasingly southwards, some even settling in forest areas. This sedentarization is not without consequences for the forests. This chapter reviews the history of pastoralism in the Congo Basin, the factors of adaptation, and their role in ecosystem functions and services.

Despite these challenges, pastoralism remains vital for ecosystem services, providing forage, water, and medicinal plants essential for livestock and herders. Rangelands, including grasslands and savannas, sustain millions of animals and hold cultural and spiritual significance for pastoral communities. Grazing patterns can promote vegetation regrowth and soil health, while pastoral rangelands act as carbon sinks in the savanna zone, mitigating climate change.

Although the importance of pastoralism, when it is practiced without respect for load capacities and the absence of management rules, causes abusive cutting of trees and leads to land degradation and deforestation, pastoralism remains a major socio-economic issue that must be taken into account in the governance of natural resources.

Keywords

Biodiversity · Livestock · Impact on forests · Adaptation · Load capacity

Introduction

Pastoralism is a key livelihood and subsistence strategy for millions in sub-Saharan Africa, involving the rearing of cattle, sheep, and goats in arid and semi-arid regions where rainfall variability limits other agricultural activities (Smith 1993, 2019; Gifford-Gonzales 2017). This system supports over 20 million people and forms the backbone of livestock economies in several African countries. The livestock sector alone accounts for about 40% of global agricultural production, contributing to the livelihoods and food security of nearly one billion people worldwide (The World Bank 2019). In many West African communities, livestock also play ceremonial roles, reinforcing social bonds and traditions (Krätli et al. 2013). Additionally, pastoral practices contribute to dryland ecosystem health by mimicking natural grazing patterns, promoting biodiversity, and maintaining ecological balance.

Despite its adaptability, pastoral livestock farming faces significant challenges, including land-use changes, climate variability, and restrictive policies

(Nori and Davies 2007; IUCN 2011). Secure access to diverse landscapes is fundamental for pastoral sustainability, allowing herders to navigate seasonal and spatial variations in resource availability. Pastoral systems typically operate under communal land tenure, enabling collective rangeland management. However, expanding agricultural activities, land privatization, and rapid urbanization increasingly strain these traditional systems, restricting rangeland availability, fragmenting migratory routes, and undermining communal resource management (Davies et al. 2018).

Pastoral livestock farming depends heavily on ecosystem services that provide essential resources such as forage, water, medicinal plants, and fuelwood. Rangelands—comprising grasslands, shrublands, savannas, and woodlands—support both livestock and herders. In the Sahel, for example, seasonal grasslands sustain millions of cattle and goats (Herrera et al. 2014). Beyond economic significance, rangelands hold cultural and spiritual value for pastoralist communities. Livestock are integral to social identity, ceremonies, and traditions, reinforcing community cohesion (Krätli et al. 2013). Pastoralists also contribute to ecological stability, as grazing patterns can encourage vegetation regrowth and soil health. Additionally, well-managed pastoral rangelands function as carbon sinks, mitigating climate change (Mohamed et al. 2025).

In response to the socioeconomic and ecological importance of pastoralism, several African countries have integrated pastoral livestock farming into public policy (Bonnet and Guibert 2012). This recognition acknowledges pastoralism's role in biodiversity conservation and regional security (Usongo and Moussa 2021). To meet the growing global demand for food, the sector must enhance meat and milk production (Vigne 2014). While pastoralism was historically concentrated in the Sahel, climate change and insecurity are driving its expansion into forested regions. Although precise livestock population estimates are unavailable, studies indicate a significant increase in livestock numbers since the 1990s (FWC 2024). The Economic Community of Central African States (ECCAS) holds an estimated 46 million cattle, 7 million camelids, 57 million goats, and 39 million sheep (FAO 2023). This growth is attributed to improved animal health, vaccination campaigns against diseases such as trypanosomiasis, contagious bovine pleuropneumonia (CBPP), and peste des petits ruminants (PPR), as well as advances in vector control (e.g., tsetse flies and ticks).

Recent trends show increasing transhumant livestock movements from the Sahel to equatorial regions, as well as rising livestock numbers in traditional pastoral areas. However, these shifts have led to socioeconomic tensions, security concerns, and environmental pressures, including illegal trafficking, national park encroachment, and resource conflicts. Neo-pastoralism—characterized by influential investors acquiring vast rural lands for livestock farming—has also contributed to livestock growth in Central Africa.

Pastoral expansion into Central Africa has exacerbated conflicts in rural areas where state governance remains weak (International Crisis Group 2014). These tensions stem from multiple factors, including insecurity, climate change-driven migration, the fragmentation of traditional transhumance corridors, expanding agriculture, and increasing competition for natural resources. While pastoral mobility has historically fostered strong socioeconomic ties between communities, it has also sparked conflicts that persist in collective memory. Furthermore, pastoralism poses

emerging threats to biodiversity, particularly within and around protected areas (Usongo and Moussa 2021). Conservation institutions are now incorporating pastoralism into protected area management plans, as Sahelian and Sudanian protected zones increasingly face incursions from both local and trans-border pastoralists.

Pastoralist presence is impacting protected areas across the Congo Basin, including complex and Chinko zone in the Central African Republic, and Garamba and Bili-Uélé parks in the Democratic Republic of the Congo (Huchon et al. 2021). Beyond conservation concerns, transhumance—though traditionally a seasonal activity managed by small groups (Lhoste 1993)—is now affecting ecosystem services in rural areas across the Congo Basin.

History and Evolution of Pastoralism in Africa

The history of pastoralism in Africa dates to the Holocene, with its origins and expansion closely tied to the development of nomadism (Holl 1998). While traditionally thought to have emerged alongside agriculture and metallurgy in the first millennium AD, archaeological evidence indicates a more complex diffusion process (Kinahan 1994). The Eastern Sahara played a crucial role in early livestock-cantered practices (Jesse et al. 2013). Over time, pastoralism in sub-Saharan Africa adapted to extreme environmental conditions, supporting specialized pastoral societies (Toutain et al. 2012). This evolution has introduced new transhumance patterns, partial decentralization, and income diversification.

According to USAID 2021, there is a deep and complex history of pastoralism in Africa, which varies across regions and communities. African populations have specialized in pastoral livestock breeding for thousands of years, as evidenced by ancient rock paintings in the Sahara and Sahel regions. Pastoral communities occupied vast pasturelands, often unsuitable for sedentary agriculture due to harsh environmental conditions and water scarcity. To diversify their diet and meet basic needs, pastoralists established trade with agricultural communities and engaged in gathering and hunting. As climate conditions shifted and populations grew, pastoralist groups migrated to more suitable areas, continuously adapting their livelihoods and production systems (USAID 2021).

Centuries of environmental, political, economic, and social changes have significantly impacted pastoral communities. However, pastoralism has persisted and expanded across many regions of Africa. Although pastoralists may appear to follow age-old practices, the pastoral system is dynamic and continuously evolving. Modern pastoralists inherit ancestral knowledge but adapt and transform it to meet contemporary challenges and seize new opportunities.

Pastoralism and Cattle Rearing in the Central African Republic

Cattle rearing was largely unknown in the French territory of Ubangi-Shari until the 1920s (Suchel 1967). However, the vast grasslands and dense river systems of the Central African Republic (CAR) have long attracted pastoralists from across the

Sahel. In addition to being an economic issue, livestock farming is increasingly becoming a safety issue. Although the practice is predominant in savanna zones, it is becoming increasingly established at the edge of forests, with impacts spilling over into forests and protected areas. Migration routes, established at least as early as the colonial period, continue to be negotiated today between pastoralists and sedentary farming communities (USAID 2021). Livestock farming in CAR is predominantly practiced by nomadic groups, particularly the Peuls and Ouddas, in search of water, natural resources, and, increasingly, security.

The Peuls, an ethnic group spread across West and Central Africa with millions of members and hundreds of sub-clans, first arrived in the French colony in the early 1920s (Boutrais 1994; Chauvin and Seignobos 2013). Colonial authorities promoted livestock development through investments in veterinary services and milk processing facilities, such as those established by the Sarki company in CAR. Post-independence governments continued this support by implementing land-use plans, known as *Plans d'Exploitation et d'Aménagement* (PEA).

These territorial development plans divided the country into protected areas, mining zones, and hunting reserves. However, enforcing these plans proved challenging. Over time, the Peuls gradually migrated toward the Oubangui River and the northwestern plateaus of CAR, spreading throughout the country in the 1970s into small settlements officially recognized by the government. Despite their Central African citizenship, these pastoral communities often face marginalization and limited access to services. The severe Sahelian droughts of the 1980s pushed pastoral groups further south (Chauvin and Seignobos 2013), while the eradication of the tsetse fly facilitated pastoral expansion into the country's sub-humid regions (Vircoulon 2021).

Recent research highlights significant changes in Central African pastoral systems. Since the 1970s and 1980s, recurrent droughts and agricultural expansion have pressured pastoralists toward sedentarization and livelihood diversification (Dongmo et al. 2012). Traditional nomadic lifestyles are being reshaped by ecological, economic, and social pressures, with notable differences between West and Central Africa (Dongmo et al. 2012). A critical transition from pastoralism to commercial livestock farming is underway, driven by increasing market integration and commoditization (Schareika et al. 2021). This shift from a "livestock logic" to a "capital logic" is exacerbating economic inequalities and altering community relationships (Schareika et al. 2021). Additionally, climate-induced southward migration of Sahelian pastoralists is reshaping regional geopolitics, introducing new conflicts and religious dynamics into the Congo Basin (Vircoulon 2021). These changes pose challenges for sustainable development, necessitating adaptive strategies within pastoral systems.

Pastoral Mobility and Adaptation in the Context of Globalization

To ensure sustainable resource use, pastoralists are continuously adapting to the challenges of globalization by modernizing their mobility systems through the integration of innovative tools essential to transhumance. Increasingly, pastoral communities are incorporating new technologies into traditional practices. Mobile phones are now widely used by herders to access critical information on pasture

conditions, crop levels, and potential conflict zones, enabling them to plan grazing routes effectively. Telecommunications tools such as mobile phones and radios play a vital role in facilitating rapid decision-making during migrations and help pastoralists avoid conflicts when moving from their home areas.

Pastoral mobility is characterized by four key variables (FWC 2024):

(a) **Predictability**: movements can be highly predictable or unpredictable, depending on hazards or events that impact herders' decisions.
(b) **Distance**: movements vary in range, extending from short distances to transboundary migrations.
(c) **Scale**: mobility may involve entire families or only herders moving with livestock.
(d) **Fixed points**: certain key points, such as watering holes with priority access rights, fields that provide land bases, salt collection sites, and social service hubs, are essential for transhumance.

Several interdependent factors drive pastoral mobility in the Congo Basin and beyond, categorized as follows:

(a) **Ecological factors**: Mobility allows pastoralists to adapt herd management to spatial and temporal variations in natural resources, including water, grazing, biomass, and soil fertility. It also reduces pressure on ecosystems and supports biodiversity conservation.
(b) **Economic factors**: Mobility enhances herd productivity and profitability by improving access to markets, veterinary services, inputs, and employment opportunities. It also diversifies income sources and mitigates risks related to climate variability, disease, theft, and conflict.
(c) **Sociocultural factors**: Mobility is integral to the identity, traditions, values, and knowledge systems of pastoralists. It fosters social ties, solidarity networks, cultural exchanges, and mechanisms for conflict resolution among various stakeholders.

Mapping Pastoralism

In 2017, the Observatoire des Forêts d'Afrique Centrale (OFAC) developed a map of cross-border transhumance, conservation (marked by protected areas), and insecurity (OFAC 2022). This map divided the region into three blocks, each containing cross-border transhumance corridors between countries such as Cameroon and Chad, Chad and the Central African Republic (CAR), and the CAR and the Democratic Republic of the Congo (DRC) (Fig. 1). An updated version of the map, published in 2022, incorporated data from the 2017 map while highlighting changes driven by the evolving dynamics of transhumance and pastoralism. Pastoral movements remain closely linked to access to critical resources, particularly water and pasture.

The abundant and accessible grazing land in much of the Congo Basin (notably in the CAR and the DRC) makes these areas prime destinations for livestock from Sahelian countries. Surveys and documentary research have identified several

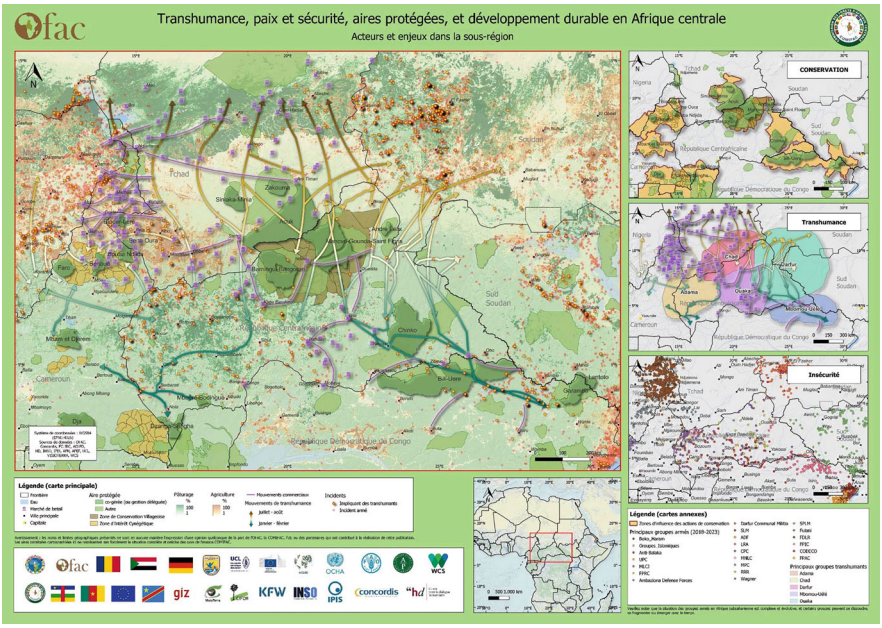

Fig. 1 Cross-border transhumance, conservation, and security in Central Africa (OFAC 2022)

transhumance corridors along national borders, including both official and unofficial routes. Official corridors are recognized by states, while unofficial routes are created by herders to avoid social conflict, such as attacks by armed groups, banditry, kidnappings, extortion by rebels, and other forms of violence.

Many transhumance corridors established since the 1950s now exist only in name, as many have been overtaken by villages and agricultural fields, leading to inter-community conflicts. Interviews with transhumant herders reveal that they no longer follow fixed routes; their movements are influenced by information from scouts and the availability of pasture and water resources.

As part of the Projet d'Appui à la Régulation de la Transhumance Transfrontalière en Afrique Centrale (PARTTAC), Component 2, titled *Transhumance and Pastoral Mobility,* aims to secure transhumance and pastoral mobility in the sub-region. Two transhumance routes have been validated between Cameroon and the CAR to ensure corridor connectivity. One route runs from Touboro in North Cameroon to Bang in Northwest CAR, while the second links Kenzou in East Cameroon to Nouffou in Southwest CAR.

A transhumance route between Cameroon and Chad has also been defined, running from Doumorou in Cameroon's Far North through Goumadji in Chad's Mayo-Kebbi department, avoiding protected areas, and re-entering Cameroon via Mayo Lopé to reach the Touboro district. Between Chad and the CAR, two routes have been identified: one from Baltoubaye in Chad to Korom Mpoko in the CAR, and another from Haraz Dimmé in Chad via Bannanke Kambol to Ngarba in the CAR.

The corridors in this area face numerous challenges, including climate change, agricultural expansion, and armed conflict. Transhumant herders are both perpetrators and victims of armed conflict, with repercussions on their activities, as well as on agriculture and protected area management. Another critical issue is the lack of pastoral infrastructure along the corridors, despite initial efforts in countries like Cameroon and Chad. The absence of watering points forces herders to water their animals in streams, often leading to the destruction of nearby crops and subsequent conflicts between herders and farmers. Similarly, the lack of vaccination points at borders raises concerns among sedentary livestock farmers, who fear that transhumant animals spread diseases.

Pastoralism and Biodiversity

Pastoralism is often viewed as harmful to the environment by many rural stakeholders, yet it is increasingly recognized for its positive contributions to biodiversity conservation (Little 1996). In arid regions, pastoralism plays a critical ecological role by regulating ecosystem services. Pastoralists facilitate the circulation of goods and services in drylands, depending on scarce resources such as fodder and water, while contributing to the stability of these ecosystems. Grazing influences plant fertility, distribution, and diversity, with animals aiding seed dispersal and soil fertilization through digestion and transport over long distances (CDB 2010). Sustainable grazing practices help sequester carbon, reduce erosion, retain soil, and preserve habitats for wildlife. Additionally, pastoral systems often incorporate cultural practices and indigenous knowledge, offering valuable "cultural services" (CDB 2010). Pastoralism also provides direct economic benefits, including meat, milk, fibers, leather, transport, income, and a system of savings and insurance.

Eco-pastoralism has proven effective in managing artificial environments, such as dykes, by maintaining open habitats and enhancing plant species diversity (Moinardeau et al. 2020). Despite challenges like overgrazing and increasing sedentarization, pastoralism remains economically vital, supporting agricultural economies and livelihoods in Sahelian countries (Toutain et al. 2012).

However, pastoralism also poses threats to biodiversity, particularly through transhumance, which impacts protected areas despite regulatory restrictions. National parks such as Zakouma (Chad), Waza, Bouba Ndjidda, and Bénoué (Cameroon) are frequently traversed by herders, even though these areas are designated for biodiversity conservation. The 2012 mass elephant poaching in Bouba Ndjidda National Park was linked to transhumant herders from Sudan. Other negative impacts of transhumance include the silting of water points, soil degradation due to overgrazing, deforestation from excessive tree cutting, and the transmission of diseases from livestock to wildlife.

Grazing pressure alters the floristic composition of rangelands, favoring species adapted to grazing and nutrient-rich soils, such as *Zornia glochidiata*, *Tribulus terrestris*, and *Cenchrus biflorus*, enhancing productivity unless erosion occurs (Usongo and Moussa 2021). Pastoralism, particularly transhumance, is a critical

issue for biodiversity management around protected areas, where wildlife habitats, farmlands, and pastures intersect, increasing conflicts over resource access among pastoralists, farmers, and conservationists.

Conflicts arise due to overlapping land use, with priorities differing by site—ranging from reducing livestock numbers to controlling agricultural expansion or addressing security concerns. Integrating transhumant pastoralism into protected area management is essential to mitigate conflicts, protect wildlife habitats, and promote local development, especially in impoverished communities surrounding these areas. This requires understanding the ecological, geographical, and socioeconomic contexts of each site, as well as the types of pastoralism practiced.

The expansion of agriculture into savannas and pastoral lands, along with the growth of livestock due to transhumant settlement and investment by resident farmers, is a primary cause of wildlife resource degradation. These dynamics fuel conflicts among herders, between herders and farmers, and between humans and wildlife. Finding mechanisms for coexistence among livestock farmers, rural land users, and governments is crucial to prevent future armed conflicts, which are already emerging in parts of the Congo Basin, including the Democratic Republic of Congo, Cameroon, and CAR. We are already witnessing the emergence of conflict and international ivory poaching. Orders of poachers coming on horseback or mixing in pastoral communities are killing elephants for ivory. Numerous cases have been reported in the forest areas of the Congo Basin countries.

Effects of Pastoralism on Drylands in the Congo Basin

Land degradation hampers sustainable development by affecting the environment, food security, agroecosystem services, and the living conditions of populations (Alexander et al. 2016). Its impacts are particularly severe in arid and semi-arid regions, where degradation linked to pastoral activities is closely tied to the carrying capacity of pastoral lands.

Pastoral carrying capacity and land degradation are critical issues in African pastoral systems. Although carrying capacity is a key concept in pastoralism, its application is challenging due to the spatial and temporal variability of biomass. Livestock-carrying capacity varies by agro-ecological zones, production systems, and practices, as well as seasonally. The average carrying capacities in this region are as follows:

- **Saharan and Sahelian zones**: Carrying capacity ranges from 4 to 15 hectares per livestock unit (ha/LSU), depending on rainfall and pasture quality (Toutain et al. 2012). Seasonal transhumance is common, with herds moving in response to available fodder.
- **Sudano-Sahelian zone**: Carrying capacity varies from 2 to 7 ha/LSU, influenced by pasture diversity and crop presence (Toutain et al. 2012). This zone sees coexistence between livestock and agriculture, requiring management of land conflicts and the use of crop residues for fodder.

- **Sudanian zone**: Carrying capacity ranges from 2 to 4 ha/LSU, depending on pasture quality and population density (Sahnone 2021). Agriculture dominates this zone, reducing available pastureland and often leading to land degradation through overexploitation or conversion to cropland.

These carrying capacities are often unknown or disregarded, resulting in degraded pastoral areas and prompting southward movements into forest regions, further impacting the land. Agricultural development policies have frequently undermined pastoralists' subsistence economies (Gebre-Mariam 2005). Indeed, nonrespect of carrying capacities, combined with climate change and insecurity, are driving herders not only to migrate to forest areas, but also to settle there, leading some of them to become sedentary. As a result, more herders are migrating from north to south than leaving. The pendular movement is no longer balanced by the sedentarization of nomads in search of resources. Significant changes in pastoralism occurred during droughts in the 1970s and 1980s, exacerbated by an influx of migrant farmers (Dongmo et al. 2012). Despite these challenges, pastoralists continue to sustainably manage natural resources through their deep ecological knowledge and capacity to negotiate resource access (Barrow 2022). The future of pastoralism largely depends on public policies that recognize its ecological and economic importance (Toutain et al. 2012).

A 2013 study on the outskirts of Waza National Park by Kabelong Banoho et al. (2016) highlighted an increase in livestock numbers with significant land impacts. Over 20 years, agricultural production in the area declined from 40 bags of 50 kg per hectare to 10 bags per hectare, forcing populations to expand their cultivated plots. Land degradation affects not only agricultural plots but also grazing areas, driving some populations to exploit protected areas for survival. This degradation poses a severe threat to local livelihoods, particularly in ecologically sensitive areas with moderate productivity, leading to declines in both crop and livestock production.

Access to land remains a major challenge for pastoralism. Pastoralists, often marginalized, lack equal land rights in many countries. Additionally, land-use planning frequently overlooks pastoral activities, making rural livelihoods increasingly difficult and conflict-prone.

Effects of Pastoralism on Forest Cover

Pastoralism can lead to deforestation and changes in the distribution of tree species (Davasse and Galop 1990). In Sahelian zones with contracted forest ecosystems, grazing has minimal impact on forest regeneration, except for highly palatable tree species (Achard et al. 2002). The integration of forestry and pastoral activities has evolved from traditional practices to a more intentional combination, benefiting both sectors (Guerin 2009). These approaches should be explored when it remains piecemeal and localized. Increasing pressure from livestock farming should enable scientists and other decision-makers to look more closely at sustainable solutions to the challenges of pastoralism and forest conservation.

In forest areas, the impact of pastoralism on forest cover has not been extensively studied. However, practices such as delimbing for constructing livestock pens and

land compaction from large livestock numbers can affect forest potential. These practices, however, have not been studied in the Congo Basin forest areas.

Effects of Pastoralism on Water Quantity and Quality

Pastoral activities, which rely on the use of natural resources, are fundamentally linked to the availability of water (Sahnone 2021). The water needs of livestock, influenced by factors such as species, age, sex, size, diet, and climate, are a key factor in organizing pastoral movements. Water is essential for animal survival and plays a crucial role in productivity, including fodder, milk production, growth, reproduction, and maintaining good health. In the context of climate change, water resources, which are already a major concern, are increasingly impacted by pastoral activities.

The size and species of livestock in a herd can significantly impact water consumption. Larger animals, such as cattle and camels, require more water than smaller livestock like sheep and goats. For example, an adult cow may need up to 100 l of water per day, and with larger herds, this can result in substantial water demands. Herd movements to pasture can also affect water availability. Trampling by livestock damages soil, increases erosion, and reduces the water-holding capacity of the land, further decreasing usable surface water.

Methane and carbon dioxide, both greenhouse gases, are produced by ruminants and pastoral fires. The disruption of the carbon dioxide (CO_2) cycle through reduced plant biomass can alter precipitation patterns, with potential impacts on water resources as well as contributing to global warming.

As for water quality, the growing common use of water resources by both humans and livestock, coupled with human population growth and rising animal numbers, poses short- and medium-term public health risks. Livestock can contaminate water sources with their droppings, potentially spreading zoonotic diseases (brucellosis and bovine tuberculosis). Pastoralism can have significant effects on both water quantity and quality through various mechanisms. Waterways used by local communities are often also used by cattle herds, leading to conflicts with other water users and increasing the risk of zoonotic diseases.

Pastoralism Fuels Escalating Resource Conflicts in West Africa and the Congo Basin

In recent years, countries in West Africa and the Congo Basin have experienced escalating conflicts among different resource users, including herders, farmers, and fishermen. These conflicts are intensifying over time, often leading to inter-community clashes with sometimes disastrous consequences. The conflicts can be categorized as follows:

(a) **Agropastoral conflicts**: Demographic pressure is a regional phenomenon, with cultivated land increasing significantly over the years, while pasture areas have decreased correspondingly. This is partly because pastoralists rarely own land,

either individually or collectively, and instead rely on shared access to pasture and water resources, negotiated with local communities. Conflicts arise from factors such as the reduction of arable land, climate change, unequal resource distribution, lack of cross-border platforms for civil dialogue, insufficient awareness of agropastoral policies, the proliferation of small arms, extremist influence, and weak governance. Violence involving pastoralists in West and Central Africa, both as perpetrators and victims, has escalated in recent years. Since 2010, over 15,000 deaths have been linked to farmer–herder violence, half of which occurred after 2018 (Brottem 2021). This surge in violence is not just about mortality rates but is often fueled by emotionally charged issues like ethnicity, religion, culture, and land disputes.

(b) **Land conflicts**: Demographic pressure in rural areas, changing land use, growing social inequalities, and declining trust between communities have weakened traditional dispute resolution methods in some regions, contributing to the escalation of conflicts. Additionally, conflict management strategies have not adapted to new dynamics and the involvement of new actors.

(c) **Conflicts linked to water resources and climate change**: Climate change and rainfall variability are major challenges for livestock farmers. Farmers and herders in the northern Congo Basin report increasingly difficult climatic conditions, with longer dry seasons and shorter rainy seasons. Forests play an important role in water regulation, both for rivers and rainfall. As a result, livestock farmers are increasingly moving into forested areas (Ellison et al. 2017). Even when total rainfall has remained similar, the region experiences more erratic weather, with sudden downpours causing floods rather than consistent rainfall. This trend forces herders and farmers to adapt, but it also exacerbates conflicts over resources.

(d) **Inter-ethnic conflicts**: These conflicts are often centered around disputes over agricultural land boundaries and resource use rights. Tensions between native and non-native communities (including displaced persons, returnees, and refugees) are heightened by differences in historical legitimacy and access to resources. Local communities, owning more land than non-natives, often claim greater rights to natural resources, leading to conflicts within and between communities.

Scale of Conflict

Faced with challenges such as demographic pressure and climate change, which intensify competition for resources, conflicts between herders (pastoralists, transhumant herders, etc.) and local populations in rural areas have become increasingly frequent and violent in recent years. These conflicts often peak in intensity during times of early arrival and high concentration of transhumant herds, particularly following rainfall disturbances. Pastoralists are both perpetrators and victims in these conflicts, which frequently result in violent confrontations.

Pastoralism and the Congo Basin Economy

In Central Africa, livestock farming is a major economic activity in countries such as Cameroon, Chad, and the Central African Republic (CAR). Its contribution to GDP is estimated at 13% in Cameroon and 9% in CAR (Union Africaine 2010). In 1997, the sector contributed 3% and 10% to the respective GDPs of Cameroon and CAR (Lhoste et al. 1997), highlighting the growing importance of this sector in these countries' economies.

In Central Africa, 80% of livestock is managed by pastoral systems (Huchon et al. 2021). This extensive system relies on natural pastures over vast areas for forage and access to surface water, primarily focusing on ruminants such as cattle, sheep, goats, and camels (Assouma et al. 2019). The human population benefits directly from milk, meat, and hides, and indirectly through the exchange of animal products for other goods (FAO 2018). Pastoralism plays a significant role in food security.

In Chad, livestock farming contributes 53% of rural GDP and provides a livelihood for around 40% of the rural population. The sector also represents financial capital of approximately 1000 billion CFA francs. The value of meat and milk production was estimated at 155 billion CFA francs in 2002. Livestock accounts for 30% of Chad's exports and over 50% of its nonoil exports (MEPA 2017).

The livestock population in Chad is substantial, with 35,749,981 million cattle, 91,520,337 million small ruminants, and 10,020,784 million camels (FWC 2024). This represents nearly one Tropical Livestock Unit (TLU) (A Tropical Livestock Unit (TLU) is a standardized unit of measurement that makes it easy to compare and aggregate different types of livestock, based on a theoretical body weight value of 250 kg) per inhabitant compared to the world average of one TLU per six inhabitants. These figures position Chad as one of the world's leading livestock-raising countries (Mahamat 2022).

In Cameroon, agriculture accounts for 40% of total exports, excluding oil. Food crops contribute 64% of agricultural GDP, followed by livestock (13%), forestry (9%), industrial and export crops (8%), and fishing (6%) (MINEPIA 2021). Cameroon is endowed with abundant natural resources, allowing for a wide range of production systems across its diverse agro-ecological zones, including Soudano-Sahelian, high savanna, highlands, monomodal rainforest, and bimodal rainforest areas.

Pastoralism and National Sovereignty

The seasonal migration of herders with their livestock southwards has long been an overlooked source of friction in Central Africa (International Crisis Group 2014). In recent years, conflicts between pastoralists and local communities have intensified due to a combination of factors: deteriorating security, climate change pushing pastoralists further south, the expansion of migration routes—particularly transnational ones—the growth of cultivated areas, and the increasing size of livestock

herds. These factors have heightened competition for natural resources and contributed to insecurity.

Despite the importance of pastoralism, it is also a source of tension and conflict, most of which arise from competition for vital resources such as water and grazing land. In Chad, these conflicts are particularly complex because pastoral ecosystems transcend national borders, and transhumance creates new settlement frontiers.

In the DRC, the migration of Peul Mbororo herders since the 2000s has led to often tense coexistence with local populations and authorities (Tamidribe et al. 2015). In 2012, the Congolese government issued a moratorium for the Mbororo Fulani to leave the country, but this has not been enforced. Their presence is linked to security instability.

Cross-border transhumance remains a sovereignty issue in border areas, as this activity is poorly controlled at the border level. In some cases, it leads to trafficking of various kinds, such as drugs and arms, and remains largely unchecked.

This phenomenon is particularly evident in rural areas that are either poorly controlled or beyond the reach of central state authorities. Despite potential conflicts, Central African states should work toward fostering peaceful coexistence between pastoralists and other resource users. They should also focus on securing rural areas and their natural resources.

Synthesis

Pastoralism is a cornerstone of livelihoods and subsistence for millions in sub-Saharan Africa, particularly in arid and semi-arid regions, where rainfall variability limits other agricultural activities. It supports over 20 million people and underpins livestock economies in several African countries, contributing significantly to global agricultural production and food security. Beyond its economic importance, pastoralism plays cultural and ecological roles, reinforcing social bonds, maintaining biodiversity, and promoting ecosystem health through natural grazing patterns. However, pastoral systems face mounting challenges, including land-use changes, climate variability, and restrictive policies, which threaten their sustainability.

Pastoralism relies on access to diverse landscapes to navigate seasonal and spatial resource variability. Communal land tenure has traditionally enabled collective rangeland management, but expanding agriculture, land privatization, and urbanization are fragmenting migratory routes and undermining traditional systems. These pressures are exacerbated by climate change, which is driving pastoralists into new regions, including forested areas, leading to conflicts with local communities and conservation efforts. For example, transhumance—seasonal livestock migration—has increased tensions in Central Africa, where pastoralists encroach on protected areas, sparking conflicts over resources and biodiversity conservation.

Despite these challenges, pastoralism remains vital for ecosystem services, providing forage, water, and medicinal plants essential for livestock and herders. Rangelands, including grasslands and savannas, sustain millions of animals and

hold cultural and spiritual significance for pastoral communities. Grazing patterns can promote vegetation regrowth and soil health, while pastoral rangelands act as carbon sinks in the savanna zone, mitigating climate change. Economically, pastoralism contributes significantly to national GDPs in countries like Chad, Cameroon, and the Central African Republic, supporting food security and rural livelihoods. However, the sector faces challenges such as overgrazing, land degradation, and conflicts with agricultural and conservation interests.

Pastoralists are adapting to globalization and climate change by integrating modern technologies, such as mobile phones, to access information on pasture conditions and avoid conflicts. Mobility remains central to pastoral systems, allowing herders to respond to ecological, economic, and sociocultural factors. However, the expansion of agriculture and the fragmentation of traditional transhumance corridors are disrupting these adaptive strategies. In response, initiatives like the Projet d'Appui à la Régulation de la Transhumance Transfrontalière en Afrique Centrale (PARTTAC) aim to secure transhumance routes and mitigate conflicts.

Pastoralism is increasingly associated with resource conflicts, particularly in West Africa and the Congo Basin. Competition for land, water, and grazing resources has escalated into violent clashes between herders, farmers, and conservationists. These conflicts are fueled by demographic pressure, climate change, and weak governance. At the same time, pastoralism is recognized for its potential to contribute to biodiversity conservation through sustainable grazing practices. However, its negative impacts, such as overgrazing and disease transmission, pose significant challenges for protected areas and ecosystem health.

In conclusion, pastoralism remains a dynamic and evolving system, deeply rooted in the socioeconomic and ecological fabric of sub-Saharan Africa. While it faces significant challenges, its contributions to livelihoods, food security, and ecosystem health underscore its importance. Addressing the conflicts and pressures facing pastoral systems requires integrated policies that balance the needs of herders, farmers, and conservationists, ensuring sustainable development and resource management in the region.

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Timber Production and Ecosystem Functions and Services in the Congo Basin

14

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Abstract

Industrial logging for timber production has long played a major economic role in the Congo Basin countries. Here, logging for timber production is carried out in two main ways: industrial exploitation, whose products are generally destined for overseas markets, and artisanal exploitation, which primarily supplies national and regional markets.

In the Congo Basin, industrial logging takes place in forest concessions. The Congo Basin has 453 forest concessions for a total area of 52,875,107 ha. For the year 2022, the Congo Basin produced 7,960,323 m^3 of logs each year.

The notion of sustainable forest management has taken root in the Congo Basin with two main variations: better involvement of local populations in forest management and sustainable management of forest concessions. Currently, it can be estimated that 70% of the forest concessions allocated are actually under management.

Logging, whether in the context of concessions or artisanal logging, inevitably leads to several negative impacts on biodiversity, carbon stocks, water resources, and forest cover. These various impacts are expected to be mitigated already through the implementation of sustainable forest management and forest certification. The prospects for sustainable timber production from the Congo Basin are based on the following approaches:

- Make a more exhaustive assessment of the management of forest concessions
- Integrate artisanal logging into national forest management policies
- Work to create incentives for further wood processing
- Promote timber production from forest plantations

Keywords

Congo Basin · Sustainable forest management · Plantations · Industrial roundwood · Production benchmarks · 2050 targets · Domestic markets · Planting program

Introduction

Internationally traded African tropical timber primarily comes from the Central African subregion. Industrial timber exploitation has long played a major economic role in the countries of the subregion, particularly in the six countries with dense forests: Cameroon, Central African Republic, Gabon, Republic of Congo, Democratic Republic of Congo (DRC), and Equatorial Guinea.

The economic role of logging is not new. Before independence, logging was the most important source of export revenue in countries such as Gabon, which is why, once independence was achieved, Gabon established the Ministry of Forest Economy. In Gabon, the forestry sector has long remained the leading economic sector after the oil sector. In the Republic of Congo, logging is the main source of salaried employment in rural areas.

However, the role of forestry in timber production is not limited solely to exports to external markets; it also plays an important role in the domestic economy. In countries such as Cameroon and the DRC, domestic and regional markets are equally important. While logging for overseas markets is done industrially, using heavy and expensive equipment to transport the logs to processing sites equipped to handle large-diameter roundwood, logging for domestic markets is generally done in the traditional way, involving the processing of trees on felling sites.

Logging for timber production has been identified as a major cause of negative environmental impacts, particularly as one of the biggest drivers of deforestation in Central Africa. To address these negative impacts, Central African countries have committed to new approaches to sustainably manage forests, particularly since the Rio Summit in 1992. These commitments led to the adoption of new legislation in Cameroon in 1994, including obligations to draw up management plans. Furthermore, the efforts of Central African countries have received a certain level of recognition through forest certification processes.

This chapter addresses timber exploitation in Central Africa, highlighting its environmental and socioeconomic impacts, the efforts made to mitigate negative impacts and proposing some prospects for the future.

Characterization and Typology of Timber Activities in Central Africa

Typology of Forest Resource Access Titles

In Central Africa, there are generally two categories of forest permits, namely concessions and authorizations to cut one or more trees. Concessions include both forestry permits that designate parcels of forest land in the State's private domain that are allocated to legal entities or individuals for timber exploitation, and forestry concessions, which designate management and exploitation units within which forestry permits are grouped. They also include circumstantial and specific authorizations for forest parcels outside the State's private domain that are subject to

occasional timber harvesting as part of an activity requiring them to be cleared. Tree permits are special or specific authorizations allowing individuals or legal entities to cut a limited number of trees for a specific purpose. All the forest titles described above have a fixed duration, which is set either in advance by the regulations or by the legal texts under which they are issued. Depending on the country in the Congo Basin, forest titles are given different names in accordance with local regulations, as shown in Table 1.

Table 1 Typology of forest resource access titles in Central African countries

Country	Surface permits	Foot permits
Cameroon	Provisional logging agreement (CPE) Definitive logging agreement (CDE) Communal forests Community forests FMU (Forest Management Unit) **Reference**: **Forestry Code 1994, Law n°94/01 of 20 January 1994, Art. 22 to 40**	Cutting sales (VC) Exploitation permit (PE) **Reference**: **Decree n°95/531/PM of 23 August 1995, Art. 110 et seq.**
Gabon	Associated Forest Permit (PFA) Convention Provisoire Aménagement Exploitation Transformation (CPAET) Forest concession under sustainable management (CFAD) Community Forest (CF) **Reference: 2001 Forestry Code, Law n°016/01 of 31 December 2001, Art. 138 et seq.**	Permis de Gré à Gré (PGG) **Suspended** Autorisation Spéciale de Coupe (ASC) **Reference: Decree n°000692/PR/MEFEPEPN of 24 August 2004**
Equatorial Guinea	Forest concession Industrial logging permit **Reference: Ley Forestal n°1/1997 de 18 de febrero**	Artisanal license (limited) **Reference: Idem, regulated by implementing decree**
Central African Republic	Exploitation and Development Permit (PEA) Provisional management agreement Community forest (CF) **Reference: 2008 Forestry Code, Law n°08.022 of 17 October 2008, Art. 33 to 51**	Artisanal logging permit (PEA) **Reference: 2008 Forestry Code, Law n°08.022 of 17 October 2008, Art. 85 to 90**
Democratic Republic of Congo	Forest concessions Community forests (Decree 2014) **Reference: Law n°011/2002 of 29 August 2002, Art. 82 to 100**	Artisanal logging permit Logging certificates **Reference: Decree n°14/018 of 2 August 2014, Art. 21 to 35**
Republic of Congo	FMU (Forest Management Unit) Forest concession with validated management plan **Reference: Law n°33-2020 of 8 July 2020 on the Forestry Code, Art. 48 to 64**	Artisanal logging permit **Reference: Law n°33-2020 of 8 July 2020 on the Forestry Code, Art. 90 to 92**
Chad	Community forests Logging permit (limited) **Reference: Law n°14/PR/2008 of 10 June 2008, Art. 17 to 30**	Artisanal permit (rare) **Reference. Law n°14/PR/2008 of 10 June 2008, Art. 50 to 55**

Types of Exploitation of Forest Resources in Natural Forests

Industrial Logging

Allocation of Forest Concessions

Industrial logging in the Congo Basin takes place in forest concessions. Outside these concessions, timber may be harvested prior to the construction of development infrastructure such as roads, hydroelectric dams and ports, or prior to the establishment of agro-industrial plantations.

Forest concessions are awarded either by invitation to tender or by mutual agreement. Invitations to tender are the norm in all countries in the subregion, whereas award by direct agreement is only practiced in the DRC. In the DRC, concessions are awarded by mutual agreement when the forest in question is difficult to access or if the public auction procedure fails.[1]

The size of concessions is regulated in some countries. For example, the maximum size of a forest concession is 200,000 ha in Cameroon and Gabon. The total area of forest concessions that can be allocated to a single company cannot exceed 600,000 ha in Gabon, although some companies have set up subsidiaries in order to exceed this limit. In the Republic of Congo, the Forestry Code sets no limit on the size of forest concessions or the maximum area that can be granted to a company. For example, IFO exploits the Ngombé FMU, which covers an area of 1,159,643 ha, while the forest concessions managed by CIB cover more than 2 million hectares.

Operating Agreements and Specifications

The operationalization of a forest concession is subject to the signing of a management agreement and a specific set of specifications. The duration of the agreement varies from country to country. For example, concessions are granted for 15 years in Cameroon and for a maximum of 30 years in the Republic of Congo. In CAR, a concession is equal to the lifespan of the awarded company, while in Gabon it corresponds to the rotation period, which is the technical validity period of the concession.

The specifications include two types of clauses: clauses common to all concessions, which the State defines unilaterally, and clauses specific to each concession. The common clauses include provisions relating to forest exploitation, such as the demarcation of concessions or the minimum or maximum diameters of species to be exploited, and clauses relating to wood processing, such as the construction of processing units. Specific clauses, on the other hand, are those for which drafting and modifications require consent from both the state and the concessionaire. In particular, they pertain to commitments negotiated between the operator and local and indigenous communities to provide a framework for the company's contribution to local development. According to Karsenty (2005), however, unilateral

[1] Decree no. 08/09 of 8 April 2008 setting out the procedure for allocating forest concessions in the DRC.

decision-making seems to prevail over consultation when specifications are drawn up. The special clauses in the specifications define how companies contribute to the construction of social works such as schools, clinics, and roads. This contribution is very important in the context of the Congo Basin, where public administrations have limited fiscal room for investment. This "privatization of the State" or "delegation of the State to the private sector" (Karsenty 2005) sometimes involves significant levels of investment, particularly for forestry companies involved in voluntary processes such as certification.

Management of Forest Concessions

There are three forms of logging in all the countries of the Congo Basin (TEREA 2022): (1) the first is based on sustainable management practices imposed by forest certification and other types of international standards; (2) the second form pertains to logging by companies that only manage concessions on the basis of administrative and regulatory requirements; and (3) the third form pertains to companies that do not comply with the Forestry Code and operate without sustainability measures. The second group, which is the most represented, accounts for almost 70% of the forest concessions in operation in the Congo Basin (Eba'a Atyi et al. 2022).

The Congo Basin has 453 forest concessions, covering a total area of 52,875,107 ha (Eba'a Atyi et al. 2022). Gabon and the Republic of Congo account for almost 55% of the subregion's production forest area, while Equatorial Guinea has the lowest proportion (2.01%). CAR and the Republic of Congo have the largest concessions, with average areas of 270,792 ha and 258,427 ha, respectively. In Congo, there is a marked disparity between the size of concessions in the north (453,513 ha) and the south of the country (141,375 ha). The smallest concessions are in Cameroon, with an average of 47,438 ha per concession.

Data from the Central African Forest Observatory (https://www.observatoire-comifac.net/) for 2022 show that the Congo Basin produces 7,960,323 $m^3$of logs each year. Cameroon and Gabon account for 36.54% and 29.14%, respectively, of the total volume of logs. The low volume recorded for some countries, such as the DRC (203,511 m^3/year), can be explained by various factors, including shortcomings in forestry statistics management.

The areas under concession and roundwood production by country are shown in Table 2.

Logging remains highly selective in Central Africa in terms of harvesting by species. Although there are more than 200 exploitable species in the subregion, the 10 most exploited species still represent 40% of the volume, despite efforts to diversify. Fifteen years ago, this share was 66%. Figure 1 shows that three species, Okoumé, Sapelli, and Ayous, account for almost 60% of the volume of the 10 most exploited species.

Furthermore, the efficiency of industrial logging remains very low. The average harvest is 0.15 m^3/ha/year. There is considerable variability in extraction levels, both locally and between countries. Harvesting can vary from 4 to 15 m^3/ha per rotation depending on the felling base. For example, with half the production area, Cameroon is second only to Gabon in log production.

Table 2 Areas under concession and log production

	Concessions granted		Log production	
Country	Area (ha)	Proportion (%)	Volume (m^3/year)	Proportion (%)
Cameroon	6.620.388	12,52	2.908.490	36,54
Congo	14.471.917	27,37	1.703.195	21,4
Gabon	14.688.311	27,78	2.320.000	29,14
Equatorial Guinea	1.064.900	2,01	186.023	2,34
CAR	3.249.505	6,15	639.104	8,03
DRC	12.780.086	24,17	203.511	2,56
TOTAL	52.875.107	100	7.960.323	100

Data source: Concessions (Eba'a Atyi et al. 2022); Production (https://www.observatoire-comifac.net/). Note, however, that there are regular changes in both total active concession area and log production

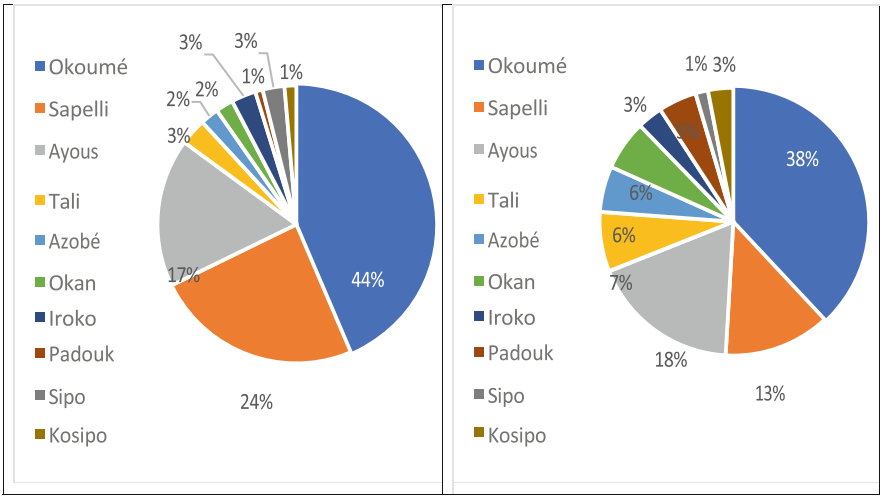

Fig. 1 Share of the 10 most exploited species in 2006 (left) and 2020 (right). (Source: OFAC)

Artisanal Logging

Community Forests

Community forests are a social forestry mechanism that designates areas of forest exploited directly by local people in associations under participatory management.

Following preliminary studies that include legal recognition of the communities' land and forestry rights, the community receives a legal title from the State that authorizes them to exploit all the natural resources included within a territorial perimeter assigned exclusively to them sustainably in order to ensure the equitable sharing of resources, guarantee their subsistence activities, and generate income that must be used to support local development. Community forests also aim to contribute to the preservation of biodiversity and the fight against deforestation and climate change through the mitigation of emissions by involving communities in forest management.

Cameroon, Gabon, Equatorial Guinea, the Democratic Republic of Congo, the Central African Republic, and the Republic of Congo have all introduced community forests into their regulations, notably in their respective Forestry Codes. The size of community forests, averaging 5000 ha overall, varies from country to country. In Cameroon and CAR, for example, it is limited to a maximum of 5000 ha, while in Gabon it can be as much as 15,000 ha.

Community forests are allocated in two major phases, namely the signing of a provisional management agreement, which gives rise to a right to reserve the land requested, and the signing of a definitive management agreement, which gives rise to the right to exploit the resources of the land requested. The process leading to the provisional management agreement involves various stages, particularly the formation of a legally declared association of local people, the submission of a request to the relevant administrative authority on the basis of a duly compiled file, verification of the inclusion of concerned local people, and their rights, and verification of the availability of the land requested. This includes studies and consultations, including a socioeconomic study and a participatory mapping study.

The final management agreement involves drawing up and approving a management plan and a community development plan. This includes an inventory of the resources on the land in question. The management of a community forest is the responsibility of the community concerned, which forms an association that complies with the approved management plan. Unfortunately, communities often lack the structural, organizational, technical, and financial capacity to implement management plans for their community forests. This is compounded by weaknesses in governance systems linked to public policy in general. As a result, there are major shortcomings in the implementation of sustainable exploitation of community forest resources, which generate little income and consequently have very little positive impact on local development. Challenges, therefore, persist, particularly in terms of implementing legislation, building community capacity, and financing forest management activities. In short, community forests in Central Africa represent a promising approach to reconciling local development and environmental conservation, but their success depends on the implementation of effective policies and capacity-building for local communities.

Felling Permits

In Central Africa, a felling permit is a forestry title generally granted to nationals as part of social forestry policies, particularly to meet the wood needs of local communities, especially for construction, heating, and other domestic uses. This authorization allows an individual residing in a given locality to exploit a limited number of trees for personal use or for the sale of sawn timber products. The procedure for granting this title generally includes a request from the applicant for the number of trees identified, verification and hammering of the trees requested, payment of a fixed fee, and issue of the authorization. The authorities then monitor the felling, sawing, and selling of the authorized trees in accordance with the established rules.

Illegal Logging

Illegal logging and the illegal timber trade are practiced at several levels, notably through false documentation and through the cutting, transport, storage, and processing

of timber. This often involves falsifying data included in technical documents (application files, management plans, operations plans, etc.) in order to acquire forestry permits and concessions, exploit them, and transport the timber for processing and export. Illegal practices take place both within legally authorized concessions, including community forests, and outside. Within legal concessions, operators may harvest prohibited species and mislabel them under different names, cut trees below the minimum legal diameter, or exceed authorized quotas. On the other hand, outside forest concessions and other regularly authorized sites, operators and various individuals cut trees illegally and then declare them fraudulently, either under the cover of official authorizations granted to them or to third parties, or under the cover of forest concessions, community forests, or legally constituted timber processing units, thereby laundering timber.

An ultimate form of fraud that has flourished over the last decade and still persists is that known as "abandoned wood," through which a mafia network has organized and continues to organize the illegal felling of wood outside permits and concessions or even within them, in order to subsequently obtain authorization to recover the wood, through an intermediary or nominee, often with the help of accomplices within the administration. To do this, they pay derisory sums to felling companies in villages to cut large volumes of wood. They then approach the forestry administration through an intermediary to declare that they have found wood that has been "abandoned" in the forest and, with internal complacency of complicitness concealing the real facts, information, and data from officials and decision-makers, they obtain the signature of authorizations to recover the wood in return for the payment of sums that are derisory in relation to its real value. This enables them to make a huge profit by legally marketing this illegal timber. In some cases, the "abandoned" timber does not exist. Using deliberately biased reports and statements relating to the existence of this wood, authorization is granted in advance to recover the declared fictitious wood, and the illegal loggers then carry out felling in the field.

Illegal logging and the illegal timber trade in Central Africa involve many different players, including forestry operators and public officials, as well as political figures and various private individuals who are involved at several levels of the timber value chain, from the allocation of permits to the issuing of authorizations, including logging, the timber evacuation circuit from concessions, timber transport, processing and export, with interference in the judicial circuit. The role of these various parties has been highlighted in numerous investigations, including that of the American NGO EIA, which revealed a major affair in Gabon and Congo in 2019 (EIA 2019). In Gabon, losses to the state have been estimated at around $300 million in fraud per year.

Sustainable Natural Forest Management Initiatives in Central Africa

Forest Management

The Rio de Janeiro summit in 1992 marked a turning point in the conception of forest management in Central Africa. The concept of sustainable forest management took root in two main ways: greater involvement of local populations in forest

management and sustainable management of forest concessions, including measures to protect wildlife resources. As a result, new forestry legislation or Forestry Codes have been introduced, requiring each forest concession to be managed in accordance with a management plan drawn up in advance or at least approved by the forestry administration.

In addition to the new legislation, pilot management projects—genuine experiments in management methods and techniques—were set up with the support of international organizations such as ITTO (Cameroon, Gabon) and/or technical cooperation, particularly French cooperation (API Dimako in Cameroon) and Canadian cooperation (DRC, Cameroon). This resulted in the production of high-quality technical reference systems for estimating key management parameters (e.g., felling rotation, allowable cut).

The preparation of sustainable management plans for forest concessions in Central Africa is based on specific studies of the forest to be managed, the most important of which are the management inventory and the analysis of the socioeconomic context in which the forest concession is to be managed. The management plan includes measures for the rational management of timber resources through the temporal and spatial planning of forestry operations, and measures designed to contribute to the economic development of localities adjacent to the forest concession.

Although forest resources belong to the State, in practice, Central Africa governments concede their management to private operators for a period of between 20 and 35 years. The size of a concession varies from country to country, but in Central Africa the average is 116,000 ha (Bayol et al. 2022). Table 3 shows the status of forest management in Central Africa by country in 2021. It can be estimated that 70% of allocated forest concessions are actually under management. The proportion of allocated forests under management is even around 95% for Cameroon and Gabon, the two largest roundwood producers in Central Africa.

The sustainable management model for forest concessions appears to have proved its worth over the first 25 years. However, there are legitimate concerns about the replenishment of the resource after the first cycle of logging concessions. When the

Table 3 Status of forest management in Central Africa in 2021

Country	Forest concessions		Concessions allocated		Concessions under development (S^2)
	Surface area	Number	Area	Number	
Cameroon	8,354,856	192	8,017,016	169	7,647,610
Congo	14,800,000	59	14,471,917	56	8,597,046
Gabon	15,999,497	116	14,688,311	108	13,800,000
Equatorial Guinea	1,064,900	98	1,064,900	98	0
RCA	3,706,106	14	3,249,505	12	3,249,505
RDC	17,410,017	182	14,124,506	132	8,500,000
Total	61,335,376	661	55,616,155	575	41,794,161

Source: Extracted from Bayol et al. (2022)

first-generation management plans were drawn up in the early 2000s, the assumptions about resource dynamics (growth rates of trees of different species) were not very well founded, as there was no long-term monitoring research on permanent plots. Such plots have since been installed and monitoring has improved. Concerns have also been expressed about social and land issues, given that the concessions have sometimes been demarcated and granted on sites where local people are claiming ownership. Here and there, depending on the density of neighboring populations, some concessions have faced problems of encroachment for agricultural purposes.

Now that the first generation of management plans has been implemented and experience accumulated, it is critical to evaluate this model in order to make corrections with a view to implementing the second generation.

Forest Certification

Forest certification was introduced in the early 1990s to promote sustainable forest management. Two types of certification are operational in Central Africa: legality certification and sustainable forest management certification.

The principle of legality certification is to verify that forestry companies operate in compliance with applicable national and international regulations in areas relating to logging, transport, processing, and trade in timber.

The main legality certificates found in the Congo Basin are

- Origin and Legality of Timber (OLB) developed by Bureau Veritas.
- Timber Legality Verification (TLV) developed by Control Union Certification.
- Legalsource, developed by *Preferred by Nature* on the basis of the requirements of the European Union Timber Regulation (EUTR). All Legalsource certificates will be invalidated after December 30, 2024, as the EUWR expires and the EU Deforestation Regulation (EUDR) comes into force.

Of these three certification systems, OLB is the most active in the Congo Basin, with 14 certificates issued covering a total area of 3,805,813 ha, including 2,239,659 ha in Cameroon (10 certificates), 929,561 ha in Gabon (2 certificates), and 636,593 ha in the Republic of Congo (2 certificates).

Sustainable forest management certification, on the other hand, goes beyond legality and seeks to determine whether the timber sold on the market comes from sustainably managed forests, that is, in accordance with a set of established and internationally recognized standards. The two sustainable forest management certification systems currently applied in the Congo Basin are the Forest Stewardship Council (FSC) and the Pan African Forest Certification (PAFC).

FSC certification was a pioneer in the region, with the first certificate issued in 2005. It underwent significant growth between 2004 and 2010, followed by difficulties that led to a drop in interest and the nonrenewal of certificates. In September 2024, the FSC had 14 active certificates in the Congo Basin, covering a certified area

of 5,829,015 ha. These certificates are held by eight companies in the following countries: Republic of Congo two companies (3,081,699 ha); Gabon four companies (2,052,062 ha); and Cameroon two companies (695,254 ha). The decline in FSC certification in the Congo Basin was most marked in Cameroon, where seven certificates were not renewed between 2012 and 2019. This situation is mainly due to the takeover of the companies of major European groups such as Rougier and Wijma by Asian capital. These two groups totaled more than 700,000 certified hectares and the buyers are not interested in FSC certification because they export to less demanding markets (Karsenty 2018).

The PAFC is an initiative endorsed by the Programme for the Endorsement of Forest Certification (PEFC) schemes. Gabon has long had its own PAFC scheme, which served as a source of inspiration for giving the regional PAFC. The PAFC Congo Basin initiative currently has three members: PAFC Gabon, PAFC Cameroon, and PAFC Congo. This label has certified 2,051,294 ha of forest in the subregion, including 1,159,643 ha in Congo (one company) and 891,651 ha in Gabon (two companies). It should be noted that two of the three PAFC-certified companies (IFO in Congo and Precious Wood in Gabon) also have FSC certificates for the same concessions.

Initiatives Linked to the European Markets (RBUE, APV, RDUE, etc.)

FLEGT VPAs

The Forest Law Enforcement Governance and Trade (FLEGT) action plan, launched in 2003, is one of the European Union's (EU) main tools in the fight against illegal logging and deforestation. FLEGT has two distinct tools: the Voluntary Partnership Agreement (VPA-FLEGT) and the European Union Timber Regulation (EUTR).

Through the VPA, the EU and producer countries undertake to work together to improve the governance of the forestry and timber sector and set up a licensing scheme to certify that timber imported and marketed in Europe is of legal origin. Three countries in the subregion have signed VPAs with the European Union (the Republic of Congo and Cameroon in 2010 and the Central African Republic in 2011) and two are in negotiation (Gabon and the Democratic Republic of Congo). The status of VPAs in the Congo Basin is summarized in Table 4.

Of the three signatories, Congo is the only country where the VPA is fully operational. The first certificates of legality are planned for the first quarter of 2025. In CAR, the implementation of the Agreement has been slowed down by the sociopolitical crises that hit the country from 2013 onward. The development of the national traceability system is due to be relaunched in 2025. The EU has decided not to renew the VPA signed with Cameroon in October 2024 because the country had not been able to fully respect its obligations under the VPA.

The EUWR and EUFR

Adopted in 2010, the European Union Timber Regulation (EUTR) aims to ensure that timber and related products marketed in the EU come from legal sources.

Table 4 Status of VPAs in the Congo Basin

Stages	Cameroon	Congo	CAR	Gabon	DRC
Signature	October 6, 2010	May 17, 2010	November 28, 2011	–	–
Ratification	August 9, 2011	July 4, 2012	July 1, 2012	–	–
Implementation	December 1, 2011	March 1, 2013	July 1, 2012	–	–
Status	Suspended	In force	In force	Negotiations relaunched in 2019	Negotiations relaunched in 2016
Progress	Two recognized certification standards Second-generation Computerized Forest Information Management System (SIGIF 2) being deployed System for monitoring the traceability of timber shipments for export operational	Control procedures validated Tax and legality modules of the computerized legality verification system (SIVL) up and running Manual of procedures	RCA VPA website Implementation SGBDC system	Legality Legality National traceability Traceability system	Legality grid project Legality grids and validated Vade-mecum for legality verifiers Development of Instruments—annexes To the agreement
To do	Reinitiate this process? Revise the legality grids following the adoption of a new forestry law	Finalize the implementation framework for the Forestry Code Revise the legality grids	Set up the national traceability system	Finalize legality grids Sign the VPA	Finalize legality grids Sign the VPA Finalize national
	Reach agreement with the EU on the assessment and implementation of the new law	Make the SIVL traceability module operational Finalize the private certificate recognition manual Issue FLEGT licenses		Finalize the national traceability system	Traceability system

Source: Adapted from Etat des forêts (2021)

EUTRs, the second instrument in the FLEGT Action Plan, are designed to complement the VPAs. The major requirement of the EUWR is the implementation of a due diligence system based on minimum traceability enabling suppliers and products to be identified. This due diligence includes three stages: access to information (on the source, supplier, country of origin, etc.), risk assessment (of illegal harvesting), and risk reduction measures (if a risk is identified).

After more than 10 years of implementation, the results of the EU DB are mixed. The evaluators found three main shortcomings (EDF 2024): (1) insufficient controls at the EU's borders, (2) the complexity of the supply chain, and (3) the weak monitoring and verification capacity of exporting countries.

Finally, in view of the mitigated success of the EUWR in limiting imports of illegally sourced timber and the ever-increasing contribution of agriculture to tropical deforestation, the EU has changed its approach by introducing the European Regulation against Deforestation and Forest Degradation (EUDR). Adopted in December 2022, the regulation came into force in June 2023 and was originally scheduled to be applied in January 2025.

In response to requests from EU Member States, producer countries, traders, and operators citing that it would be difficult to fully comply with the EU RD rules by the end of 2024, the European Commission postponed its application date to December 31, 2025.

Unlike the RBUE, the RDUE does not just apply to timber. Its scope has been extended to other areas, notably agriculture, with the aim of curbing exports of goods and products associated with deforestation and forest degradation, to EU markets. In all, the EUBP includes the following seven commodities: cattle products, cocoa, coffee, oil palm, rubber, soya, and timber, as well as a list of products that contain, have been fed with, or are produced from these commodities. A EUBD-EUDR comparison is presented in Table 5.

Wood Processing

Since the arrival of the new paradigm initiated in Rio in 1992, Central African countries have introduced into legal frameworks requirements to better link logging and domestic wood processing. Countries have included links between the granting of access rights to the resource and the setting up of appropriate processing units in their respective laws. In its 1994 Forestry Law, Cameroon decided to stop exporting logs 5 years later, a policy that has not been respected. Gabon, on the other hand, adopted a voluntary policy to stop exporting logs from 2010. Table 6 gives a description of the forestry industries by country in Central Africa. It can be seen that Gabon, the largest producer of logs, also has the largest number of industrial units.

Table 5 Comparative analysis EUBD-EUDR

Obligations under the regulations	EUBP	EU RD
Collection of information demonstrating compliance of products is required	Accurate information about the timber supplied must be recorded in appropriate registers Collected information must cover the entire supply chain and must have been verified	In addition to afore-cited reporting requirements, the following information must also be collected: Geolocation of all parcels from which the products in question originate Information certifying that the product in question is deforestation-free Information attesting that the commodities in question have been produced in accordance with the relevant legislation of the country of production, including any agreement conferring the right to use the area concerned for the production of the commodity in question
Assessment of risks associated with illegal products entering the market	The risk assessment should reflect these five criteria: (1) Compliance with relevant legislation (2) Supply chain complexity (3) Widespread illegality or the presence of illegal practices in certain forest operations or regions (4) Prevalence of illegal harvesting of specific forest species (5) Sanctions that may have been imposed on timber imports and exports.	Risk assessment must consider eight additional criteria: (1) Presence of forests or indigenous populations in the country of production (2) Consultation of indigenous populations (3) Existence of claims by indigenous populations (4) Reliability of information collected to ensure the compliance of products placed on the market (5) Extent of deforestation in this country and concerns regarding the level of corruption and risks of falsification of documents (6) Risks of circumventing regulations (7) Conclusions of the Commission's expert groups (8) Documents demonstrating risk of noncompliance

(continued)

Table 5 (continued)

Obligations under the regulations	EUBP	EU RD
Implementation of risk mitigation measures	Such measures must be taken unless the risk is negligible These are "adequate and proportionate measures and procedures to reduce the risk as effectively as possible"	Such measures must be taken unless the risk is zero or negligible The operator must therefore take additional steps such as (1) Carrying out investigations (2) Gathering additional information (3) producing Producing reports or keeping records (4) Appointment of a compliance officer (5) Setting up an independent audit function

Source: Delille and Seranne (2024)

Table 6 Description of forest industries in Central African countries

Country	State of industrialization	Description of industries	References
Cameroon	Moderate level: incentives but little secondary processing	More than 150 sawmills, with few second/third transformation units	Law n°94/01; Decree 2020/3217/PM; CIFOR 2022
Gabon	Advanced level, obligation to process 100% of wood cut locally since 2010	Around 200 sawing, peeling and veneering units, including the Nkok SEZ (wood processing ecosystem)	Law n°016/2001; Decree n°00099/PR/MEF; FAO 2022; ATIBT
Equatorial Guinea	Low to moderate level: beginning of local processing efforts	Processing still primary	Law n°1/1997; OFAC 2021; FAO 2022
CAR	Low level: industry disrupted by instability	Around 10 licensed companies; sawmilling only	Law no. 08.022; FAO 2021; IUCN 2020
DRC	Very low level: embryonic industrialization	Small-scale cottage industry; log exports	Law n°011/2002; WRI DRC 2020; OFAC
Congo Republic	Moderate to good level: compulsory processing before export	Nearly 80 sawmills; 2 SEZs under development (Oyo and Pointe-Noire) Log export ban since 2023	Law n°33-2020; Decree n°2009-274; FAO 2023
Chad	Very low level: underdeveloped industry, dominated by the informal sector	A few small units in N'Djaména; no structured industry	Law n°14/PR/2008; FAO 2020; REDD+ 2021

Table 7 Industrial production by Central African country (2020/§2021)

Country	Sawn timber	Veneer	Plywood	Total
Gabon	872,331	624,808	80,724	1,577,863
Cameroon	984,412	71000[a]	18000[a]	1,073,412
Congo	319,297	39,119	–	358,416
CAR	51,044	–	–	51,044
RDC	*29,636*	–	–	29,636
Equatorial Guinea	*1540*	–	–	1540
Total	**2,258,260**	**734,927**	**98,724**	**3,089,217**

Source: FOCA portal (https://www.observatoire-comifac.net/)
[a]ITTO portal—figures in italics deducted on the basis of assumptions, in the absence of official data

Considering that the subregion produces 8.4 million m^3 of industrial logs, wood processing units in the six countries currently absorb 77% of this production. The proportion of log production processed in the countries of Central Africa has risen dramatically, from 42% in the early 2000s to almost 80% today. Gabon is the most impressive example of this change, where the proportion of logs processed locally has risen from 15% at the end of the 1990s to 100% today. Almost 90% of locally processed log production is concentrated between Gabon and Cameroon, which processes 75% of its production.

However, wood processing in Central Africa is still largely dominated by sawmilling, that is, primary processing. Table 7 shows that sawn timber accounts for 73% of industrial production, followed by veneer (another primary processing product) at 24% and plywood (3%). Here too, Gabon is an exception, producing 85% of the subregion's veneer and plywood. It should be noted that planed sawn timber (paneling and parquet) is recorded in the sawn timber category, which is an anomaly in the sector's statistics, since planed sawn timber should be considered as second or third transformation products.

Forest Plantation Management

Generally speaking, the supply of tropical timber from natural forests is set to decline or, at best, stagnate. On the other hand, demand for timber products is expected to increase, because even if demand for tropical timber in industrialized countries remains stable, domestic and regional demand in tropical countries is already growing due to demographic and economic growth. As a result, forest plantations are set to play an increasingly important role in supplying tropical timber. ITTO statistics show that in 2015 the proportion of industrial roundwood from plantations was 67%, and this is expected to rise to 73% by 2050 (Held et al. 2021). These planted wood resources come from both large-scale industrial plantations and agroforestry systems.

Even though plantation activities have been carried out in Central Africa for many years, the subregion is lagging far behind in this transition toward a major role for

plantations in tropical timber production. They generally consist of **experimental plantations**, used to test innovative silvicultural techniques, and **industrial plantations**, designed to meet growing needs for timber resources while reducing pressure on natural forests (Rubilar et al. 2018).

As data on forest plantations is not systematically archived, a recent study (Biwole et al. 2025) attempted to take stock of these forest plantation activities based on a sample of six sites in Cameroon, CAR, Congo, and DRC. Forest plantations in these countries were established as early as 1930 and continue to this day. These plantations are located in four forest types, namely wet savannas and dry savannas (Cameroon), forest-savanna transition zones (Bangui, CAR), and dense humid forests (Cameroon, Republic of Congo and DRC). Seventeen species were studied in these plantations. These species are distributed as follows: 10 local species (*Aukoumea klaineana, Autranella congolensis, Entandrophragma angolense, Entandrophragma cylindricum, Millettia laurentii, Nauclea diderrichii, Pericopsis elata, Triplochiton scleroxylon, Terminalia superba, Terminalia ivorensis*) and 6 exotic tropical species (*Eucalyptus camaldulensis, Gmelina arborea*, *Pinus caribeae*, *Pinus kesiya*, *Pinus oocarpa*, *Tectona grandis*).

Typology of Forest Plantations in Central Africa

Experimental Plantations: A Laboratory for Innovation

Experimental forest plantations offer unique opportunities for developing silvicultural itineraries adapted to African tropical forests. Initiatives at the Mbalmayo site in Cameroon and the Yangambi site in the DRC have tested local and exotic species in experimental plantations to determine their suitability for domestication (De Wasseige et al. 2014). Another striking example is the limba (*Terminalia superba*) plantations in the Republic of Congo, where advanced techniques have enabled productivity of over 10 m^3/ha/year to be achieved, reducing the optimal exploitation age and demonstrating their economic and ecological viability (De Wasseige et al. 2014).

Industrial Plantations: Meeting Growing Demand

Industrial plantations, often established on savanna or degraded land, are designed for large-scale production. In Pointe-Noire (Congo), clonal eucalyptus plantations cover 42,000 ha, producing an average of 15 m^3/ha/year for the pulp industry (De Wasseige et al. 2014). In Cameroon, teak plantations in Bassama generate 4–5 m^3/ha/year, while ayous projects in Batouri illustrate the potential of local species to support industrial sectors thanks to their rapid natural regeneration and juvenile growth (De Wasseige et al. 2014).

Silvicultural Practices and Innovations

Proper plantation management requires appropriate silvicultural techniques to optimize production while preserving the ecological functions of ecosystems. Species selection is an essential and commonly used technique (Barrette et al. 2014; Masiero et al. 2015). Indeed, according to some authors, it is essential to choose species adapted to local ecological conditions, which are frequently used in the Congo Basin

because of their rapid growth, ability to improve soil fertility, and role in reducing the risk of erosion (Rubilar et al. 2018). Furthermore, planting density is another key factor: optimal spacing between trees minimizes competition for resources while maximizing yield. In addition, natural regeneration management, supported by enrichment techniques such as line or pocket planting, encourages the introduction of key species, often indigenous, into underexploited or degraded areas to increase biodiversity and strengthen ecological resilience (Gabira et al. 2023).

These practices are complemented by regular interventions, such as thinning and selective felling, to encourage the development of the most vigorous trees and improve stand quality. The integration of agro-ecological methods, such as combining trees with crops or livestock systems, is also a multifunctional strategy that combines economic productivity with ecological sustainability. At the same time, the use of modern tools, such as remote sensing mapping and forest growth models, makes it possible to identify areas requiring specific interventions or to adjust management practices according to local conditions (Clay 2016; Kellomäki 2024).

Policy Frameworks and Certification of Forest Plantations

Policies and laws relating to forest plantations in the nations of the Congo Basin reflect government commitment to the sustainable management of natural resources. Although these legal frameworks vary from country to country, they are often aligned with regional principles promoted by organizations such as the Commission des Forêts d'Afrique Centrale (COMIFAC), which coordinates efforts toward sustainable management in the region (COMIFAC 2014). In the Democratic Republic of Congo, the Forestry Code establishes the legal basis for plantation management, incorporating provisions on the rights of local communities and environmental assessments. Similarly, in Cameroon, the 1994 Forestry Law provides a framework for the creation and management of plantations, while incorporating measures to conserve biodiversity and share benefits with communities.

In the Congo Basin, forest certification plays a key role in ensuring that plantations comply with recognized environmental, social, and economic standards. Certification schemes, such as the Forest Stewardship Council (FSC) and Pan-African Forest Certification (PAFC), impose rigorous criteria, such as maintaining biodiversity, respecting the rights of indigenous populations and improving social conditions for workers (Cerutti et al. 2017). An FSC-certified plantation must, for example, draw up a management plan that includes measures to protect the soil and surrounding ecosystems while ensuring the sustainable use of resources. These requirements are accompanied by independent audits, thereby reinforcing the transparency and credibility of the processes.

Challenges and Solutions

A recent study (Biwole et al. 2025) shows that forest plantations are often a source of conflict with local populations. These conflicts concern both land ownership and the use of timber resources. In the past, large-scale plantations were established on

ancestral lands managed by low-density local populations. The local people were expropriated without much complaint. With increasing population densities and attempts to democratize states, today's populations often seek to reappropriate land resources and claim the right to exploit the timber resources found there. This situation is exacerbated by the fact that the management of these plantations is often entrusted to state structures lacking logistical and financial resources.

To improve the role of forest plantations in timber production in Central Africa, it is therefore recommended to involve the private sector in the management of old plantations, integrate plantation timber into processing plants, and capitalize on the results obtained in national reforestation programmed.

Illegal deforestation also affects plantations due to a lack of effective forest governance and insufficient controls, facilitating the unauthorized exploitation of resources (Cerutti et al. 2017). Intensive monocultures, often favored for their economic returns, compromise biodiversity, and increase the risks of soil degradation and pest outbreaks. In addition, the lack of rigorous monitoring and reliable data makes it difficult to develop appropriate policies and implement sustainable management (Nasi et al. 2006).

To overcome these obstacles, integrated and participatory approaches are needed. Involving local communities in the management of plantations can not only enhance their sustainability, but also ensure that benefits are shared equitably. Adopting agroecological forestry practices, such as planting native species, helps to restore ecological functions while diversifying sources of income. In addition, scientific research and public policy must support these transitions by promoting financial incentives, better regulation, and technical support (Karsenty et al. 2017).

Valuing Other Environmental Services in Production Forests

REDD+ and Carbon Credits in Forest Concessions

Only Gabon has registered national REDD+ results under the UNFCCC REDD+ process, with a total of 187 million tons of results registered on the Lima Hub. There are currently 26 voluntary forest carbon projects in Central Africa. For all projects with a Project Description Document (PDD) validated by a carbon standard, the estimated carbon potential over the total duration of these projects amounts to just under 255 million tCO2e (FRM 2024).

Of the 26 forest carbon projects in Central Africa, 9 are supported by forest concessions. Forest concession carbon projects account for 42% of the surface area of all forestry projects in Central Africa, with an average surface area of around 380,000 ha. Most of the carbon projects in forest concessions involve activities related to improving logging techniques to minimize their impact on the environment, that is, improved forest management.

Biodiversity Credits

Basic Concept of Biodiversity Credits

The inclusion of biodiversity in environmental finance is one of the most significant, if not the most controversial, emerging concept of the moment. It is true that the idea dates back to the 1970s (CDC Biodiversité 2024; Karsenty 2024) with the "wetland mitigation banks." The recent emergence of the concept of financializing biodiversity follows on from that of carbon markets, but in all likelihood is much more complex. Basically, the idea is to create mechanisms so that the loss of biodiversity in one place can be offset by a gain elsewhere. This logic of offsetting, and the desire to structure financing mechanisms based on biodiversity, are now part of the Kunming-Montreal global framework for biodiversity. The objective of this new economy is clear: to integrate biodiversity into economic and political decisions while guaranteeing the integrity of ecosystems. To achieve this, the framework calls for the mobilization of hybrid financing (public, private, multilateral), the harmonization of standards, the creation of transparent registers, and, above all, the involvement of local communities in the implementation and sharing of benefits.

Implementing this concept in practice is fraught with a number of intellectual and technical difficulties. One of the first difficulties concerns setting up a measurement system. Unlike carbon, for which a single unit of measurement was easily established, biodiversity involves a multitude of dimensions that cannot be captured by a single indicator. This difficulty of measurement is compounded by the diversity of methodologies promoted by several initiatives and standards, which vary according to the objectives and contexts of their application (Nasi et al. 2025). However, the implementation of biodiversity credits can benefit from the experience accumulated with the experimentation of carbon credits.

Impacts of Timber Production Activities on Forest Ecosystems in the Congo Basin

Timber production is an important economic activity in the Congo Basin, contributing to national and regional economies and supporting millions of livelihoods. However, it has multiple impacts on forest ecosystems, influencing ecological, social, and environmental dimensions. While timber exploitation brings economic and social benefits, it can also lead to ecosystem degradation, loss of biodiversity, disruption of water cycles and changes in carbon storage capacity. Understanding these impacts is essential to finding a balance between economic development, sustainable forest management, and conservation objectives (see Table 8).

Table 8 Summary of the impacts of timber production activities on forest ecosystems in the Congo Basin

Impact category	Description	Main effects
Economic and social impacts	Contribution to livelihoods, employment and income generation	Job creation; local and national income; inequalities in the distribution of benefits; social conflict
Ecosystem functioning	Changes to ecological processes, including soil stability and nutrient cycling	Soil erosion, impaired regeneration, and soil impoverishment in affected areas
Impacts on biodiversity	Effects on flora and fauna due to habitat loss and species disturbance	Decline in species diversity, endangerment of key and endemic species, and reduction in habitat connectivity
Water resources	Changes in availability, quality, and hydrological cycles	Increased sedimentation, reduced water flow, and contamination of water bodies due to logging activities
Carbon balance	Impacts on the role of forests as carbon sinks and sources of CO2	Release of carbon by logging activities, reduction in carbon sequestration capacity, and impacts on climate change mitigation

Economic and Social Impacts

Timber production is one of the most important sources of income in the Congo Basin, directly and indirectly supporting millions of people's livelihoods. Indeed, in countries such as Cameroon, the Democratic Republic of Congo (DRC), and Gabon, logging is a major economic driver, providing jobs for workers in logging, processing, and transport. According to Cerutti et al. (2017), more than 60,000 people are employed in the formal logging sector in Central Africa. This workforce is not limited to industrial loggers but also includes smallholders and informal workers in local timber markets.

However, the economic benefits of logging are generally unevenly distributed. Karsenty (2018) points out that local communities rarely benefit from timber revenues, as the wealth is concentrated in the hands of logging companies. This situation creates tensions between local populations and external actors, leading to conflicts over land rights and access to resources. Furthermore, while timber contributes to national economies, unsustainable logging can undermine long-term economic stability by depleting forest resources.

In addition, the influx of workers from outside communities has social implications. While logging provides jobs, it also disrupts local social structures. Problems such as overcrowding, alcohol consumption, and the spread of diseases such as HIV/AIDS are common in logging towns and camps. Thus, timber production, while economically beneficial, presents significant social challenges, notably due to inadequate infrastructure, poor living conditions, and increased social conflict.

Impacts on the Functioning of Forest Ecosystems in the Congo Basin

Timber production activities have profound and widespread repercussions on the functioning of forest ecosystems. These activities disrupt essential ecological processes such as soil stability, nutrient cycling, and water regulation. When logging operations remove trees, they not only remove biomass, but also disrupt the delicate balance of soil health and ecosystem resilience. Logging significantly reduces soil fertility in areas where trees are felled. The organic matter that trees bring to the soil, through leaf litter and root systems, is essential for maintaining soil structure and nutrient cycling. Once trees are felled, this vital organic matter is no longer replenished and the health of the soil deteriorates rapidly. Without the canopy and root systems to protect the soil, erosion becomes a serious problem. The loss of soil structure leads to compaction, which reduces the water-holding capacity of the soil, further exacerbating water runoff during rainfall (Tchiofo Lontsi et al. 2019).

Forest roads are often built to access timber-rich areas. This is an important contributing factor to habitat fragmentation. Kleinschroth et al. (2015) found that the opening up of forest roads in the Congo Basin leads to the fragmentation of vast tracts of forest. This disturbance isolates wild animal populations, making it more difficult for species to migrate, find food, or locate suitable habitats. These roads not only facilitate timber extraction, but also access to illegal hunting, poaching, and the collection of nontimber forest products, all of which place more pressure on already threatened species. In addition, much research highlights that many species, particularly those that require large continuous tracts of forest, are facing increased mortality due to habitat loss and poaching. Species such as forest elephants, gorillas, and chimpanzees, which depend on large contiguous forests, are particularly vulnerable to these changes (Laurance et al. 2006; Poulsen et al. 2017).

In addition, the removal of trees and the opening up of the forest canopy modify local microclimates. Research in the Congo Basin has noted that reduced forest cover leads to increased local temperatures and reduced humidity (Bell et al. 2015). This alteration in microclimate can have a negative impact on species adapted to stable, humid conditions, which can lead to declines in plant and animal populations that depend on constant temperatures and humidity levels (Ernst et al. 2013). Altered microclimate can also hinder forest regeneration, as many plant and tree species that require shady and humid conditions to germinate may not thrive in the new exposed environment.

Fragmentation caused by logging and changes to the microclimate also affects the regeneration process. The forests of the Congo Basin depend on a delicate balance between seed dispersal, soil fertility, and natural regeneration processes (Vanden Abeele et al. 2021). When logging disrupts these processes, regeneration is often slow or incomplete, particularly in areas where soil quality has deteriorated (Douh et al. 2023). Kleinschroth et al. (2016) reveal that the presence of forest roads and clearings limits the ability of tree species to regenerate naturally, as the broken structure of the ecosystem hinders seed dispersal and reduces the availability of suitable sites for seedlings to take root.

Impacts on Biodiversity

Logging activities in the Congo Basin have profound and widespread impacts on biodiversity, with habitat destruction being one of the most immediate and visible consequences. According to de Wasseige et al. (2012), timber extraction contributes significantly to the loss of forest cover, which directly threatens the survival of many species, particularly those that are endemic or already threatened. The felling of commercially valuable tree species disturbs the habitats of many animals, including key species such as forest elephants (*Loxodonta cyclotis*), gorillas (*Gorilla gorilla*), and chimpanzees (*Pan troglodytes*). These animals depend on vast tracts of unbroken forest for food, shelter, and movement. Fragmentation caused by logging reduces the availability of these resources, pushing species into smaller and often less suitable habitats.

Selective logging, often perceived as less destructive than clear-cutting, presents significant risks for biodiversity nonetheless. It disproportionately targets mature and valuable trees, altering the structure of the forest and leaving behind ecosystems dominated by a reduced number of species. This selective pressure reduces ecological resilience and functional diversity, as highlighted by some research (Cazzolla Gatti et al. 2015; Cazzolla Gatti 2018). Mature trees play an essential role in forest ecosystems, providing habitat, stabilizing microclimates, and facilitating nutrient cycling. Their removal has cascading effects, impacting both the flora and fauna that depend on these trees for their survival.

Impacts on Water Resources

Timber production activities in the Congo Basin have significant impacts on water resources, altering hydrological cycles, water quality, and aquatic ecosystems (Shah et al. 2022). In Cameroon, deforestation and land-use changes have led to a decline in river flows in some regions, with a 5.1% decrease in average flows in the Nyong river basin due to a 16% reduction in forest cover between 1987 and 2014 (Ewane and Lee 2020). In the Democratic Republic of Congo (DRC), for example, deforestation linked to logging in the Lomami region is increasing runoff by 35%, leading to accelerated soil erosion and reduced groundwater recharge (Mushi et al. 2019). In the Kasai basin, this erosion reaches up to 8.92 t of sediment per square kilometer each year, causing significant soil degradation and a reduction in the water available in the dry season (Mushi et al. 2019). Increased erosion accelerates sediment transport, making rivers more turbid. The massive deforestation favors the influx of sediments rich in nutrients such as phosphorus and nitrogen, causing eutrophication of watercourses and affecting aquatic habitats. Cases of increased turbidity have been observed in tributaries of the Oubangui, threatening aquatic biodiversity and making the water less drinkable for local populations. In Gabon, the construction of logging roads in logging areas disturbs wetlands, reducing their water retention capacity by 20% and increasing the risk of flooding in downstream basins, particularly around the River Ogooué (Megevand 2013) .

Impacts on the Carbon Balance

The forests of the Congo Basin are among the largest carbon sinks in the world, storing around 25–30 billion tons of carbon in their biomass and soils (Baccini et al. 2017). These forests play a key role in climate change mitigation by absorbing and sequestering large amounts of atmospheric carbon dioxide (CO_2). However, timber production activities in the region are altering this balance. Logging operations not only remove trees that store carbon, they also degrade the surrounding ecosystem, releasing stored carbon and reducing the forest's ability to sequester it in the future.

When trees are felled, the carbon stored in their biomass is released into the atmosphere through decomposition, combustion, and transformation. Pan et al. (2011) have estimated that deforestation and logging activities in the Congo Basin account for a significant proportion of regional carbon emissions, contributing to global greenhouse gas (GHG) levels. For example, selective logging, which often targets high-value, large-diameter trees, disproportionately affects the species that store the most carbon. This loss is compounded by collateral damage to surrounding trees and vegetation during felling operations, resulting in additional emissions.

The impact of logging on carbon storage extends beyond above-ground biomass. Houghton (2012) has pointed out that forest soils, which are important carbon reservoirs, are also affected. Logging activities, particularly those involving heavy machinery, compact the soil, reducing its porosity and organic matter content. Compacted soils are less able to retain carbon, leading to an increase in emissions from soil respiration. In addition, the removal of vegetation cover exposes the soil to direct sunlight and higher temperatures, which accelerates the decomposition of organic matter and releases even more CO_2.

Recommendations

In an effort to achieve sustainable timber production that better contributes to national economies while respecting the environment and moving toward carbon neutrality, it is recommended to

- Carry out a more exhaustive assessment of forest concession management in the subregion since the implementation of the first generation of management plans. Such a technical, scientific, and economic assessment will make it possible to revise the technical reference frameworks for forest concession management in Central Africa, taking into account the experience gained over the past 25 years of implementing sustainable forest management in Central Africa.
- Integrate artisanal logging into national forest resource management policies, as this type of logging, which is primarily geared toward satisfying national demand for timber, is expanding over time and removing increasing quantities of timber from Central Africa's forests.

- Create incentives for further processing of timber in the countries of the subregion, including public procurement policies for timber products that would favor locally processed timber products.
- Promote timber production from forest plantations by involving the private sector and local populations. Forest plantations, as is already the case in other tropical regions of the world, have the potential to produce a greater volume of wood per unit, thereby reducing the pressure on natural forests.

Competing Interest Declaration The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

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Mining and Ecosystem Functions and Services in the Congo Basin

15

Bila-Isia Inogwabini, Verina Jane Ingram, and Pascal Mambwe

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Abstract

This chapter reviewed the importance of mining and economic and environmental impacts on human communities and biodiversity. Economically, the review found that, despite the fact that mining-generated incomes were unable to ignite the sustainable development communities expected of mining companies, most of the Congo Basin's countries heavily depend on the mining industry. Pre- and post-mining data to compare the well-being of local communities were difficult to find as it was the case for studies documenting wildlife species loss due to mining, suggesting, therefore, that gaps remain to be filled by researchers in the years to come. Reviewed records have documented heavy impacts of mining on the overall biodiversity and the environment, constituting negative externalities of mining. Both large-scale mining (LSM) and artisanal-small mining (ASM) have a high impact on forest, land clearing, and other forms of habitat loss and degradation; however, ASM was reported to have a higher impact than LSM in the reviewed published materials across the Congo Basin. Other negative environmental externalities of mining included pollution of air, soil, and water, with mercury documented in fish species and water stream. The opening of mining sites increased bushmeat trade and human rights abuses. To curb the biodiversity losses due to mining, the Congo Basin's governments will need to further reform both ASM and LSM sectors.

Keywords

Artisanal-small mining · Biodiversity · Congo Basin · Habitat loss · Large-scale mining · Pollution

Introduction

This chapter looks at one of the most land- and water-consuming economic activities, with many forms of impact on both milieus. The history of mineral exploration (e.g., energy minerals, base, critical and rare earth elements) and mining activities across the Congo Basin is disparate, which implies that this chapter provides a country-specific description and analysis. While looking at regional trends, these country-specific analyses are presented, in some instances, as short case studies from which general trends are discussed at the end of the chapter. The chapter assesses the impact of artisanal and industrial mining activities where peer-reviewed materials exist. Superimposing conservation biodiversity status over mining activities, the chapter looks at correlations between mining activities and trends in biodiversity persistence and ecosystem health across the Congo Basin. The habitat conversion magnitude of the generic Surface Ecosystem Index is drawn from maps and remote sensing land conversion rates. Other mining effects on ecosystem functions and services are drawn from an Ecosystem Health Indices level, focusing on water quality indices. Both large-scale mining (LSM) and artisanal and small mining (ASM) have direct effects on forest and land clearing; these have been documented over decades across the Congo Basin. The more insidious and probably more profound effects mining activities have on freshwater ecosystems are

only beginning to be documented (e.g., Kesler and Simon 2015; Abernethy et al. 2016). This chapter provides currently available knowledge on the effects of mining activities on freshwater fish species diversity. Beyond cleared forest metrics, water quality metrics help measure the possible functional degradation mining causes by extirpating some species, and the bushmeat trade mining encourages through road networks and the markets it creates in sites where it is conducted.

An Overview of Mining History in the Congo Basin

Mining in the Congo Basin has a very long history. For example, iron smelting is thought to have started 2500 years ago and trade in minerals across the region dates even before that time as evidence of copper from DRC and Congo was found in jewelry in a cave in southern Gabon dated to 800 BP. However, current mining history in the Democratic Republic of Congo (DRC) began before the first European expedition in 1883. According to John (1873) and Verbeken and Walraet (1954), local communities living in the Garanganze area (today the greater Katanga Province) were exploiting minerals as early as the sixteenth century. They mined ores of copper oxide, which outcropped the host rocks from the Katanga in such areas as Etoile, Kipushi, Luishya, Kambove, Tenke, Fungurume, and Dikulwe. Several smelting sites discovered around these sites had 5-m-long metallic bares in the form of a cross (*croissette*), which were used as a tradable value by local businesses (De Hemptinne 1926). Up to 1850, ca. 700 metric tons in total copper was estimated to be produced in that area.

After the Berlin Conference, several expeditions were organized in DRC and throughout the Congo Basin. From a historical point of view, the most important of these was the Bia-Francqui expedition between 1891 and 1892. The Bia-Francqui expedition was funded by the Compagnie du Katanga (1891) and led by Jules Cornet, a Belgian geologist who rediscovered the Etoile copper deposit. Etoile copper was important because it was larger than other deposits such as Kipushi, Luishya, and Kambove (Pirard 2011). The Bia-Francqui expedition marked the beginning of a detailed geological exploration throughout Katanga, which lasted until 1909. The Compagnie du Katanga, Tanganyika Concessions Limited (TCL), began explorations in 1899, followed by Comité Spécial du Katanga in 1900. The results from these explorations led to the creation of the Union Minière du Haut-Katanga Katanga (UMHK) in 1906, subsequently becoming Gécamines in 1967 (Hillman 1997). Since its creation (1906), Gécamines worked in joint ventures with other international companies to produce copper, cobalt, zinc, lead, and germanium (Cheneval 1944; Cailteux et al. 2005; Mambwe 2017; Mambwe et al. 2024a).

Beyond Katanga region, geological explorations extended across the country (Kennes 2002), including Kasaï in the central southern DRC, which borders Angola. The Forminière company conducted explorations and discovered alluvial diamonds in 1907, 4 years after the first diamond was found in 1903 in the Katanga region. Diamond extraction began in Tshikapa in 1912 (De Wit and Jelsma 2015), followed by Mbuji May in 1920 (De Wit et al. 2011; Mukonki et al. 2022). Alluvial gold

deposits were discovered in 1903 along the Ituri River and later in Namoya Kamituga (in 1930) (Twangiza 1938). The Régie des Mines de Kilo-Moto, subsequently named Société des Mines d'or de Kilo-Moto (SOKIMO) in 1926 and now owned by Barrick Gold Company, conducted the first industrial gold mining (Mpaka et al. 2023). Meanwhile, the Minière des Grands-Lacs (MGL) [Société Minière et Industrielle du Kivu (SOMINKI after 1960)], pioneered gold exploration in Kivu and Maniema and extracted its first gold in 1930. Manganese production started in 1951 at Kisenge (De Putter et al. 2015). Coal was also produced in Luena between 1922 and 1974 and Lukuga from 1923 to 1931.

ASM was not initially prohibited in DRC. Local communities were allowed to extract and traffic both gold and diamonds. This trend persisted and was extended to new minerals as they were discovered. Hence, artisanal mining, which is described below, is not limited to any specific type of mineral and includes cobalt, copper, tin, tantalum, and tungsten, ranging from Katanga to Ituri and from Ituri to Bas-Uélé, then the northern part of the Greater Equateur.

France also conducted extensive exploration for potential mines throughout its colonial territories in the Congo Basin during the same period. Several exploratory missions in French Equatorial Africa (Fig. 1) looked at economically exploitable resources (Saucier 1939), in parallel to the scramble in the Belgian Congo (Bruel 1914). These included Cameroon (Koch 1959), Central African Republic (CAR) (Pouit 1959; Boulvert and Salomon 1988), Gabon (Manot 1950; Dévigne 1959), and the Republic of Congo (ROC) (Sonet 1955; Massengo 2004). According to Entreprises Coloniales (2025), the exploration phase ended with the formation of mining companies, of which the first was the Afrique Minière Equatoriale (AME), established in 1921. Other companies followed, principally Société Afrique Minière Equatoriale (1927), Société d'Exploration Minière Equatoriale and Union Minière et Financière Coloniale (both founded in 1928), Consortium Minier Congo-Niari (1931), and Compagnie Minière du Congo Français (1932).

Vennetier (1967) suggested that colonial mining in ROC comprised small quantities of copper ore (Renéville and Mindouli), gold (Chaillu, Mayombe, Western Sangha), lead and zinc (Mfouati and Niari), and cassiterite (tin ore). These were depleted by the late 1960s. In parallel, oil exploration in the coastal basin in Congo and Gabon began in 1928–1929 when the French Service des Mines dispatched a geological mission to study hydrocarbons in the colony. This mission concluded that there was a need to carry out a detailed study throughout French Equatorial Africa (Sirven 1973). Hence, the French Office National des Combustibles organized the 1931 mission, and then commissioned full-blown research that was interrupted by World War II in 1939 (Sirven 1973). Twelve years after World War II, the Société des Pétroles de l'Afrique Equatoriale extracted its first oil (1957) from Pointe Noire, although full exploitation only began in 1961, when Gabon's first oil was also extracted offshore of Libreville (Daverat 1977). In CAR, the search for minerals continued until very late (Censier and Claude 1996; Censier and Lang 1999) when alluvial diamonds were discovered.

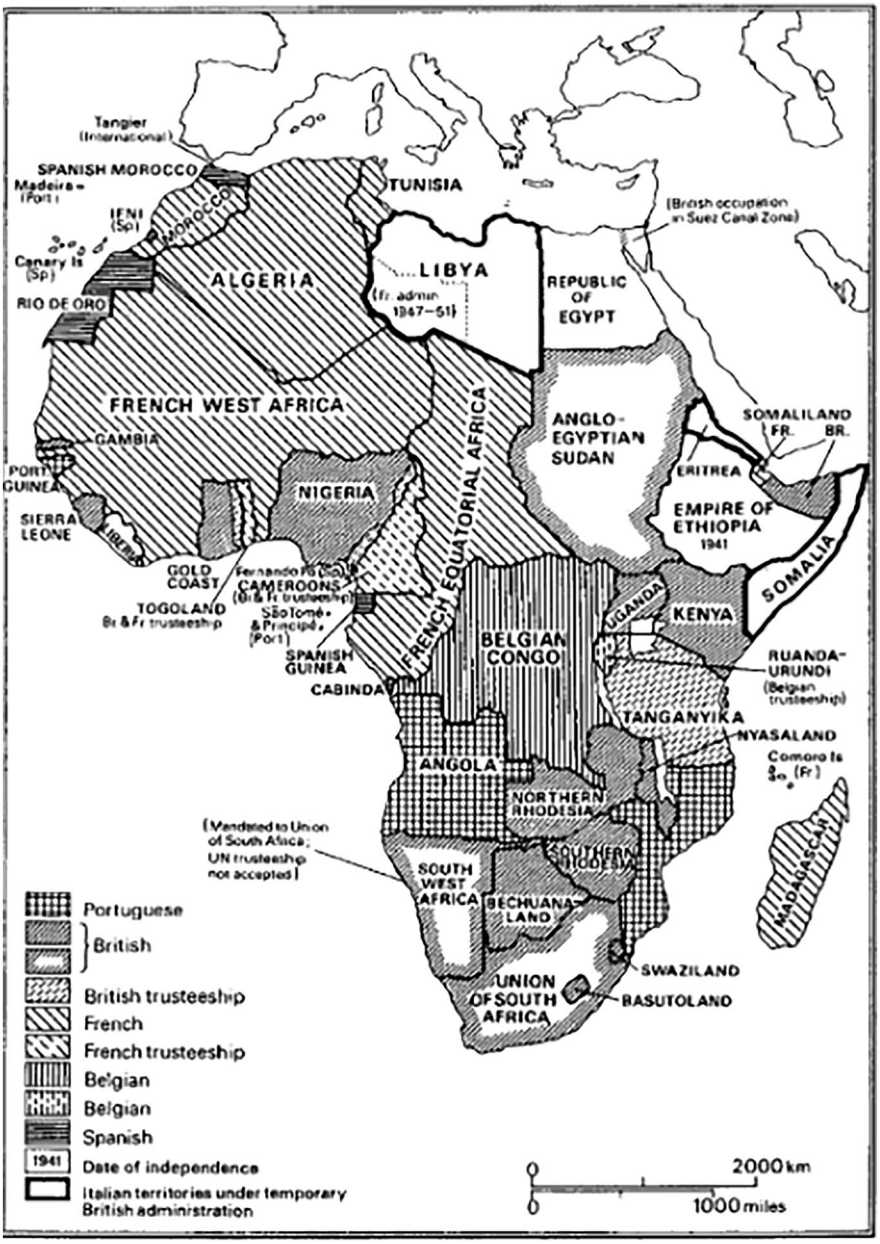

Fig. 1 Map of Colonial Africa with both French Equatorial Africa and Belgian Congo. (Source: **Maps on the Web** charts and infographics RSS)

Current Status of Mining Across the Congo Basin

Megevand et al. (2013) wrote that the Congo Basin shelters mineral resources worth billions of dollars on world markets, with 25 valuable metals found across all the Congo Basin in different quantities (Fig. 2).

To give a sense of the magnitude of minerals, Pitte et al. (2021) indicate that Cameroon has 28 million tons of oil, 700 million tons of bauxite, and 135.1 billion m^3 of natural gas. The same authors indicate that Congo holds 224 million tons of oil and 90.6 billion m^3 of natural gas and Equatorial Guinea 38.6 billion m^3 of natural gas and DRC has 60 billion m^3 of methane. Cameroon has 15 of the 25 resources of Fig. 2, both Congo and Gabon have 9, though tin has been entirely exploited. With 150 million tons of reserves, Gabon holds significant manganese. The huge reserve in DRC is also noted. Autesserre (2010), Megevand et al. (2013), and Trefon (2016) note that minerals occur across DRC with higher concentrations along a band from the southeastern border, with Tanzania to the northeastern border with South Sudan, with a westerly prolongation that reaches Bas-Uele, located at the northwestern border with CAR (Fig. 1). Trefon (2016) reported that DRC held 46% of the world's known cobalt, 11% of copper and diamonds, and 7% of coltan; and ranked as the world's first producer of cobalt and diamond, second producer of iron, fourth producer of copper, and fifth of coltan. Mahonghol (2024) showed that minerals are spread across the Congo Basin, with sites in southwestern Congo to eastern and central Gabon, southeastern Cameroon, and along the southern border with Gabon and Equatorial Guinea. In CAR, sites are mostly along its southern border with both Congo and DRC.

Mineral	Contries of Distribution				
Diamonds	Cameroon	CAR	Congo	DRC	Gabon
Gold	Cameroon	CAR	Congo	DRC	Eq. Guinea
Oil	Cameroon	Congo	DRC	Eq. Guinea	Gabon
Iron	Cameroon	Congo	DRC	Gabon	
Natural gas	Cameroon	Congo	DRC	Eq. Guinea	
Aluminum	Cameroon	Congo	DRC		
Copper	Congo	Congo	DRC		
Lead	Congo	DRC	Gabon		
Manganese	Cameroon	DRC	Gabon		
Titanium	Cameroon	Congo	DRC		
Tin	Cameroon	DRC	Gabon		
Bauxite	Cameroon	DRC			
Cobalt	Cameroon	DRC			
Limestone	Cameroon	DRC			
Nickel	Cameroon	DRC			
Niobium	DRC	Gabon			
Phosphate	DRC	Gabon			
Uranium	Cameroon	DRC			
Cadmium	DRC				
Coltan	DRC				
Lithium	DRC				
Methane	DRC				
Rutile	Cameroon				
Tungsten	DRC				
Zinc	DRC				

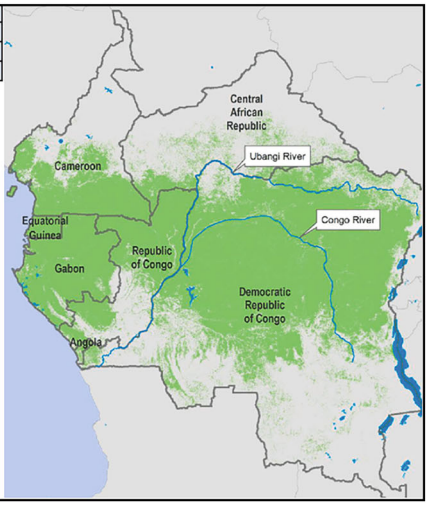

Fig. 2 Presence of 25 important minerals across the countries of the Congo Basin. (Compiled based on Pitte et al. (2021); the map is from Shapiro et al. (2021))

Mining and the Economies of the Countries of the Congo Basin

Countries in the Congo Basin rely heavily on the extractive industry, exporting raw materials to acquire hard currencies to support economic, social, and political activities. Exports of minerals and oils constitute a large portion of the trade balance, contributing significantly to the national gross domestic product (GDP) (Fig. 1).

Although the proportion that minerals and oil contribute to GDP (Fig. 3) changes over time, it demonstrates that countries such as Congo, Gabon, and DRC are highly dependent on minerals and oil and would economically collapse if their mineral extractive industries stopped. The situation is similar for Equatorial Guinea, of which about 83% of its GDP in 2000 came from oil; according to the World Bank (2020), there was a decline from 16% in 2017 to 15% in 2020 in Equatorial Guinea. Despite the importance of mining for GDP, Megevand et al. (2013) argued that the mineral wealth of the Congo Basin is underexploited in most countries, and the high contribution toward GDP in Congo, Gabon, and Equatorial Guinea came mostly from oil. Lack of infrastructure and poor business climate explain the underusage of other mineral resources. The exception is DRC, which has long depended on mining since early colonial times (Young and Turner 1985; Trefon 2016). Despite civil unrest over the last three decades, the mining industry has continued to boom, even when conflicts are associated with mining activities.

Overall, despite the 2008 world recession that affected the mining sector, world demand for mineral resources has been increasing significantly since 2000 (Megevand et al. 2013; Yu et al. 2023; IEA 2024), mostly driven by global economic development and the emergence of new economic powers such as Brazil, China, India, and South Africa (Prichard 2009). Apart from the emergence of these new economies with decades-long strong growth, new technology in transportation, construction, electronic components for computers, and green energy fueled greater demands in traditional minerals that Congo Basin countries were already exploiting, such as aluminum, cobalt, copper, iron ore, lead, manganese, and also in new ones, such as titanium (Prichard 2009).

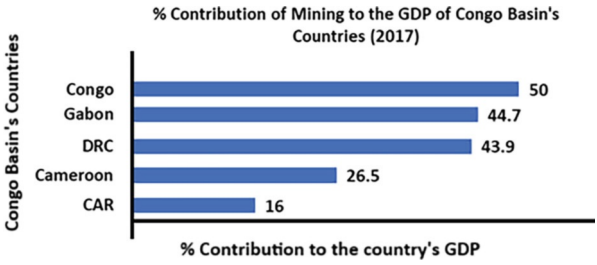

Fig. 3 Contribution of exports in minerals to national GDPs in the Congo Basin. (Compiled based on Pitte et al. 2021)

An Overview of the Mining Legal Framework in the Congo Basin

Unlike for forests (COMIFAC 2004, 2005), in the absence of any regional treaty or agreement, oil and minerals are governed by national legislation in the Congo Basin. Hence, the analysis of the mining legal can be assessed only country by country, as done in the following sections.

The first full-fledged postcolonial mining code for DRC was only enacted in 2002 (Présidence de la RDC 2002). It was modified in 2018 (Présidence de la RDC 2018). ROC issued its code in 2005 (Présidence de la République du Congo 2005); Gabon promulgated its mining law in 2019 (Présidence de la République du Gabon 2019a); in Cameroon, the mining code was made public in 2023 (Presidency of the Republic of Cameroon 2023), and CAR enacted its mining code only in late 2024 (Présidence de la République Centrafricaine 2024). That countries of the Congo Basin have all now adopted modern mining codes shows that mining activities have become a center of interest for all of these countries. The new mining legislations share the fact that they are all sufficiently long and very detailed. While detailed laws have clarity and would limit the need for application decrees, so much details sometimes make them complex to grasp and fully deployed in terms of enforcement. For example, the new DRC mining code, for example, has 343 articles, plus annexes comprising 17 titles and 2 introductory preambles to motivate the law itself. Lengthwise, the new DRC mining code has 236 pages that replaced the previous 137 pages. Gabon's mining code has 298 articles, whereas CAR and Congo, respectively, have 259 and 193 articles.

In Cameroon, prior to the 2023 Cameroonian mining code, the regulatory mechanisms were embedded in legislation from 1964 regulating mineral substances, with the country's 1978 legislation outlining taxes, royalties, and mining taxes. The National Assembly was empowered to approve mining permits for the country prior to 2001 when the law shifted the approval to the Ministry of Mining because the route through the National Assembly was felt to be overly encumbered by bureaucracy. This change has been said to reduce the legitimacy and transparency of the process of obtaining mining permits.

These new legal frameworks follow a long history, which began during the colonial era. For example, DRC has a long history of promulgating legislation on mining. The Royal Decree of 8/6/1888 organized mining activity (Bakandeja 2000). For Bakandeja (2000), the royal decree set the tradition affirming the State's ownership of mineral substances in motion. This tradition also demarcated mineral ownership and the land rights, with the latter having primacy over mineral wealth; the royal decree also presented a list of conditions to obtain mining concession from the Congo Free State. The 1888 law recognized the rights of indigenous people to mine on land they occupy, which preluded the current scramble for artisanal mining. The 1888 decree was amended on 20/3/1893 but the same principles continued to apply until the 24/9/1937 article 1, which stipulated that all mines belonged to the State. This was a big shift as artisanal mining became illegal. Two decrees were specifically aimed at the Province of Katanga: 16/12/1910 and 16/4/1919 (Orban 1938). After independence, DRC continued to use the 1937 mining law. Even the "Bakajika Law" (Ordinance-Law n°66–33 of 7/6/1966) left many issues about

mining out of its scope. The first post-independence Ordinance-Law n°67/231 of 11/5/1967 on general legislation on mining and hydrocarbons officially abrogated the 1937 decree. The May 1967 Ordinance-Law was modified shortly after it was rendered public by the Ordinance-Law n°67/416 of 23/9/1967, which appeared in September the same year under the shortened name of mining regulation. The preceding law remained valid until 1981 when it was modified and completed by Ordinance-Law n°81/013 of 2/04/1981. In their global spirit and respective letters, the laws of 1967 and 1981 did not depart significantly from the 1937 decree, whose shift toward state monopoly on mining made everything else illegal, including artisanal mining. This was corrected by Ordinance-Law n°82/039/ of 5/11/1982, which established the selective liberalization of artisanal mining to combat clandestine exports of mineral substances. This was followed by another major shift by Law n°86/008 of 27/12/1986, which enjoined industrial mining and oil extractors to extend their corporate purpose to include agricultural and social activities and construct durable buildings in areas where they extracted natural resources. It is following that long history that the 2002 mining code was crafted, which gives the Prospecting Research Permit holder exclusive rights for 4 years. If an economically viable resource is found, the permit holder has the potential to extend and then apply for a Permit of Exploration.

The Code Minier Gabon Law No. 37/2018 follows a long historical chronicle after Law n°15/62 of June 2, 1962, that established the Gabonese Mining Code, Law n°14/74 of January 21, 1975, regulating oil exploration and exploitation activities, and Law n°14/82 of January 24, 1983, regulating hydrocarbon exploration and exploitation activities. Gabon's legislatures have separated mining from oil extraction due to the importance of oil in the national economy. Even the 2019 law on mining (Présidence de la République du Gabon 2019a) runs in parallel with the Gabonese hydrocarbon Code (Law n°002/2019 of July 16, 2019) (Présidence de la République du Gabon 2019b).

The current mining codes in Cameroon, CAR, and DRC share some common features; they all aim at increasing the transparency in reporting and accountability of taxes, and usage of sustainable standards and practices in respect to host states and communities (Gerner et al. 2023). While for Cameroon and Gabon the question is to accrue and diversify their mining portfolios, in CAR and DRC, the reforms to the mining sector are mostly aimed at bringing to light and stopping illegal activities that steal a lot of resources from the governments and people of these countries (e.g., Childs 2008; Katz-Lavigne 2020). Both CAR and DRC have been suffering from weak governance, institutions, and monitoring capabilities, which have encouraged illegal mining and banditry.

Mining and Ecosystem Health and Functional Degradation in the Congo Basin

The impacts of mining on biodiversity can be seen using traditional measures such as loss of habitats. Mining activities cause water, air, and soil pollution. This section reviews available date on such metrics.

Mining Activities and Habitat Fragmentation and Loss Across the Congo Basin

Surface and pit mining change and fragment habitats through infrastructure development for accessing the mining site and for extraction. Both fragment habitats by clearing the land in the mining sites, as well as along the commercial routes to where minerals are treated or shipped out (Giljum et al. 2022). No basin-wide studies on the extent of habitat surface and ecosystem conversion or country-indexed land conversion rates exist. Even detailed mining-specific assessments such as Reed and Miranda (2007) and Hund et al. (2013) have not been able to quantify habitat losses from mining. Tyukavina et al. (2018) found that mining caused 0.04% (about 141 km^2) of total forest loss by area in the Congo Basin over the last three decades. To many researchers, this figure seems very small. Tyukavina et al. (2018) argue that their estimate of forest area loss due to mining had low relative precision, but quantified forest loss in the Congo Basin due to mining with high relative precision at around 14,736-ha.

Although the above figures are rather small, there are good reasons to think that they are underestimated. Firstly, these figures do not count road networks and other infrastructures that accompany the mining industry, including residential camps and, secondly, they do not factor the land cleared to produce the food that is sold in the mining sites. Indeed, Ladewig et al. (2024) have shown in the case of ASM that each mining site triggers deforestation at least 5 km from mining sites; in total, the indirect deforestation caused by mining through the expansion of other land uses is 28 times larger than the forest area directly cleared for mining. For Ladewig et al. (2024), most of the indirect mining deforestation is caused by increased farming around mines, followed by forest cleared for settlements. Extrapolated habitat loss caused by LSM in the Congo Basin was about 141 km^2, with an associated area of 4230 km^2 habitat lost for activities such as settlements and farming to support the mining operations. Estimated habitat loss in DRC due to mining was about 130 km^2, with an extrapolated area of 3900 km^2 to accommodate activities associated with mining over three decades. These extrapolations include roads, settlements, and food production sites. In Gabon, the manganese mine in Franceville was a major factor in the decision to build the railway from Libreville to Franceville and opened the entire country up to logging. Similarly, oil and major deposits of iron and manganese. As this example shows, mining operations need massive infrastructure to be viable, and unless there is strong environmental governance in place, they can catalyze massive changes, including development of hydroelectrical power to run them. Logging and mining roads and emplacement of both waste and tailings have long been described to have negative impacts on forest ecosystems, including habitat fragmentation in the Congo Basin (Wilkie et al. 2000; Laurance 2008a; Kleinschroth et al. 2019) and all over the world (Laurance 2008b; Dobson et al. 2010).

ASM has received more attention and has been assessed in more ways than LSM, which leads to relatively modest destruction of habitats. Tieguhong et al. (2009), Schure et al. (2011a), Gerner et al. (2023), and Ladewig et al. (2024) found indirect effects of AM to have a significant impact on habitat fragmentation. Indeed,

Ladewig et al. (2024) suggested that this impact has a much larger significance in deforestation dynamics than previously assumed, going as far as concluding that, at least in the case of eastern DRC, 6.6% of the total deforestation is a result of AM activities. For Ladewig et al. (2024), each newly opened artisanal mining site triggers a 5 km radius of deforestation beyond the actual mining site. The onset of mining causes an additional 4% of forest loss after 10 years (Ladewig et al. 2024). Confirming what previous studies (e.g., Kelly 2014; Otamonga and Poté 2020) have been suggesting, Ladewig et al. (2024) concluded that most of the indirect deforestation linked to mining is caused by increased farming around mines, followed by forest cleared for settlements. Obviously, there are significant differences in the magnitude of the situation described by Ladewig et al. (2024) for DRC and other Congo Basin countries. However, DRC's situation is not singular to this country and represents a trend that seems to be being repeated across other countries of the Congo Basin, transforming the effects of artisanal mining into pan-basin features. Studies in both Cameroon and CAR reached similar conclusions (Ingram et al. 2011; Funoh 2014; Mumbfu et al. 2023).

Mining not only fragments the physical characteristics of habitats; other physical effects include diverting water courses, extracting sands, increasing water sedimentation, degrading lands, opening forest understoreys, and opening pits, which are difficult to detect from the satellite images that are commonly used to document the physical effects of mining on habitats (Funoh 2014). Some mining operation may also cause air pollution, generating thick layers of dust, while also sometimes causing a lot of noise pollution (Funoh 2014; Peša 2020). Pollution is particularly intense and severe in areas neighboring mining sites, which use radionucleotides, lead, mercury, cadmium, and chromium (Abernethy et al. 2016). For Peša (2020), air pollution and water pollution have long been acknowledged by all stakeholders, including the mining industry itself, as true negative externalities.

Mining Activities, Petroleum Extraction, and Pollution Across the Congo Basin

While metrics of habitat fragmentation caused by mining are difficult to find in peer-reviewed published materials on the Congo Basin, a significant bulk of literature exists on soil and water pollution caused by both ASM and LSM. Mercury (Hg) pollution has been described to be of the most concern across the Congo Basin because it has been revealed to have long-term impacts on ecosystems and human health (Tieguhong et al. 2009; Funoh 2014; Nkuba et al. 2019).

In DRC, mining operation were almost always coupled with the concentration of metals, including titanium ($_{22}$Ti), cobalt ($_{27}$Co), nickel ($_{28}$Ni), copper ($_{29}$Cu), zinc ($_{30}$Zn), arsenic ($_{33}$As), cadmium ($_{48}$Cd), lead ($_{82}$Pb), or mercury ($_{80}$Hg) that leak out into the immediate environment (air, sediment, soil, or water), causing pollution. However, levels of pollutions vary across countries and provinces. For example, Atibu et al. (2023) found that some of these minerals occurred in low concentrations, with the exception of Hg and As, in Maniema, one of the provinces of the Kivu Massif, eastern

DRC. However, Mutombo et al. (2022) found high concentrations of Ni, Cu, Zn, As, Cd, and Hg in water samples, with concentrations of As, Cd, and Hg exceeding national legal limits; same high concentrations of Cu, Cr, Zn, As, Cd, Pb, and Hg were also found in river sediments. Cu, Co, As, and Cd enriched the sediments and Cu and Co also highly contaminated rivers (Atibu et al. 2013; Mutombo et al. 2022).

In both Eastern and Western Cameroon, Ayiwouoa et al. (2020, 2021, 2022), and Ngueyep et al. (2021) found the same patterns, whereby concentrations of As, Cd, Fe, I, Ni, and Pb at mean values that exceeded World Health Organization's (WHO) limits. Ayiwouoa et al. (2020, 2021, 2022), Ngueyep et al. (2020), and Ngueyep et al. (2021) concluded that these levels of concentration made the surface water in the rivers unsuitable for drinking purposes, though concentrations of Pb, As, Cd, and Hg were seasonally driven, decreasing in the dry seasons.

In ROC, increasingly higher and higher concentrations of Cd, Cu, Pb, Zn, Mn, and Mg were detected in freshwater rivers and in the basins of the Congo River Basin. They were also documented in coastal waters and sediments (Kaya et al. 2024). Kaya et al. (2024) found that these increasing concentrations were strongly correlated with organic matter. Even though these concentrations were increasing in the coastal area, Kaya et al. (2024) indicated that Cd, Pb, and Cu accumulation indices and load indices were still low compared to thresholds that constitute high ecological risk on biota and ecosystems in some sites they sampled. This picture from the coastal zone is not representative of the country as a whole. Diahou et al. (2023) found that phosphate (P) highly contaminated the mining area in Hinda District, southwestern Congo. In Gabon, Ndong (2023) discussed the extraction of uranium in Mounana and the social and environmental damages this caused between 1961 and 2010 when mining activities were active; air, soil, and water pollution were documented to last even after active mining ceased. It was difficult to find peer-reviewed articles on mining's effects in CAR, a country where mining for diamonds and gold has been ongoing for several decades. However, the country's Ministry of Environment and Sustainable Development reported the unquantified existence of environmental (air, soil, and water) pollution by Hg in 2019 (Ministère de l'Environnement et du Développement Durable 2019). Soil and water contamination by mining activities were reported to last long after the cessation of mining activities across the Congo Basin in DRC (e.g., Pourret et al. 2016; Atibu et al. 2013, 2017) and Gabon (e.g., Ndong 2023).

Petroleum exploration and extraction onshore and offshore are underway in DRC, Gabon, and ROC along the Atlantic coast since 1956 (Vidal et al. 1975; Mounguengui et al. 2003). In the eastern part of DRC along the Tanganyika–Albert–Kivu lakes as well as in the central part of the Congo basin, the petroleum and/or methane gas potential were already mentioned but an advancing exploration based on the environmental challenge is recommended. However, national parks such as the Virunga National Park for biodiversity conservation (e.g., mountain gorillas, fish in Tanganyika Lake) have evolved a strict application of environmental regulation.

This exploration and extraction in DRC, Gabon, and ROC are common and also have a negative impact on the ecosystem as in the case of the mining operation

(Shengo et al. 2020; Mambwe et al. 2024b). For several years, the oil extraction caused the leakage of crude oil and natural gas. The source of pollution is due to the pipeline breaking, followed by the burning of the natural gas and the oil discharge into the rivers, lakes (e.g., Lake Anengué in Gabon), and the Atlantic Ocean. The oil flow on the surface affects several kilometer squares, where there is a potential risk of the population (e.g., air pollution by the burning gas, toxic waste) and the biodiversity is also destroyed (e.g., Mangroves National Park and Farm).

Effects of Mining Activities on Freshwater Fish Species Across the Congo Basin

Fish species in water polluted by heavy metals have been found to concentrate these metals in their tissues. For example, in Lake Tshangalele (DRC), Squadrone et al. (2016) documented that fish specimens they collected closest to the copper mining plant had higher concentrations of Co, Cu, Fe, Mn, Zn, and Al; not surprisingly, they identified a decreasing gradient in concentrations along the lake, as one moved away from the mining site. In Gabon and ROC, freshwater fishes have been observed to have a very high mercury pollution due to mining activities (Abernethy et al. 2016).

Chemical Water Pollution: Comparing Artisanal and Industrial Mining Across the Congo Basin

As is the case across Africa, ASM in the Congo Basin is essentially practiced by communities as a livelihood strategy that allows them to make financial incomes to support their families (Hilson 2011). In many cases, small-scale artisanal mining alternates with other activities throughout the year. In some cases, small-scale artisanal mines grow to attract thousands of miners from surrounding regions, taking on the scale, appearance, and impact of an industrial mine. LSM is poised to help countries in the Congo Basin augment their economic profiles by contributing significant incomes that provide resources for development (Peša et al. 2024). However, both forms of mining come with the above-described impacts on habitats and the environment (air, soil, and water). Studies (e.g., Ladewig et al. 2024) documented evidence that habitat fragmentation and land clearance are generally higher in ASM than LSM activities. The same pattern seems to be present when other aspects of environmental impacts caused by mining activities are screened. Indeed, mercury utilization, for example, was higher in sites where ASM activities were practiced than where industrial activities were undertaken, perhaps because these installations are generally subject to national and international scrutiny and norms. Mercury utilization remains a dangerous source of water and soil pollution (Keane et al. 2023); it has been reported by Barthélémy et al. (2008) in the transborder area where Cameroon, CAR, and ROC come together. Atibu et al. (2016), Atibu et al. (2023), and Nkuba et al. (2019) found it in eastern DRC as well and in a global review of its use; Keane et al. (2023) confirmed its usage in

CAR. Keane et al. (2023) indicated that three countries of the Congo Basin that used remarkable levels of mercury for mining in 2018 were DRC (ca. 16 tons annually), CAR (ca. 8 tons annually), and ROC (ca. 2–3 tons annually). Keane et al. (2023) also assessed the usage of the four worst practices, which they defined following the Minamata Convention, as including whole ore amalgamation, open burning of amalgam (i.e., without a mercury capture device), burning of amalgam in residential areas, and use of cyanide on mercury containing tailings or sediment without first removing mercury (Schwartz et al. 2023). The three countries appeared on the table of countries that used worst practices that caused health risks for ASM's miners. DRC was negatively scored on all four criteria, CAR scored negatively on the first criterion (whole ore amalgamation) and was data-deficient in the other three, and ROC was totally data-deficient (Keane et al. 2023). Atibu et al. (2021) also described radio activity in the air in Katanga.

ASM in the Congo Basin is often associated with uncontrolled chemical water pollution (Hinton et al. 2003; Mazalto 2005). However, instances where and when LSM caused severe and geographically significant pollution have also been described. An illustrious case is the one provided by the Catoca diamond mine (Angola), whose tailing spills in 2021 significantly impacted water quality and aquatic biodiversity. After the incident was reported, a study by Ruppen et al. (2023) showed that the Catoca mine tailing spills polluted rivers from Angola to DRC, with the pollution front traveling as far as about 1400 km from the mining site. According to Ruppen et al. (2023), the Catoca tailings spill significantly affected the water quality of the Tshikapa and the Kasaï Rivers, with total suspended solids concentrations that were several orders of magnitude above drinking water standards in Lunda Norte Province (Angola) and Kasaï Province (DRC); they concluded that this chemical spill severely impacted the public health of residents of these two provinces and also reported high probabilities that the chemical spill would cause fish mortality downstream.

Large-scale air, water, and soil pollution linked to LSM were also reported in some other areas of DRC. Mazalto (2005) reported that the Kimilolo aquifer, which supplies 70% of the city of Lubumbashi, was polluted by the copper and cobalt ores treatment of some mining. Mazalto (2005) documented pollution affecting the Lubumbashi, Lufira, Likasi, and Kolwezi rivers. The Lubumbashi River was affected by the activities of the Terril de Lubumbashi, using chemicals to treat minerals (Mazalto 2005). The fact that there are many more LSM pollution studies in DRC than in any other country of the Congo Basin reflects the reality that LSM has been ongoing in this country for longer and at a larger scale than in other countries of the basin. This should serve as a stark warning to the other countries that careful environmental monitoring and management are critical to ensure that the economic benefits of mining are not associated with enormous environmental costs.

Mining and Biodiversity Loss in the Congo Basin

Drivers of biodiversity loss include land clearance, habitat fragmentation, and accidents such as the Catoca diamond mine's tailings spill in 2021, resulting in

pollution. Many instances of impacts remain undetected even when mining has been posing serious threats to biodiversity. Indeed, the undetected or unquantified impacts include such phenomena as roads, including principal roads for transport of minerals and secondary roads that bring food supplies and other commodities to the mining sites. Roads, whether principal or secondary in nature, have often been described as having severe impacts, not only due to the fragmentation of habitats but also in terms of bushmeat trade (Wilkie et al. 2000; Engert et al. 2025). Declining wildlife populations are often due to hunting caused by the market created to feed people living in mining sites. Furthermore, many mining sites in the Congo Basin overlap with protected areas, which have been set aside to provide protection for wildlife species and their habitats. In contradiction to national laws, mining activities sometimes occur inside protected areas in the Congo Basin, as has been documented in DRC, and the trinational border of Congo–Cameroon–CAR (Schure et al. 2011b). Similar activities have been observed in the Amazon and in other forest ecosystems in the developing world (e.g., Asner and Tupayachi 2017).

Mining, Economic Development, and Human Rights in the Congo Basin

As shown in Fig. 3, exports in minerals contribute very high percentages to national GDPs in the Congo Basin. However, the impacts of mining often evoke mixed reactions from local communities. This is sometimes linked to corruption and the associated lack of transparency related to LSM (Gulley 2023; Deberdt and DiCarlo 2024), social injustices, and weak human rights records (Anderson 2023). As indicated above, most of the recent national mining legislations in the Congo Basin aim to increase transparency in resource use, improve wealth redistribution, and respect human rights requirements. However, only a meager portion of the financial revenue generated by cobalt in 2023 went to the development of DRC, and very little reached the sites where the cobalt was produced. Chinese firms present in the country remained central in cobalt mining, processing, and battery manufacture (Deberdt and DiCarlo 2024). Because they added value to raw materials outside DRC, China captured most of the financial revenues, significantly reducing the financial resources available to support the development of DRC (Anderson 2023). In the mid-1960s, Vennetier (1967) described the same pattern throughout the Congo Basin, where high hopes were created among communities when mineral deposits were discovered in their regions but only resulted in meager changes after minerals were exploited (Vennetier 1967).

In the example above, China clearly profited from the cobalt exported from DRC, but Deberdt and DiCarlo (2024) also found that Chinese firms spent as much as US$55 million to corrupt one single political leader, demonstrating what they called the complex dependence of international mining companies on local, provincial, and national systems. Corruption is not the monopoly of Chinese firms nor can it be singly attributed to the new political leadership in DRC, as we know that it has been ongoing since the country became independent in 1960 (Young and Turner 1985;

Nzongola-Ntalaja 2002; Trefon 2016; Gulley 2022). Corruption in the mining industry has also been reported in Cameroon (Nguepjouo 2017; Kamga et al. 2017; Knutsen et al. 2017) and Gabon (Jansson et al. 2009). This betrayal of communities' expectations for sustainable development that mineral resources would bring is the same pattern that has been recorded in other countries of the Congo Basin. Tsassa (1987) and Malonga and Samir Saul (2010) suggested that being naturally endowed with oil has turned out to be a nightmare in ROC. As Kamga et al. (2017) rightly suggested for the case of Cameroon, due to the lack of transparency in how financial yields from mining are distributed, the participation of the mining industry in the sustainable development of the Congo Basin has remained, at best, very challenging to quantify. Lesueur (2014) came to the same conclusion when he tried to chronicle the situation of mine deposits in CAR and their mostly negative impact on communities and the nation's sustainable development.

Abuses of human rights by mining activities have been documented throughout the Congo Basin (Gerner et al. 2023). The first abuse is related to land rights; when mining sites are discovered, countries often forcibly evict communities for industrial operations (Gerner et al. 2023). Katz-Lavigne (2019) reported evictions in DRC. Other common abuses of human rights include gender-based violence (Rustad et al. 2016), forced child labor, and abuse of minorities and vulnerable communities such as indigenous people.

In contrast, many people—both local communities and economic migrants—see positive socioeconomic impacts of engaging in ASM to provide a short- or longer term, albeit often highly variable, source of cash income—generally alongside subsistence farming and forest exploitation (timber, nontimber, bushmeat, and fishing; Ingram et al. 2011, Girard et al. 2022, Radley 2020). This is despite the largely informal, generally illegal and often dangerous nature of the work and its negative health impacts (Geenen 2012; Schure et al. 2011a; Radley 2022). ASM is associated with no or very low levels of regulation (Schure et al. 2011b; Reed and Miranda 2007; Radley 2020). Lawlessness is heightened where armed gangs and groups use forced labor, as in eastern DRC since the 1994 civil war (Kelly et al. 2014); Rustad et al. 2016), CAR (Vlavonou 2020) and in the area around the Congo–Cameroon–CAR border (Schure et al. 2011b).

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Hunting, Fishing, and Ecosystem Functions and Services in the Congo Basin

16

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Abstract

Hunting and fishing have long been central to the traditions, culture, and livelihoods of rural communities in the Congo Basin, supporting both rural and urban populations. Wildmeat and freshwater fish are key protein and nutrient sources, central to both rural and urban diets, and support informal economies, employment, and traditional medicine. Culturally, they are embedded in ceremonies, prestige, and social cohesion. These activities are governed by a mix of customary and statutory laws, though traditional regulations have weakened over time and national laws, especially for inland fisheries, are often incomplete or outdated. Enforcement is uneven and weakening. Currently, wildmeat harvests, estimated at 1.6–11.8 million tons annually, are dominated by ungulates, rodents, and primates, while fish production, notably in the DRC, reaches about 230,000 t yearly, with high post-harvest losses. Both sectors feed

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a significant illegal international trade in bushmeat, fish, and exotic pets. Wildlife populations show marked decline from habitat disturbance and overexploitation: large mammals are scarce in hunted areas, replaced by small, resilient species; top predators and key herbivores are reduced; and inland fisheries face shrinking catches, smaller fish sizes, and market-driven pressures. Overhunting disrupts seed dispersal and ecosystem dynamics, while overfishing degrades aquatic biodiversity and habitats, with long-term catch declines of 65–80% threatening food webs and resilience. These losses endanger rural and Indigenous livelihoods, heighten nutritional insecurity, and expose communities to zoonotic disease risks through unsafe wildlife handling. Given the importance of these sectors in the Congo Basin, there is a need for integrated governance and management models that align human needs with ecological sustainability (see chapter 26).

Keywords

Hunting · Wildmeat · Fishing · Inland fisheries · Livelihoods · Cultural identity · Customary law · Statutory law

Introduction

In the Congo Basin, hunting and fishing have been an integral component of the traditions and cultural identity of rural communities for millennia (Abernethy et al. 2013; Dounias 2016; Fa and Shunk, 2024; Kandza et al. 2023; Walters et al. 2014; Wilkie et al. 2016).

Hunting and fishing activities are locally regulated through customary laws, which have largely eroded over time due to various factors that shape the way in which hunters and fishers comply with customary law (Mavah et al. 2022). At the national level, hunting and fishing practices are regulated by laws and regulations, most of which are incomplete or outdated, especially the inland fisheries sector that is often poorly regulated.

Clearly, hunting and fishing continue to play a major role in the food security, traditions, and livelihoods of rural and urban populations in Central Africa, despite a poor recognition of those sectors at national and regional levels and in food systems in general (Coad et al. 2019). In the meantime, hunting and fishing practices are increasingly leading to resource depletion with major impacts on ecosystems services, biodiversity, and local livelihoods (Abernethy et al. 2016; Ickowitz et al. 2024).

In this chapter, we first synthesize the most recent literature on the role of hunting and fishing in providing key ecosystem services. Then, we describe the legal and customary frameworks that regulate their practice. Subsequently, we synthesize available knowledge on the levels of offtake and the current status of terrestrial and freshwater wildlife populations. Finally, we discuss the ecological and livelihood impacts related to overexploitation.

Ecosystem Services Provided by Freshwater and Terrestrial Wildlife Throughout the Congo Basin

There are numerous ecosystem services provided by hunting and fishing in the Congo Basin, including as sources of food, income, medicine, and cultural significance (Coad et al. 2019; Ingram et al. 2021; Trefon 2023).

Food

In rural areas of the Congo Basin, wildmeat is often the primary source of animal protein, though fish also plays a major role in local diets (Abernethy et al. 2016; van Vliet et al. 2015, 2019, 2021). Wildmeat contributes significantly to nutritional security and dietary diversity, supplying proteins, fats, and minerals essential for both rural and urban populations (Coad et al. 2019; Ingram et al. 2021). For Twa hunter-gatherers in the Democratic Republic of Congo (DRC), wildmeat and honey are the most important forest resources (Cuni-Sanchez et al. 2019). In the DRC, where poverty levels are high, wildmeat remains the most affordable and widely consumed meat (Batumike et al. 2021; Van Vliet et al. 2012). Similarly, in Nigeria's Cross River region, over 90% of respondents had eaten wildmeat in the previous month, reflecting its status as the most preferred and frequently consumed meat (Friant et al. 2020). Among the Baaka people in Cameroon, hunting provides an estimated 7.5 t of meat annually per village, nearly half of which is consumed directly by hunters and their families (Martin et al. 2020).

Wildmeat is valued not only for its nutritional benefits (Rickenbach et al. 2017; van Vliet et al. 2022) but also for its taste and cultural significance (Fa et al. 2015; Fargeot et al. 2017; Semeki et al. 2014). In urban areas such as Bertoua and Ebolowa (Cameroon), wildmeat is perceived as tastier, healthier, and more prestigious than domestic meat (Nguyen et al. 2021). While urban consumption is often driven by preference rather than necessity, towns closely connected to hunting grounds with limited access to imported meat still rely on it as a staple. Some urban dwellers also attribute "wild power" to wildmeat, a quality not found in domestic animals (Ichikawa and Hattori 2016).

In Pointe Noire (Republic of Congo), wildmeat retains its popularity despite high prices, seen as a natural, healthy delicacy and status symbol (Chausson et al. 2019). In Port Gentil (Gabon), 24% of households reported wildmeat as their main source of meat, especially consumed on weekends (Bachand et al. 2015). Conversely, in cities like Kindu, Kisangani, and Bangui, smoked wildmeat is regarded as an affordable, readily available staple rather than a luxury, particularly where access to alternative proteins is limited (Batumike et al. 2021; Fargeot et al. 2017; Van Vliet et al. 2012). Patterns of preference and consumption in urban settings also vary according to gender, age, and wealth, reflecting broader socio-demographic influences (Chausson et al. 2019; van Vliet et al. 2021).

Alongside wildmeat, river fish are an equally critical protein source across the Congo Basin, providing essential nutrients such as omega-3 fatty acids, vitamins, and minerals that underpin health and well-being (Inogwabini 2014). Fish can

account for over 50% of total protein intake in rural households, significantly contributing to diets, particularly for vulnerable groups (Béné et al. 2010). Small fish harvested from the large lakes of Central Africa are especially important due to their ease of preservation and transport: they are typically sun-dried whole, unlike larger fish that require gutting, salting, or smoking (Kolding et al. 2019).

Fishing also plays a critical role in livelihoods. In rural DRC, poorer households rely heavily on fishing, with women often contributing substantially to catches (Béné 2008). In northeastern DRC, species such as *Clarias*, *Labeo*, *Protopterus*, *Stolothrissa tanganyicae*, *Limnothrissa miodon*, and *Distichodus* are among the most commonly consumed, ranking second only to wildmeat in importance (Van Vliet et al. 2019). During times of civil unrest or economic crisis, particularly in central DRC, fish became a fallback food source when forest mammals were overhunted or scarce (Kimura et al. 2012). Among the Bakwele of Cameroon, fishing remains an essential subsistence activity throughout the year, especially in the dry season when fish are easier to catch in shallow waters (Oishi 2010, 2016).

Income

Wildmeat is a crucial income source for rural and urban households across the Congo Basin, generating millions of dollars annually (Coad et al. 2019; Fa et al. 2022). Operating largely within the informal economy, the trade involves hunters, brokers, and traders (Van Vliet et al. 2019). In Cameroon alone, it is valued at around US$112 million per year (Lescuyer and Nasi 2016). Commercial hunters typically sell 35–89% of their catch, depending on market access and urban demand (Coad et al. 2019). Earnings vary widely by context. In the Yangambi landscape (DRC), hunters earn an average of $40 per month—twice the official minimum wage in 2017 (Van Vliet et al. 2019). Where wildlife remains abundant, hunting yields high profits with little material investment, attracting young men seeking stability. However, as populations decline and urbanization expands, reliance on hunting decreases. In Tchibanga (Gabon), hunters are turning to alternative livelihoods (Van Gils et al. 2019). Around Korup National Park (Cameroon), over 66% of hunters sell primarily to Nigerian markets (Ervis et al. 2024), while near Douala Edea National Park, hunting supports 13% of households (Fonkwo 2023). Wildmeat sales sustain rural economies by funding essentials such as school fees, healthcare, and food in places like Befale and Boende (DRC) (Ngolela et al. 2023). Demand peaks during the agricultural lean season, school year openings, and festivities. In urban areas with few job options, women increasingly engage in wildmeat trade, which, despite bribes and preservation costs, is considered less risky than farming. Kinship and ethnic networks underpin the trade, shaping ties with hunters, peers, and enforcement officers. In Cameroon, the trade has offered women greater economic independence and financial security (Randolph et al. 2022).

Fish is equally vital as a commercial resource. Freshwater fisheries underpin local economies across the Congo Basin, offering both income and stability (Brummet 2005). In the DRC, the inland fishing sector employs about 600,000 people, making it the country's largest job provider. It contributes an estimated USD 63.4–166.3 million annually to national GDP (FAO 2023). Small-scale freshwater fishers can be grouped

into "full-time fishermen," who rely on specialized gear such as long lines and seines, and "farmer fishermen," who integrate fishing into broader livelihood strategies (Béné 2009). While the former are more productive, they are also more vulnerable to stock fluctuations, whereas the latter maintain more resilient but less efficient economies. Fish also plays a vital role in food security. Small fish, often sold in affordable portions, are eaten whole, including bones and viscera, providing concentrated nutrients (Longley et al. 2014). Fishing households typically earn more than nonfishing households, highlighting its importance in poverty alleviation (Béné 2008). In Kinshasa markets, surveys recorded 20 fish species from 7 orders and 14 families, with imported oceanic species such as *Trachurus capensis* and *Sardina madarensis* more frequently sold than local catches (Tchomba et al. 2020).

Medicine

In the Congo Basin, wild animal products serve not only as a key food source, but also as a key component in traditional medicinal practices. Various animal parts are utilized in traditional, with each species or part believed to possess specific healing properties. Examples include hard parts like bones, shells, and teeth, internal organs, and other elements like fur, blood, and bile (Friant et al. 2022). This knowledge underpins the health and healing practices in these communities (Mpoyi et al. 2024; Swiacká et al. 2022). Different animal parts are employed to treat a wide range of ailments, from joint pain and digestive issues to more complex conditions like convulsions, anemia, asthma, and infertility (Van Vliet et al. 2017a). Central African species, such as the pangolins, are also highly sought after in the international Asian market, with a volume currently estimated at 0.4–2.7 million pangolins hunted annually for medicinal purposes over the past four decades (Ingram et al. 2018). Additionally, wildmeat plays a role in ritualistic and cultural practices with medicinal uses. In Ouesso, in the Republic of Congo, for instance, pangolins are used in various ways, including for spiritual and physical healing (Swiacká et al. 2022). Zootherapies involve using live animals, raw or processed animal parts, or by-products through various methods like cooking or soaking in liquor (Friant et al. 2022). Gender also influences the use of animals in traditional medicine, with women generally displaying greater knowledge and attachment to these practices, particularly for maternal and childcare (Mutombo et al. 2022; Shephard et al. 2023).

Cultural Identity

Wildmeat carries deep cultural significance in the Congo Basin, shaping nutrition, identity, rituals, and social structures. Its value extends beyond food, reinforcing traditions and symbolic practices. For many, wildmeat evokes prestige, nostalgia, and childhood memories, making it a "biocultural food" central to community identity (Dounias and Ichikawa 2017; van Vliet and Mbazza 2011). It is often viewed as natural, tasty, healthy, and a rare luxury, symbolizing social status, particularly in urban areas (Brashares et al. 2011; Wilkie et al. 2016).

Cultural taboos also govern consumption. Pregnant women, newly circumcised boys, or entire communities may be restricted from eating specific animals, including leopards, buffalo, elephants, monkeys, bats, snakes, pangolins, or snails (Kyale Koy et al. 2024). Such prohibitions reflect beliefs about disease, misfortune, or spiritual danger. Wildmeat also features in ceremonial contexts: for example, the Benga of Gabon use sea turtle meat during baptisms, marriages, and funerals, embedding animal consumption into major life events.

Similarly, river fish play a vital cultural role. Fishing is not only a subsistence activity but also a collective practice that strengthens community ties (Jang and Boyette 2021; Ngole 1986). Successful fishing trips and the sharing of catches foster social cohesion, while rare or large fish can signal higher social standing. Beyond nutrition, fish consumption and preparation symbolize hospitality, unity, and continuity, often marking festivals or rites of passage (Davis and Harasti 2020). Among the Punu of Congo-Brazzaville, the dance *ikoku* represents fishing activities and links them to fertility and the water spirit world (Plancke 2011).

Overview of the Legal and Customary Framework Regulating Hunting and Fishing in the Congo Basin

In the Congo Basin, hunting and fishing are traditional activities that follow customary practices, regulated by statutory legal frameworks since colonial times. National regulations on hunting and fishing are critical for the sustainable management of wildlife resources. Effective regulation can balance ecological health, biodiversity conservation, and local livelihoods, ensuring that hunting and fishing practices do not lead to the depletion of wildlife populations. In this section, we compile information on the legal hunting and fishing frameworks in the Congo Basin, based on the consolidated legal analysis tools developed by the Sustainable Wildlife Management Programme and the available scientific literature. At the time of writing, the analysis was only available for Gabon, Congo, Cameroon, and DRC.

Legal Framework Regulating Hunting

The hunting regulations of Gabon, Cameroon, the Republic of Congo, and the Democratic Republic of Congo (DRC) share common features but differ in their treatment of customary rights, licensing systems, species protection, and hunting methods. All require permits for most hunting activities, but they vary in how traditional use is recognized and how conservation measures are enforced.

Gabon regulates hunting under the Forest Code, which requires permits or licenses from the Water and Forestry Administration. Exceptions are made for customary use rights, allowing subsistence hunting by communities bordering harvesting areas. Permits are issued depending on residency and nationality, covering small and large game, scientific capture, and commercial use. Hunting is permitted year-round, though certain species are restricted through quotas for non-resident hunters. Wildlife is divided into three categories: fully protected, partially

protected, and unprotected species. Pangolins and bats are now banned from hunting, capture, and consumption as a health precaution. Harmful techniques—such as fire, poisoned bait, explosives, or fixed rifles—are prohibited. However, the 2023 Forest Code revision introduced exceptions for customary rights, authorizing the use of snares, nets, and pits for community subsistence.

Cameroon regulates wildlife under Law 94-01 of 1994 and Decree 95-466 PM of 1995. Commercial hunting requires licenses and payment of taxes, while subsistence hunting is restricted geographically and must be consumed locally. Game is classified into three categories: Class A (rare/endangered, fully protected), Class B (huntable with commercial licenses under management), and Class C (all other species). Hunting zones include sport hunting areas (ZIC), community-managed areas (ZICGC), and co-managed zones (COZIC). In ZICs, most trophy revenues go to the state, with a smaller share to the Ministry of Forests and Wildlife. In ZICGCs, fees are shared equally with communities, while in COZICs, revenues go mainly to the ministry with additional community benefits. Prohibited practices include hunting with explosives, poisons, firearms, electric currents, or diving gear, as well as the transportation of game without a license.

The Republic of Congo requires permits for hunting, except under customary rights or contractual rights in certain protected zones. Law No. 37-2008 mandates hunter associations for village hunting and requires a weapons permit. Species are divided into fully protected (Class A), partially protected (Class B), and unprotected (Class C). Fully protected species may not be hunted or marketed except for scientific purposes, while Class B species may be hunted and marketed under controlled conditions. Class C species may be hunted permanently as part of traditional practices. Although a 1972 law established hunting seasons, these mainly cover sport hunting, leaving traditional and subsistence practices less clearly regulated. Decree No. 6075 of 2011 further regulates hunting by prohibiting night hunting and methods that cause undue suffering or environmental harm.

The Democratic Republic of Congo (DRC) regulates hunting through Law No. 82/002. All forms of hunting—traditional, sport, tourism, and commercial—require a license. Obtaining one requires legal ownership of weapons and passing a skills test, though the latter has never been fully implemented. Wildlife is classified as fully protected, partially protected, or unprotected. Hunting in protected areas is generally forbidden, but exemptions may be granted by the Congolese Institute for Nature Conservation (ICCN) for food security or public interest. Harmful hunting methods are banned, but unlike neighboring countries, the DRC lacks fully defined seasonal regulations, as no official hunting calendar has been adopted.

Legal Framework Regulating Fishing

Fishing regulations in Gabon, the Republic of Congo, and the Democratic Republic of Congo (DRC) share some similarities but also highlight different approaches to managing aquatic resources and recognizing customary rights. Gabon and the Republic of Congo have relatively modern frameworks emphasizing licensing, conservation,

and restrictions on destructive practices, while the DRC maintains traditional fishing rights but relies on outdated regulations that allow largely open access.

Gabon regulates fishing under Law No. 15/2005, the Fisheries and Aquaculture Code. All activities beyond subsistence fishing require licenses specifying permitted quantities. Categories include commercial, artisanal, sport, scientific, and aquarium fishing. Licenses are issued by the fisheries minister after consultation with the Technical Commission. Fishing is permitted year-round but can be restricted to protect species. Destructive or nonselective methods—such as explosives, toxic substances, gas-powered harpoons, monofilament nets, and obstructive seines—are banned. The framework prioritizes conservation while distinguishing between small-scale subsistence and commercial exploitation.

Cameroon governs fishing under Law 94-01 of 1994. Industrial fishing requires licenses subject to exploitation taxes, while small-scale and traditional fishing are exempt. Three license types cover fish, shrimp/crustaceans, and tuna/high-seas fishing, complemented by four permit categories: semi-industrial (A), sport (B), small-scale profit-making (C), and research (D). Prohibited practices include trawling within three nautical miles, obstructive gear that reduces net selectivity, diving suits with breathing devices, and the use of explosives, poisons, firearms, or electricity. Construction of dams or discharge of toxic substances without prior approval is also banned, reflecting strong environmental safeguards.

The Republic of Congo regulates inland fishing and aquaculture under Law No. 03-2010. The law covers capture, processing, and marketing, while also recognizing traditional fishing for self-consumption. Professional fishing requires registration cards and boat registration. Although quotas are not fixed, temporary restrictions may be applied to protect rare species, and fees are required for exploitation. Fishing zones must be classified, with potential conservation measures for nurseries, spawning areas, and migration routes, though implementation remains unclear. The law defines permissible and prohibited techniques but lacks size limits for aquatic species. It also regulates processing facilities and oversees fishery imports and exports, signaling a more complete but uneven system.

The Democratic Republic of Congo (DRC) relies on older laws, primarily from 1932 and 1937, with partial updates in the 1980s. The framework recognizes traditional fishing rights for communities but provides limited structure for broader management. Fishing is generally free and does not require authorization under the 1937 decree, though concessions can be granted. Prohibited practices include the use of explosives, toxins, and electric devices, except for research. While there are no formal categories of fishermen, three types of annual permits—industrial, artisanal, and individual—exist in Lake Tanganyika, expiring each year on December 31. Overall, the DRC maintains open access to fisheries but lacks comprehensive regulations for conservation or industry oversight.

Customary Rules Regulating Hunting and Fishing

Customary rules on hunting and fishing in Central Africa are deeply rooted in local traditions, ecological knowledge, and cultural practices. While varying among ethnic

groups and regions, these rules generally regulate resource use and maintain social cohesion through seasonal and spatial restrictions, species-specific taboos, and protection of totemic animals. Some scholars interpret these norms as expressions of an ethic toward nature, whereas others argue that economic incentives often override conservation logic (Duda 2017). Nevertheless, there is growing consensus that understanding and integrating customary practices into wildlife and fisheries policies are critical for sustainable resource management (Bérard et al. 2005; Roussel 2005).

Over millennia, rural communities have developed norms governing hunting and fishing, including periodic bans and food taboos targeting specific groups. Pregnant women, newly circumcised young men, and sometimes entire communities are prohibited from consuming species such as leopards, buffalo, elephants, monkeys, snakes, snails, and pangolins (Ichikawa 1987; Kyale Koy et al. 2024). In the Yangambi landscape (DRC), the Turumbo tribe values 43 animal species for political, zootherapeutic, and social purposes, with 27 species restricted from commercial hunting to protect sacred customs (Mpoyi et al. 2024).

Communities also safeguard sacred spaces that host initiation rites and are considered seats of ancestral spirits and totems. These areas are traditionally free from hunting, fishing, and agriculture, serving both cultural and ecological functions as refuges and breeding grounds (Butare 2001; Soumbane et al. 2017). Historically, compliance with these rules was enforced through sanctions or believed spiritual repercussions, including illness or death for violators (Bigombe and Toukéa 2023). However, adherence has declined, particularly among younger generations, reducing the effectiveness of customary norms in conserving wildlife and fish populations today.

Wildmeat and Fish Offtake Levels and Consumption Patterns

Species and Quantities Traded

Estimates of wildmeat harvest in the Congo Basin vary widely, ranging from 1.6 to 11.8 million tons annually (Coad et al. 2019). Consumption is substantial, with 60,000 t per year in the Republic of Congo and 691,000 t in the DRC (Valimahamed et al. 2017). Per capita consumption generally decreases with urbanization: smaller towns tend to have higher reliance on wildmeat than large cities. For example, in Ouesso (Republic of Congo), 273 t were traded in 2008 for a population of about 80,000 (Hennessey and Rogers 2008), while the Yangambi landscape (114,000 people) saw 103–145 t annually (Van Vliet et al. 2019). By contrast, Kisangani (1.6 million people) recorded only 293 t in 2016 (Van Vliet et al. 2017a). Near Lomami National Park, more than 40,000 carcasses are sold annually in Kindu, valued at USD 725,000 (Batumike et al. 2021). Across sub-Saharan Africa, at least 318 species are hunted, 72% of them mammals (Ingram et al. 2018). In Central African forests, ungulates, rodents, and primates dominate consumption (Abernethy et al. 2013; Coad et al. 2019; Fa et al. 2006). Frugivores contribute more than 60% of harvested biomass, with hunters often targeting larger animals for their higher yields (Abernethy et al. 2013). Species composition varies

geographically. In Angola, roadside surveys documented duikers, monkeys, snakes, and pangolins (Gonçalves et al. 2019). In Kindu, rodents (*Atherurus africanus*), duikers, bushpigs, and red-tailed monkeys are most traded (Batumike et al. 2020). In Basankusu, red-tailed monkeys and red river hogs dominate sales (Dupain et al. 2012). Kisangani and Brazzaville markets feature blue and bay duikers alongside brush-tailed porcupines (Mbete et al. 2011; Van Vliet et al. 2012), while porcupines are also common in Nigeria and Cameroon (Macdonald et al. 2012). Due to poor transport and storage facilities, most carcasses are smoked before reaching markets (Batumike et al. 2020; Van Vliet et al. 2012).

Fish are another major food source in the Basin. In 2018, the DRC produced 230,000 t of freshwater fish, with annual per capita consumption averaging 5 kg (FAO 2023). By comparison, per capita intake is far higher in Gabon (30.9 kg), Angola (20.2 kg), and Cameroon (18.1 kg). In Kinshasa, popular smoked species include *Parachanna* spp. (27.6%), *Protopterus doloï* (26.3%), *Clarias* spp. (19.4%), and *Channalabes apus* (19.1%) (Tchomba et al. 2020). In Uvira, Latidae and Clupeidae dominate commercial sales (Christian et al. 2020). Artisanal fishers mainly use smoking, salting-drying, and sun-drying techniques, though spoilage remains high, with up to 45% lost along the value chain (FAO 2023).

Urban and Rural Wildmeat Consumption Levels

The average consumption of wildmeat in rural regions of the Congo Basin varies considerably by location. For instance, studies in the Republic of Congo have shown an average consumption of around 2.7 kg per person per month (Linder 2013), while in the Democratic Republic of the Congo (DRC), some rural communities report higher rates of up to 4 kg per person per month (Fa et al. 2015). Wildmeat can account for 30–50% of the total meat intake in rural households (Nasi et al. 2008; Wilkie et al. 2016). In urban areas, wildmeat consumption depends on various factors that differ by region, with consumers having access to a broader range of meat options (Wilkie et al. 2016; Fa et al. 2019; Van Vliet et al. 2017b). Annual per capita wildmeat consumption is estimated at 7.2 kg in Libreville (Gabon) (Wilkie et al. 2005), 14.6 kg in Bangui (Central African Republic) (Fargeot and Dieval 2000), and 2 kg in Mbanjock (Cameroon). Even though urban per capita consumption of wildmeat is relatively low, total consumption in cities exceeds that of rural areas due to higher population densities (Nguyen et al. 2021).

The Illegal International Trade in Wildmeat, Fish, and Pets

The scale of international wildmeat trafficking is increasingly recognized. Seizures at Brussels Airport suggest 3.9 t of wildmeat are smuggled monthly from West and Central Africa, including at least ten CITES-listed species (Chaber et al. 2010; Chaber et al. 2023). At Paris Roissy-Charles de Gaulle Airport, weekly seizures average 5 t, indicating trade for profit rather than personal consumption. Prices in

Europe remain high, reinforcing wildmeat's status as a luxury item (Chaber et al. 2010). In Switzerland, annual inflows are estimated at 8.6 t (Falk et al. 2013). Despite illegality, wildmeat is openly sold in African grocery stores in Brussels, Paris, and London, supported by regular shipments (Gombeer et al. 2021). Cultural ties help sustain demand among African expatriates, with wildmeat valued for its traditional and familial significance (Bair-Brake et al. 2014; Walz et al. 2017). This evidence underscores the need for stronger enforcement, clearer regulations, and targeted awareness campaigns in consumer countries (Chaber et al. 2023).

Illegal fish exports are even less documented, but one Paris-based study estimated 57.95 t of fish smuggled weekly from West and Central Africa (Chaber et al. 2010). Exotic pets also drive wildlife trade. Globally, thousands of species and millions of individuals are sold annually (Harfoot et al. 2018; Scheffers et al. 2019). With online platforms replacing physical markets, tracking volumes has become more difficult (Fukushima et al. 2020). The Congo Basin is known to contribute to this trade, though data are limited. Grey parrots (*Psittacus erithacus*), listed as Endangered by CITES, are among the most trafficked birds worldwide and continue to decline in Central and West Africa due to the pet trade (Bush et al. 2014). Reptiles, including venomous species, are also exported illegally (Jensen et al. 2019; La Laina et al. 2021).

Status of Terrestrial and Aquatic Wildlife

Status of Terrestrial Mammals

The population status and distribution of medium and large mammals in the Congo Basin are strongly influenced by the distribution of suitable, undisturbed habitats and the level of access available to hunters (Gallego-Zamorano et al. 2020). For example, many mammal species (e.g., forest elephants) tend to be more abundant as distance from roads increases (Blake et al. 2008), with the exception of Gabon (Laguardia et al. 2021). In hunted forests, larger animals are typically found at lower densities, since they usually have lower reproductive rates, whereas small sized species (especially small duikers and rodents) tend to become prominent, as they usually reproduce faster. In Cameroon, around the Dja Fauna reserve, Bruce et al. (2018) demonstrated that the hunted areas showed high abundance of some disturbance-tolerant species and low abundance of larger-bodied species. Yasuoka et al. (2015) showed that the proportion between red duikers and blue duikers decreases as the hunting pressure increases in the remote forest. Fonteyn et al. (2024) found in Gabon that degraded sites are dominated by rodents (up to 76%), while, in well-managed protected areas, the medium- and larger-sized mammals dominate. In the Yangambi landscape (DRC), the terrestrial mammal community is largely degraded and dominated by two species of rodents: Emin's pouched rat (*Cricetomys emini*) and the African brush-tailed porcupine (*Atherurus africanus*), which are known to be highly resilient, while large ungulates and medium-sized carnivores have particularly low abundances (Van Vliet et al. 2023). In the Yangambi landscape, the mammal community globally exhibits lower occupancy (<10%) and species richness is

lower compared to other conservation areas in the Congo Basin (Van Vliet et al. 2023). In Luki Biosphere Reserve and Phalanga village territory, two degraded landscapes in the DRC, rodents were the most important species detected by camera trap studies (Djami et al. 2023). Similar results were observed in the Yangambi Biosphere Reserve, which is characterized by a degraded species composition profile (Van Vliet et al. 2017a). Top predators also tend to decrease in highly hunted areas. For example, in Gabon, Henschel et al. (2011) showed that leopards exploited smaller prey where competition with hunters was strong, resulting in reduced leopard densities at highly hunted sites.

Status of Inland Fish Stocks

Freshwater fish in the Congo Basin are generally in decline, as attested by perceived changes in fisheries resources by fishers, declines in catch-rates, reduced size of fish, and increased prices on the markets (De Keyzer et al. 2020). Fish stocks are less abundant where terrestrial wildlife has been depleted, given the complementarity and interchangeable nature of fishing and hunting (Inogwabini 2014). The main fish stocks are present along the Congo River and the major large lakes. Along the Congo River Basin, which includes the Congo River and its tributaries such as the Uganga, Lualava, Lulonga, and Tshuapa, about 800 fish species have been identified, among which Zambezi cichlids (*Oreochromis macrochir* and *Haplochromis mellandi*) and Nile species (*Protopterus aethiopicus* and *Polypterus senegalus*) are the most prevalent. In the middle course (between Kisangani and Kinshasa), approximately 50 species from 20 families dominate catches. Notable fish families include Protopteridae, Clariidae, Cichlidae, Mormyridae, Characidae, Bagridae, Cyprinidae, and Mochokidae. The middle Congo River is highly productive due to nutrient enrichment from major tributaries, especially between Makanza and Irebu. The ichthyological fauna in this region includes forest species from Mormyridae, Alestidae, Bagridae, Cyprinidae, and Mochokidae families. Other notable species include Protopteridae (*Protopterus dolloi*), Polypteridae (*Polypterus* spp.), and various other families. *Heterotis niloticus*, introduced from West Africa, has adapted well and spread throughout Central Africa, particularly in this river complex. The various large lakes in the Congo Basin also form major fish stocks. Lake Tumba and tributaries (765 km^2) host about 30 fish species, with *Auchenoglanis occidentalis*, *Clarotes laticeps*, *Clarias buthopogon*, and others being prevalent. In the Equateur Province, popular species include "mongusu" (*Parachanna obscura*), *ngolo* (*Clarias gariepinus*), and nzombo (*Protopterus dolloi*). In Lake Maï-Ndombe (2300 km^2), principal catches include species from Channidae, Cichlidae, Mormyridae, Claroteidae, Cyprinidae, and Alestidae families. Lake Tanganyika (32,900 km^2) serves as a major water reservoir for the Congo River and supports pelagic fish species like *Stolothrissa tanganicae* and *Limnothrissa miodon*, as well as endemic Latidae species like *Lates stappersii*. Lake Albert (5270 km^2) hosts diverse fish species, with commercial catches primarily, including *Alestes baremoze*, *Hydrocynus forskahlii*, and *Lates niloticus albertinus*. Lake Edward (2300 km^2)

hosts mostly *Tilapia* species, *Bagrus docmak*, *Protopterus aethiopicus*, and others. Lake Kivu (2370 km^2) is the least diverse ichthyologically, with the introduced *Limnothrissa miodon* now constituting about 90% of the catch. Katanga Lakes are also crucial for commercial fish production with *Oreochromis macrochir, Clarias* spp., *Synodonti*s spp., and various *Tilapia* species being the most common.

Impacts of Hunting and Fishing

Ecological Impacts of Overhunting and Overfishing

The demand for wildmeat in Central Africa, driven by local consumption and international markets, has resulted in unsustainable hunting practices and rising pressure on wildlife (Ingram et al., 2021). Hunters now operate across most forest lands, including protected areas (Abernethy et al. 2013). In the Congo Basin, 39% of forests are under high hunting pressure from villages (Ziegler et al. 2016). Road construction amplifies these impacts by opening new hunting areas, fragmenting habitats, and altering mammal communities (Blake et al. 2008; Fa et al. 2005). Hunting often targets large mammals, particularly keystone species such as apex predators, large herbivores, and frugivores, whose ecological roles are vital (Ripple et al. 2014, 2015). Elephants, gorillas, and chimpanzees are among the most affected (Maisels et al. 2013; Plumptre et al. 2016; Strindberg et al. 2018). Declines in frugivores compromise seed dispersal and forest regeneration (Abernethy et al. 2013; Wright et al. 2007). Hunting pressure directly influences population densities: duikers, for example, range from 0.2 ind/km^2 in heavily hunted sites to 20.6 ind/km^2 in protected areas (O'Brien et al. 2020). In some cases, smaller and medium-sized species exhibit stability or growth under high hunting pressure, a pattern known as density compensation (Fa and Brown 2009). Species' resilience also depends on reproductive rates, home-range, dispersal capacity, and behavioral flexibility, such as shifting activity patterns to avoid hunters (Mockrin 2010; Van Vliet et al. 2023). However, hunting yields are short-lived without regulation. Wilkie et al. (2019) found that although hunted areas initially provide high biomass, unsustainable offtake leads to rapid declines. Recovery requires reduced hunting for 3–13 years, a challenge without alternative food or income sources.

Similarly, river fish populations face growing threats from overfishing, habitat degradation, and climate change. These species are central to aquatic food webs, supporting larger predators and nutrient cycling. Overfishing disrupts these roles, reducing predator populations and altering species interactions with cascading ecological effects (Levêque et al. 2008). Many fish in the Congo Basin are highly specialized; overharvesting can cause severe reductions or even local extinctions, undermining biodiversity and ecosystem resilience (Allan et al. 2005). The ecological consequences extend further: overfishing hampers detritus processing, nutrient redistribution, and habitat quality, leading to algal overgrowth, siltation, and reduced spawning grounds (Cohen et al. 2014; Dugan et al. 2010). According to the (FAO 2023) Priority Plan for the Revival of Fishing in the DRC, fish habitats are severely

degraded, a problem often overlooked by fishermen. Historical accounts show that fish catches in the Congo Basin have dropped by 65–80% over the past 50 years. The loss of once-dominant species has led to more homogeneous catches, decreasing the diversity of exploited fish (Castello et al. 2023). Illegal, unreported, and unregulated fishing, along with destructive gear use, worsens overexploitation and habitat decline. These practices not only erode aquatic ecosystems but also undermine the food security and livelihoods of riverine communities.

Livelihoods Impacts of Overhunting and Overfishing

The economic repercussions of overhunting are potentially significant, particularly for communities that depend on hunting and the sale of wildmeat for their livelihoods. To illustrate this statement, Nasi et al. (2011) proposed the concept of "Empty forests, empty stomachs." In a global comparative study, Nielsen et al. (2017) argue that bushmeat is most important to rural households as a source of protein and micronutrients unavailable through domestic animal and staple crop production. Various studies conducted worldwide have shown that wildmeat consumption improved food security and dietary diversity among the most vulnerable groups (Friant et al. 2020; Golden et al. 2011; Sarti et al. 2015; Van Vliet et al. 2017a). However, this topic remains understudied in Central Africa (Ingram et al. 2021). Most literature in the Congo Basin focuses on understanding wildmeat consumption frequencies and volumes (Nasi et al. 2011) but the importance of bushmeat in people's diets cannot be merely assessed by volume consumed (Fa et al. 2015). Across the Congo Basin, Fa et al. (2015) showed that child stunting was lower in areas where wildlife is still abundant and increased in defaunated regions, particularly around urban areas. A recent study by Booth et al. (2021) showed that the Republic of Congo and Central African Republic could be at especially high risk of protein deficiencies if access to wildmeat was to be lost without immediate replacement. The COVID-19 pandemic, with its related temporary market shutdowns, also drew some lessons learnt about what the implications would be of losing access to wildmeat for stakeholders involved in the trade (Enns et al. 2023). In Cameroon, vendors generally agreed that the pandemic had a negative impact on their activities and the number of clients (Gaubert et al. 2024). In Brazzaville, some traders lost their jobs, while others shifted to different types of food trade. These disruptions also heightened stress among traders and their families, impacting their food and nutritional security, as well as their immune system resilience against diseases (Mialoundama et al. 2020).

Similarly, overfishing reduces the number of fish available for harvest, leading to lower yields, decreased income for local fishers, and the need to exert more effort. In Salonga National Park and Lac Tumba regions (DRC), Inogwabini (2014) showed that overfishing was mostly due to specialized fishermen coming from nearby urban areas, who can invest time and resources in efficient fishing gear (such as nylon nets), therefore impacting on the food security of rural families, who can only afford to fish with traditional fishing gear (hooks and lines). Overfishing, as observed in the

Tshopo Province (Busanga et al. 2023) and Lake Tumba (Zanga et al. 2019), threatens food security by reducing the availability of this crucial resource. As fish resources become scarcer, conflicts can arise among local fishers and between communities and external commercial interests (Namwira et al. 2024).

Unregulated Wildlife Trade and Associated Risks to Human Health

Globally, the consumption of wildmeats represents a major vector for the transmission of zoonotic pathogens (Loh et al. 2015; van Vliet et al. 2022; Wolfe et al. 2004). Public health crises related to zoonoses have led to political calls for the closure of wildlife markets (van Vliet et al. 2022). The absence of food safety standards in informal trade chains—covering the harvesting, transportation, butchering, and preservation of meat—further exposes hunters, butchers, vendors, and consumers to the risks of zoonotic and foodborne diseases (FAO et al. 2020). Various pathogens present in wildmeat, including viruses, bacteria, protozoa, and parasites, are transmissible to humans. In the Congo Basin, for example, there are 25 types of parasites (such as *Trichuris* sp., *Ancylostoma* sp., *Ascaris* sp., *Toxoplasma gondii*, and *Strongyloides fulleborni*), 9 major viruses (including SIV, HTLV, Marburg virus, Lassa virus, Ebola virus, Nipah virus, and herpes virus), and 8 types of bacteria (such as *Escherichia coli*, *Salmonella* spp., and *Campylobacter* spp.) found in wildmeat (Van Vliet et al. 2017a). However, these pathogens are not exclusively transmitted through the consumption of wildmeat. Most zoonoses spread through exposure to bodily fluids and feces during the handling and butchering of meat before cooking. To the best of our knowledge, there is no evidence to suggest that individuals who have contact with wildmeat have a higher parasite load than the general population. In general, wildmeat traders, hunters, and consumers believe that zoonotic disease risks are low despite high exposure to wildlife (Saylors et al. 2021). In Yangambi and Kisangani (DRC), only a small percentage of hunters are concerned about health and food safety risks, but most traders and consumers express concerns about food safety and foodborne diseases (van Vliet et al. 2022).

Neglected Positive Impacts of Hunting for Ecosystems and People

Across the globe, hunting and fishing are known to provide several services to both ecosystems and people, through mechanisms such as population control, prevention of invasive species, maintenance of biodiversity balance, disease or pest control, and reduction of human–wildlife conflict (Garshelis et al. 2020). In the Congo Basin, very little research has been directed toward better understanding and managing the benefits of hunting and fishing to nature and people. Nevertheless, hunting is known to be practiced as a way to reduce agricultural pests and as a way to mitigate human wildlife conflicts (Nasi et al. 2008). One further neglected benefit of hunting and fishing in Central Africa is that these activities, if they remain sustainable, do not result in the alteration of natural habitats (the forest itself), which is a key positive

aspect when compared to many other income-generating human activities such as agriculture and industrial logging.

Through these services, hunting may play a role in both supporting ecosystems and benefiting human populations, a concept known as people's services to nature, but more efforts need to be placed in understanding the complex and interlinked processes between hunters/fishers and ecosystems.

Conclusions

This chapter examines the ecosystem services provided by hunting and fishing in the Congo Basin, the governance frameworks shaping these activities, current offtake levels, wildlife and fish stock status, and the consequences of overexploitation.

Freshwater and terrestrial wildlife underpin food security, livelihoods, health, and cultural identity for millions across the Basin. Wildmeat and river fish are primary sources of protein and essential nutrients, supporting both rural and urban populations. Their consumption is driven by necessity, taste preferences, and cultural values. These resources also sustain rural economies through informal hunting, fishing, and trade, offering employment and safety nets, particularly for women and marginalized groups. Beyond food, wildlife contributes to traditional medicine and spiritual practices, while fish and wildmeat feature prominently in ceremonies, hospitality, and social identity. Fishing practices, often collective, reinforce community cohesion. Together, these services demonstrate the ecological, economic, and cultural significance of wildlife to regional resilience.

Hunting and fishing are governed by statutory laws and customary norms that vary widely across Gabon, Cameroon, the Republic of Congo, and the Democratic Republic of Congo (DRC). All require permits or licenses, classify species for protection, and prohibit destructive methods, though recognition of customary rights differs. Gabon provides broad subsistence rights and allows traditional techniques; Cameroon limits hunting without licenses and manages sport hunting zones with revenue-sharing; Congo requires hunter associations and permits year-round hunting of unprotected species; while the DRC retains a bureaucratic, outdated framework with minimal seasonal regulation. Fishing laws in Gabon and Congo are relatively conservation-oriented, whereas DRC regulations remain antiquated and poorly enforced. Alongside statutory rules, customary norms—such as species taboos, seasonal bans, and sacred site protection—have historically fostered sustainability but are weakening under modernization and generational shifts. Integrating customary and statutory systems remains a critical governance challenge.

Wildmeat and fish offtake are substantial. Annual wildmeat harvests are estimated between 1.6 and 11.8 million tons, dominated by mammals, with frugivores contributing over 60% of biomass. Rural households obtain 30–50% of their meat from wild sources, averaging 2.7–4 kg per person monthly, while urban volumes are higher overall due to dense populations. Freshwater fish are equally vital: the DRC alone produces 230,000 t annually, though post-harvest losses can reach 45%. Preservation relies heavily on smoking, salting, and drying. International trade

adds pressure, with tons of wildmeat—including CITES-listed species—smuggled weekly to Europe to meet diaspora demand. The region also supplies the global exotic pet trade, including endangered parrots and reptiles.

Wildlife and fish populations show widespread decline. Large mammals such as elephants and ungulates are severely reduced, leaving rodents and small duikers dominant in disturbed areas. Predator declines further disrupt prey dynamics. Fish stocks are shrinking, reflected in reduced catch sizes and rising market prices, compounded by overfishing and reliance on aquatic resources when terrestrial fauna decline. Though the Congo River and major lakes remain biodiversity hotspots, mounting pressures threaten both species composition and local livelihoods.

Unsustainable exploitation carries severe ecological, economic, and health costs. Overhunting erodes biodiversity, seed dispersal, and ecosystem dynamics, while road expansion exacerbates pressures. Overfishing reduces aquatic diversity and has driven catch declines of 65–80% over the past half-century. These trends undermine food security, livelihoods, and nutrition for rural and Indigenous peoples, leaving them vulnerable to shocks such as COVID-19 market closures. The unregulated trade also heightens zoonotic risks, with pathogens such as Ebola and Salmonella linked to wildmeat. Nonetheless, sustainable use can yield ecological benefits, such as pest control, conflict reduction, and forest cover maintenance, underscoring the need for balanced management approaches (see chapter 26).

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Climate Change and Ecosystem Functions and Services in the Congo Basin

17

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Abstract

The Congo Basin, home to the world's second-largest tropical rainforest, is a biodiversity hotspot and a critical carbon sink. Its varied habitats—including rainforests, savannas, miombo woodlands, freshwater systems, peatlands, and coastal mangroves—support essential ecosystem functions. The Cuvette Centrale peatlands alone store an estimated 30 gigatons of carbon, underscoring the Basin's climate significance. This review examines climate change impacts on the Basin's ecosystems, focusing on ecological processes, carbon dynamics, and species responses.

The region is increasingly vulnerable to climate change and human pressures. Temperatures are rising faster than the global average, projected to increase 1.5–2 °C by century's end, while rainfall is becoming more erratic, driving longer dry seasons, flash droughts, and altered flood cycles. These changes, combined with deforestation and land-use conversion, disrupt ecosystem processes. Forests show shift in phenological cycles affecting frugivores and herbivores; savannas face woody encroachment under rising CO_2; freshwater systems experience reduced water quality and declining fish populations; peatlands risk carbon release from lowered water tables; and mangroves are threatened by sea-level rise and reduced freshwater inflows. These ecological shifts have cascading effects, altering carbon and water cycles, nutrient dynamics, and species interactions. Changes in evapotranspiration and rainfall recycling further influence global climate patterns, including the Intertropical Convergence Zone, highlighting the Basin's role in Earth system regulation.

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Maintaining the Congo Basin's ecological integrity is critical for regional resilience and global climate mitigation. Integrated research, targeted conservation, and sustainable land-use practices are urgently needed to safeguard these ecosystems against intensifying climatic and anthropogenic pressures.

Keywords

Biodiversity responses · Carbon sequestration · Drought and heat impacts · Freshwater ecosystems · Hydrological stress · Mangrove vulnerability · Peatland hydrology · Phenological shifts

Introduction

An Overview of Ecosystem Services in the Congo Basin

The Congo Basin, in a broad sense, is understood to include both the Congo Basin and the Ogooué Basin that, when combined, make up the forests of Central Africa. This rainforest is often called the "lungs of Africa" for its vital ecosystem services for climate, biodiversity, and its inhabitants (Cuni-Sanchez et al. 2019). Over the past three decades, it has remained a stable carbon sink, absorbing 0.66 t of carbon per hectare per year (Hubau et al. 2020; Bennett et al. 2021), although increasing emissions from deforestation, particularly in the DRC, partially offset this.

The Congo Basin forests, the second-largest contiguous tropical rainforest block worldwide, host tremendous biodiversity. While the full potential of biodiversity services remains uncertain, this forest massif harbors an extraordinary diversity of plant and animal species. A significant proportion of these species are endemic, endangered, or emblematic, including Okapis, Bonobos, forest elephants, and mountain gorillas (Doran and McNeilage 1998; Blake et al. 2007; De Wasseige et al. 2015). These forests also serve as a vital genetic reservoir and are home to indigenous communities whose knowledge contributes to sustainability (Verdu et al. 2009; Faye et al. 2016). This biodiversity serves the ecological and economic interests of the ~120 million people living in the region. Most national economies rely on direct and indirect services from this biodiversity, including revenues from timber, ecotourism, hydroelectric power, fisheries, agriculture, and transportation (Nasi et al. 2012; Pemunta et al. 2019). For instance, 25–40% of animal protein is harvested from Lake Tanganyika by the surrounding indigenous populations (O'Reilly et al. 2003). Nontimber products like medicinal plants are also collected yearly (Clark and Sunderland 2004).

The Congo Basin ecosystems also regulate hydrological flow by absorbing and releasing water, which helps prevent floods and maintains water quality through sediment and pollutant filtration (Tshimanga et al. 2022). Moreover, the forest cover plays an important role for cross-continental transfer of atmospheric moisture (Ellison et al. 2017). In addition, the contribution of different ecosystems to soil fertility, soil formation, and nutrient cycling cannot be overemphasized (Vitoussek and Sanford 1986).

An Overview of the IPCC-Modeled Climate Change in the Congo Basin

The IPCC forecasts significant climate change for the Congo Basin, which could have major impacts on this vital region. According to projections, the average temperature in the Congo Basin could increase by 1.5–2 °C by the end of the century, leading to more frequent and intense heatwaves (IPCC 2021). This is in line with Sridhar et al. (2022), who evaluated four global circulation models and projected temperatures to rise from the historical mean of 24.7 °C to 26.3 °C under RCP4.5 and 27.5 °C under RCP8.5, with average monthly increases of 1.6 °C and 2.7 °C by the end of the century. Currently, a severe lack of on-ground meteorological data collection is hampering model validation, calling for the urgent need for a dense observation network. Similarly, historical records are sparse and, if they exist, they are often not digitized (Kasongo et al. 2023).

Precipitation might slightly increase overall but with greater seasonal variations, including prolonged drought periods and more frequent extreme rainfall events (IPCC 2021). These changes could disrupt the hydrological balance, increasing the risks of flooding and drought in certain areas. The rise in temperatures could also enhance evaporation and reduce soil moisture, exacerbating the vulnerability of forests to fires and degradation (IPCC 2021).

Climate change would impose severe impacts on Congo Basin ecosystems, affecting biological processes such as plant growth and phenology, species migration, and/or breeding periods. Long-term impacts are expected on species composition, water availability, food security, and livelihoods (Bush et al. 2020; Muluneh 2021).

An Overview of Habitat Types and Quantities of Sequestered CO_2 in the Congo Basin

The Congo Basin is home to a variety of ecosystems, ranging from tropical forests at the center to savanna ecosystems located north and south of the basin. Each contributes differently to the functioning of the Congo Basin and provides a myriad of ecosystem services.

The dense tropical rainforests span about two million km^2 across six Central African countries [Cameroon, Equatorial Guinea, Gabon, Central African Republic, Republic of Congo, and Democratic Republic of Congo (DRC)], following the Congo River and its tributaries (De Wasseige et al. 2014; Eba'a Atyi et al. 2022). These evergreen forests with a closed canopy include emergent trees exceeding 40 m. The understory is rich in shrubs and herbaceous plants, while the forest floor remains relatively open. Various types have been documented, including Atlantic forests, evergreen forests, semi-deciduous seasonal forests, deciduous forests, and sandstone forests (Réjou-Méchain et al. 2021). Storing about 25–30 billion tons of carbon in their vegetation, the Congo Basin rainforest absorbs about 0.66 tons of carbon per hectare annually (Hubau et al. 2020).

The savannas north and south of the tropical forests form the interface with drier regions around nine countries (DRC, Republic of Congo, Central African Republic,

Cameroon, Angola, Zambia, Tanzania, Burundi, Rwanda) (Letouzey 1982; Hiol-Hiol et al. 2014). Botanically, savanna refers to tall grass formations at least 80 cm with herbaceous plants and sparse trees (Letouzey 1982). They span about 1.5 million km^2 and are divided into three complexes:

- Southern border savannas in Niari valley and Batéké Plateau extending into the DRC (Hiol-Hiol et al. 2014)
- Northern and southern edge savannas forming mosaics with forests, such as Lopé and Odzala
- Integrated savannas within dense forests, for example, Lopé in Gabon and northern Impfondo in Congo (Hiol-Hiol et al. 2014)

Savannas contribute over one-quarter of terrestrial primary productivity (Still et al. 2003), host iconic species like elephants, antelopes, and lions, and support agriculture and grazing. Carbon storage in Congo Basin savannas is estimated at 100–220 tC/ha (Grace et al. 2006).

The Miombo woodlands are prevalent in the southern and eastern regions of the Congo Basin, specifically in the DRC. The global surface area of the Miombo woodland is undocumented but estimates of 1.21–2.7 million km^2 that extends beyond DRC (Angolan, Zambia, Tanzania, Zimbabwe, and Mozambique) (Shirima et al. 2011; Saatchi et al. 2017). The Miombo woodland of the Congo Basin is approximately 200,000–500,000 km^2 and lie within the southern border of the DRC as defined by the Science Panel (map xx) (Shirima et al. 2011; Saatchi et al. 2017). These clear forests are open woodlands dominated by *Brachystegia* spp. alone or in association with *Julbernardia* spp. and *Isoberlinia* spp. (Hiol-Hiol et al. 2014). The Miombo woodlands support large mammals like elephants and antelopes, as well as diverse bird species (Sankaran et al. 2005). The carbon storage potential of the Miombo woodlands is lower than tropical rainforests. They have been estimated to store between 13 and 30 Mg C/ha in aboveground biomass (Shirima et al. 2011; Saatchi et al. 2017).

Freshwater ecosystems of rivers, lakes, and wetlands contribute to hydrological cycles. The Congo Basin drainage extends over 3.7 million km^2 with an annual flow of 1300 billion m^3 (Lehner et al. 2008; Tshimanga et al. 2022), draining nine countries (Angola, Rwanda, Burundi, Cameroon, Central African Republic, DRC, Republic of Congo, Tanzania, Zambia) (Fatras et al. 2021). Although carbon fluxes are uncertain, Borges et al. (2019) estimated the Congo River releases 7.7 Gt CO_2 per year, partly from terrestrial organic carbon processing.

Peatlands occur in the central Congo Basin over more than 145,500 km^2 (Dargie et al. 2017). They store ~30 Gt carbon, equal to three years of global fossil fuel emissions (Dargie et al. 2017). Peatlands also host key wildlife (Biddulph et al. 2021) but are vulnerable to climate change (Garcin et al. 2022). Their degradation would release vast amounts of carbon and other GHGs (Biddulph et al. 2021).

Mangroves are intertidal habitats that store carbon in soils and vegetation (Hamilton and Friess 2018). They cover extensive areas along Cameroon, Gabon, Republic of Congo, and DRC. Average total carbon stocks reach ~1520 ± 164 t C/ha, with ~538 t C/ha in aboveground biomass and ~983 t C/ha belowground (Ajonina et al. 2014).

Soils across the Congo Basin vary by habitat and store significant carbon. Forest soils can contain up to 20% of global organic carbon, estimated at 15–20 billion tons globally (FAO 2015). They sequester more carbon than savanna or agricultural soils but are also significant CO_2 sources (Baumgartner et al. 2020).

Land-Use Changes and Greenhouse Gas Emissions

The Congo Basin plays a crucial role in the global carbon cycle, but in situ data on greenhouse gas emissions from its natural and agricultural ecosystems are scarce. Most knowledge is inferred from other tropical regions using models despite biogeochemical and ecological differences. This paucity is severe since land-use changes significantly affect greenhouse gas (GHG) emissions and ecosystem health. Tropical deforestation is a main driver of climate change, affecting the global GHG balance twofold: it removes aboveground carbon stock and an important natural CO_2 sink.

Besides being a sink for CO2, tropical lowland forests of the Congo Basin are also a strong sink of methane (CH_4) and a weak source of nitrous oxide (N_2O) (Barthel et al. 2022). Continued deforestation will eventually remove this important sink of CH_4 and CO_2. Deforestation in DRC has risen to over 1 million ha per year in the last 25 years, resulting in about 500 million tCO2 emissions annually (Bennett et al. 2021). In the Congo Basin, deforestation and fragmentation are mainly driven by shifting agriculture (slash-and-burn) and charcoal production, with mining and urban expansion contributing less. This contrasts with other tropical regions where agricultural expansion and timber production dominate.

Facing exponential population growth, agricultural expansion will exacerbate GHG emissions due to fertilizer use and resulting nitrous oxide, as well as methane emissions from livestock populations. The loss of biodiversity due to land conversion reduces ecosystem resilience and its ability to regulate climate (Butler and Laurance 2008).

The extent to which these changes will affect GHG emissions in the Congo Basin remains uncertain. Recent projects such as CongoFlux, which aims to quantify atmosphere–biosphere GHG exchange of tropical lowland forests in the Congo Basin, are an important first step toward understanding land-use change effects on GHG emissions.

Available Data and Measured Trends in Climate

Measured Changes and Trends in Temperature

The size and geographical position of the Congo Basin expose it to a variety of climate types that can be grouped into tropical and equatorial. In addition, the presence of high-altitude zones allows certain areas to be characterized as montane climates, notably around the Albertine Rift (toward the east of the DRC) and the Cameroon volcanic line (Tsalefac et al. 2015). The bimodal two-season equatorial

climate extends to southern Cameroon and the Central African Republic, central DRC, Republic of Congo, Gabon, Equatorial Guinea, and Sao Tome and Principe (Mpounza and Samba-Kimbata 1990). The climate is hot and humid, with temperatures between 22 °C and 30 °C.

Temperature trends were analyzed in the Central Africa subregion by the World Meteorological Organization (WMO) in 2024 and by Kasongo et al. (2023). The data show that the African mean near-surface air temperature in 2023 was 0.61 °C [0.47 °C–0.81 °C] higher than the long-term average of the 1991–2020 climatological standard normal (Fig. 1) and 1.28 °C [1.18 °C–1.40 °C] higher than the 1961–1990 average.

According to the dataset used, 2023 was one of the three warmest years for Africa in the 124 years of record. The African continent has continued to observe a warming trend, with an average rate of change of about +0.3 °C/decade between 1991 and 2023, compared to +0.2 °C/decade between 1961 and 1990. The recent trend is slightly higher than the global average warming trend (land/ocean), which is about +0.2 °C/decade for the period 1991–2023.

In 2023, temperatures were above the 1991–2020 average across Africa (WMO 2024). Reports based on the analysis of 61 years of digital data revealed increased temperatures and temperature extremes since the 1960s, with marked upward trends since the early 1990s (IPCC 2021). This climate change has led to longer dry seasons and shorter but more intense rainy seasons since 2000 (Fig. 2). Observations made in some parts of the Congo Basin (North and East Cameroon, CAR, DRC) show that the crop-growing seasons have been disrupted, leading to famine. Climate change

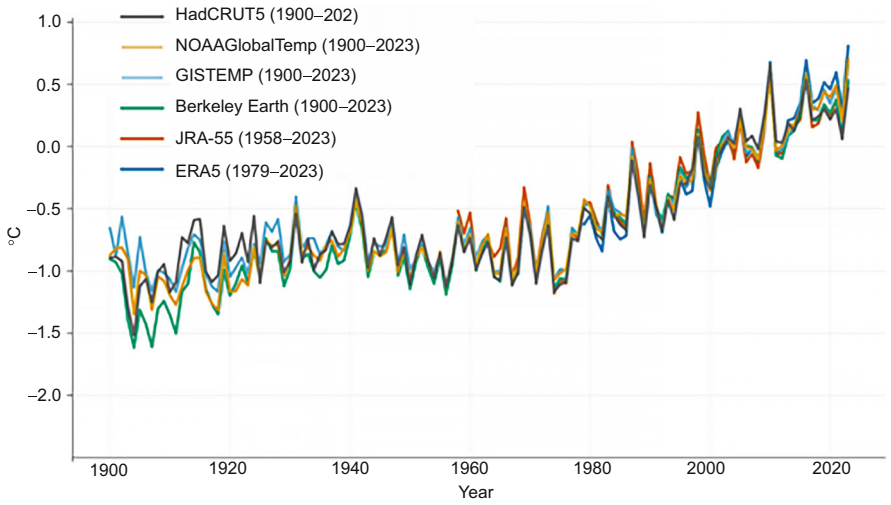

Fig. 1 Temperature difference in °C for the 1991–2020 climatological period for Africa (WMO Regional Association I) from 1900 to 2023, based on six datasets, including observational datasets. [Source: Data are from the following six datasets: Berkeley Earth, ERA5, GISTEMP, HadCRUT5, JRA-55, NOAAGlobalTemp (WMO 2024)]

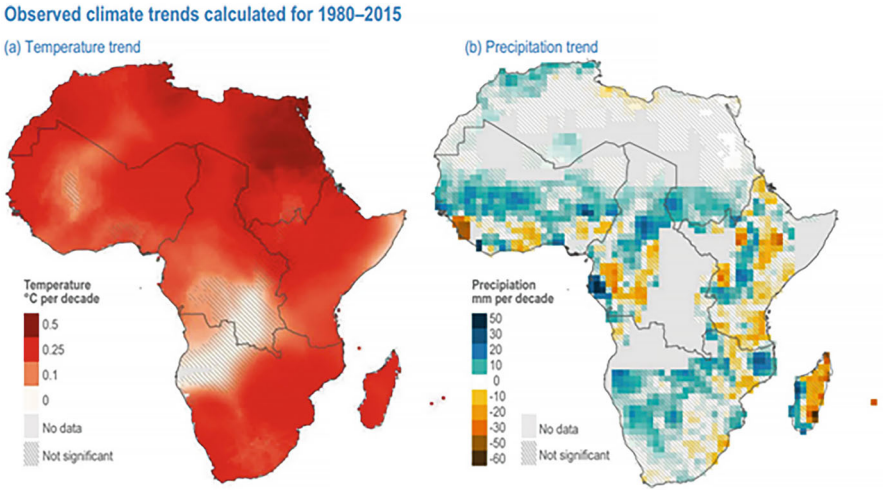

Fig. 2 Temperature (left) and precipitation (right) trends for 2023. [Source: Global Precipitation Climatology Centre (GPCC), Deutscher Wetterdienst (DWD), Germany (WMO 2024)]

has profoundly altered the agricultural calendar, shortening the rainy and dry seasons, incurring significant crop losses. Temperature anomalies recorded in Central Africa were 1.17 °C [0.96 °C–1.34 °C] between 1961 and 1990. This rate decreased to 0.59 °C [0.37 °C–0.86 °C] between 1991 and 2020.

Measured Changes and Trends in Rainfall

The region has experienced accelerated warming of about +0.3 °C per decade—faster than the 1961–1990 rate of +0.2 °C, resulting in shifting rainfall patterns that are more pronounced than pre-1990 trends (WMO 2024). The Central African Republic warmed +0.75 °C (1961–2015), while Congo and Gabon saw increases of +0.5 to +1 °C since the 1980s, with fewer cool days (WMO 2024).

In 2023, modeled precipitation anomalies in most parts of Africa were slightly above the reference US climate normal established by WMO and NOAA in 1991–2020 (WMO 2024). Strong precipitation anomalies were observed in much of central and eastern Central Africa, and coastal areas north of the Gulf of Guinea (IPCC 2021; Sridhar et al. 2022). During this time, wetter-than-normal conditions prevailed across most of the region, with precipitation anomalies exceeding 40 mm above average in many parts of the Democratic Republic of the Congo, Angola, and eastern Central African Republic (Fig. 2). In the Central African region, a drying trend of rainfall during April–May–June prevailed between 1979 and 2014 (Nicholson et al. 2022). However, the meteorological factors responsible for the wetter conditions appear to be significantly different among wet periods (Nicholson et al. 2022). The wetter conditions of 1979–1993 were related to changes in the tropical Walker circulation, moisture flux and flux divergence, and Pacific Sea surface

temperatures (SSTs), namely a warmer central and eastern Pacific and a cooler western Pacific, relative to the dry phase of 2000–2014 (Nicholson et al. 2022). This resulted in a below-average trans-Pacific SST gradient. In contrast, SSTs were almost universally higher during 2016–2020 than during the two preceding periods.

Measured Changes and Trends in GHG and Other Climate-Driven Factors

GHG measurements in the Congo Basin are rare and reflect the general data scarcity of such measurements on the African continent. However, a growing body of literature over the recent decade has considerably contributed to aquatic (e.g., Borges et al. (2015)) and terrestrial (e.g., Barthel et al. (2022)) GHG measurements. Only recently the first eddy covariance tower was built at a lowland forest site in the Congo Basin, which will deliver important data on net ecosystem CO_2 exchange (CongoFlux; Sibret et al. 2022).

Most studies so far have examined the riverine carbon cycle in the Congo Basin, revealing complex interactions between land use, hydrology, and carbon fluxes. Dissolved organic carbon (DOC) and inorganic carbon concentrations (DIC) in streams are influenced by vegetation cover and hydrological regime (Mann et al. 2014). Deforestation has a significant impact on river carbon biogeochemistry, with forest loss leading to increased DIC concentrations and biolabile dissolved organic matter in streams (Drake et al. 2019). The Congo Basin has lower CO_2 consumption through rock weathering than the Amazon Basin, with 0.5×105 moles $year^{-1}$ km^{-2} and 3.1×105 moles $year^{-1}$ km^{-2}, respectively (Probst et al. 1994). This weathering CO_2 flux contributes significantly to total riverine bicarbonate fluxes in both basins. Long-term trends show a slight increase (0.7%) in CO_2 fluctuations in the Congo Basin over the past century (Probst et al. 1994), highlighting the importance of monitoring carbon cycle changes in this region. Bauters et al. (2019) found tight soil nitrogen cycles in various forest types, with organic nitrogen contributing significantly to input–output balances. This contrasts with many neotropical forests, suggesting that unaccounted-for losses (such as N_2) may play a major role.

Habitat and Biota Responses to Climate Change

Forest Species Phenological Changes and Forest Response to Climate Change

Climate change exerts a profound influence on a range of phenological events in the Congo Basin rainforest, affecting both plant processes such as leaf emergence, flowering, fruiting, and senescence, and animal behaviors, including migration and reproductive timing. These phenological shifts have significant implications for critical ecosystem functions such as carbon cycling, water and energy fluxes, nutrient turnover, and canopy conductance. However, despite increasing research

attention, the precise interactions between climate variables and phenological responses remain poorly understood across the African continent (Yan et al. 2017; Adole et al. 2019; Bush et al. 2020; Kearsley et al. 2024). Most parts of the region's distinct bimodal rainy seasons introduce further complexity, creating uncertainties in projecting the impacts of global warming on these ecosystems.

Among the least studied, yet most critical, aspects of this phenomenon are the seasonality of leaf phenology in Central African forests (Couralet et al. 2013; Abernethy et al. 2018; Kearsley et al. 2024). Remote sensing analyses have revealed a clear bimodal pattern of leaf growth, which varies in duration across forest types, woodlands, grasslands, and shrublands (Gond et al. 2013; Liu et al. 2024). This pattern generally aligns with the region's two wet and dry seasons (Yan et al. 2017), indicating strong climatic control. Solar radiation and moisture availability have emerged as key drivers of this bimodal leaf phenology, where declining moisture prompts leaf shedding to reduce transpiration and mitigate hydraulic stress, while increasing solar radiation stimulates leaf replacement to maximize photosynthetic productivity (Liu et al. 2024). Historical observations further highlight the role of drought events in shaping these seasonal rhythms (Kearsley et al. 2024).

Research on reproductive phenology in the Congo Basin dates to the early twentieth century, notably at the Yangambi Research Station in the 1930s and the Luki Reserve in the 1950s (Couralet et al. 2013; Kearsley et al. 2024). These early studies reported that leaf shedding, flowering, fruiting, and fruit dispersal displayed annual cycles, ranging from sharply defined peaks to more continuous patterns. Subsequent findings established a positive relationship between rainfall and leaf shedding in shade-tolerant canopy species, as well as between rainfall and reproductive events in long-lived heliophilous and understorey species (Couralet et al. 2013).

Long-term studies have since reinforced the sensitivity of tropical rainforest phenology to climatic variability. Notably, at La Lopé National Park in Gabon, studies have revealed marked seasonal patterns in tree phenology, challenging earlier assumptions of equatorial rainforest aseasonality (Bush et al. 2020a, b). At La Lopé, leaf flushing and flowering are closely aligned with the onset of the rainy season, while fruiting peaks shortly thereafter. These findings emphasize the central role of rainfall in regulating phenological events. Furthermore, the impacts of interannual climate anomalies, such as El Niño events, significantly reduce fruit availability (Bush et al. 2020b). Such declines have profound cascading effects on frugivorous species—particularly primates, elephants, and large birds—that depend on predictable fruiting cycles for sustenance (Bush et al. 2020a, b). Beyond their effects on fauna, phenological shifts influence ecosystem processes more broadly, altering litterfall dynamics, nutrient cycling, and carbon sequestration, and ultimately affecting forest resilience to climate change.

Savanna Responses to Climate Change

Paleo-vegetation records reveal that the steep decline in atmospheric CO_2 linked to consistent regional climate drying around the late Miocene (around 7–5 million

years ago) was responsible for the origin and proliferation of African savannas (Cawthra 2019; Polissar et al. 2019). The spatial extent and biodiversity of this ecoregion are sensitive to climate change; reduced precipitation, temperature decline, and human activities (Higgins and Scheiter 2012; Hiol-Hiol et al. 2014; Mejía et al. 2017; Cawthra 2019; Polissar et al. 2019). African savannas and grasslands are therefore susceptible to the prevailing climate. First, their origins and proliferation were the direct cause of declining atmospheric CO_2 levels linked to declining temperatures that occurred some ten million years ago (Polissar et al. 2019). The stable carbon isotope signature testifies that mainly C4 vegetation proliferated and adapted to low atmospheric CO_2 levels associated with sea surface temperature cooling of up to 17 °C (Mejía et al. 2017; Cawthra 2019; Polissar et al. 2019). However, climate change forcings spur rising atmospheric CO_2 and warmer temperatures. Current and future climate models predict average monthly increases of 1.6 °C and 2.7 °C by the end of the century (Sridhar et al. 2022). Under such climate scenarios, tropical grassland, savanna, and forest ecosystems will likely shift to alternative states. Specifically, there is evidence that increasing atmospheric CO_2 concentration will force transitions to vegetation states characterized by higher biomass and/or woody-plant dominance anew (Higgins and Scheiter 2012). Studies have therefore emerged suggesting that climate-driven atmospheric CO_2 has been and will be a major factor shaping African savanna ecoregions (Prentice et al. 2011; Higgins and Scheiter 2012).

Freshwater Responses to Climate Change

Apart from the freshwaters of the Congo River network, an estimated 70–100 lakes are found across nine countries of the Congo Basin. Some prominent ones cut across countries like Lake Tanganyika (~ 32,900 km^2 across DRC, Burundi, Tanzania, and Zambia), Lake Albert (~ 5300 km^2) and Lake Edward (~ 2300 km^2) across DRC and Uganda, Lake Mweru (~ 5200 km^2 across DRC and Zambia), Lake Kivu (~ 2700 km^2 across DRC and Rwanda), Lake Mai-Ndombe (~ 2300 km^2 in DRC), and Lake Upemba (~ 530 km^2 in DRC) (Ramsar Convention Secretariat 2010; Ramsar 2022). Besides, there are large areas of temporarily or permanently inundated forests and grasslands that are characterized by soils with poor drainage and vegetation adapted to water-saturated soils, and anaerobic conditions. The major flooded forests and wetlands include the wetlands of the Cuvette Centrale (e.g., Lac Télé-Likouala, Tumba-Ngiri-Maindombe) and other wetlands that affect the flow in the region such as the Bangweulu wetlands that extend to Zambia (c. 190000km^2) and the DRC and Republic of Congo alone (Campbell 2005).

Fish populations are experiencing range shifts and declines due to habitat changes. Key species like *Alestes baremoze* show reduced catches as flood cycles become less predictable (Welcomme et al. 2010). Endemic species with narrow habitat requirements, such as the blind cichlid *Lamprologus lethops*, face particular risk from warming waters (Schelly and Stiassny 2004). Studies estimate a 60–80% reduction in floodplain habitats critical for fish reproduction over the last

half-century (Castello et al. 2023). Overfishing and habitat changes, including reductions in floodplain habitats critical for fish reproduction, were identified as key drivers of this decline.

Food web dynamics are being disrupted by changes in nutrient cycling. The flood-pulse system, responsible for 80% of fish productivity, is becoming less reliable (Bola et al. 2022). Lake Mai-Ndombe has seen a 25% reduction in phytoplankton biomass since the 1990s due to warming (Descy et al. 2017), affecting species at all trophic levels.

Changes in climate have strongly impacted the water quality of the major rivers. Higher temperatures leading to increased evaporation rates over the Oubangi and Congo rivers were reported to cause a decrease in water quality, with an additional effect on the aquatic ecosystems due to of less oxygen (Laraque et al. 1998). Warmer temperatures affect fish populations in different ways ranging from reduced body sizes, change in migration pattern, increase disease risk, and predation shrinkage in habitat (Pauly and Cheung 2018; Magoulick et al. 2021).

Peatland Responses to Climate Change

The largest tropical peatland in the world is found in the Cuvette Centrale peatland complex of the Congo Basin. Recent estimates between 2017 and 2021 show that the central Congo Basin peatlands span approximately 145,500 km^2 (Dargie et al. 2017), accounting for c. 77% of 187,061 km^2 of all African peatlands (Xu et al. 2018). Current knowledge on the Congo Basin peatlands focuses on the Cuvette Centrale peatland complex (mainly concerning the Democratic Republic of Congo (DRC) and Republic of Congo) (Biddulph et al. 2021), whereas remotely sensed maps suggest there may be isolated peat patches throughout tropical Africa (Xu et al. 2018), including potential areas in Cameroon, the Central African Republic, Gabon, and Equatorial Guinea. Owing to the lack of available data on peatlands in other Congo Basin countries, most analyses and reviews are limited to the central Congo Basin peatlands.

As reviewed by Sonwa et al. (2022), water and maintenance of saturated anoxic conditions are key factors determining their occurrence and growth. Climate change can regulate many factors, changing the hydrological balance of peatlands. Water determines two types of peatlands in the Central Congo peatland: minerotrophic (nutrient-rich peats that are fed by rain- or groundwater) and ombrotrophic (nutrient-poor raised bogs that are fed mainly by rainwater) peatlands (Dargie et al. 2017). The mean annual rainfall for peatlands is around 1758 mm since 1981–2019 (Fick and Hijmans 2017) but significant decreases have been noticed over the past four decades, suggesting a shortening of the wettest rainy season (Sonwa et al. 2022). Further decreases in annual rainfall would lead to a drop in the water table and potentially cause loss of peatlands to droughts and wildfires. Assuming future predictions of rainfall for the next three decades, a gain of about +300 mm of rainfall is expected (Dargie et al. 2019; Sonwa et al. 2022).

Changes in local and regional temperatures and consequently evapotranspiration rates will impact the hydrological balance and, as a result, the balance between

organic matter accumulation and decay (Biddulph et al. 2021). Average temperatures are projected to rise by approximately 2.5 °C by the year 2050 while temperature increases are expected to be between 3 and 5 °C by 2100 under high emissions scenarios (IPCC 2021), which in turn may increase evapotranspiration rates. Warmer temperatures can alter the hydrology of peatlands, leading to changes in water levels and increased evaporation. This can stress plant communities and disrupt the delicate balance of these ecosystems.

Mangrove Responses to Climate Change

The mangroves of the Congo Basin represent a fragile and fragmented ecosystem along coastal lagoons and estuaries. Spreading over about 7000 km^2 in Central Africa (Das et al. 2022) and representing about 10% of the world's mangroves, the largest blocs occur in Cameroon (2200 km^2; Ajonina (2022)), Gabon (1598 km^2), Equatorial Guinea (253 km^2), the Democratic Republic of Congo (193 km^2), and the Republic of Congo (16.7 km^2) (Spalding et al. 2010).

Congo Basin mangroves are resilient but vulnerable to climate change, with their response depending on whether critical thresholds are reached. Further insights into how mangroves respond to global environmental change depend on past and current climatic disturbances. Sea-level rise, warmer temperatures, storm intensity, and reduced rainfall have strong negative impacts on mangrove ecosystems (WWF-Climate Crowd 2021; Alongi 2022). Climate change-induced sea-level rise poses a major threat (IUCN 2024) because mangroves are adapted to specific tidal ranges, and rapid sea-level rise can submerge this ecosystem. This is possible when sea-level rise affects the inundation period, productivity, and sedimentation leading to dieback and migration landwards. Reports from the Cameroon Estuaries show that mangroves have experienced up to 3 m per year retreats from the shoreline over three decades (1975–2012) (Ellison and Zouh 2012). Dominant mangrove species like *Laguncularia racemosa* and *Avicennia germinans* are less tolerant to sea-level rise compared to *Rhizophora racemosa* (Ellison and Zouh 2012).

Changing rainfall patterns have great significance for mangroves, with reduced rainfall impairing sediment accretion and increasing salinity (Krauss et al. 2014). Warm temperatures can contribute to higher salinity through increased evaporation, but increased rainfall can reduce salinity; both can reduce mangrove growth. Warmer temperatures are likely to shift the timing of flowering and fruiting, affecting reproductive cycles (Alongi 2021). Frequent and intense storms, likely associated with warmer temperatures, caused physical damage (WWF-Climate Crowd 2021). Elsewhere, the shift toward hotter, drier conditions has reduced freshwater flows, causing mangroves to dry out and die (WWF-Climate Crowd 2021). Climate projections indicate Congo Basin mangroves face critical threats from sea-level rise, reduced rainfall, and intensified storms. Rising seas risk submerging mangroves, while diminished freshwater flows exacerbate salinity stress. Warmer temperatures may disrupt reproductive cycles and cause storm damage. Without adaptive measures, these combined pressures could exceed ecological thresholds, leading to habitat loss.

Soil Responses to Climate Change

Soils are vital to Earth's ecosystems, driving crucial processes that sustain life. They interact with climate in complex ways, being negatively impacted but also having the potential to be critical tools in the fight against climate change (Telo da Gama 2023). Recognizing this, the UN declared 2015 the International Year of Soils. Organizations like the IUSS, founded in 1924, emphasize the role of atmospheric composition, land use, and climate in soil health, acknowledging soils' importance in addressing environmental, health, social, and resource issues (Vienna declaration, 2015). However, soils' significance is often overlooked in global sustainability agendas, such as the UN's Sustainable Development Goal 15 (SDG #15), which focuses on terrestrial ecosystems but does not explicitly mention soils (Huck 2022).

In the Congo Basin, research on climate-driven changes in soil nutrient cycling, carbon dynamics, and greenhouse gas emissions is limited. Soil responses to climate are complex, involving physical, chemical, and biological processes that affect carbon storage and release (Rumpel 2009), microbial activity (Castro et al. 2010), soil erosion, nutrient cycling, and respiration (Chatterjee et al. 2024). Climate change impacts soil nutrients by altering their cycling, availability, and transformation through factors like increased rainfall variability, temperature fluctuations, and erosion, leading to nutrient losses (Das et al. (2024). Deforestation and increased rainfall in the Congo Basin exacerbate soil erosion and nutrient leaching, reducing fertility (Biddulph et al. 2021). Extended dry seasons and rising temperatures can lead to fire susceptibility in ecosystems like peatlands. Changes in the water table from prolonged dry seasons may destabilize carbon-rich peat soils (Dargie et al. 2017). Climate-driven changes in rainfall intensity, deforestation, and global warming directly impact soil erosion and nutrient loss (Mandal and Roy 2024). Although erosion levels in the Congo Basin are generally low, 32% of the area is prone to topsoil loss through water erosion, and 21% is prone to nutrient and organic matter loss through chemical degradation (Mushi et al. 2019). Tropical soil microbial communities are sensitive to warming, potentially increasing organic matter decomposition and carbon release. Warming experiments in Panama showed that raising soil temperatures by 4 °C increased CO2 emissions by 55% (Wood et al. 2019; Nottingham et al. 2020).

Climate-Driven Water Stress Across the Congo

The region has experienced extended dry seasons, with a reported increase of 6.4–10.4 days per decade between 1988 and 2013 (Jiang et al. 2019), together with a decline in greenness of Congolese forests (Zhou et al. 2014). This variability affects water storage and the basin's capacity to support agriculture and hydropower. Sridhar et al. (2022) used a hydrological modeling tool, the Soil Water Assessment Tool (SWAT), to simulate water budgets and streamflow under different climate and land-use scenarios. These models help illustrate how ongoing changes are likely to intensify water scarcity, with reductions in soil moisture and increased risks of flooding, fires, and agricultural drought. Prolonged droughts are exacerbated by

already documented rising temperatures in the Congo Basin (Kasongo et al. 2023). Future climate scenarios project even higher temperatures and more erratic rainfall, which will place further strain on the basin's water resources. Consequently, drought severity and frequency are expected to increase in the future, although interannual variability will persist. Uncertainties in these projections are linked to factors like precipitation, temperature, and soil moisture estimates based on vegetation assumptions. Drought severity is influenced by a combination of projected precipitation decreases (or small increases of less than 2%) and temperature rises of up to 3 °C. These temperature increases are projected to cause up to an 11% rise in evapotranspiration, further intensifying drought conditions. As such, less precipitation would mean less clouds, thus negative feedback cycle, that leads to drier conditions. Flash droughts and floods are occurring due to rainfall variability, and several basins around the world are facing this disaster (Kang et al. 2022). The Congo Basin might also face similar drought phenomena when the variability in rainfall can exacerbate water stress.

Mapping the Potentially Climate-Aridified Ecosystems in the Congo Basin

Studies suggest that the northern, southern, and southeastern edges of the Congo Basin are witnessing shorter rainy seasons and prolonged dry seasons, while the central parts dominated by dense wooded vegetation remain relatively stable (IPCC 2013). Vegetation satellite observations for a period of 12 years between 2000 and 2012 found a continued gradual decline of photosynthetic capacity (vegetation greenness) and moisture content driven by the persistent drying conditions and potential aridification in the northern region of the Basin (Zhou et al. 2014). Decreased soil moisture and lesser vegetation due to drier condition lead to expansion of arid lands (drought). Studies using numerical model experiments show that valley formations are central to the development of dry conditions in East African highlands (Munday et al. 2023).

Potentially Climate-Aridified Ecosystems and Shifts in Ecosystem Functions from Drought and Heat

Due to the high sensitivity of tropical forests to climate change, their structure, dynamics, and functions may be affected, which could impact the services they provide. Among 10 environmental factors likely to impact tropical forests (Lewis et al. 2004), climate is the most prominent. The specific characteristics for African tropical forests include (i) relatively low initial temperatures that are increasing, (ii) rising CO2 concentrations, and (iii) a strong trend of decreasing rainfall, rarely influenced by ENSO-related droughts (Lewis et al. 2004).

Tropical forests may be particularly susceptible for several reasons: (1) phenological events are closely aligned with climatic conditions; (2) strong coevolutionary

interactions, such as pollination and seed dispersal, with a high degree of specialization; (3) due to high species diversity, species tend to have narrow ecological niches; and (4) deforestation can significantly impact hydrology (Bazzaz 1998). Consequently, Congo Basin forests are vulnerable to drought and heat. For instance, leaf mass per area (LMA) decreases with rising temperatures (Doughty et al. 2018). Climate change is also likely to impact seedling growth, affecting regeneration and potentially altering canopy structure (Whitmore 1998). Whitmore (1998) emphasizes that tropical rainforests continually regenerate, so changes in seedling establishment, survival, and canopy gaps could alter species composition. While all plants will be affected, some, like epiphytes, will be more impacted (Benzing 1998). Thus, cloud forests where epiphytes occur face high risk (Foster 2001). Changes in climate will directly influence the distribution of biomes, ecosystems, and species (Bawa and Dayanandan 1998).

Climate change affects vegetation and trophic chains. Interactions between plants and herbivores are particularly susceptible (Coley 1998). Functional diversity is also impacted, with drier forests showing less diversity and resilience (Aguirre-Gutiérrez et al. 2022). With modifications to forest components, coverage, and functionality, Congo Basin functions will be impacted. Cusack et al. (2016) indicate ecosystem responses such as changes in plant growth, carbon storage, nutrient cycling, and biodiversity, with overall negative effects of global change. One primary impact is on carbon and water cycles. The sub-Saharan water cycle is linked to the Congo Basin's structure and will be modified by heat and drought. Carbon storage capacity is vulnerable (Koch and Kaplan 2022), with risk of forests becoming carbon sources (Mitchard 2018). Cusack et al. (2016) note decreased rainfall and deforestation are well understood, while warming, CO2 fertilization, and other factors need more research. New studies focus on long-term changes, mechanisms, and tree-level impacts to better understand Congo Basin responses.

Potential Impacts of Climate Change in Congolian Forests on Global Weather Patterns

Moisture cycling in the form of evaporation and precipitation are fundamental components of global hydrological cycle (Brubaker et al. 1993; Sridhar and Anderson 2017). They affect global and regional climates by redistributing water and latent heat. Most of the rainfall at any location originates from evaporation transported for several hundreds to thousands of kilometers away (Wei and Dirmeyer 2019). As a result, the impact of climate change on the forest cover in the Congo Basin will influence global weather patterns, through the disruption of the water cycle and impacts on atmospheric circulation (Bell et al. 2015; Ellison et al. 2017; Tuinenburg et al. 2020).

Anthropogenic land cover changes that affect evaporation have regional and global consequences for drought and groundwater storage (Kang and Sridhar 2018; Kumar et al. 2021). Through evapotranspiration, the Congo Basin forests release water vapor into the atmosphere, which sustains rainfall both locally and in downwind regions. In fact, the Congo Basin has a higher precipitation recycling ratio, estimated at 47%, compared to 36% for the Amazon (Tuinenburg et al. 2020).

The highest evaporation recycling ratios occur in the Amazon and Congo basins, with respective ratios of 63% and 60% (Tuinenburg et al. 2020).

Studies using regional climate models have been able to confirm that the complete removal of the Congo Basin rainforest would result in a dipole rainfall anomaly pattern. Such removal is predicted to result in approximately a 42% decrease over western Congo and 10% increase over eastern Congo (Bell et al. 2015). This study further confirms that the Congo Basin plays a critical role in shaping the Intertropical Convergence Zone (ITCZ)—a band of low pressure that drives tropical rain systems (Barry and Chorley 2003)—and that changes in forest cover and climate within the basin can shift the ITCZ, affecting rainfall across tropical and subtropical regions (Barry and Chorley 2003; Bell et al. 2015).

Potential Impacts of Climate Change on Biotic Interactions

The consequences of climate change on species have mainly focused on phenological and physiological changes or on changes in their distribution. However, species are embedded in a network of complex biotic interactions. Therefore, the combinatorial population dynamics responses of species to climate change are probably not linear or additive (Walther 2010). Spatial and temporal correspondences between species determine biotic interactions, and both may vary depending on climate parameters whose change is likely to generate temporal and/or spatial dislocations (Montoya and Raffaelli 2010).

Shifts in phenology have been observed in Africa in response to climate change (Sullivan et al. 2024). For example, plants can respond by altering resource allocation or the timing of life cycle events (Sullivan et al. 2024). Such changes can have major cascading effects on the species that depend on plants. The phenology of forest trees can affect food availability for herbivores, pollinators, or frugivores. Such changes are likely to impact the survival of consumer populations or generate distributional shifts (Sullivan et al. 2024). Evidence of climate-induced phenological shifts between plants and other species has been well documented in temperate and arctic ecosystems (Renner and Zohner 2018). Such mismatches are very likely in Congo Basin forests, but tropical forest phenology is more complex and less studied. In Lopé National Park, such shifts have been documented, and the collapse of fruit production of some trees has a significant impact on forest elephants (Bush et al. 2020b). It is therefore likely that cascading effects on pollinators and frugivores occur following such shifts. Climate change can also generate significant changes in the nutritional quality of plant organs. A comparative study in Kibale National Park showed that mature leaves of most species increased in fiber concentration (by 10%) and young leaves showed increased fiber and decreased protein (Rothman et al. 2015). Such changes strongly impact the population dynamics of folivore species, such as colobus monkeys.

Because species have differential rates of movement, some will move faster and further than others, and spatial dislocations are likely to occur (Walther 2010). Climate change-induced species range shifts can have multiple effects on biotic interactions.

Since species dispersal capacities are not equivalent, some species will come into contact and interact with new species, while others will show a decrease in the intensity of interactions, or even a total disappearance (Blatrix et al. 2013). Obligatory interactions are expected to be particularly sensitive because the two partners may respond differently to changes but each still depends on the other (Blatrix et al. 2013).

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Urbanization, Biodiversity, Ecosystem Functions and Services in the Congo Basin

18

Bila-Isia Inogwabini, Caroline Michellier, Stoffenne Binsangou, and Louis Zapfack

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Abstract

This chapter reviews the Congo Basin's urbanization focusing on its effects on biodiversity and the environment. An unprecedented rate of unplanned urban growth was one of the clearest patterns to emerge with the majority of people in the Republic of Congo (ROC), Gabon and Equatorial Guinea living in urban areas. The urban population is increasing and will continue to rise in the Democratic Republic of Congo (DRC) and Central African Republic (CAR) in the next decades. Rural populations migrate to urban areas in search of better living conditions.

Rapid urbanization and continuous rural–urban migration flow impact biodiversity, the environment and social conditions. Construction and fetching fuel wood clear habitats to support expanding cities whose ecological footprint reaches far into remote areas through bushmeat trade and other commodity demands.

Heavily populated urban areas occur in the western Albertine Rift (DRC) and the Douala–Kumba–Bamenda belt through (Cameroon), regions of high altitudes and species richness. Congo Basin's urban areas are polluted with largely of organic matter waste, but solid waste is also significant. Air quality is below the WHO's standards in most cities, partly as a result of emissions from obsolete equipment imported from developed countries. Minimal urban planning results in the development of slums in cities; it exacerbates the geohydrological hazards and associated risks.

There are significant gaps in urbanization data across the Congo Basin and present challenges to drawing general trends. This review recommends further investment in urban research, planning, implementation of environmental standards and infrastructure development.

Keywords

Increasing urbanization · Rural–urban emigration · Increasing human populations · Habit degradation · Slums · Break-down of social norms · Pollution

Introduction

Urbanization is a global, historical and social phenomenon that has been accelerating over time, as human populations have increased and become more and sedentary (Heurgon 1970). It is manifested by a continuous increase in the population of urban areas and by the physical expansion of conurbations (Véron 2006). In ancient times, cities such as Rome and Athens gradually developed to become political, religious and economic centers; they constituted areas where people could exchange goods and ideas. Urban areas were geographic spots from which knowledge and skills passed from one civilization to another (Heurgon 1970).

The industrialization era that began in England and the economic growth it instilled contributed to the urbanization of Europe and the countries that were

subsequently conquered by industrialized powers (Reader 1998). Just as the United States were colonized and urbanized by Europe, so were other parts of the world, including Africa. Even though the initial situation was not the same throughout Africa, and given that there were already ancient cities on the continent, colonization accelerated the process of urbanization, because the power and economic activities tend to be concentrated in urban centers. In the Congo Basin, urbanization further accelerated following independence, as people were free to live where they wanted and cities were the place that many had dreamed of for years.

After independence, most urbanization in the Congo Basin involved increases in the size of towns that originated in the colonial period (Atshimadja 1992). Medium-size towns have grown larger and larger, while some large towns have become extended megalopolises. Threats to biodiversity and ecosystem functioning in urban areas are numerous and increase proportionally with town expansion (Ayeni et al. 2023). The use of firewood for energy, the collection of other nontimber products from savannahs and forests, and the reliance on groundwater are all activities that are damaging biodiversity and other ecosystem services.

This chapter reviews the existing knowledge on urbanization in the Congo Basin and examines the changes to ecosystem functioning in this region caused by the increase in large human settlements across the various ecosystems that compose the Congo Basin. First, past and present demographics are compared for the Congo Basin's major towns; and town expansion rates and data on newly created towns are presented, for cities where data sets are available. Then, the chapter reviews the available quantitative data on firewood, mushrooms, wild fruits and extraction from the areas surrounding the large cities of the Congo Basin. How far towns influence biodiversity (through commerce or through direct off-takes) is mapped out and the effects of biodiversity documented. Impacts on plant and wildlife species driven out of their ecological niches by construction, and the habitat functions affected and the ecosystem services severed by vegetation clearance during urbanization are re-appraised. This chapter also discusses the influence urbanization has on ground and surface water pollution. The physical pollution of urban areas by the material goods (plastics, pesticides, light etc.) will also be assessed. This chapter analyzes the dynamics of urbanization in the Congo Basin and its ecological consequences, based on quantitative and qualitative data.

A Historical Overview of the Growth of Urbanization in the Congo Basin

There is no tradition of the development of ancient towns and cities, such as Timbuktu or Djenné, in the Congo Basin. However, the absence of large cities does not mean early forms of urbanization did not occur (Pillet-Schwartz 1996). Indeed, early European travellers in Central Africa found some cities that were comparable in their size with the towns they left in their native countries. Some of these embryonic urban areas consisted of market points where numerous people could come together and exchange goods and ideas; many were on the Atlantic coast

of the Congo Basin. The major points of juncture inside the Congo Basin mainland included Insasa (Leopoldville, now Kinshasa), Nkuna (now Brazzaville), Mbandaka, Kisangani and Bangui (Soret 1978; Cantournet 1986; Etudes Aequatoria 1990; Villien et al. 1990; Muketa 2011; Ikoli 2014), to name but a few, whose increasing size in modern times will be discussed below. These sites that served as embryonic development of future large cities were mostly located along the Congo and its tributaries. This is not surprising because, as stated in ▶ Chap. 5, "The Hydrology of the Congo Basin," major rivers and the Congo River itself served and continue to act as major communication routes through which people and their goods travel through the forests (Vansina 1991; Inogwabini 2020). On the Atlantic façade of the Congo Basin, towns and commercial nodes such as Mbanza Kongo[1] and Libreville[2] (Bucher 1975; Heywood 2014) were already populated by local ethnic groups and made trading hubs whose significance in size and organization was noted by the Portuguese in the fifteenth century and by other Europeans who followed. Douala was exceptional because the indigenous people, who gave the name to the town, settled on the banks of the Wouri River estuary in the eighteenth century after Portuguese sailors had explored the region in 1472 (Gouellain 1975).

Beyond these well-known installations, the Congo Basin's historic empires or kingdoms developed some well-populated human settlements. For example, at the southern edges of the Congo Basin, in present-day Democratic Republic of Congo, the Kuba and Lunda empires had flourishing cities called Mushenge and Musumba, which constituted their capitals (Margarido 1970). According to Margarido (1970), Musumba had a meticulous layout and grew out of the unification and transformation of several small villages into towns in the sixteenth century. Musumba comes from the Lunda's word *Musumb*, which means an agglomeration, bringing together diverse populations that coexisted under the authority of the Emperor, Mwat Yav. The people living in a Musumb came from different corners of the countryside. In that sense, Musumb was a generic name, which was given to sites where the King resided. In line with the idea of shifting urban areas (Coquery-Vidrovitch 1988), the specific location of Musumba has changed frequently due to numerous migrations caused by many ecological and social conditions, of which the most important included intertribal wars, diseases and epidemics.

Urbanization in the Congo Basin During the Colonial Era

Literature on urbanization in the Congo Basin during the colonial era is rather limited, especially when it comes to compiled and systematic documentation. Despite this limitation, major cities where colonial powers were installed have distinct historical trajectories. An attempt to systematize the conceptual thinking of

[1] Also known as São Salvador

[2] Formerly Fort-d'Aumale

how cities were built is found in the work of Coquery-Vidrovitch (1993, 1988), which covers the entire continent.

After introducing the idea of shifting urban areas, Coquery-Vidrovitch (1988) argues that colonialism became a decisive factor behind modern African urbanization. As was the case all over sub-Saharan Africa, the newly created colonial cities were almost all characterized by a clear juxtaposition of two contradictory settlements, divided between indigenous and colonial (white) areas (Balandier 1985; Baumanova et al. 2017). Some of these new towns emerged on sites that people of the Congo Basin had historically occupied, or where historically they conducted their trade activities. This was the case of the current large cities of Brazzaville (Republic of Congo), Douala (Cameroon) and Libreville (Gabon). Other towns were simply created from scratch, including, for instance, Bangui (founded in 1889) in the Central African Republic (Saulnier 1998), and Kananga (founded in 1895) and Lubumbashi[3] (founded in 1910) in the Democratic Republic of Congo (DRC).

According to Coquery-Vidrovitch (1993, 1988) and Soret (1978), colonial towns were initially intended to serve as seats of colonial political power. However, practical concerns, such as accessibility, health conditions and the safety of colonizers, dictated the site selection. Consequently, most of the major colonial towns were established along the Atlantic coast (e.g., Moanda, Pointe Noire, Libreville, Douala) or near major waterways such as the Congo or Ogooué rivers and their tributaries (e.g., Bangui, Brazzaville, Boma, Bolobo, Franceville, Kinshasa, Kisangani, Lambarené, Matadi, Mbandaka, etc.).

Regardless of their location, these cities shared similar features, including administrative offices, health facilities, colonial houses and, distantly situated, indigenous suburbs where paid-workers resided. In a nutshell, they provided social services that the modern world brought to the Congo Basin and began to act as magnets that attracted numerous people in search of better living conditions. This dynamic marked the beginning of a rural exodus that intensified over time.

Evolution of Major Cities in the Congo Basin Since the Colonial Era

Capital Cities Over Their History

Available data on the major cities of the Congo Basin illustrates that there has been rapid population growth in the capital cities. For example, Bangui, Brazzaville, Kinshasa, Libreville or Yaoundé harbored less than 500,000 residents during the 1950s. Indeed, even Kinshasa, with just 443,000 inhabitants, had less than that figure in 1960, while Bangui, Brazzaville, Libreville and Yaoundé had 94,350, 124,000, 29,000 and 75,000, respectively. However, in 1970, Kinshasa had already reached one million individuals; this figure would rise to more than two million inhabitants by 1980. All the other capital cities remained below the one-million figure until 1995, when Yaoundé joined the group (1.025 million people). Brazzaville would

[3] Formerly Elizabethville

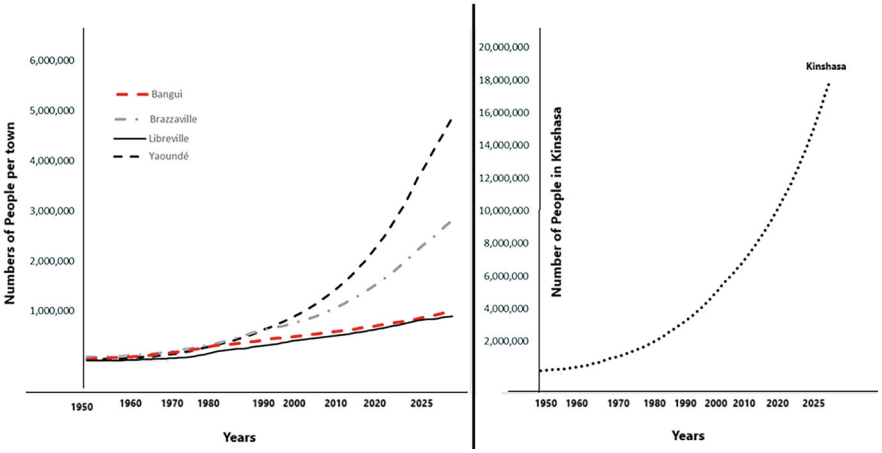

Fig. 1 Evolution of the urban populations in the capital cities of the countries of the Congo Basin. (Figure has been created with data from https://www.macrotrends.net/global-metrics/cities/)

reach that threshold in 2000 (1.022 million people; World Population Review 2024). The evolution of the population in the capital cities of the countries of the Congo Basin is shown in Fig. 1.

As shown in Fig. 1, Brazzaville, Kinshasa and Yaoundé have experienced exponential population increase over the last 75 years. The case of Yaoundé, whose population of about 5 million in 2025, an increase of 152 times compared to its 32,000 people in 1950, is particularly striking. Similarly, Kinshasa's population has grown from less than 500,000 individuals in 1950 to an estimated 18 million residents in 2025 (Mufungizi and Akilimali 2024). According to Mufungizi and Akilimali (2024), Kinshasa's population multiplied sevenfold from 2005 to 2009 and has undergone urban spatial growth of more than 4% per year since 2010. The other two major cities—Bangui and Libreville—have also experienced population increase over the years, but only gradually, following a trend that is quite linear. Still, the increases are large enough to merit the qualification of "demographic boom," increasing from about 42,200 and 15,000 people in 1950 to about 1.016 million and more than 1.17 million today. In addition to these past trends, population of the Congo Basin countries (in decreasing order: DRC, CAR, Equatorial Guinea, Cameroon, Republic of Congo and Gabon) are expected to continue growing (UNDESAPD 2025), which will further enlarge existing cities and likely lead to the emergence of new ones.

The exponential population growth of Bangui, Brazzaville, Kinshasa, Libreville and Yaoundé has been accompanied by the spatial expansion of each town, moving from an initial node during colonial times to increasingly larger areas. As Fig. 2 shows, Bangui has grown from its tiny initial post of about 2 km^2 (1912) to its current size of about 340 km^2 (Nguimalet 2007); with a current city center size of about 100 km^2; Brazzaville went from about 82 km^2 in 1978 to a total surface area of 394 km^2 when its suburbs and cultivated areas are included (Moutsara 1986;

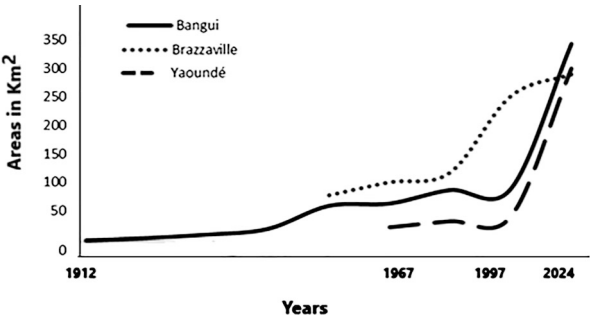

Fig. 2 Spatial evolution of the towns of Bangui, Brazzaville and Yaoundé. (Figure has been created compiling data from the following studies: Moutsara (1986), Sietchiping (2003), Nguimalet (2007) and Yekoka (2010))

Yekoka 2010); and Yaoundé, whose total surface in 1967 was about 25 km^2, is now over 300 km^2 (Sietchiping 2003; Zogo et al. 2017; Voundi et al. 2018).

Looking at the trends provided in Fig. 2, only Brazzaville seems to have reached a plateau and begun a transition from exponential spatial growth to a logarithmic trend. However, compiling the data from Wolff and Delbert (2002), Muketa (2011), Kayembe et al. (2013) and Ikoli (2014), Kinshasa can be said to have surpassed all expectations with regard to its geographic extension: this city expanded geographically by 27 times its size—from 356 km2 in 1957 to its current (2024) size of 9965 km^2. This represents an average annual increase of about 145% over 68 years.

Other Large Cities of the Congo Basin and Their Growth

In 2024, besides Bangui, Brazzaville, Kinshasa, Libreville and Yaoundé, the Congo Basin has eight towns with more than one million dwellers. These were built through the same process and have been growing following similar patterns to those described above. These large cities are listed in Fig. 3. One particularity is that the city of Douala, which was a small trade center in 1472 (Gouellain 1975) and had only 153,000 people at independence, is now a large city, with more than 4.3 million inhabitants making it comparable to Yaoundé. Otherwise, most of the cities with more than one million people in the Congo Basin are in DRC, which is understandable given its galloping population growth of about 3.8 annually (De Saint Moulin 1991; Fig. 3).

Medium-Sized and Small Cities and Towns Across the Congo Basin

The colonizers have also contributed to building towns and cities of different sizes across countries they colonized. The World Population Review (2024) recorded 231 cities of varying sizes across the Congo Basin, 38 of which had more than 100,000 residents in 2024. This category of cities is not new in the history of these countries; they were built either by the Belgians, the French or the Germans. Of these 38 cities, 13 have more than 300,000 residents, 8 have more than 200,000 people and the remaining 17 cities have more than 100,000 people (Fig. 4). Some of these towns, such as Bamenda (Cameroon), Bandundu and Mbandaka[4] (DRC), were just

[4]Formerly Coqlatville

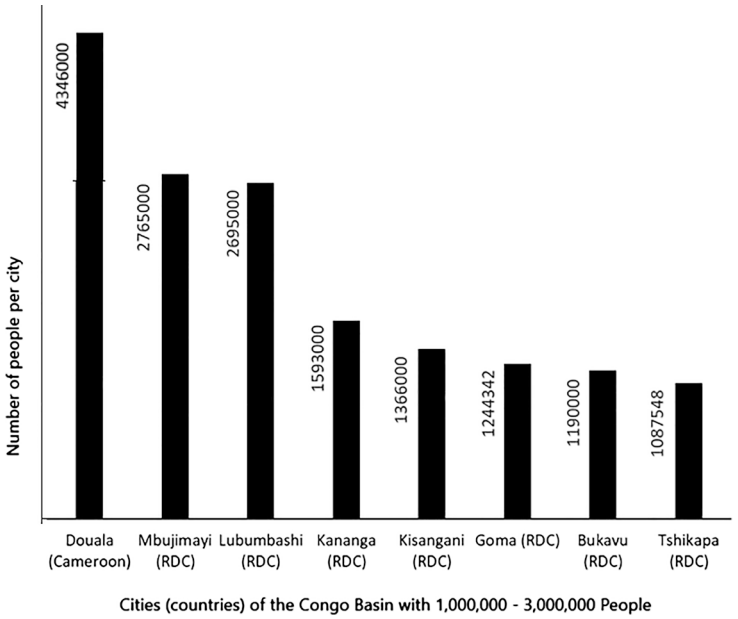

Fig. 3 Cities of the countries of the Congo Basin with more than 1 million inhabitants in 2024 (except capital cities). (Figure has been created with the data from https://www.macrotrends.net/global-metrics/cities/)

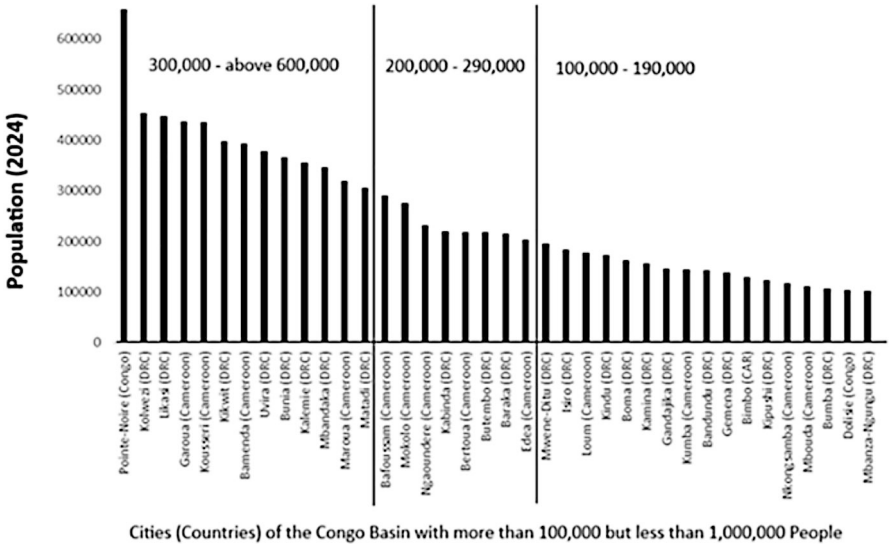

Fig. 4 Cities of the countries of the Congo Basin with populations between 100,000 and 1,000,000. (This Figure has been created with the data from World Population Review (2024))

outposts for the colonial authorities (Etudes Aequatoria 1990; Mbah 2016), whereas others (Butembo, Kolwezi, Likasi (DRC)) were established as extractive industry hubs, or served as commercial nodes, like Pointe Noire. Only the latter is located in the Republic of Congo, while the other 12 cities with more than 300,000 residents are found in DRC and Cameroon, the two Congo Basin countries covering the largest areas of the region (2.34 million km^2 and 475,440 km^2 respectively).

The existence of large cities and towns does not tell the whole picture of urbanization in the Congo Basin. Indeed, as suggested by Ayeni et al. (2023), based on the proportion of each country's population living in urban areas, Gabon and the Republic of Congo are among the most urbanized countries in the Congo Basin and even in Africa since 2016.

Infrastructure: The Dilemma of Urbanized Population and the Development of Slums in the Congo Basin's Cities and Towns

While urban studies in the Congo Basin have predominantly focused on infrastructure and planning, urban biodiversity remains poorly documented. Yet, it plays a crucial role in maintaining ecological balance and enhancing residents' well-being. One of the recurring issues is the contamination of subsurface water with pit latrines, reflecting broader infrastructural challenges across urban areas. A key concern is the large deficit in social infrastructure in most cities of the Congo Basin. In this context, "social infrastructure" should be understood not only as "places that allow people to gather, to support community life, to spend time together, to care for each other, to crowd together, experience culture together, to encourage people to exercise, play sport, dance and allow people to live comfortably alone and alongside one another" as Latham and Layton (2022) defined them, but also as infrastructure that comprises housing services, health facilities, education facilities, electricity and water distribution networks, public transportation and infrastructure where people can find safety and security services. Figure 5 illustrates the rapid urbanization that has characterized the Congo Basin's development over the last three decades. This urban expansion has significantly transformed the region's physical landscapes and redefined social dynamics. As a result, the way people experience their environments and relate to one another is increasingly shaped by urban conditions and the availability—or lack—of adequate infrastructure.

Pitte et al. (2021) indicated that the CAR and the DRC were the least urbanized countries in the Congo Basin, with only 44.5% and 45% of their population living in urban areas, respectively. In contrast, Gabon and Equatorial Guinea ranked as the most urbanized. However, when looking at the rates of urbanization over the last three decades, the DRC and Cameroon exhibit the most rapid urbanization, with both recording the highest rates in sub-Saharan Africa. Indeed, Cameroon saw its urban population rise from 45.5% in 2000 to 57% in 2021. Such accelerated urbanization has profoundly transformed of the Congo Basin's physical landscapes. Most cities in the region have expanded in an unplanned manner, leading to impacts on land, vegetation

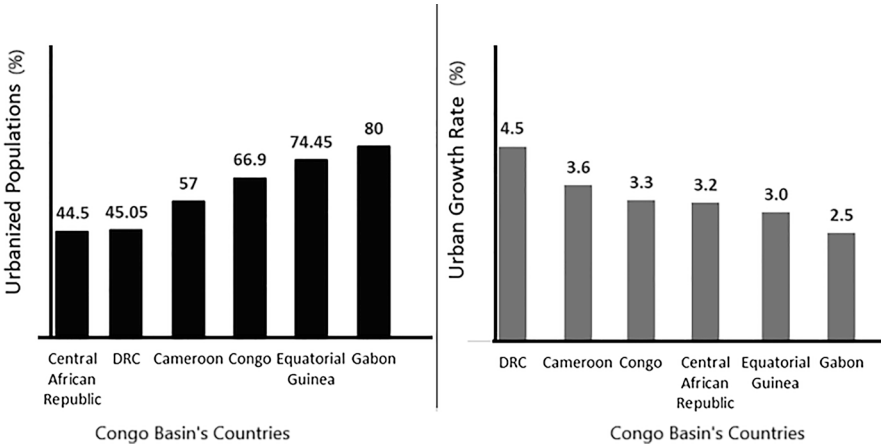

Fig. 5 Total urban populations and annual urban growth rates in the Congo Basin in 2021

and degradation of surface and ground water. In the absence of traditions in urban planning and land use regulations, cities like Kinshasa have experienced uncontrolled growth. Kinshasa, one of the continent's largest mega-cities, is currently witnessing the fastest urban population growth in the world. This rapid expansion has resulted in the development of large slums, some reported to be larger than the formal city itself (De Boeck 2020; He et al. 2021). According to Batana et al. (2021), approximately 75% of the urban population in the DRC lived in slums in 2014. These informal settlements not only lack basic social infrastructure such as roads, health facilities, clean drinking water, schools and police stations but are also characterized by economic, environmental and social challenges. They are peopled by economic minorities, who generally come from rural areas, seeking improved living conditions, including employment opportunities. Environmentally, slums are full of unregulated dumping sites, where microbial biodiversity cohabit with humans, and sewage is deposited in open air, causing significant health problems. Socially, these slums provide conditions where promiscuity easily prospers, which often leads to breakage or loosening of social norms. As Davis (2007) argues, banditry in such areas often emerges as a reaction from those who feel socially and economically betrayed and excluded by the State (Davis 2007). Economic exclusion fosters a broader sense of social marginality, contributing to phenomena such as street children, including the "little witches of the streets" of Kinshasa, and the rise of armed gangs (Davis 2007). For Davis (2007), "little witches of the streets" are children abandoned because their families accuse them of being sorcerers and kicked out their respective families; they end up living on streets the town. The same situation has been reported for other large cities of the Congo Basin. In Yaoundé, 60% of the population was reported to live in shantytowns. The figure was 37.6% Cameroon-wide, whereas in both Republic of Congo and Gabon, 44% of their respective populations lived in slums in 2018 (World Bank 2024). The CAR reported an even higher figure, with 68.9% of its urban population living in slum conditions (World Bank 2024).

What Explains the Population Densities and Spatial Increases in the Congo Basin's Cities?

Population Density in and Around Congo Basin Cities

The Congo Basin hosts high human population densities in urban areas (Fig. 5). As Atshimadja (1992) suggested, the increase in urban population can be explained by demographic dynamics internal to the mega-cities themselves. Mufungizi and Akilimali (2024) suggest that some of the population increases are a direct result of the population growth in the countries of the Congo Basin. Kinshasa's demographic trajectory parallels that of the DRC as a whole (where population has multiplied between fourfold or even sixfold since the independence).

Moreover, the rural exodus, which was originally mainly motivated by the search for better living conditions, is now further amplified by conflicts in certain regions of the Congo Basin. Civil unrest in remote areas has pushed populations into cities, where humanitarian organizations have provided assistance to displaced people. Cases of this situation include Bangui (De Clermont 2015), Brazzaville (e.g., Dorier-Aprill 1999), Kinshasa and other towns of the DRC, such as Goma and Bukavu (e.g., Stearns 2021). Not only do displaced people arrive in these towns when conflicts heighten, but they often stay there even after tensions cease, due to lack of prospects and limited infrastructure in their rural areas of origin.

Shapiro et al. (2021a) found a strong correlation between urban population density and environmental degradation. Moreover, based on Fig. 6, it appears that intercity connexion by practicable roads favors higher population densities by strengthening intercity influence (Megevand et al. 2013). This seems evident in regions like the western part of Cameroon, the north-western part of Gabon and the North-eastern part of Equatorial Guinea (Fig. 6). A similar trend is visible in the southern belt of the DRC, where a road corridor runs from Kinshasa to Lubumbashi, passing through cities like Tshikapa, Kananga and Mbuji-Mayi, each with populations exceeding one million. These roads are heavily used to transport charcoal, nontimber forest products and minerals from interior regions to Kinshasa. Like cities, they play a dual role: while supporting economic development, they also cause significant ecological impacts.

Cities' Geographical Zones of Influence

The **zone directly influenced by a city** is an area where vegetation cover is cleared, soils are eroded, and water sources are sullied by urban activity. Assessing each city's zone of influence in the Congo Basin would require knowledge of the ratio of the built-up area to the total area it exploits. Unfortunately, such metrics are difficult to obtain for each of the capital cities, let alone other cities. We can however infer the general trend from the data available for Brazzaville and Kinshasa, even though these data come from a limited number of studies conducted some time ago. An analysis of the work of Moutsara (1986) and Yekoka (2010) leads to the conclusion

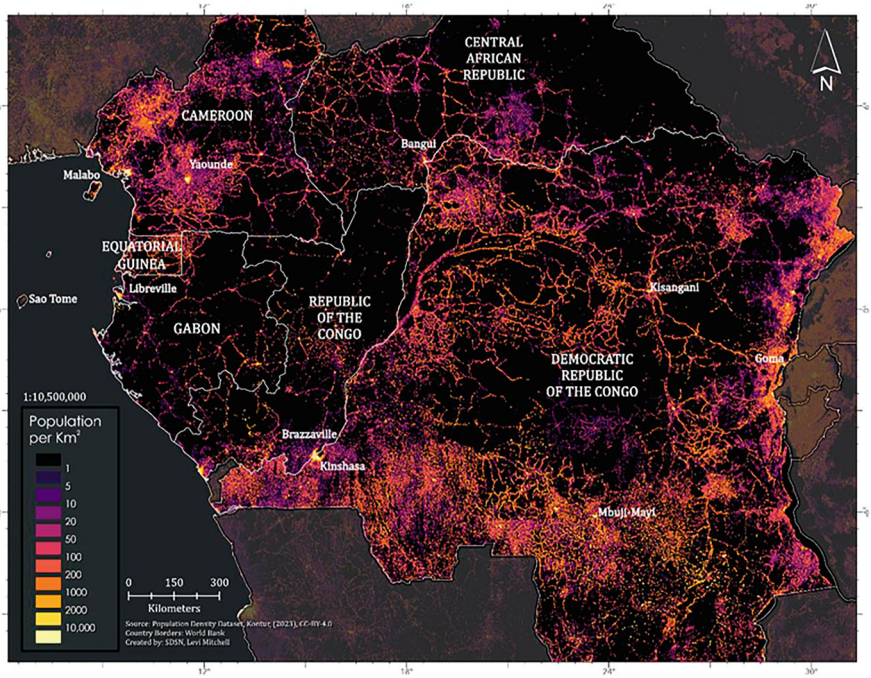

Fig. 6 Human population distribution and major human settlement axes in the Congo Basin. (Map produced using Human Populations, World Bank Dataset, 2023)

that Brazzaville has an influence zone of 394 km^2 for a built area of 100 km^2. This means that Brazzaville has a ratio of 4 km^2 of influence zone for every km^2 built. For Kinshasa, Kayembe et al. (2013) suggested that the main built-up area was centered around low-altitudes (i.e., 300-m a.s.l.), which they mapped over an area of 200 km^2. However, De Saint Moulin (2010) suggested a higher effective occupancy rate—approximately five times more. Given the widespread presence of informal settlements throughout Kinshasa, the figure of about 1000 km^2 is likely to reflect the reality in 2010 and has certainly been surpassed today, given the continued influx of people from other provinces to the capital. With that caveat in mind, Kayembe et al. (2013) calculated the ratio between the zone of influence and built-up area of Kinshasa by mapping the total surface of houses and roads and overlaid it on the land and habitat degradation map; they found this ratio to be 10 km^2 of affected area for every km^2 built (Kayembe et al. 2013). The rough estimate for Kinshasa aligns with Shapiro et al. (2021a), who modeled the impact of developing 1 km^2 of urban area would impact an area 10 times larger.

Applying the above assertion of direct influence zones, the location and land layout of some of the large cities poses direct **threats to wildlife species and their respective habitats**. For example, the cities of Bunia, Butembo, Goma, Bukavu and Uvira (Figs. 3 and 4) are located along the western flanks of the Albertine Rift, a region of the Congo Basin known for being its richest ecoregion, due to the wealth of

biodiversity it shelters (e.g., Plumptre et al. 2007). Indeed, several protected areas of international importance are located in this region, including Virunga and Kahuzi-Biega National parks, as well as many other categories of protected areas, such as Itombwe Reserve. Several studies (e.g., Wils et al. 1986; Kejuni et al. 1998; Plumptre et al. 2007; Ernst et al. 2010; Inogwabini 2021) have shown that the region is one of the most densely populated areas of Africa, where the local population depends on forest resources. The burgeoning demography of this area relies on forests not only for clearing land to grow food (Inogwabini 2021), but also for charcoal as a primary energy source—both of which has taken a huge toll on habitats of species such as chimpanzees, elephants and gorillas. Agriculture, wood extraction and charcoal production destroy habitats and wipe out species, as documented by several studies across sub-Saharan Africa in general, and the Congo Basin in particular (e.g., Chidumayo and Gumbo 2013). Table 1 provides figures that illustrate how urban expansion has contributed to vegetation loss across the Congo Basin between 2001 and 2023 (Global Forest Watch 2023).

Although these data (Table 1) do not include other major cities of the Congo Basin, such as Douala, Libreville and Yaoundé, they indicate that cities in the region have cleared **significant areas of surrounding forest** over the last two decades. In terms of forest loss percentage, Kisangani leads the list, whereas Bangui and Brazzaville show slower rates of degradation than all other cities. Notably, the cities with the highest level of forest loss—Kisangani and Mbandaka—are located at the heart of the Congo Basin Forest. As discussed above, this pattern appears to be largely driven by the rapid growth of these cities, which reflects the broader trend of urban expansion across the DRC. The increasing need for land—for housing, agriculture and energy—has likely intensified pressure on nearby forests (Nackoney et al. 2022; Nteranya 2024). Indeed, this trend predates the 2000s. Tshibangu et al. (1997)

Table 1 Tree cover loss in some cities of the Congo Basin: from 2001 through 2023

Town	Tree cover loss (Ha)	Decrease (%)[a]	CO_2E emissions (KT)
Bangui	195	4.8	84.3
Brazzaville	4	4.9	1.44
Bukavu	65	5.8	33.8
Bunia	79	7.1	32.6
Goma	35	3.7	14.5
Kananga	12,200	27	6550
Kinshasa	79,900	20	37,000
Kisangani	103,000	50	71,300
Matadi	69	10	28.0
Mbandaka	20,000	30	12,400
Pointe Noire	61	22	15.7
Tshikapa	63	5.9	19.9
Uvira	15.9	9.2	7.74

Source: Global Forest Watch (2023)
[a]All figures come from Global Forest Watch Report where the methodology is provided in details

analyzed a sample of 1243 km^2 around Kinshasa, which represent the limits of the province of Kinshasa. Using three sets of cartographic data—an aerial photograph from 1960 and satellite images from 1982 and 1987, Tshibangu et al. (1997) digitized them to calculate the percentage of the 1243 km^2 land cover changes over 27 years. They found that 6% of the land was converted into urban areas, while savannah-forest mosaic and cultivated areas respectively increased by 23% and 3%. In the meantime, forest cover declined by 31%, and aquatic vegetation and marshes by 7%.

Beyond increasing human population densities, vegetation degradation around most cities in the Congo Basin is mainly driven by **charcoal production** for energy (Schure et al. 2013a). Schure et al. (2013b) described charcoal use widespread across the region. In Brazzaville, charcoal production was already recognized as a factor degrading vegetation cover half a century ago (Gibert 1978). Lamoureux and Boundzanga (1994), as well as Boundzanga (2004), found that this practice had intensified over time. Similar trends have been reported in other urban centers, including Bangui (CAR) (e.g., Drigo 2009), Kinshasa and Kisangani (DRC) (e.g., Dubiez et al. 2012; Schure et al. 2013a). As a consequence, trees surrounding towns and cities play a vital role in local livelihoods, especially for charcoal production, the region's primary energy source. Schure et al. (2011a) found that Kinshasa consumes five million tons of wood annually for charcoal production. This pressure resulted in the loss of 79,900 ha of forest around the city between 2001 and 2023 (Table 1). Schure (2012) argued that rising charcoal and firewood prices in urban areas reflect increasing pressure on the periurban supply zone, including ecologically sensitive areas, such as the mangrove forests around Douala (Cameroon) and the fragile Afromontane ecosystems of the Virunga National Park (Eastern DRC), where millions of people continue aggregating with limited access to alternative energy sources. With 69,500 km2 of mountain forest (Achille et al. 2021), DRC holds about 90% of the Congo Basin Mountain forests (77,600.71 km^2) and ca. 7% of the eastern Afromontane forests (1,000,000 km^2; Ayeni et al. 2023). Ayeni et al. (2023) suggested that 91% of the total eastern Afromontane forests degraded over the last decades. If this rate is applied in the case of eastern DRC, only 6255 km^2 would be still in good ecological conditions. Human densities in this area are very high and range between 89 and 112 individuals/km^2 (Inogwabini 2021), which may explain why Shapiro et al. (2021b) found notable areas of degradation in eastern mountains of DRC in a Congo Basin-wide assessment of forest ecological integrity.

Moreover, charcoal production has important economic and social dimensions, as well as ecological impacts (Schure et al. 2011a, 2014; Schure 2012). For instance, Schure et al. (2011a) estimated that Kinshasa's annual consumption of 5 million tons charcoal generates approximately 143 million USD, excluding the indirect employment associated with packaging, transportation, handling, storage and other supply-chain roles. Transitioning Kinshasa away from charcoal dependence would therefore not only require scaling up clean energy access (e.g., electricity, gas), but also mitigating social impacts by compensating for job losses. Moreover, the health benefits for the population of such a transition would be significant.

Beyond Cities' Direct Physical Influence on Landscapes

In addition to their direct influence zones, cities also exert indirect ecological impacts that extend across much a larger radius. Indeed, the sourcing of energy charcoal reaches well beyond city boundaries. Charcoal supplies for Kinshasa, for example, travel a distance of more than 100 km before reaching the first outskirt markets, the average transport distance being ca. 30 km (Schure et al. 2011b). Urban markets are also supplied with a wide range of food items, including bushmeat, dried cassava tubers and various nontimber forest products.

Indeed, Shapiro et al. (2021a) suggest that cities influence ecosystems far beyond their immediate surroundings. Specifically, they noted that demand for bushmeat alone impacts forests well beyond the cities' estimated spatial neighborhood. This long-distance ecological footprint is amplified by infrastructure, particularly roads and navigable rivers, which expand cities' access to remote areas. This finding aligns with the discussions in ▶ Chap. 16, "Hunting, Fishing, and Ecosystem Functions and Services in the Congo Basin" (see this report), which indicate that total bushmeat consumption in cities exceeds that in rural areas, primarily due to higher urban population densities. Moreover, the overexploited terrestrial wildlife has also led to increased reliance on fish, placing additional pressure on aquatic ecosystems, given the complementarity and interchangeable nature of fishing and hunting (Inogwabini 2014).

Internal Problems Cities in the Congo Basin Face

Cities of the Congo Basin, particularly capitals and other major cities face several environmental, material and immaterial challenges that affect the quality of life, health and life-expectancy of their residents. Among the most pressing environmental problems are those related to waste and its management, including organic and plastic waste, air pollution and (surface) water pollution. This section of the report examines the current state of knowledge with respect to these critical and persistent urban environmental issues.

Waste Production and Management in Cities of the Congo Basin

Waste issue is discussed in many cities across the Congo Basin, where many view unmanaged waste discharges as chaotic and uncontrolled dumping sites (Tchuikoua 2020). While some data are collected in various cities, there is no consistent or systematic approach across the region. However, existing studies (e.g., Sotamenou 2012; Mangenda et al. 2020; UN Habitat 2018a, b, c, 2019; Tchuikoua 2020) provide the basis for Fig. 7, which presents data for Kinshasa, Yaoundé and Brazzaville.

With ca. 11 million tons per year, Kinshasa generates more waste than any other city in the Congo Basin. Yaoundé follows with ca. 7.3 million tons annually, while

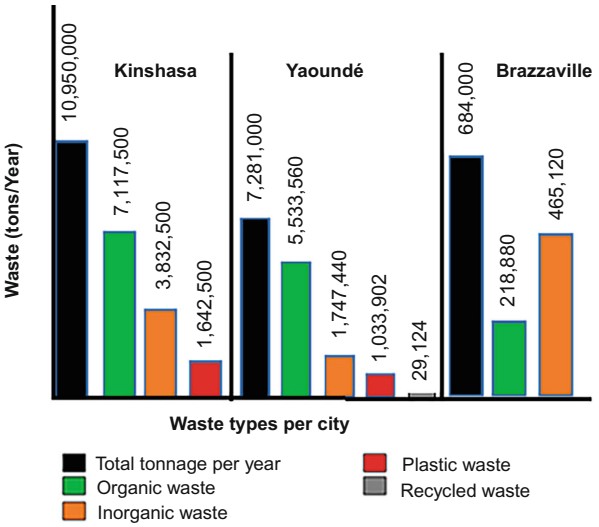

Fig. 7 Waste production per waste types in some cities of the Congo Basin between 2019 and 2020 (UN Habitat Data)

Brazzaville produces just under 700,000 t/year. The general trend is that larger and more densely populated cities produce more waste than smaller cities. Hence, it is not surprising that Garoua and Nkongsamba (Cameroon) generate respectively about 19,000 and 12,500 t of waste annually, significantly less than Yaoundé. However, this pattern does not always seem to be consistent: for instance, Libreville produces more than 1.2 million tons annually (Mvele-N'dango'o 2007), a figure far higher than Brazzaville, and Douala—despite having a similar population to Yaoundé—shows lower levels of waste production. However, these discrepancies may stem from differences in sampling or data collection methods.

Plastic waste constitutes a relatively small proportion of total waste across the Congo Basin—15% in Kinshasa and 14.2% in Yaoundé—but specific data are lacking for cities such as Brazzaville, Bangui and Libreville. Where figures exist, methods used are often unclear, and values vary widely—sometimes by factors of 1 to 100—making reliable assessments difficult. Nonetheless, an informed estimate suggests (e.g., Onyeabor 2024) that plastics likely make up around 10–15% of waste in most cities of the Congo Basin. In terms of volume, plastics occupy a disproportionately large share, contributing to the widespread impression of plastic waste inundating urban environments. Factually, plastic wastes have become a nightmare for most cities in the Congo Basin (e.g., Sotamenou 2012; Tchuikoua 2020; Kang et al. 2023). While plastic recycling activities likely exist in cities like Brazzaville, Kinshasa and Libreville, reliable peer-reviewed data remain scarce.

Finally, **organic waste** constitutes the majority of waste in Yaoundé (76%) and Kinshasa (65%), whereas **inorganic waste** dominates in Brazzaville. This surprising trend may reflect data collection gaps, particularly for organic waste, which is often dumped in informal and inaccessible sites, complicating measurements. A further data gap concerns recycling rates. In Yaoundé, almost 30,000 t of waste are recycled

annually, representing just 0.4% of the waste stream, though it is unclear what types of waste this figure includes. According to UN Habitat (2018a, b, c, 2019) and Kang et al. (2023), poor planning, weak law enforcement and constrained municipal budgets hinder effective daily waste management.

Pollution in Urban Areas of the Congo Basin

The discussion about waste production and management is inherently linked to pollution; indeed, solid waste—whether organic or inorganic—pollutes the environment in the cities of the Congo Basin. The lack of adequate waste treatment infrastructure results in the massive accumulation of garbage, contributing to soil and groundwater pollution. Beyond these issues related to solid waste, air quality in cities of the Congo Basin has also become a growing concern.

Air Quality in the Congo Basin's Cities

Studies of **air quality** often look at fine particulate matter ($PM_{2.5}$) and compare them with the World Health Organization (WHO) guideline, currently set at 10 μg m^{-3} (Pai et al. 2022). Unfortunately, $PM_{2.5}$ datasets remain scarce for most cities of the Congo Basin.

However, combining available studies (e.g., Sotamenou 2012; McFarlane et al. 2021) with data from the WHO's Air quality database (WHO 2022), it is clear that $PM_{2.5}$ concentrations in cities with population exceeding one million people consistently surpass the WHO threshold (Fig. 8). For instance, between 2010 and 2019, Kinshasa recorded $PM_{2.5}$ levels six times higher than the recommended standard, while nearby Brazzaville follows with an average 43.5 μg m^{-3}—over 4 times more than WHO guidelines. The overall trend suggests that larger urban centers tend to exhibit proportionately higher $PM_{2.5}$ levels over time. In mining cities such as Lubumbashi, Mpoyo et al. (2021) reported solid atmospheric deposits with elevated concentrations of heavy metals including Cd, Ni, Cu, Fe, Zn and Pb, all exceeding WHO standards.

Air pollution in Congo Basin cities and urban areas is exacerbated by the influx of old vehicles and obsolete industrial equipment imported from Western countries. Aveling et al. (2003) and Inogwabini (2024) noted their contribution to increased CO_2 emissions and general air quality degradation. However, few published studies document the types and magnitudes of pollution caused. A regional overview by the United Nations Environment Programme (Baskin et al. 2020) indicated that only Gabon had implemented effective regulations for monitoring used vehicle imports, with measurable success. In contrast, other countries assessed (Cameroon, CAR, DRC and Equatorial Guinea) were found to lack both emissions standards and enforcement capacity to regulate imported vehicles or industrial machinery.

Open and Subterrain Water Quality in Large Congo Basin's Cities

Once again, published systematic studies on water quality in major cities of the Congo Basin are scarce, with most available information stemming from grey literature. For instance, in a city as large as Kinshasa, Aveling et al. (2003) could

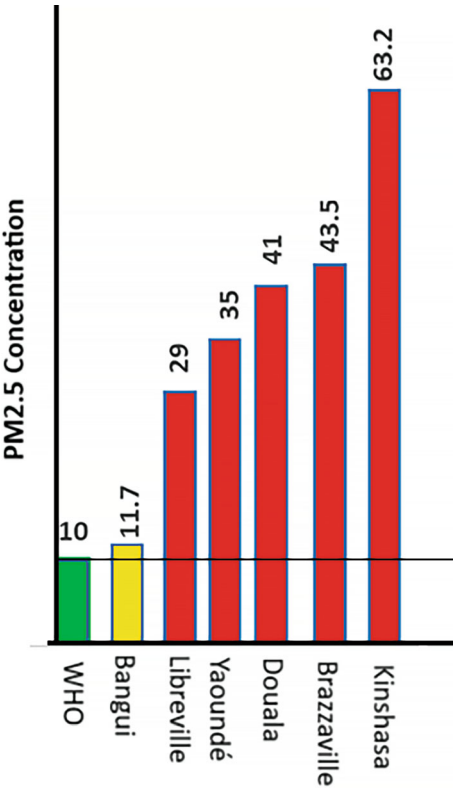

Fig. 8 $PM_{2.5}$ Concentrations in some cities of the Congo Basin. (Figure created using data from Sotamenou (2012) and McFarlane et al. (2021))

only find one thorough study on water quality, commissioned by the national water agency and conducted by affiliated research institutions. The study shows that the subterranean water—widely used for drinking—was acidic (mean pH = 4.42), indicating high carbonic gas content. The reported turbidity was 5533.35 mEq-g and callosity was 15.23 TH^{o}_{f} (thorium oxyfluoride). Additionally, Aveling et al. (2003) reported that the sources of 13 creeks flowing through Kinshasa had low turbidity (mean 3.35 mEq-g, due to the sandy nature of the zone, remaining within WHO-recommended limits. However, Aveling et al. (2003) also reported that all rivers traversing Kinshasa were heavily polluted with solid organic matter (0.63 mgO_2/L), which significantly altered the color of the water and contributed to waterborne diseases, such as diarrhea, typhoid fever and amebiasis. Further studies by Kilunga et al. (2017) and Kayembe et al. (2018) confirmed high concentrations of heavy metals in river sediments across Kinshasa. Reported values included 190.2 $mg.kg^{-1}$ for Cu, 58.6 $mg.kg^{-1}$ for Cr, 1117.9 $mg.kg^{-1}$ for Zn, 1.2 $mg.kg^{-1}$ for Cd, 149.2 $mg.kg^{-1}$ for Pb and 11.8 $mg.kg^{-1}$ for Hg. These concentrations varied by sampling period and site, with Kayembe et al. (2018) noting a general increase in metal levels over a 3-year monitoring period, suggesting that urban population growth correlates with rising water pollution.

In Yaoundé, Sotamenou (2012) found that both surface and ground water were contaminated by solid and liquid waste. He attributed ground water pollution to leachate from landfills, which infiltrated the soil and carried organic, mineral and metallic pollutants. Though precise quantities of released gases were not provided, he detected the production of CO_2 and H_2 during the percolation process, as well as flammable and hazardous gas mixtures—comprising 55% methane, 45% CO_2 and small quantities of H_2S, CO, N_2 and NH_4—due to methanogenic bacterial activity. Similar findings on organic waste methanization and water contamination were reported for Kinshasa (Mangenda et al. 2020) and Douala (Tchuikoua 2020). Moreover, Kilunga et al. (2017) found elevated concentrations of persistent organic pollutants (organochlorine pesticides,[5] polychlorinated biphenyls,[6] and polybrominated diphenyl ethers[7]) in Kinshasa's rivers, surpassing levels reported in other sub-Saharan African rivers.

Djebebe-Ndjiguim et al. (2013) identified that anthropogenic activities—such as waste dumping, laundering, dishwashing and the use of pit latrines—were widespread across Bangui and had a significant impact on the city's shallow aquifer. These activities affected water quality parameters including electrical conductivity (EC), sodium, potassium, nitrate and sulfate levels. Particularly, the study found elevated concentrations of chloride in water wells, making chloride the dominant anion in Bangui's shallow groundwater. After exploring alternative explanations for the high sodium and potassium concentrations, the authors concluded that these concentrations were primarily the result of polluted household waste water and the use of domestic detergents contaminating surface and subsurface water sources. Similar patterns of anthropogenic pollution have been documented in other Congo Basin cities such as Brazzaville (Nzila et al. 2018), Doula (Nwamo et al. 2016) and Libreville (Mombo and Edou 2005; Pambou et al. 2022).

A specific but understudied category of urban waste is untreated hospital effluents. Although there is a lack of comprehensive data on its impact across the region, research by Mubedi et al. (2013) in Kinshasa highlights that such effluents significantly degrade water quality and aquatic biodiversity, with potentially serious public health implications.

Geohydrological Hazards and Urbanization in the Congo Basin

Rapid urbanization in the Congo Basin has intensified the exposure and vulnerability of cities to geohydrological hazards such as floods, landslides and gully erosion (Dille et al. 2022; Attipo et al. 2023). These threats are exacerbated by factors like unplanned urban expansion, deforestation, inadequate water drainage systems and

[5] Organochlorine pesticides: Insecticides to protect crops and control vector-borne diseases.

[6] Polychlorinated biphenyls: Used as coolants and insulating fluids in electrical equipment, and in sealants, paints and plastics.

[7] Polybrominated diphenyl ethers: Added to plastics, textiles and electronics to reduce flammability

the foreseen effects of climate change. Scientific studies have documented these issues across various urban centers in the region (Attipo et al. 2023).

Flood Hazard Across the Congo Basin Cities

In Kinshasa, Tshimanga et al. (2016) reported that in 2015 after floods of the major rivers, 2112 families were affected, 8480 individuals displaced and 31 people died. The same year, floods were also reported in other towns of the DRC, including Boma (Kongo Central), Mbandaka (Equateur) and Kisangani (Tshopo). According to Tshimanga et al. (2016), the 2015 flood event had only two precedents in the previous century, which occurred in 1903 and 1961–1962. Iroume et al. (2022) also reported a similar extreme event in Douala (Cameroon) in 2020 and computed about 2210 affected buildings and 12,376 victims in an area of over 82 hectares. The same year—2020—the city of Uvira (eastern DRC) was the scene of devastating flash flooding events. Two flash floods impacted large parts of this city of about 314,000 inhabitants, killing more than 50 people, leaving over 100,000 homeless and damaging houses, food storage facilities and other basic infrastructure (Mugisho Bachinyaga et al. 2022).

Given the likely increased frequency and intensity of heavy precipitation as a result of climate change, fast-growing tropical cities in developing countries will be even more impacted by severe flooding (Tshimanga et al. 2016; Seneviratne et al. 2021). The cities of the Congo Basin are no exception to such events, with increasingly severe impacts (Ndille and Belle 2014; Tshimanga et al. 2016; Iroume et al. 2022). This increase is the result of the lack of urban planning, the very rapid population growth (mainly due to insecurity in the rural areas) and the resulting deforestation (Mugisho Bachinyaga et al. 2022; Deijns et al. 2022). Moreover, the flooding results in long term economic and social consequences, as it destroys crops, homes and infrastructure, leading to an increase poverty and food insecurity, as well as other potential subsequent threats, such as uncertain drinking water availability.

Landslide Risk Assessment: The Case Study of Bukavu City (Eastern DRC)

Risks associated with landslides are particularly high in Bukavu, a city where urban sprawl is extensive and the process of landsliding is particularly acute (Dewitte et al. 2023). Some of these landslides are due to pervasive slow-moving deformation of a few centimeters to up to a few meters per year, mainly as a result of urbanization (Balegamire et al. 2017; Nobile et al. 2018; Dille et al. 2022). Specifically, Dille et al. (2022) demonstrated that over 70 years of urban growth have disturbed the stability of a densely inhabited landslide. The study found that changes in slope hydrology associated with infrastructure development (housing, roads, etc.) have contributed to increased landslide activity, highlighting the complex interplay between urban development and natural hazards in tropical environments.

Bukavu is also impacted every year by relatively smaller and shallower seasonal landslides, whose occurrence is linked to the alternation of wet and dry seasons (Nobile et al. 2018). The at-risk areas of such seasonal events are usually rather small and their impacts can be very localized. However, the velocity of these shallow processes can be particularly high. As a result, they generally have a limited impact

on infrastructure with solid foundations, but can potentially cause great damages to less robust ones. Their sudden and unexpected character frequently causes injuries, and even sometimes fatalities, especially if they occur in densely populated areas (Nobile et al. 2018).

Urban Gully Erosion

Kinshasa, the capital city of the DRC, with more than 14 million inhabitants, is affected by large urban gullies, with over 570 identified (Ilombe et al. 2022; Lutete et al. 2023). These gullies are typically very large (more than 30 m in width and 10 m in depth) and can reach lengths of several hundred to thousands of meters (Lutete et al. 2023, 2025). Their rapid expansion, particularly in the sandy hills where Kinshasa has undergone chaotic growth, creates extreme exposure and vulnerability for the dense urban population (Ilombe et al. 2024; Lutete et al. 2025). The resulting impacts include major infrastructural damage to properties, buildings and roads, and crucially, cause displacement, injuries and tragic casualties (Ilombe et al. 2022; Lutete et al. 2025).

Across the DRC, an estimated 1.3 million people living near gullies are currently at risk or experiencing significant impacts, such as reduced land value and stress (Ilombe et al. 2022). Efforts to fight this phenomenon involve various prevention and mitigation measures, but their effectiveness is often limited by cost and the challenging socio-economic context (Lutete et al. 2023). Community-based measures have already been implemented to fight urban gullies, but they remain largely ineffective in significantly slowing gully expansion (Lutete et al. 2025).

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History, Development, and Politics of Protected Areas in the Congo Basin Countries

19

Bila-Isia Inogwabini, Claudine Augée Angoué, Fiona Maisels, and Lee J. T. White

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Abstract

This chapter shows that biodiversity conservation is not a new tradition in the Congo Basin; it has been practiced using different models, including taboos preventing access to sacred areas of hunting of certain species and prohibitions to hunt or fish in certain periods coupled with alternative resources usages. The suggestion that biodiversity conservation and stewardship came with colonization is a blinkered view. The chapter recalls practices to conserve biodiversity that existed before colonization and shows that they may have been sufficient during that period. However, the chapter also describes the creation of protected areas in the era between 1885 and 1960 and beyond in line with other centralized models for resource management adopted during the colonial period. Despite abuses of human rights (rights to lands, right to decent livelihoods, right to political participation, etc.) that accompanied the creation of protected areas during that period, they have remained the only areas where biodiversity thrived and are now the only remaining biodiversity refuges in the Congo Basin, where galloping human demography and the corresponding economic need to cater for increasing human populations exerting untenable tensions on both renewable and non-renewable natural resources (Dixon and Sherman 1991; Inogwabini 2020). The chapter also documents the lessons learnt from the history of creating protected areas and concludes that, in view of these abuses, the Congo Basin countries have begun to use categories of protected areas that reconcile the need to preserve biodiversity with human development needs, including such models as IUCN category VI reserves, large biodiversity landscapes, community conservation areas and high biodiversity value areas within other land use areas (Sanderson et al. 2002; Toham et al. 2006). Modern protected areas are the sacred forests of nations, created at a scale in proportion to modern threats to biodiversity.

Keywords

Protected areas · Sacred forests · Traditional taboos · Biodiversity conservation

Introduction

Doumenge et al. (2021) and Eba'a Atyi et al. (2022) give excellent summaries of the history, distribution and status of protected areas in the Congo Basin as well as the key conservation issues that impact their management. We will not duplicate their work here, but rather discuss the history and philosophy of protected area creation and how these have evolved over time, in order to document their place in the Basin in 2025.

Protected areas are not a modern invention. Protected gardens, sometimes including collections of animals, have existed for millennia. Both the Bible (Genesis 2:8) and the Quran (verse 9:72 from Surah At-Tawbah - The Repentance) speak of gardens, where humans live as part of Nature in an earthly paradise (Masson

1967). Temple gardens existed in Ancient Egypt as early as about 1500 BC, while the Hanging Gardens of Babylon date to the eighth century BC (Herodotus 1996). The Pharaohs of Ancient Egypt reserved areas along the Nile Delta for hunting lions, hippos and crocodiles. Indeed, hunting grounds reserved for the nobility, or other leaders, have been prevalent across many cultures in Africa, Europe, Asia, the Middle East and North America for hundreds, even thousands of years (Keswick 2003).

There is no written record of the Congo Basin before the arrival of Arab and European traders, so it is not possible to know whether formal protected areas were a part of traditional culture. However, notions of sacred forests, taboo species that were not killed and/or eaten by certain tribes or sectors of society and areas that were only exploited seasonally are prevalent in peoples all across the Congo Basin.

The modern notion of setting aside protected areas because industrial humans' capacity to destroy nature had become a threat to its very survival dates to 1872, when President Teddy Roosevelt signed the Yellowstone National Park Protection Act. This established the first national park in the world in the United States of America. The creation of the Yellowstone National Park launched a biodiversity conservation paradigm, analogous to the Royal hunting reserves, of "*fence-and-fine*" or "*fortress conservation,*" which aimed to protect biodiversity from direct human use and influence.

In this chapter, we describe the history of conservation and protected areas and the shift in paradigm from "*fence and fine,*" or "*fortress conservation,*" to more inclusive models. We focus on four periods, before and after 1885, the date of the Berlin Conference, which imposed the current geo-political map on the African peoples (Meredith 2014) and marked the beginning of more formalized colonial rule, between 1960 and 1990, when independent central African states started to emerge, and 1990 onward. The section covering biodiversity conservation in the Congo Basin before 1885 draws on early texts written by European explorers, anthropological studies and published oral stories.

Biodiversity Conservation in the Congo Basin Before 1885

In modern times, protected areas have become the backbone of biodiversity conservation, the sacred forests of nations created at a scale in proportion to modern threats to biodiversity. However, conserving biodiversity can and has been done using different methods, including alternating usages of geographical space and biological resources across time (Phillips 2004). Thus, the mainstream idea that to conserve biodiversity one must set aside special spaces for species (e.g., Anderson and Grove 1987) is, at best, incomplete (Duffy et al. 2015). Despite lack of written records, anthropological work has shown that notions of sustainable use and preservation of Nature are deeply rooted in the prehistory of Central Africa (Carruthers 2004). Some examples are given below.

Intermittent Forest Usage, Seasonal Activities and Taboos: A Traditional Conservation Toolbox

Cameroon's Kilum-Ijim region has always been ruled by a traditional paramount chief (the Fon) and his parliament (Kwifon), and they used to be solely responsible for management of the Kilum forest (Nurse et al. 1995). They managed watersheds, catchment areas and fragile forest ecosystems for generations, protecting the entire ecosystem, but this started to break down in the 1970s (Fisiy 1994; Stewart 2003). Unusually, for Central Africa, the Fon and parliament remain in charge of the area today and still maintain some degree of control over the extraction of natural resources and have, above all, managed to maintain much of the forest cover within the Nso-Oku area (also known as Kilum-Ijim).

In the Democratic Republic of Congo, historical records indicate that seasonality of human activities has helped protect and manage wildlife and their habitats. Harms (1989) described fishing, the principal activity in some villages near the Congo River and its surrounding lakes and major tributaries from the nineteenth century through the early twentieth century. He found that people maintained fish stocks by agreeing nonfishing seasons when they relied upon a wide range of other natural resources to replace fish in their diet. Communities used seasonal fishing as a mechanism to manage stocks. A series of studies document that seasonal use is a feature in traditional fishing communities across the Democratic Republic of Congo (e.g., Turnbull 1997; Buleli et al. 2011; Etambala et al. 2011; Bawele et al. 2016; Léonard et al. 2018; Tshonda et al. 2018).

Traditional communities also enforce seasonal hunting bans in many areas across Democratic Republic of Congo (e.g., Nicolaï 2012; Pouillard 2016; Batumike et al. 2021). In some cases, these bans are linked to periods when traditional initiation ceremonies are undertaken. One of the best described examples in Democratic Republic of Congo is *Kimbilikiti,* among the Warega (Walega) of South Kivu and Maniema (Dalhaise 1909). *Kimbilikiti* is "the forest's spirit" (Burk 1940). The process to transmit *Kimbilikiti's* secrets to younger generations is done through the *Lutende* rite, which is held deep in the forest over a period of weeks or months, during which all other access is forbidden (Verhaegen 1969). Despite being known as hunters (Clarke 1930), the Walega suspend hunting and fishing in the areas where *Kimbilikiti* is underway. Thus, the initiation process and ceremonies provide a rest period allowing forest ecosystems to rejuvenate. Many similar examples have been documented across Democratic Republic of Congo (Boelaert 1973; De Rop and Boelaert 1983; Vansina 2010; Burssens 2017) and more widely across the Congo Basin (e.g., Raponda-Walker and Sillans 1962; Vansina 1991).

UICN (2010) mapped 194 Kimbilikiti sacred sites time in the Itombwe forest where destructive human activities have been prohibited or scaled down by tradition. Here, traditional conservation activities provided the inspiration for a modern protected area. Across the Congo Basin, the extent of sacred areas varies, ranging from very small to quite large areas. At one end of the spectrum, they consist of small

areas of less than 1-ha, such as open fishing ponds (e.g., lake Kandoja in the Salonga National Park), traditional cemeteries (e.g., Kabanza Forest Ancestral Cemetery at Tshikongo, Bushimaie Reserve) (UICN 2010; Anahendo et al. 2021) or minor portions of large lakes (e.g., Inogwabini et al. 2009). At the other end of the spectrum, they can be large enough (greater than 10-ha) to provide shelter to a variety of species.

Taboos are a traditional way to preserve species without putting parks in place. Indeed, taboos that serve to protect some species have prevailed throughout the Congo Basin for millennia. Taboos are prescriptions by which whole tribes, or some hunters, or women, or clans, or families, have totems they do not eat (kill). In Democratic Republic of Congo, Mbuti pygmies and other local tribes consider Okapi as a sacred species in the Ituri Forest and only the tribal chief is allowed to wear or sit on an okapi skin. These tribes consider the slaughter of an Okapi to be a major event and mourn the dead animal (Hart and Hart 1986; Kümpel et al. 2015). Similarly, the Téké people of the Malebo (Bolobo) region in Democratic Republic of Congo, consider bonobos to be their ancestor and don't kill or eat them (e.g., Inogwabini et al. 2007a, b, 2013; Inogwabini and Leader-Williams 2012, 2013). Surveys in this area have found significantly larger populations of bonobos. The same story is told by the Punu people of southern Gabon, who consider gorillas to be their ancestors and traditionally do not eat them (Tutin and Fernandez 1983).

In Gabon, populations are highly syncretic and respect various initiation rites that characterize the nation's sociocultural traditions. Raponda-Walker and Sillans (1962) gave an exhaustive list of these traditions, among which the most important include the Bwiti, Mweli and Moungala. The knowledge transferred during these numerous rites creates a special link between people and the forest, or nature in general. This was highlighted during the swearing in ceremony of General Oligui Nguéma as interim president after the seizure of power by the military on August 30 2023, when a traditional ceremony organized by Babongo peoples followed on from the formal civil ceremony. During the second phase of the ceremony, they performed the Bwiti Mbomo (mystical snake) and then the Ngomba (porcupine) rites, clearly indicating that the new political leader intended using a mix of politics and tradition to govern (Angoué 2024).

In Lopé in central Gabon, location of a national park that is also a mixed natural and cultural World Heritage Site, the residents of Okandé have a special rite called *Diyandzi,* a branch of Mweli, whose initiates are specialized in the management of forests and natural places (rivers, hills, savannas) that make up their environment (Angoué 2004). In Lopé and throughout central southeastern Gabon, a system of fallow land, typical of shifting cultivation, is applied to rivers where young people have been initiated into *Mweli,* forest areas where people go to meet good spirits, ancestors or genies, and forested areas where trees marking the birth of twins grow (there is a tradition of burying the placenta and umbilical cords of twins and triplets under trees, in a special rite in southern Gabon). These traditional African rites recognize nature as a divine creation, in the same way as the first book of Genesis (1: 1–30). As a result, the Gabonese forest contains numerous forbidden areas,

sacred forests and animal species that must not be consumed by noninitiates, men, women or children, all enforced by traditional institutions.

Also in Gabon, stretching into central and west Republic of Congo, the Bateke Plateau supports an extensive savanna ecosystem, populated by the Teke-Alima people. The traditional, clan-based, hunting management system here was supplanted by the 1960s by more individualistic, firearms and wire snare-based hunting, due to the new systems entailed in colonial and postcolonial governments and new technologies (Walters 2015; Walters et al. 2015), but prior to that, fire was used as a directional hunting tool, and areas were kept "fallow" (i.e., unhunted) for a year before using fire to drive wildlife into waiting hunters (Walters 2010; Gowlett 2016).

Protected Areas in Central Africa 1885–1960

Hunting Reserves, Wildlife Reserves and National Parks

Figure 1 shows a map of all the protected areas across the Congo Basin and gives their year of creation.

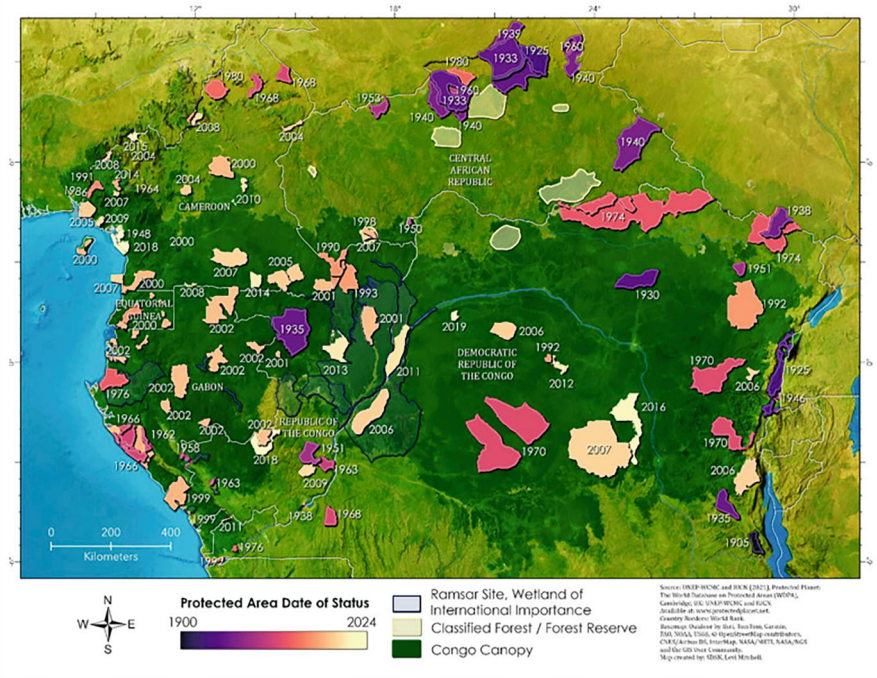

Fig. 1 Protected areas across the Congo Basin and their years of creation

Africa's first national park, Albert National Park (now Virunga National Park) was created in 1925 by the King of Belgium, with support of a small number of internationally well-connected naturalists, diplomats and royals. In many respects, it was no different to the royal hunting domains in Europe. The park was decreed with no consultation of the local people, who were excluded from it by force, while royals and their friends essentially owned the land and could hunt big game such as buffaloes, elephants, hippopotamuses and lions (Hubert 1947, 1948; Inogwabini 2014). This resulted in local communities rejecting the presence of the park (Van Den Dries 1939; Van Schuylenbergh 2009).

Further protected areas were created in the 1930s, 1940s and 1950s across the Congo Basin, both in DRC under the Belgium colonial authorities and by the French across French Equatorial Africa. Here the majority of protected areas were hunting reserves, reserved for sport hunting by paying expatriate guests. Odzala and Lopé National Parks, created in the modern Republics of Congo and Gabon in 1935 and 1946 respectively, are partial exceptions to this rule.

Lopé was created on the initiative of the Governor of Gabon at the time, M. Roland Pré, who on 31 Octobre 1946 wrote to the Governor General of French Equatorial Africa that: "I attach great importance to protect the most beautiful natural sites in the territory from any threats." He went on to say that the reasons for creating Lopé were to: (1) preserve the natural beauty of the landscape, with its mosaic of forest and savanna in the north, the virgin forests in the south, the rapids and small islands of the Ogooué and the du Chaillu mountains; (2) to protect its important populations of large mammals; (3) to preserve a historic site for posterity; and (4) to limit the increase in forest exploitation, which even then was seen as a threat to the regions ecosystems. Lopé was gazetted in three blocks, with a hunting reserve in the north (la réserve de chasse de la Lopé-Okanda), a national park in the center (le Parc national de l'Okanda) and a totally protected reserve in the south (la réserve intégrale de l'Ofoué), covering about 5000 km^2 in all.

Pré's letter is insightful. As early as 1946, the post war boom in forestry and oil palm cultivation were seen as threats to the natural treasures of Central Africa. Indeed, over the previous three to four centuries, the European, American and Brazilian (Portuguese) traders who had exchanged ivory, ebony, palm oil, pepper and red wood (*Pterocarpus soyauxii*) with coastal tribes, as well as their sinister trade in human slaves, had had a huge impact on the peoples and wildlife of extensive areas, penetrating hundreds of kilometers into the interior. The guns, tractors, lorries and bulldozers that arrived postwar were set to magnify this impact and extend it into the heart of the continent (Hymas 2016). However, Lopé was inhabited by nine lineages of Bantu Okandé and Babongo Pygmy peoples, with traditional beliefs and value systems for managing natural resources. They were forcibly relocated to the Ogooué and Offoué rivers that marked the northern and eastern boundaries of the Lope protected area and became "strangers," forbidden from practicing their traditional activities in their ancestral lands (Angoué 2013).

Lopé and Virunga are not unique examples. Over 20 protected areas, of all categories, were created without the local communities' consent during this period (Fig. 1). Their management was more enforcement-oriented than inclusive of

stakeholders (e.g., Mkumbukwa 2008; Prendergast and Adams 2003; Brockington 2002). When Europeans arrived in the Congo Basin, with their colonial policies of conservation through the creation of national parks and hunting reserves, local cultures already had traditional sacred and protected areas, resulting in a conflict of interest between tradition and imposed legal systems (Roe 2008). The colonial conservation laws reinforced the power of violence reserved exclusively for the State and over-ruled the legitimate rules of conservation practiced by ordinary citizens. The act of sending people who have traditional conservation laws to prison based on conservation laws adopted by the State, is seen as a terrible injustice by people who have always lived by principles of mutual respect and dependence with an environment that they are an active part of (Inogwabini 2014; Ndemezogo 2014).

This was compounded by the fact that in many protected areas access was prohibited for local populations, while European hunters were allowed to hunt for trophies and entertainment (Adams and McShane 1996; Neumann 1998, 2004). Many of today's protected areas have their origins in the colonial-era desire for exotic African game hunting. Even though these events occurred over seventy-five years ago, they continue to impact the relationship between protected areas and traditional peoples across the basin. In recent times, Virunga, Lopé and Odzala National Parks have all been subject to multiple recriminations from communities that feel excluded (Hecketsweiler et al. 1991; Angoué 2013; Vikanza 2018).

Protected Areas of the Congo Basin in the Period of 1960–1990

Most of the Congo basin countries gained independence in 1960, with Equatorial Guinea following in 1968 and Angola in 1975. Between 1960 and 1990, a number of national parks and hunting reserves were created, including Kahuzi-Biega, Maiko and Salonga, Africa's largest national park, which were all gazetted by President Mobuto Sese Seko in 1970 in DRC (then Zaire), and a series of hunting and wildlife reserves in Gabon, including the Presidential Hunting Reserve: Wonga Wongué, used exclusively by guests of the president.

In Democratic Republic of Congo, it is thought that President Mobutu's motivation was to demonstrate that he could do better than the former colonial power. According to Verschuren (2001), during a visit to the Albert National Park (now Virunga) with King Baudouin I and Queen Fabiola, President Mobutu was asked why his country was proud of its parks but had not created one since independence. His ego piqued by this question, he promised to do better not only than the former colonial power but also than other neighboring countries. This resulted in the creation of Salonga National Park, which was visited before it was gazetted in 1956 by King Leopold III (Schoonbroodt 1987; Verschuren 2001) and which had long been discussed. Mobutu announced during the Virunga visit that he would establish 12–15% of the national territory as protected areas (Verschuren 2004), an engagement he confirmed at the 1992 Rio de Janeiro Earth Summit.

Some have suggested that Giscard d'Estaing may also have played a role in the creation of some of the protected areas in Democratic Republic of Congo, given his

passion for sport hunting. While he probably did play a role in the creation of the Wonga Wongué Presidential Reserve, where he traveled to hunt on a number of occasions as President Omar Bongo's guest, Verschuren (2001) shows that the decisions to increase the number of protected areas in DRC were made before Giscard visited in 1975. However, French sport hunters, such as Henri Guizard, Claude Pradel and Maurice Patry, played a part in convincing the Gabonese Government to create sport hunting reserves, where they could entertain their clients. These later all became wildlife reserves when President Omar Bongo banned sport hunting in the 1980s, although exclusive hunts continued in Wonga Wongué for official guests of the President. The early autocratic heads of state were behaving no differently to the colonial administrations they had replaced, with which they generally maintained close relations.

Protected Areas of Central Africa in the Period Between 1990 and 2025

The writings of early explorers described wildlife as dangerous and aggressive. Du Chaillu's "savage gorillas" and "aggressive forest elephants" were widely popularized by sport hunters. For them, as Malbrant and Maclatchy (1949) stated, the wildlife of the Congo Basin remained a mystery. When George Schaller published "The Mountain Gorilla: Ecology and Behaviour" in 1963, it was the first serious study of the ecology of one of the Congo Basin's spectacular mammals, albeit in the montane forests on the eastern edge of the basin (Schaller 1963). Schaller refuted the myth that gorillas are savage, aggressive creatures, showing that the males only attack to defend their group (explaining the behavior of the silverbacks when du Chaillu was shooting their families). Schaller's work inspired a generation of developed nation biologists to travel to the forests of Central Africa and study the wildlife.

When in 1984, Caroline Tutin and Michel Fernandez published their national survey of apes in the forests of Gabon, estimating populations of 35,000 gorillas and 64,000 chimpanzees at a time when scientists thought there were no more than 5000 of each species in Africa (Tutin and Fernandez 1984), it opened the eyes of the conservation world to the importance of the region's forests and the biodiversity they contained. Tutin and Fernandez's use of line transects to estimate ape numbers inspired Richard Barnes to use the same methodology to estimate that Gabon had a population of about 60,000 forest elephants (Barnes et al. 1995), confirming that there were vibrant wildlife populations hidden in the forest. Other biologist pioneers included Jacques Verschuren, who pushed for the creation of protected areas in Democratic Republic of Congo between the 1970s and the 1980s, and Adrien Deschryver who instigated the creation of Kahuzi-Biega National Park focusing on the conservation of Grauer's gorillas. In 1983, Kes Hillman-Smith conducted an aerial survey of elephants and rhinoceros in the Garamba National Park, leading to a long-term ecological project to protected the park. Steve Gartlan began working on primates in Cameroon, Mike Fay and Stephen Blake worked on gorillas and

elephants in CAR and the Republic of Congo, Juichi Yamagiwa worked in gorillas in DRC, and Lee White and Andrea Turkalo started working on forest elephants in Gabon and CAR.

These scientists were funded by international conservation organizations, such as the Wildlife Conservation Society (before 1993 this was the New York Zoological Society) and the World Wildlife Fund (now known as the World Wide Fund for Nature), who began to create national research and conservation programs across the Congo Basin from the late 1980s onward, gradually increasing their influence in the run up to, and following, the Rio Earth Summit in 1992. In that same year, the EU launched its ECOFAC program (Forest Ecosystems of Central Africa, EU 1992), working in a demonstration site in each Central African country (Sao Tomé, Equatorial Guinea, Gabon, Cameroon, CAR, Republic of Congo and the Democratic Republic of Congo). This program and its sister program, APFT (Future of the Peoples of the Tropical Rain Forests) had a major influence on protected areas and their management across the Congo Basin. ECOFAC operated over 6 phases from 1992 to 2022, an unprecedented long-term donor commitment to conservation and protected areas.

As the 1992 Rio Earth Summit approached, in 1990, with support from the GEF and UNDP, Equatorial Guinea announced the creation of Monte Alen National Park, Dzanga-Sangha was created in CAR, with Nouabalé-Ndoki in Republic of Congo following in 1993, along with the enlargement of Odzala-Kokoua, first created in 1935 and the creation of Conkouati-Douli National Park, which included a marine section. Similarly, in 1991, with support from the Nigeria Conservation Foundation (NCF) and WWF, Nigeria created the Cross River National Park, covering almost 4000 km^2 of intact forests. The creation of Nouabalé-Ndoki National Park was particularly influential, led by Mike Fay of the Wildlife Conservation Society and actively supported by USAID and by influential members of the US Congress, who had visited as part of a congressional delegation led by David Barron, a Washington DC lobbyist. Nouabalé-Ndoki was designed to protect an unpopulated area of northern Congo, on the border with CAR and Cameroun, using a concept of a well-managed national park extending its influence to promote sustainable management and sound environmental stewardship out into the surrounding landscape, working closely with local communities and forestry concessions following an "enlightened self-interest" approach by the local community. The approach saw a strong partnership develop between conservationists and foresters in the CIB concessions (Clark & Poulsen, 2012) as well as the creation of the Lac Télé Community Reserve in 2001, covering 4390 km^2, which in 2010 became part of an enormous trans-national community area: Lac Tele is now a RAMSAR site, surrounded by another RAMSAR site (Grand Affluents in Congo: 59,080 km^2) and contiguous with yet another (the Ngiri-Tumba-Maindombe Ramsar site: 65,696 km^2) in neighboring DRC.

Then, in the run up to the World Summit on Sustainable Development (WSSD) in Johannesburg in 2002, the Rio plus 10 Earth Summit, President Omar Bongo announced the creation of a network of 13 national parks covering 11% of Gabon, implementing recommendations from a national protected areas survey, led by Emile

Mamfoumbi at the Gabonese Wildlife Department, Lee White from WCS and André Kamden-Toham from WWF. As President Obiang of Equatorial Guinea had in 2000, Omar Bongo, inspired by Mike Fay's "megatransect" walk from northern Congo to the beaches of Gabon, and the magnificent photographs of the natural wonders it passed through taken by National Geographic's Nick Nichols, transformed the conservation landscape in Gabon, creating an optimized network of national parks and cancelling almost two million hectares of forestry concessions (White 2007). At the time, most of Gabon's protected areas were under active forestry exploitation, so the decision was of particular importance, creating a balance between exploitation and preservation, in line with the commitment President Bongo had made a decade earlier in Rio, where he had lamented that "all too often in Africa, we have chosen to develop at no matter what the cost." The announcement was based on a national evaluation of plant and animal biodiversity in coastal marine, freshwater and terrestrial ecosystems, densities of timber species, mineral and oil reserves, tourism potential and human population distribution and their use of natural resources.

Even though mapping and consultation of rural communities' land use was a key feature of the protected areas evaluation, in 2002 the concept of "full prior informed consent" was not fully mature. It is true that when some of the early national parks were created, either in the colonial era, or during the rule of strong, autocratic leaders who characterized the first three decades or so after independence, there were human rights abuses when people were displaced from protected areas by force. However, 1990 had seen a weakening of the power of heads of state as countries in the region passed from one-party to multiparty systems, where people were demanding democracy and greater participation in the political decision-making process, as well as greater equity in the redistribution of wealth (Boulaga 2009). In this new context, it would not have been feasible to relocate people by force, even had there been a will to do so.

Gabon's legal framework does not allow displacement of people from protected areas. Given the low human population density in rural Gabon, it was possible to create a three-million-hectare network of 13 national parks with less than an estimated 300 people resident within them. Those people continue to reside peacefully in their villages within demarcated community exploitation zones that are provided for in Gabon's national parks law, which completed the process of park creation in 2007 (Curran et al. 2009).

Omar Bongo's announcement in Johannesburg of the creation of 13 national parks was the catalyst for the launch of the Congo Basin Forest Partnership (CBFP), a concept written by Mike Fay and David Barron and adopted by Colin Powell, the US Secretary of State, who travelled to Gabon from the Johannesburg meeting to congratulate the president (Quammen 2003). Powell had actively encouraged Omar Bongo to create the parks, through his Assistant Secretary of State for Africa, Walter Kansteiner, and it is probable that part of his motivation was geopolitical, favoring an American conservation rather than a French forestry and hunting world view. It resulted in the US government significantly increasing its funding for conservation in Central Africa, following the Nouabalé-Ndoki model.

After the rush of park creation in the 1990s and 2000s, the rate reduced, and few new terrestrial parks were created. Notable exceptions are Ntokou-Pikounda in the

Republic of Congo, that had been shown by Mike Fay's "megatransect" walk to have exceptional gorilla numbers and was created in 2012; Ogooué-Leketi National Park, also in Republic of Congo, and the Lomami National Park in DRC, created in 2016 after the discovery of a new primate species. Otherwise, the tendency has been to create protected areas with more flexible law enforcement rules, mostly IUCN Category VI reserves. These include Itombwe (2006), Tumba-Lediima (2006) and Ngiri Triangle (2011), based on an international agreement which relies on countries adopting national management guidelines. However, in 2014, President Ali Bongo Ondimba of Gabon announced a plan to create a network of marine protected areas, to compliment the terrestrial protected areas and tasked Gabon's National Parks Agency with the coordination of the initiative. The network was formally created in 2017, with 9 marine parks in Gabon's territorial waters and 11 aquatic protected areas in its EEZ, covering 53,000 km^2, 26% of Gabon's marine ecosystems, following a full consultative process with local communities. A list of all protected areas is provided in Doumenge et al. (2021) and is also available from the IUCN World Conservation Monitoring Centre (WCMC).

Ramsar, Man and Biosphere and World Heritage Sites

Gabon classified Wonga-Wongué, Petit Loango and Setté Cama as Ramsar sites in 1986. Democratic Republic of Congo then classified Virunga National Park and Mangroves National Park in 1996, and Republic of Congo classified Lac Tele-Likouala-aux-Herbes in 1998. Besides these six sites, every other Ramsar site in the Congo Basin was classified after 2000. In total, there are presently 38 Ramsar sites across the Congo Basin. These wetlands of international conservation importance include 14 Ramsar sites covering 138,139 km^2 in the Republic of Congo, nine covering 35,466 km^2 in Gabon, six in Cameroun, four in Democratic Republic of Congo and three in both Central African Republic and Equatorial Guinea (see the table in annex 2). In Congo, Gabon and Democratic Republic of Congo, some national protected areas are also RAMSAR sites. These include the Conkouati-Douli National Park and the Lac Tele/Likouala-aux-Herbes Reserve in Congo, Loango, Akanda, Birougou, Loango and Pongara National Parks and Wonga Wongué Reserve in Gabon, and Virunga and Mangroves National Parks in DRC, and several others, so for these sites it is clear what the national laws are regarding any activities permitted inside them. However, Gabon's other Ramsar sites do not fully correspond to national protected areas and two, including the Lower Ogooué, Gabon's largest protected area, has no national protected status at all.

To qualify as UNESCO World Heritage Sites, sites need first to have national protection and a management plan, so do not suffer from the confusion that may occur for RAMSAR sites. Currently there are 10 World Heritage Sites in the Congo Basin. These are Garamba (added in 1980), Kahuzi-Biega (1980), Virunga (1979) and Salonga (1984) National Parks and the Okapi Wildlife Reserve (1986) in DRC; Lopé-Okanda Ecosystem and Relict Cultural Landscape (2007), a mixed natural and cultural site including Lopé National Park and nine Historic Cultural Sites, and the

Ivindo National Park in Gabon (2021); the Odzala-Kokoua Forest Massif in Republic of Congo (2023); Dja Faunal Reserve in Cameroon (1987); and the Sangha Trinational (2012), including three National Parks, Nouabalé-Ndoki National Park in Republic of Congo, Lobeké National Park in Cameroon and the Dzanga-Ndoki National Park in Central African Republic. Of these, Garamba, Kahuzi-Biega, Virunga and Salonga National Parks, and the Okapi Wildlife Reserve, all in DRC, are listed as "Sites in Danger."

Apart from the UNESCO World Heritage Sites, UNESCO's Man and Biosphere (MAB) program, established in 1971, has also played a key role in identifying sites and implementing projects where both local sustainable development and biodiversity conservation are followed as objectives. Democratic Republic of Congo was the first in the Congo Basin to place some of its sites under the MAB framework: both Luki Reserve (created in 1937) and Yangambi Reserve (created in 1939) were aligned under the UNESCO MAB Program in 1977. The same year, Central African Republic placed Basse-Lobaye under the UNESCO MAB umbrella, subsequently adding Bamingui-Bangoran in 1979. In Cameroon, the Waza National Park was admitted into the program in 1979 and the country subsequently added four other sites: Bénoué (1981), Dja (1981), Doumba-Rey (2022) and Korup (2023). In Gabon, the Natural Integral Reserve of Ipassa-Makokou (150-km^2) was admitted to the status of UNESCO MAB Reserve in 1983, but subsequent to its integration into Ivindo National Park, it was degazetted by UNESCO.

Extractive Reserves

In 1992, the Democratic Republic of Congo established the Mangrove National Park and the Okapi Faunal Reserve. Both were created with the intent to leave the people who resided within their boundaries to continue with their traditional activities. Assigning these protected areas to IUCN Category VI was a means to reassure human rights organizations, who had argued that there was a risk of making people landless and depriving them of their livelihoods through the creation of protected areas. Since then, all new protected areas created in Democratic Republic of Congo include measures to allow local communities access and/or use of certain areas and/or resources, subject to certain conditions. Some of the older protected areas have also been re-assessed and access conditions discussed and agreed upon between local communities and management authorities. As noted above, Gabon took a similar approach when creating its national parks in 2007, although they remain in IUCN Category II.

If we accept the principle of permitting some use of natural resources (other than tourism) in protected areas, it is interesting to consider whether or not sustainable forestry concessions in the Congo Basin could be considered to be protected areas (Hutton & Leader-Williams 2003). The system of National Forests in the United States consists of government-owned lands that are set aside to protect forests and watersheds, provide habitat for wildlife, recreation and sustainable resource extraction, including timber, grazing and mining. They are considered to be IUCN

Category VI protected areas. However, they were closed to logging and road building in 2001 and now are about to be re-opened to logging again in 2025.

The forestry concessions that cover large parts of the Congo Basin are government lands that are destined to remain as forests and which are formally defined in law, managed under legally binding concession agreements and management plans, which protect forests and wildlife, preserve ecosystem services and provide a sustainable harvest of timber. They also generally include the delimitation of both conservation, watershed protection and community areas. Were these permanent forests to be assigned IUCN Category VI status in Gabon, for example, the terrestrial protected area network would be approximately 20 million hectares, 75% of the land surface area, far in excess of the Convention on Biological Diversity's 30% target. Bayol et al. (2021) estimate that across the Congo Basin protected areas cover 274,558 km^2 (13.9%) while forestry concessions cover 537,379 km^2 (27%), making a total of 40.9% of the Congo Basin forests managed in protected areas and sustainable timber production. They also mention the creation in Democratic Republic of Congo of millions of hectares of "conservation concessions," but were unable to verify this information. Democratic Republic of Congo remains the country with the largest forest area neither in protected areas nor logging concessions, with 893,955 km^2 unallocated, representing 45.2% of the entire Congo Basin Region.

In the Amazon, 22% of lands have been designated as Indigenous Territories and these, along with Community-based Conservation Areas, national parks and nature reserves, account for approximately 62.4% of all land (Nobre et al. 2021). The distinction between indigenous and nonindigenous that is applied in South America is not appropriate in the Congo Basin, although some organizations and even nations (e.g., Republic of Congo, Democratic Republic of Congo), assign "indigenous" status to the Aka, Bagyeli, Bakola, Bakoya, Baka, Babenjelle, Babi, Bacwa, Babongo, Batwa and Mbuti peoples, living in the rainforest regions of Cameroon, Central African Republic, Democratic Republic of Congo, Gabon, Equatorial Guinea and the Republic of Congo. In Democratic Republic of Congo, the Baka, Batwa and Mbuti peoples are officially designated as the "the Indigenous Pygmy People."

However, the presence of Bantu tribes in the forests of the Congo Basin goes back over 2500 to 5000 years (e.g., De Saulieu et al. 2021), and the Indigenous Pygmy People and the Bantu have developed close associations that make the creation of "Indigenous Territories" extremely problematic in the Congo Basin, given how different the context is from that in the Amazon. Community Forests delimited around villages are becoming more widespread in both Cameroon and Gabon, but in this case they are not currently considered to be protected areas, although again IUCN Category VI would likely apply.

Threats and Critics

In his book "Invention of Green Colonialism," Blanc (2020) argues that protected areas are nothing more than an extension of colonialism and that rural Africans have paid and continue to pay a heavy price for their creation. However, many of the parks

on the modern map were created following commitments made by enlightened leaders of independent Congo Basin nations at the earth Summit in 1992 and the World Sustainable Development Summit in 2002. All of the Congo Basin countries were represented in the Convention on Biological Diversity COP15 negotiations in Montreal in 2022, which agreed for the need to protect 30% of the Earth's ecosystems—its natural life support mechanism—by 2030. Indeed, Gabon and Republic of Congo were members of the High Ambition Coalition that played a key role in the adoption of the agreement. That decision was informed by science and was adopted by consensus by all nations. The devil is in the details of how protected area creation and management are undertaken.

Professional management of parks is essential and there is a need for military to support protected areas authorities in the most extreme examples (White 2014). Unfortunately, protected areas often become a sanctuary for criminal and terrorist groups in areas of weak governance, generally resulting in severe impacts. If the region's protected area network is to continue to protect biodiversity and contribute to the sustainable development, there is a need for sustainable financing to support national authorities and their partners to manage them effectively.

Across the Congo Basin, finance for protected area management is a permanent issue as is the lack of capacity of protected area managers to fulfill their task. Protected area management authorities, be they government administrators or para-statal agencies, have struggled for allocation of adequate budgets in national finance laws and while donor money has helped, it is nowhere near the levels needed and is rarely allocated to governments. Because of transparency issues, donor money tends to be instead granted to international NGOs active in the region, with the exception of Gabon—the nation that scores lowest (i.e., most transparent) in terms of its transparency index among the Central African countries.

In recent years, the lack of resources has seen central management of protected areas in several Congo Basin countries replaced by a public-private management model (Hatchwell 2014; Baghai et al. 2021). In the Democratic Republic of Congo, the public-private park management model was first implemented in Garamba and Virunga National Parks. The success of the model in these two parks encouraged Congolese Institute for the Conservation of Nature (ICCN) to contract similar agreements for other protected areas, including Salonga, Kundelungu, Kahuzi-Biega and Lomami-Lualaba National Parks and the Okapi Faunal Reserve, while Bombo-Lumene and Mangroves were under PPP management until very recently. Discussions are on-going for Maiko National Park and the Mangai Hunting Reserve. Other protected areas under PPP management in the Congo Basin include Chinko and Dzanga Sangha (Central African Republic) and Nouabale-Ndoki, Odzala-Koukoua, and Conkouati-Douli National Parks (Republic of Congo) (Brugière 2020; Baghai et al. 2021).

External threats posed by illegal hunting and extraction of natural resources (e.g., timber and minerals) are common issues in many countries (Abernethy et al. 2016). For example, Maisels et al. (2013) documented a 62% fall in forest elephant numbers across Central Africa between 2002 and 2011, and a subsequent study indicated a decline of over 90% of all forest elephants (96% of which are in Central Africa: Maisels et al. 2025 in press) between 1981 and 2015 (Edwards et al. 2024).

Strindberg et al. (2018) similarly showed that gorilla populations in western Equatorial Africa (i.e., Cameroon, Gabon, Equatorial Guinea and Congo) declined by 2.7% annually between 2002 and 2013 and that, worryingly, over 80% of both the gorillas and chimpanzees across this enormous area (almost 700,000 km^2) were *outside* protected areas, showing that management of both protected areas and other forests for wildlife is essential for great ape survival in the long term.

The issue of emerging diseases is also a potentially severe threat (Abernethy et al. 2016). Walsh et al. (2003) documented a 56% decline in the population size of western lowland gorillas in Gabon over a period of 20 years, mostly due to a series of outbreaks of the deadly hemorrhagic fever Ebola. Almost all the gorillas and most of the chimpanzees died during this epidemic in Minkebe, Gabon's largest national park, which had previously had high numbers (Huijbregts et al. 2003). It is thought that the likelihood of similar epidemics or pandemics such as the recent spread of COVID19 are likely to become more frequent because of climate change, forestry and hunting for wild meat (Abernethy et al. 2016).

Human-induced climate change represents an existential threat to the Congo Basin Forests. As temperature increases and rainfall patterns are disrupted, heat stress and droughts will become more frequent and severe. The forests in the southern Amazon are already in regression (Hubau et al. 2020; Sullivan et al. 2020). Bush et al. (2020) documented a long-term collapse in fruit availability linked to climate change that threatens Central African forest fauna—their work showed a decline in elephant body condition, but this may also be occurring across the entire frugivore community in the forested tropics. Bush et al.'s work is an early indication that climate change is starting to impact the forests of the Congo Basin. To date we have not yet witnessed the large-scale fires that have occurred in the Amazon and Southeast Asian forests in the Congo Basin, but Oslisly et al. (2013) documented evidence of large-scale fires in the region about 2000 years ago, during a warm, dry climatic period, so we should not simply assume this will not be an issue in the future.

Looking to the Future

The adoption of the 30:30 agenda at COP15 of the Convention on Biological Diversity, whereby all nations committed to the principal of protecting 30% of the planet by 2030, was a landmark decision that has potential to both increase the coverage and the funding for protected areas in the future. The Congo Basin countries all actively supported this target and are relatively well advanced in the 30:30 process (Doumenge et al. 2021), with Republic of Congo (52%) and Sao Tomé and Principé (40%) already well beyond the 30% target when national and international protected areas are combined and Gabon, Equatorial Guinea and CAR at or above 25%. If sustainably managed logging and hunting concessions are included in the calculation, Cameroon, Congo, Gabon and CAR all have well beyond 50% of their forest lands under some form of formal protection. Gabon further developed the concept into 30:30:30, through a commitment to protect 30% of its land, freshwater and ocean ecosystems by 2030. This shows that the Central

African nations today remain committed to maintaining and expanding protected areas as part of their sustainable development strategies.

While some of the protected areas under management by NGO partners such as African Parks Network are well funded, this is not the case for most parks managed by national institutions. However, a number of sustainable finance initiatives show promise to begin to resolve the financing deficit. The Sangha Tri-National Trust Fund (FTNS) was established in 2007 as a UK-based nonprofit and today manages an investment capital of about €66.5 million, disbursing €1.8 million annually to support operational costs of Lobéké in Cameroon, Dzanga-Ndoki in CAR and Nouabalé-Ndoki in Congo. In 2008, the Virunga Alliance, a public-private partnership between the Congolese Institute for Nature Conservation (ICCN) and the Virunga Foundation, launched efforts to promote socio-economic activities to support the Virunga National Park. In 2015, the Matebe hydroelectric plant with a capacity of 13.6 MW was inaugurated, with revenues reinvested into conservation efforts in the park. Similarly, Gabon created its Fonds de Préservation de la Biodiversité au Gabon Inc. in 2023 in collaboration with TNC and Enduring Earth as part of a Project Finance for Permanence (PFP) initiative. A $500 million debt restructuring operation via a Blue Bond was signed in August 2023 and will generate $163 million in new funding for Ocean conservation, while also creating the financial architecture to attract additional funding for Gabon's protected areas network.

Following the adoption of the REDD+ process at the 2009 UNFCCC Climate COP and its integration as Article 5 of the Paris agreement in 2015, there was great optimism that this would lead to sustainable financing for forest and protected areas preservation in the region (Eba'a Atyi et al. 2022). Unfortunately, to date Gabon is the only country in the region to register REDD+ results on the UNFCCC Lima Hub, with 187 million tons of reduced emissions validated in 2022, but to date only 3.4 million tons have been rewarded with results-based payments, through a bilateral agreement signed in 2019 between Gabon and Norway, for up to $150 million. The first payment of just over $17 million was made in 2021 and is contributing to national parks management, although it covers less than 20% of annual costs. In 2023, African Parks and the Landbanking Group introduced an innovative biodiversity financing mechanism known as Verifiable Nature Units (VNUs) with the objective of valuing and monetizing conservation outcomes across diverse African ecosystems. This scheme has been successfully piloted in Malawi in the Majete Wildlife Reserve and has potential to be rolled out in other countries.

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Ecosystem Functions and Services in the Congo Basin

20

Salvius Amuri Bakari, Valentin Chribagula Bashige, Cedrick Shakalenga Mutombo, and John Byanga Kahumba

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Abstract

The Congo Basin, the second-largest tropical forest in the world, is vital to global ecological balance. This chapter explores its ecosystem functions and services, highlighting the immensity of its contribution through: (*i*) global climate regulation services by storing large amounts of carbon from plants. The region also plays a significant role in regulating water cycles; (*ii*) provisioning services by supplying numerous direct resources: wood, nontimber forest products and food for the region's populations; (*iii*) supporting services, including soil formation, pollination and nutrient cycling, which are fundamental to other services and are maintained due to the exceptional biodiversity of the Congo Basin, which is the driving force behind them; (*iv*) cultural services for humanity in general, based on the immense spiritual, recreational and aesthetic value of the region's rich

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biodiversity, which offers opportunities for tourism and scientific research. However, the Congo Basin faces enormous challenges related to human activities and economic pressures, which threaten its ability to provide vital services. Analysis of available data highlights the inadequacy and sometimes total absence of scientific data that could guide local and regional policies on sustainable development in the Congo Basin. Urgent and substantial investment in research is essential for the optimal use of the region's natural resources.

Keywords

Sustainable development · Congo Basin · Ecosystem services · African tropical forests · Climate change

Introduction

Ecological function refers to the natural processes, products or services that living and nonliving environments provide or perform within or between species, ecosystems and landscapes, including hydrological functions and biological, physical, chemical and socio-economic interactions. These interactions between biological and physical elements and processes enable ecosystems to be maintained and function. In addition, the functions of ecosystems and their contributions to the functioning of our society and our general well-being are known as ecosystem services (Garland et al. 2021). These are the free services Mother Nature provides mankind, enabling us to live and function as a society. Knowledge and understanding of ecosystem services allow us to look at nature differently because we understand that human existence depends on a certain quality of the environment (Geneletti et al. 2020).

In the following paragraphs, we will focus on the Congo Basin's ecological functions and the ecosystem services it provides to people in the region and around the world.

The Congo Basin in question is one of the largest and most important river basins in the world, second only to the Amazon, covering an area of around 3.7 million km^2 and spanning six countries: Cameroon, Gabon, Equatorial Guinea, the Central African Republic (CAR), the Republic of Congo and the Democratic Republic of Congo (DR Congo) (Jiang et al. 2023). The climate in this part of Africa is tropical, hot and humid, with variable rainfall depending on the region, favoring the growth of the tropical dance forest characteristic of the Congo Basin.

The Congo Basin is home to the world's second-largest rainforest, commonly referred to as the "lungs of Africa" because it is the world's largest carbon sink, absorbing more carbon than the Amazon. Thus, the Congo Basin rainforest plays a major role in global climate regulation.

The Congo Basin region is also home to many species, some of which, such as mountain gorillas, bonobos and forest elephants, are threatened with extinction. The area has a wealthy biodiversity, including many endemic species. Although various

trends in the estimated populations of fauna and flora colonize the region, it is estimated that there are around 1000 plant species in the Congo Basin, 30% of which are endemic. The area is also home to over 400 species of mammal, 1000 species of bird and 700 species of fish (Beekmann et al. 2024).

The Congo Basin region is also a densely populated human habitat, with an overall population for the six countries estimated at around 155 million, according to the World Population Review. This population is made up of a large number of distinct ethnic groups that are in constant interaction with each other, depending on their socio-cultural and economic interconnections, with some ethnic groups spread across several countries at the same time (Boyette et al. 2022).

The Congo Basin's population is growing rapidly and is expected to double by 2050. This rapid population growth poses numerous challenges regarding sustainable development and natural resource management. This context requires that the current state of scientific knowledge on ecosystem functions and services in the Congo Basin be brought within the reach of stakeholders, primarily political decision-makers, to develop better natural resource management models for the well-being of present and future generations.

Currently, Knowledge on Key Ecosystem Functions and Services in the Congo Basin

Due to its large tropical forest, the Congo Basin is vital in maintaining the world's ecological balance. This African region provides cardinal ecological functions and essential ecosystem services, including regulating the climate, maintaining or regulating the water cycle, maintaining or protecting biodiversity, regulating the soil and providing subsistence services.

Climate Regulation

One of the primary functions performed by the tropical forests of the Congo Basin is carbon absorption. Scientific estimates put tropical forests' average annual carbon absorption at around 1.5 billion tons of carbon dioxide (CO_2). This represents 4% of global fossil fuel emissions. The peat swamp forest of the Congo Basin, meanwhile, stores approximately 29 billion tons of carbon, equivalent to around 3 years' worth of greenhouse gas emissions on a global scale (Crezee et al. 2022). This absorption of large quantities of carbon dioxide by forests reduces the rate at which it accumulates in the atmosphere, thereby helping to slow climate change.

In addition to carbon sequestration, there is a phenomenon of evapotranspiration. In tropical forests, evapotranspiration is an essential source of moisture for regional and global climate cycles (Burnett et al. 2020). It helps to cool the ambient air. Through this process, vegetation can reduce the temperature of the surrounding air by 2–8 °C. Evapotranspiration allows water to return to the atmosphere, essential for precipitation. In tropical rainforests such as the Congo Basin, around 90% of atmospheric water vapor

comes from evapotranspiration. This mechanism influences rainfall and local temperatures. Because of the paucity of studies based on direct observations, the magnitude, seasonality and interannual variability of evapotranspiration in the Congo Basin remain poorly defined (Burnett et al. 2020). Therefore, studies are needed to gain an in-depth understanding of the phenomenon of evapotranspiration in the Congo Basins and its impact and influence on climate regulation.

The third phenomenon that helps to regulate the climate is atmospheric tropical convection, defined as the movement of tropical clouds and thunderstorms, often organized into clusters containing many individual cells. Organized convection significantly contributes to tropical precipitation and cloudiness, and as clouds become more clustered, they modify cloudiness and humidity in the surrounding environment on a large scale. Consequently, the behavior of tropical convection and its coupling with circulation is essential for understanding tropical and global climate and climate sensitivity (Carstens and Wing 2022, 2023). Indeed, convection is a vital process that helps redistribute energy from warmer to colder areas of the Earth, thereby facilitating temperature circulation and reducing abrupt temperature differences. The Congo Basin is one of the most active convection regions, crucial in regulating regional and global climate. Rainfall in this region is dominated by deep convection, particularly thunderstorms.

In addition to carbon sequestration, evapotranspiration and tropical convection, the Congo Basin forests provide essential ecological services such as maintaining biodiversity and regulating water cycles. The following paragraphs will develop these two points.

Regulating the Water Cycle

The water cycle, or hydrological cycle, refers to all transfers of liquid, solid or gaseous water between terrestrial water reservoirs. Water circulates on earth in different forms, passing from the sea to the atmosphere, from the atmosphere to the land and then from the land to the sea, following a cycle including evaporation, transpiration, condensation, precipitation, runoff, infiltration and underground circulation, which repeats itself indefinitely, keeping all aquatic environments (lakes, rivers, sea, groundwater…) interdependent within the same basin. The regulation of the water cycle in the Congo Basin is an important parameter, with a significant impact on rain-fed agriculture, the resources of the tropical forest environment and hydroelectric power, which form an important part of the economy and livelihoods in the Congo Basin.

It is organized around the Congo River, some 4700 km long with an average annual flow of 41,000 m^3/s, its tributaries, the main ones being the Ubangi (1060 km with a flow of 11,000 m^3/s at Bangui), the Sangha (790 km; 1714 m^3/s at Ouesso) and the Kasaï (2153 km; 9873 m^3/s), and Lake Tanganyika considered the second deepest and largest freshwater lake in the world. The Congo watershed covers the Republic of Congo, Cameroon, Central African Republic, Democratic Republic of Congo, Angola, Rwanda, Burundi, Tanzania and Zambia. Total freshwater storage in the Congo Basin is currently estimated at between 476 and 502 km^3, unevenly

distributed across the region, with 63% stored in the southern subbasins of Kasai (220–228 km^3) and Lualaba (109–169 km^3), while the northern subbasins contain only around 173 ± 8 km^3 (Tourian et al. 2023). Annual precipitation is around 1900 mm/year with an east-west trend across the basin, decreasing toward the north and south to around 1100 mm/year, with historical studies suggesting annual potential evapotranspiration varying between 1100 and 1200 mm/year across the basin (Alsdorf et al. 2016).

In fact, the different forms of water in the Congo Basin offset each other, demonstrating the significant impact of climate change, particularly on evaporation and recycling rates, as well as runoff. Analysis of the moisture responsible for precipitation shows that the Indian Ocean and evaporation from the Congo Basin (northern and southern regions) are the main sources, with the south-western Indian Ocean (30°S-10°S, 30°E-90°E) alone contributing around 21%. The Atlantic Ocean contributes most of the moisture between September and November, but its contribution is relatively small. The surrounding African land areas also contribute a considerable fraction (20.6% between March and May and 16.6% between September and November), given the surface area they cover. While the recycling rate (ratio of precipitation from evaporated moisture in the Congo Basin to total precipitation) is high in all seasons (>24% year-round), the periods from June to August and December to February see very different contributions of moisture from other source regions than the periods from March to May and September to November. The driest season, from June to August, benefits from significant contributions from the southern Indian Ocean and little from the northern Indian Ocean, while the December to February period benefits from significant contributions from the northern Indian Ocean, the Arabian Sea and the Horn of Africa (Dyer et al. 2017). Estimates of the percentage change in precipitation, potential evaporation and runoff due to climate change in the Congo Basin show an increase of around 10% for precipitation, 10–18% for evapotranspiration and 10–15% for runoff. However, these forecasts are based on a global response of large-scale hydrological processes given the difficulty of adequately monitoring river flows and therefore ignore the spatial variability of different subbasins with intrinsically different hydrological regimes (Tshimanga and Hughes 2012; Kechnit et al. 2024).

Factors such as climate change, progressive land use and land cover affect the atmospheric water balance, i.e., evapotranspiration subtracted from rainfall in the Congo Basin. These changes can have a direct impact on evapotranspiration and/or rainfall or affect river flow and terrestrial water. In the Congo Basin, it should be noted that mean evapotranspiration is the second highest moisture flux in relation to rainfall (the highest moisture flux), river flow and the convergence of moisture fluxes. This observation shows that a significant proportion of the moisture entering the Congo Basin is recycled (Sorí et al. 2022). Changes in evapotranspiration due to climate or human activity could therefore considerably alter the water balance in the Congo Basin (Worden et al. 2024).

Long-term trends in precipitation, drought and flooding, as well as future projections, have been studied in the Congo Basin. These studies have shown negative seasonal and annual trends in precipitation and drought, highlighting the increased

risk of drought in the Congo Basin. This decline in rainfall has affected not only surface and groundwater resources in the Congo Basin, but also the entire region, its water cycle and ecosystems, endangering the populations that depend on the services they provide. However, research in the Congo Basin has mainly focused on long-term fluctuations in surface and groundwater resources in response to climate fluctuations and ocean–atmosphere interactions (Lisika et al. 2024).

Maintaining Biodiversity

The Congo Basin is home to exceptional biodiversity, with many endemic plants, animals, insects and fungi species. Current knowledge indicates the existence of 10,000 species of tropical plants in the region. The region is also home to 1000 species of birds, 700 species of fish and more than 400 species of mammals (Harrison et al. 2016). As can be seen, estimates for other species, including snakes, insects, or fungi, still need to be increased, preventing us from presenting approximate figures. In addition, apart from a short list of species that have been sufficiently studied either because of their endemicity or because of the threat of extinction that weighs on them, the geographical distribution of species already identified in the Congo Basin is not sufficiently known (Melville and Gaugris 2019). This is mainly due to the unavailability of data in these areas due to a scarcity of in-depth inventory studies in these areas. It should be emphasized that, even for species for which population figures are given, inventories still need to be exhaustive and deserve to be updated by new data collections extended to all components of biodiversity (Van der Hoek et al. 2023). And yet, the size, density and demographic structure of a species' population must be considered to understand how it performs interactions and fulfills roles and functions in the ecosystems in which it is integrated (Akçakaya et al. 2020). This also shows that it is very possible to discover new species during in-depth discoveries. Furthermore, while species counting and inventory studies are still essential to carry out in the Congo Basin, studies aimed at understanding the determinants of the coexistence of species in complex and rich communities are just as necessary to understanding ecological connections and their influence on biodiversity (Van de Perre et al. 2020). Thus, the overall observation of knowledge of the biodiversity of the Congo Basin highlights an incomplete level of available information that deserves to be enriched to enable optimal management of this biodiversity. These in-depth inventory studies are even more urgent given the threat of significant erosion of biodiversity caused by deforestation, increased exploitation of natural resources and illegal trafficking of wild species.

Soil Regulation

Soil regulation is an essential aspect of environmental management, as soils perform several vital functions in ecosystems and human activities, including water filtration and purification, carbon storage, water cycle regulation, habitat for biodiversity and

erosion control. Soil regulates the natural cycle of water, air and organic and mineral substances. It filters and purifies water by acting as a natural filter, purifying water by eliminating pollutants and impurities before they reach the water table; stores and transforms substances, thus representing an essential link in the permanent flows of energy and materials of the Earth's ecosystem. Soil is the second largest carbon reservoir on the planet, after the oceans. They play a crucial role in regulating the climate by storing carbon and reducing greenhouse gas emissions (Lal et al. 2021).

The Congo Basin is a geologically diverse region. For example, the Ubangi Basin is characterized by iron-clad soils, while the Sangha Basin has sandy soils. Due to their nature, the soils of the Ubangi Basin amplify variations in precipitation, leading to significant drops in flow during drought (Mushi et al. 2019). However, the soils of the Kouyou Basin mitigate these effects through their water retention capacity. The geological characteristics of the Congo Basin soils make this region a unique space, with soils that significantly modulate climate impacts. These geological differences in soils strongly influence the effects of precipitation and drought.

Studies on the knowledge of soil characteristics in tropical rainforests suggest that geomorphological variability is a major parameter to account for differences in floristic richness, forest structure and carbon stocks as well as edaphic variations and that there is a close link between soil characteristics and reliefs (Hofhansl et al. 2020; Zhao et al. 2022). In the Congo Basin, there are sufficient data on studies focused on soil analysis or landscape and relief mapping. However, these data still need to be updated, cover only some of the region's surface and remain heterogeneous regarding their presentation. In addition, in geomorphology, most existing maps are old and generated by diverse methods, limiting their generalization and applicability across the region (Viennois et al. 2022). In this context, there is a need to update available data and produce new geomorphological data within the Congo Basin using approaches that allow the superposition of information and its generalization to inform policies on the optimal management of spaces and resources.

Monetary Valuation of Ecosystem Services and Biodiversity Conservation Efforts in the Congo Basin

Data on the monetary valuation of ecosystem services to reconcile them with biodiversity conservation efforts in the Congo Basin are available but insufficient to establish a correlation between the two and thus do not allow for good financial assessment of the natural capital of the Congo Basin. Indeed, some studies have attempted to assess the contribution of natural capital by considering key parameters; however, they are unable to provide a complete picture without the contribution of other important data (Ninan 2014; Bush et al. 2024). Other studies, such as that by Filewod et al. (2025), have been able to carry out a monetary assessment of natural capital, based in part on the mapping of customary land tenure systems using a cumulative cost method, linking value production and incentives associated with economic agents who manage forest natural capital, taking into account parameters such as artisanal and industrial timber exploitation, firewood, bush meat, tourism and

carbon sequestration. Based on this approach, this study estimated the total annual gross value of the Congo Basin's forests at US$7.8 billion in 2019, or 6.3% of regional gross domestic product. It is well known that studies on the monetary valuation of ecosystem services require the consideration of numerous independent parameters involving a variety of fields and actors. These parameters thus become obstacles to conducting reliable studies in this field (Ntirumenyerwa Mihigo and Cliquet 2020; Yan et al. 2023; Bush et al. 2024). The availability of partial resource inventory data within the Congo Basin and the lack of data in certain areas, such as understanding the determinants of species coexistence in complex and prosperous communities, as highlighted above. The poor accessibility of some regions of the Congo Basin may justify the existence of data on the monetary valuation of ecosystems, mainly in protected areas, offering the desired facilities for these kinds of studies. In addition, experts' differing perceptions of the value of economic valuation studies of ecosystem services give rise to reticence about the acceptability of specific studies, particularly concerning the relationship between economic valuation of ecosystem services and biodiversity conservation (Fanny et al. 2015). In this global context of insufficient data in the field of economic valuation of ecosystem services in the Congo Basin, as well as the difficulty of currently conducting reliable studies in this field due to their complexity, we have seen fit to present the resources and the ecosystem services they offer, with the hope that this should contribute in the future to the realization of more or less comprehensive studies.

Despite the difficulty of conducting monetary valuation studies of ecosystem services in the Congo Basin, significant efforts are being made to ensure biodiversity conservation in this region. Actions aimed at biodiversity conservation focus on: (i) reducing deforestation and environmental degradation (Reyniers 2021). The amount of the Congo Basin Forest disturbed by human activities has increased annually. The annual rate of net deforestation in the Congo Basin is estimated to 0.09% between 1990 and 2000, and of net degradation to 0.05%. Between 2000 and 2005, estimated annual net deforestation at 0.17% and yearly net degradation at 0.09%. Between 2010 and 2020, there was an overall increase in deforestation rates, even within some protected areas (Wade et al. 2020).

Contribution of the Congo Basin in Food and Medicinal Resources: Diversity, Challenges and Perspectives

The Congo Basin offers an impressive diversity of food resources, ranging from aquatic products to nontimber forest products.

Aquatic Products

The rivers and lakes of the Congo Basin, one of the largest river basins in the world, are home to a remarkable diversity of fish and other aquatic resources (Kassouri 2021). Fishing is a crucial activity for local populations, providing up to 50% of their dietary protein (Comptour et al. 2016; Ickowitz et al. 2024). The basin is home to about 1300 fish species, 70% endemic (Cormier-Salem et al. 2018). Among the most

caught fish species in the region are tilapia (*Tilapia* sp.), catfish: silure (*Ameiurus melas*), skipper (*Polydactylus quadrifilis*), Labeo (*Labeo cyclorhynchus*) and Mormyrus: *Mormyrus* sp. (Sonwa et al. 2022). However, the largest fish in the region, becoming increasingly rare, is the elephant fish: *Hydrocynus goliath* (Yang et al. 2023; Gonzaleze 2023). Some areas of the Congo Basin are rich in freshwater shrimp and mollusks, while others are home to crustaceans, algae and various aquatic plants (Ickowitz et al. 2024). Local communities also use aquatic resources to make handicrafts, such as nets, fishing arrows and other equipment.

Congo Basin's Wealth in Edible Agricultural and Veterinary Products

The Congo Basin is a veritable biodiversity sanctuary with many edible plant species. There are various fruits, such as safou, okra, plantains, yams and oil palm. Among the endemic wild fruits, we have the mongongo (*Schinziophyton rautanenii*), the njangsa (*Ricinodendron heudelotii*), the kola (*Cola acuminata*), the wild pawpaw (*Asimina triloba*), the wild banana (Musaceae), as well as the fruits of various palms, including those of the baobab (*Adansonia digitata* L) and some fruit vines (Kassouri 2021; Batumike et al. 2021). As for vegetables, the most mentioned include cassava (*Manihot esculenta* Crantz), fumbwa (*Gnetum africanum* Welw.) and moringa leaves (*Moringa oleifera* Lam) (Mondo 2024). The fauna also presents great game diversity, with species such as antelopes (Sitatunga and kob), monkeys, porcupines and various birds and poultry. The products gathered also include edible saps and resins, such as benzoin resin (*Terminalia bentzoe* (L.) L.f.), palm sap (*Elaeis guineensis* Jacq), Arabic gum (*Acacia* sp.), as well as resins and saps of rubber trees (*Ficus elastica* Roxb. ex Hornem). According to a recent report, 742 new species of animals and plants were discovered in the Congo Basin between 2013 and 2023, including 430 plants, 140 invertebrates, 96 fish, 42 reptiles, 22 amphibians, 10 mammals and 2 birds (Thompson 2024).

Traditional Agricultural Systems

Indigenous peoples of the Congo Basin have developed agricultural systems that reflect deep adaptation to local ecosystems. Agroforestry, which combines crops and trees, is crucial in maintaining soil fertility and conserving biodiversity (Fahad et al. 2022; Jose and Udawatta 2021; Kaur et al. 2023). This approach contributes to land regeneration and helps diversify income sources while reducing reliance on single crops. Slash-and-burn agriculture, although often criticized for its environmental impacts, is traditionally practiced by many communities. It clears land for new crops while temporarily enriching the soil with ash (Nair et al. 2021; Güldner et al. 2021). However, it is essential to manage this practice sustainably to avoid deforestation and soil erosion. Staple crops such as cassava, maize, rice, plantains and yams are pillars of food security in the region (Ndip et al. 2023; Seidensticker and Jungnickel 2023; Karume et al. 2022). These crops are adapted to the basin's diverse climatic and soil conditions. In addition to meeting the food needs of communities, they play an important economic role, mainly through sales in local and regional markets (Karume et al. 2022). Commercial coffee plantations (*Coffea* sp.), cocoa (*Theobroma cacao* L.) and palm oil also illustrate the evolution of agriculture in

this region (Kamath et al. 2024; Ngouhouo-Poufoun et al. 2024). Although these crops can offer interesting economic opportunities, they also pose environmental and social sustainability challenges. Competition for land and resources can lead to conflicts and affect traditional agricultural practices.

Nontimber Forest Products

The Congo Basin is a region rich in biodiversity that offers many nontimber forest products (NTFPs). These resources play a crucial role in the daily life of local communities, both in terms of food and economy. Among them are mushrooms, honey and nuts (Mondo et al. 2024; Amusa et al. 2024). The Congo Basin has nearly 300 species of edible mushrooms, of which species such as *Volvariella volvacea* (straw mushroom) and *Lentinula edodes* (shiitake) are not only sources of nutrients but also the most prized for their economic value. Mushrooms of the Boletaceae family and those of the Termitomyces and Pleurotus genera are often harvested in the forests and can be sold on local markets (Mjaika 2022; Sileshi et al. 2023). Honey production is another important activity. Wild honey, often harvested in the forests, is a nutritious food and a material used in traditional medicine for many indigenous ethnic groups (L'Roe et al. 2023). Nuts, such as those of Cola acuminata and *Elaeis guineensis* Jacq., are a source of fats, proteins and minerals. Local communities often consume them, which may also be commercialized or incorporated into sociocultural rituals (Kamga 2022; Essouman et al. 2021). These nontimber forest products contribute significantly to the informal economy, allowing families to generate additional income. Selling these products in local markets helps support livelihoods and improve the economic resilience of communities.

Medicinal Resources in the Congo Basin

Traditional Medicinal Knowledge of the Indigenous Peoples of the Congo Basin

The indigenous populations of the Congo Basin have a rich tradition of non-conventional medicine based on a deep knowledge of the local flora and its medicinal properties. This knowledge, often acquired through experience and observation, is not only essential for the treatment of common diseases but also plays a vital role in the prevention and maintenance of health (Kimpouni et al. 2024). Traditional medicine in this region uses a variety of plants through their various organs, such as roots, barks and leaves, to treat pathologies. It also draws on other natural resources such as animals, birds, insects and mineral products (Mushobekwa and Muhaya 2018; Matandirotya et al. 2022). The medicinal practices of the region are often integrated into cultural and spiritual rituals, reinforcing their importance within the communities. Traditional healers, often respected and well-known in their communities, are key figures in transmitting this knowledge (Adu-Gyamfi and Anderson 2019; James et al. 2018). In rural areas of the Congo Basin, where modern medical infrastructure can be inadequate, traditional medicine is often the first line of defense against disease. It offers accessible and often less expensive solutions for

populations who cannot always afford to turn to biomedicine (Muchemwa 2023). Moreover, the use of traditional medicine and biomedicine, as observed in this setting, enriches health care and benefits patients by offering them a variety of choices adapted to their cultural and economic needs (Sifuna 2022). However, it is essential to recognize and value these practices while ensuring they are respectfully and ethically integrated into modern health systems. Research on medicinal plants and their efficacy can also contribute to a better understanding and global recognition of this knowledge while preserving biodiversity and supporting local communities.

Rich Biodiversity of the Congo Basin as a Source of Medicinal Recipes

The Congo Basin's biodiversity richness is truly impressive, especially when it comes to medicinal resources. Indeed, this ecosystem is home to a multitude of plant, fungal and animal species that are used by local populations for their medicinal properties. The botanical families most renowned for their medicinal uses include Asteraceae, Fabaceae, Lamiaceae, Rubiaceae, Euphorbiaceae, Apocynaceae and Cucurbitaceae (Van Wyk 2020). These families include many species often used in traditional remedies and contribute to the health of populations.

With over 10,000 species of vascular plants, of which about 3000 are known for their medicinal applications, the Congo Basin offers a variety of natural resources with therapeutic potential. Among these plants, several are endemic and have unique characteristics that make them particularly valuable (Tata Ngome et al. 2017). Plants such as *Kigelia africana* (Lam.) Benth (Sausage Tree) treat various skin conditions (Patel et al. 2024), and *Sida acuta* (Tcheghebe et al. 2017) and *Zanthoxylum gilletii* (also known as *Fagara gillette),* frequently used for their anti-infectious and anti-inflammatory properties, are examples of the botanical wealth of this region in medicinal plants. Besides these two plants, other popular plants are also reported in the traditional pharmacopoeias of the region. The leaves, fruits and seeds of *Balanites aegyptiaca* are used to treat digestive disorders and various infections (Dey and Shaili 2023), while the leaves of *Azadirachta indica* are famous for their antiparasitic, antifungal and anti-inflammatory effects (Asghar et al. 2022). The root barks of *Albizia adianthifolia* are frequently sought for diabetes mellitus, erectile dysfunction and malaria (Maroyi 2018). *Cissus quadrangularis* L is sought for its role in the management of sexually transmitted infections, urinary tract infections and gastrointestinal disorders (Pal et al. 2024), while *Rauvolfia vomitoria* Wennberg is used for its sedative and antihypertensive properties (Cutler 2023) and *Voacanga africana* is used for the treatment of mental disorders (Bekoe et al. 2024a). *Nauclea latifolia* is known for its antipyretic, anti-inflammatory and antimalarial effects (Bekoe et al. 2024b), while *Bridelia micrantha* is used for its antiseptic and wound-healing properties (Asumang et al. 2021). *Hygrophila auriculata* and treats urinary and digestive disorders, while *Alstonia boonei* is often used to treat malaria and diabetes mellitus (Okoye et al. 2021). *Uvaria chamae* is used for various conditions, including malaria, cancer and diabetes mellitus (Agbebi et al. 2024). These plants, among the 20 most widely used medicinal plants in the Congo Basin, illustrate the richness and diversity of herbal remedies in this region.

In the Congo Basin, medicinal plants, insects, birds, snakes, fish, toads, frogs and mammals are used for therapeutic purposes. Insects, such as bees (*Apis* spp.) and some leaf-cutter ants, are used in traditional medicine in the Congo Basin region (Van Huis 2021). For example, propolis produced by bees is known for its antimicrobial (Almuhayawi 2020; Chuttong et al. 2023) and healing effects (Da Rosa et al. 2022). In addition, fly larvae (such as the genus Lucilia) are used in wound debridement, promoting healing through their ability to clean necrotic tissue (Ouango et al. 2022). Snail shells treat wounds and some eye conditions (Cilia and Fratini 2018). Some bird species, such as the hornbill (*Buceros* spp.), have their feathers used in healing rituals, as good luck charms, or as symbols of protection in various rites. In addition, birds such as the pigeon (*Columba livia*) are sometimes associated with attributes of fertility and prosperity in traditional medicinal practices (Oluwole et al. 2021; Su et al. 2024).

The oil of certain snakes, such as the cobra, is used in some cultures for its healing properties. Although the cobra is toxic due to its venom, cobra oil preparations are applied in treating wounds and conditions such as arthritis due to their supposed anti-inflammatory effects (Mishra et al. 2020). Snake body parts, such as scales, are also incorporated into traditional remedies for their supposed protective properties (D'Cruze et al. 2020). Some fish species, such as tilapia (*Oreochromis* spp.), are consumed for their nutritional values and omega-3 fatty acids and medicinal uses (Van Boeckel et al. 2024). Fish oil extracts can be applied to treat skin conditions, such as eczema, due to their anti-inflammatory properties. Secretions from some toad species, such as the cane toad (Bufo bufo), are used in local traditional medicine for their antimicrobial and antitumor effects (El-Naggar et al. 2024; Rodriguez et al. 2020). These secretions, rich in bioactive substances, are also used in ritual contexts to induce altered states of consciousness or neutralize toxins' effects. Several mammals play a key role in traditional medicine in the Congo Basin. Pangolin scales are traditionally used to treat diseases such as inflammation or infections, although their trade is illegal in many countries due to the species' vulnerable status (D'Cruze et al. 2020). Similarly, some species of hippopotamus (Hippopotamus amphibius) are hunted for their organs, which some cultures believe can cure diseases (Ouoba et al. 2020). The mongoose treats joint pain, the rhesus macaque for coughs and the milk of the female cat (Felis catus) for epilepsy (Mussarat et al. 2021). As for the porcupine hairs, they are used to treat intestinal worms (Nieman et al. 2019). These examples illustrate how local communities exploit the Congo Basin is biodiversity in various ways, highlighting the importance of interactions between man and nature in traditional medicine.

Dangers and Threats to the Fauna and Flora Resources of the Congo Basin

Despite their nutritional, decorative and medical-religious interests, the resources of the Congo Basin mentioned above are threatened by several risk factors, such as deforestation, climate change, overexploitation and illegal trade in biological

resources, as well as ethnic conflicts and political instability. All these elements constitute significant challenges to the conservation of this precious biodiversity.

Deforestation and Loss of Biodiversity

Deforestation in the Congo Basin is a significant issue with both environmental and social implications. Activities such as illegal logging, intensive agriculture and urbanization are putting intense pressure on this region, which is rich in biodiversity. Deforestation is accelerating at a rapid pace. In some regions, such as Lubumbashi, half of the miombo forest cover was lost between 1990 and 2022, largely due to the production of charcoal for energy purposes (Shapiro et al. 2021; Muteya et al. 2023). Forest destruction results in habitat loss for many animal and plant species, leading to a worrying decline in biodiversity. In addition, many local communities depend on these forest resources for food, traditional medicines and other livelihoods, making deforestation more worrying for food security and human health (Shapiro et al. 2021; Aquilas et al. 2022; Dargie et al. 2019). In addition, deforestation plays a key role in climate change by reducing the capacity of forests to absorb carbon dioxide, thereby exacerbating environmental conditions (Joshi and Singh 2020). Biodiversity loss can also reduce the resilience of ecosystems, making them more vulnerable to disease and disturbance (Psistaki et al. 2024).

Climate Change

Climate change exerts considerable pressure on plant biodiversity, notably by modifying the geographical distribution of species and altering their pharmacological properties and, in some cases, their nutritional values (Muluneh 2021; He et al. 2019). These changes also impact populations of insects, fungi and animals that live in harmony with the disturbed flora. Transformations of natural habitats lead to a shift in the distribution areas of plant species, making some medicinal and/or food species less accessible to communities that depend on them for their health and well-being (Shackleton et al. 2019). In addition, variations in environmental conditions, such as temperature and precipitation fluctuations, can influence plants' chemical composition. These modifications can induce variations in the concentration of bioactive and/or nutrient compounds, thus compromising the therapeutic efficacy of medicinal plants and their nutritional value (Applequist et al. 2020).

The Congo Basin region is heavily impacted by climate change, as evidenced by numerous signs manifesting at various levels, including: (*i*) *rising temperatures and heat waves*. Average temperatures have been increasing, with a notable rise in extreme temperatures. For instance, the temperature on the hottest days seems to have increased by about 0.25 °C per decade (Cook et al. 2025); (*ii*) *changes in precipitation patterns.* We are witnessing an increase in extreme precipitation and flooding. A resurgence and intensification of extreme rainfall has been clearly established in the Congo Basin region. This leads to increased runoff and river flow during the rainy season, significantly increasing the risk of flooding, particularly in the central and western parts of the basin. Exceptional flooding was observed in late 2023 and early 2024. While general increases in rainfall are expected in the long term, some regions have also experienced an increase in drought episodes

during the rainy season. This irregularity in rainfall poses a significant threat to the livelihoods of rural populations. Additionally, some regions that previously received substantial rainfall are now experiencing reduced rainfall, which can lead to prolonged droughts (Lenzoabcd et al. 2024; Mabrouk et al. 2022); (*iii*) *the negative impact on water resources is particularly evident in the variability of river flows*. This variability is attributed to increased runoff during the rainy season, which leads to a rise in the flow of rivers such as the Congo River. However, it is essential to note the irregularity of rainfall, which can also lead to a decrease in river flow, resulting in significant deficits. This situation poses a real threat to agriculture, which is already affected by variability in rainfall patterns, thereby reducing food security. Certain savanna regions on the periphery of the basin may be affected by water shortages, which could impact agricultural production (Sonwa et al. 2020; Karam et al. 2022, 2023); (*iv*) *negative socioeconomic and health effects* are to be expected, including an increase in poverty due to lower labour productivity caused by heat stress. Rising temperatures, deforestation and many other factors are contributing to the spread of disease vectors (mosquitoes, etc.) and increasing the transmission of infectious diseases (malaria, dengue fever, etc.). Other environmental factors linked to climate change are contributing to an increase in the occurrence and development of noncommunicable, emerging and re-emerging diseases (Shafiee et al. 2023; Dang et al. 2024; Ngongo et al. 2025).

Overexploitation and Illegal Trade

The increase in demand for medicinal, food and artistic products in local and international markets leads to overexploitation of certain biological species (Aquilas et al. 2022). The illegal trade in medicinal plants and other local products, often characterized by insufficient regulatory framework, exacerbates this problem, endangering species already classified as vulnerable.

Conflicts and Political Instability

Armed conflicts in the region, often linked to competition for the appropriation of natural resources, aggravate food insecurity and expose populations to inefficient traditional medical care (Shapiro et al. 2021). Population displacements resulting from violence disrupt food production and medical care systems, thus contributing to the deterioration of living conditions in affected communities. Areas occupied by displaced people for long periods are often victims of unsustainable exploitation of natural resources by vulnerable communities on whom it is impossible to impose rules in a precarious humanitarian context (Bapolisi et al. 2021).

Prospects for the Preservation of Medicinal and Food Resources

The prospects for preserving the food and medicinal resources of the Congo Basin are based on four main axes: sustainable management of resources, strengthening of local capacities, scientific research and sustainable development, as well as regional and international cooperation.

Adopting sustainable natural resource management practices is essential to addressing current challenges. This includes implementing conservation policies, promoting agroecology and supporting traditional agricultural systems.

Developing training programs for farmers, traditional medicine practitioners and local communities on sustainable cultivation and harvesting practices can strengthen resilience to climate change and biodiversity loss (Kurtsal et al. 2023; Khan et al. 2021; Kennedy et al. 2022). Access to innovative technologies and adapted seeds is another exploitable and crucial alternative.

Research into the Congo Basin plants' medicinal and nutritional properties requires increased support. Rigorous studies are essential to identify new molecules with therapeutic properties, allowing innovative drugs to be developed while ensuring sustainable and rational resource exploitation. At the same time, it is crucial to immediately encourage biotechnological studies to optimize the cultivation and reproduction methods of highly prized food species (Khan et al. 2021; Kennedy et al. 2022).

Collaboration between the nations of the Congo Basin and international organizations is essential to implement sustainable development projects. Promoting reforestation and ecosystem conservation initiatives is imperative to preserve food resources, ensure long-term food security and guarantee an uninterrupted supply of natural medicinal resources. Above all, international cooperation must advocate for the establishment of peace and the promotion of good governance in this region, which are significant factors contributing to the sustainable management of natural resources (Trefon 2017; Huge et al. 2020; Resende and Meikengang 2023).

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Effects of Diseases on Wildlife Species in the Congo Basin

21

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Abstract

The Congo Basin, spanning eight Central African countries, harbors the world's second-largest tropical forest and some of the planet's richest biodiversity. Despite its ecological importance and relatively intact habitats, the region's wildlife faces threats from both infectious and noninfectious diseases. Infectious diseases caused by viruses, parasites, fungi and bacteria impact wildlife health and biodiversity and increase the risk of zoonotic spillovers. Environmental changes, including deforestation and habitat degradation, alter these threats. Noninfectious diseases—such as those linked to toxic exposure and malnutrition from declining food availability—further compromise wildlife resilience and reproductive health. Disease surveillance capacity in the region remains fragmented, with most countries having limited capacity for livestock and public health. The One Health approach offers a framework for coordinated surveillance and response, but is challenged by under-resourced veterinary and environmental sectors. Addressing these gaps through improved monitoring, ecological research and cross-sectoral coordination is essential for safeguarding biodiversity, supporting human health and mitigating future outbreaks in this globally critical ecosystem. This chapter reviews evidence for the presence and impact of infectious and noninfectious diseases on vertebrate wildlife in the Congo Basin.

Keywords

Wildlife · Infectious · Disease · Mammal · Amphibian · Reptile · Fish · Bird · Congo Basin

Introduction

Disease, in its broadest sense, refers to any disturbance of normal physiological function that impairs the health, survival or reproductive success of an individual. Infectious Diseases result from a wide range of infectious agents that spread within or between species. Noninfectious diseases, in contrast, arise from environmental, nutritional, genetic or toxic factors, including exposure to pollutants, habitat degradation, climate extremes or injury. Diseases can have severe clinical symptoms or impact hosts more subtly through reduced body condition, fertility or behavior that increases vulnerability to predation or other stressors. Disease can influence population-level host abundance, genetic diversity, species interactions and ecosystem function with consequences not only for conservation but also for human health and livelihoods where wildlife and people intersect.

Pathogen emergence events can be potentially devastating, because a newly infected species or population will often have no or only limited immunity to that pathogen. These *emerging infectious diseases* (EIDs) increasingly affect free-living wild animals and often arise through spillover from domestic animals living close to wildlife populations, human activity that moves animals or pathogens to previously

unaffected regions or direct spread between wildlife species into new areas due to changes in range. EIDs affecting wildlife pose a threat to the conservation of global biodiversity, but EIDs originating from wildlife can also be a threat to domestic animal and human health (Daszak et al. 2000; Schmeller et al. 2020).

The movement of a pathogen from one species to another is referred to as a *spillover* or *cross-species transmission event*. Typically, species that are more phylogenetically related are more likely to share susceptibility to pathogens because of similarities in cellular receptors, immune system mechanisms and body temperatures. As an example, Great apes that share genetic similarities with humans are especially susceptible to reverse zoonoses, and the impact of these reverse zoonoses is felt in many great ape populations in the Congo Basin region (Negrey et al. 2019; White et al. 2023).

Surveillance of Wildlife Diseases

Long-term surveillance at the wildlife–human–livestock interface is essential for understanding pathogen dynamics and threats, but such surveillance remains extremely limited in the Congo Basin (Barroso et al. 2021). Pathogen surveillance in wildlife often does not neatly fit into one sector and frequently falls under the joint responsibility of government ministries of agriculture, livestock and the environment. While surveillance systems are relatively well-established for domestic animals in the Congo Basin, their extension to wildlife is often minimal or absent. Most national surveillance systems still prioritize public health and livestock, with wildlife health receiving limited attention and resources (Delgado et al. 2023).

Given the absence of national wildlife health surveillance programs, so far academic research projects and partnerships with international conservation and health organizations are largely responsible for what we know about wildlife diseases in the Basin. This includes some active surveillance efforts conducted in collaboration with ministries and international institutions, focusing on monitoring of key wildlife populations during outbreaks (Seifert et al. 2022). Event-based surveillance in which unusual wildlife morbidity or mortality triggers sample collection has proven an effective approach for detecting emerging diseases in some remote forest areas. These programs have been used in connection with monitoring, research and ecotourism activities for detection of reverse zoonoses, especially respiratory infections, in great apes (Gogarten et al. 2024). For example, in the Republic of Congo and Gabon, such initiatives have enabled rapid responses to gorilla and chimpanzee die-offs suspected to be linked to pathogens like Ebola virus and anthrax (Antonation et al. 2016). Assessing the impact of disease on populations over time can be aided by long-term wildlife biomonitoring (Brncic et al. 2018).

As wildlife health surveillance systems are still scarce, inconsistent and poorly integrated into broader animal health frameworks in the region, data on disease outbreaks and their impacts on wildlife are also consequently minimal. The evidence presented in this chapter comes from wildlife health surveillance activities made publicly available through scientific publications and reports made

to WOAH-WAHIS. Details of the national surveillance capacity as summarized by WHO and WOAH are provided in Table 1. Notably, only Cameroon has reported wildlife diseases to WAHIS.

Infectious Diseases Threatening Wildlife in the Congo Basin

Animals in the Congo Basin can be infected by wide range of known and yet unknown viruses, bacteria, parasites and fungi. These micro-organisms and the diseases they cause can endanger conservation efforts and sometimes threaten human health. Rare species can be driven to unsustainably low population numbers, or even extinction, when outbreaks alone or additional comorbidities lead to high mortality (Osofsky et al. 2023). For example, in the mid-2000s, a series of Ebola virus disease outbreaks led to a sharp decline in great apes in the Congo Basin (Vogel 2006) and in 1997 an underlying parasitic heartworm infection (*Elaeophora sagitta*) alongside a plague of blood sucking flies (*Stomoxys omega*) caused a dramatic crash in threatened Bongo antelopes (*Tragelaphus eurycerus*), from which the species has not yet recovered (Koopmans et al. 2021).

This section summarizes available evidence on wildlife diseases known to be present in the region in each vertebrate group (amphibians, birds, fish, mammals and reptiles). A more comprehensive list of microorganisms and pathogens known to be present in the region are detailed in table in https://doi.org/10.5061/dryad.8kprr4z07. Importantly, the absence of a specific pathogen does not indicate its true absence; rather it may simply reflect limited research or surveillance in the region.

Amphibians

Two landscapes in the Congo Basin—the Cameroonian Highlands and the Albertine Rift in the DRC—have been identified as having particular importance for amphibian diversity. The region has received considerably less research effort into amphibians than the rest of the world (IUCN SSC Amphibian Specialist Group 2023).

Infectious diseases are acknowledged as a significant threat to amphibians, and before 2004, when climate change became the biggest driver of loss, disease (primarily chytridiomycosis) was suspected to have been the dominant factor in every known amphibian extinction globally since the 1980s. There is a severe lack of research on the impact of disease on amphibians within the Congo Basin. However, disease is currently considered a major threat to 26% of the 310 species in the Cameroonian Highlands, and 10% of the 54 species in the Albertine Rift (Luedtke et al. 2023).

Chytridiomycosis: *Batrachochytrium dendrobatidis* (Bd)

Chytridiomycosis, a WOAH-notifiable disease caused by the fungus *Batrachochytrium dendrobatidis* (Bd; also known as chytrid fungus), has caused devastating amphibian declines globally (Fisher and Garner 2020). Africa has been proposed as a potential source for its global expansion.

Table 1 National disease surveillance capacity

Country	1. Disease surveillance activities in wildlife	2. Surveillance system in place for priority zoonoses (WHO)	3. Data sharing between health agencies	4. Reports of disease in domestic animals through WAHIS (WOAH)	5. Reports of disease in wild animals through WAHIS (WOAH)
Gabon	Yes	Score 1 no capacity	Yes	Peste des petits ruminants virus (2024, 2011); HPAI virus H5N1, (2024, 2022); African swine fever virus (2022); and contagious bovine pleuropneumonia (2010)	No reports made
Central African Republic	Yes	Score 1 no capacity	No	African swine fever virus (2013, 2014); mycoplasma mycoides (2007)	No reports made
Republic of Congo	Yes	Score 2 limited capacity	No	Rabies virus (2013); contagious bovine pleuropneumonia (2010); and Peste des petits ruminants virus (2005)	No reports made
Democratic Republic of Congo	Yes	Score 3 capacity developed	No	Anthrax (2023, 2021, 2011); HPAI viruses H5N8 (2017); foot and mouth disease virus (2017); and Peste des petits ruminants virus (2012, 2006)	No reports made
Cameroon	Yes	Score 3 capacity developed	Yes	Pox viruses (2016); HPAI viruses H5N1 (2022, 2016, 2006); African horse sickness virus (2019); and influenza A viruses of high pathogenicity H5N8 (2017)	*Aphanomyces invadans* (EUS) (2000); monkey pox—wild chimpanzee, sanctuary (2014); and influenza A viruses of high pathogenicity H5N8 (2017)
Equatorial Guinea	No	Not available	No	No reports made	No reports made

(continued)

Table 1 (continued)

Country	1. Disease surveillance activities in wildlife	2. Surveillance system in place for priority zoonoses (WHO)	3. Data sharing between health agencies	4. Reports of disease in domestic animals through WAHIS (WOAH)	5. Reports of disease in wild animals through WAHIS (WOAH)
Rwanda	Yes	Not available		Rift Valley fever virus (2024, 2018, 2022); Peste des petits ruminants virus (2023); and foot and mouth disease virus (2023, 2020)	No reports made
Burundi	No	Score 1 no capacity	No	Rift Valley fever virus (2022); Peste des petits ruminants virus (2018); lumpy skin disease virus (2016); and African swine fever virus (2016)	No reports made

WHO (2025)

Capacity within Congo Basin countries for disease detection and surveillance for wildlife, domestic animals, and public health

1. Activities of disease surveillance in wildlife exist in the country through governmental or nongovernmental organization, or research collaborations
2. Surveillance system in place for priority zoonotic diseases, evaluated by WHO JEE. These systems are mainly targeting public health and in some cases livestock (scores: 1 = no capacity; 2 = limited capacity; 3 = developed capacity; 4 = demonstrated capacity; and 5 = sustained capacity)
3. Data sharing between human and animal health agencies, evaluated by WHO JEE
4. Reports of disease in domestic animals through WAHIS (WOAH)
5. Reports of disease in wild animals through WAHIS (WOAH)

A survey of the native frog species (order *Anura*) identified dramatic declines between 2004 and 2012 in the montane habitats of western Cameroon (Hirschfeld et al. 2016), primarily attributed to Bd. A study in Cameroon revealed the presence of Bd in seven protected areas across the country with prevalence ranging from 9.2% to 33.3% in the 360 samples analyzed (Miller et al. 2018). In a survey in Gabon, Bd was detected in 20 of the 42 species examined in 2009 and was present at Monts de Cristal National Park and Ivindo National Park with prevalence between 19.6% and 36.0% across different sites, elevations and habitat types (Bell et al. 2011).

The most widespread and virulent type of Bd (Global Panzootic Lineage, *Bd*GPL) was present in all surveyed island and continental amphibian communities in Cameroon since 1966, indicating this lineage likely has a historical presence in Central Africa (Hydeman et al. 2017). Surveys conducted in the Albertine Rift area between 2010 and 2014 found a prevalence of 19.5% in the 1018 samples from 17 amphibian genera in 39 sites positive for Bd by PCR and confirmed that the fungus has been present in the DRC since at least 1950 (Seimon et al. 2015).

Overall, studies evaluating the impact of Bd on populations are scarce. Despite the impact of Bd in the amphibian diversity hotspots of the Cameroonian Highlands, none of the other studies documenting the presence of Bd have reported sick, dead or dying amphibians. Bd virulence is multifactorial, including variation in genetic pathogenicity between lineages, host susceptibility, immune responses and prior exposure and abiotic environmental variables, such as temperature and rainfall (Seimon et al. 2015), water system properties, presence of pesticides or fertilizers (Fisher and Garner 2020).

Given the impact of climate and land-use change on host–pathogen interactions, the projected increase in global temperatures and the anthropogenic changes in the Congo Basin region may worsen the impact of Bd.

Other Amphibian Pathogens

Few publications describe other microorganisms in amphibians in the Congo Basin region. Two studies evaluate parasite presence in endangered goliath frogs (*Conraua goliath*) in Cameroon. Although sample sizes are small, the authors suspected a link between parasite prevalence and land-use patterns. The survey of 30 goliath frogs from different land use profiles found a higher intensity of gastrointestinal parasites in frogs in areas with intensive agriculture. In total, 85% of the individuals were infected with a range of gastrointestinal parasites with 973 different helminths identified. A second study detected microfilariae in 42.3% of 78 frogs, with higher infection rates in the dry season and in larger males. DNA analysis linked the microfilaria to *Icosiella neglecta* (Nguiffo et al. 2019).

The impact of these microbes remains unclear. Amphibians commonly host blood parasites transmitted by blood-feeding vectors in their environments without experiencing clinical disease but some parasites, especially filarial nematodes, can spread from the lymphatic system, causing lethargy or even death in severe cases (Klaphake 2009).

Mammals

The Congo Basin region harbors many mammalian species, including populations of critically endangered wildlife. Microorganisms in mammals have been studied more extensively than pathogens in other vertebrates, and consequently mammals, especially apes and bats, are known to host a wide range of pathogens (Shi et al. 2018).

Great Apes

Central Africa has the highest densities of great apes in the African continent (Ordaz-Németh et al. 2021) including important populations of critically endangered Cross-river gorilla (*Gorilla gorilla diehli*), Bonobo (*Pan paniscus*) and Western Lowland gorilla (*Gorilla gorilla gorilla*). Importantly, only a tenth of great apes are found within defined IUCN protected areas, while the remainder live in habitats outside formal protected areas, which often brings great apes and humans into closer proximity (Ordaz-Németh et al. 2021).

The *State of the Apes—Disease, Health and Ape Conservation* (Arcus Foundation 2024; White et al. 2024) provides a comprehensive summary of the infectious diseases documented to have an effect on wild ape fitness, primarily in chimpanzees, gorillas or both. Infectious diseases known to have impacted wild ape health or to have caused mortality include Mpox (monkeypox virus), sarcoptic mange (*Sarcoptes scabiei*), yaws (*Treponema pallidum pertenue*) and leprosy (*Mycobacterium leprae*). Certainty around the extent to which these diseases impact species survival as well as their case fatality rate in populations, requires more robust epidemiological data. Conversely, infectious diseases with a measured effect on wild ape survival and population fitness include sylvatic anthrax (*Bacillus cereus* biovar *anthracis*), Ebola virus disease (EVD), simian immunodeficiency virus (SIV) and several human-borne respiratory pathogens.

Great apes are closely related to humans, making them susceptible to many human-borne pathogens. Human respiratory viruses are a leading cause of death in some chimpanzee communities (Negrey et al. 2019). Risk of transmission is particularly elevated for great ape groups that are habituated to humans and/or are frequently visited by tourists or researchers. Human metapneumovirus (hMPV), human respirovirus 3 (HRV3, formerly known as parainfluenza virus 3) and human respiratory syncytial virus (HRSV) have all been documented to cause clinical disease and mortality in both western lowland and mountain gorillas (Köndgen et al. 2008; Mazet et al. 2020). These diseases continue to pose a threat to wild great ape populations, where individuals can be directly infected by humans in their shared environment or indirectly through fomites—inanimate objects that can act as vehicles for transmission of infectious agents from one individual to another, such as discarded food waste. Western lowland gorillas are susceptible to SARS-CoV-2 and develop clinical disease; however, to date, all known infections have been documented in captive zoo settings only (Nagy et al. 2022). This negates neither the risk of the virus to wild apes nor the possibility of infection having occurred undetected in free-ranging great ape populations.

Many other pathogens have been documented in wild great ape populations; however, the clinical significance on their ape hosts largely remains unclear or appears negligible. In Central Africa, free-ranging gorillas and chimpanzees have been found to host a wide range of viruses, including herpesviruses, adenoviruses, picobirnaviruses, partitiviruses and picornaviruses (Seimon et al. 2015; Duraisamy et al. 2018). Gorilla-specific cytomegaloviruses and lymphocryptoviruses have been identified across sites in Rwanda, Uganda and the DR Congo (Smiley Evans et al. 2023). Enteroviruses circulate widely, with a 29% prevalence found in fecal samples from gorillas and chimpanzees in the Republic of Congo (Amona et al. 2020). Hepatitis B and C viruses circulate in wild gorillas and chimpanzees (Njouom et al. 2010). Parasites are also prevalent and widely studied, including numerous protozoans and helminths characterized in both lowland and mountain gorillas, and western chimpanzees (Petrželková et al. 2021), and anoplocephalids in mountain gorillas (Červená et al. 2023). Although great apes commonly harbor multiple endoparasite species without exhibiting clinical signs, a recent study investigating parasitic helminth infections in mountain gorilla populations across the Virunga Massif and Bwindi Impenetrable National Park revealed marked geographic variation in infection intensity, with higher helminth egg counts occurring in regions where clinical gastrointestinal disease in gorillas is more frequently observed (Petrželková et al. 2021). Similarly, severe gastritis, both clinically and histologically, was shown to be associated with helminth infection in mountain gorillas between 1985 and 2017 (Muhangi et al. 2021).

Blood parasites, such as various *Plasmodium* species, also infect great apes. At least six *Plasmodium* species are known to circulate in gorillas and chimpanzees (Boundenga et al. 2018). The zoonotic *Schistosoma mansoni* has been detected in western lowland gorillas and central chimpanzees in Loango National Park, Gabon (Červená et al. 2023), highlighting shared health risks across species.

Research on great apes across sites in Central Africa has also detected bacteria with antimicrobial resistance (AMR). A review of 16 studies found resistance to multiple antibiotic classes and suggested a correlation between increased human contact and higher AMR rates in the great apes, indicating potential transmission of resistant bacteria between humans and wildlife (Tanga et al. 2024).

Ebolaviruses and Ebola Virus Disease

Ebolaviruses are a genus of viruses including *Zaire ebolavirus* (EBOV), *Sudan ebolavirus, Taï Forest ebolavirus, Bundibugyo ebolavirus* and *Reston ebolavirus*. Between the 1990s and mid-2000s, there were a series of die-offs of tens of thousands of gorillas and chimpanzees in large, mostly intact forested areas of Gabon and Congo. Overall, three-quarters of the gorilla population in six protected areas died, with mortality rates reaching 95% in the worst-affected locations. In the mid-2000s, ebolavirus was confirmed in some carcasses and is widely considered the cause of these die-offs (Maisels et al. 2013). In the Lokoué forest clearing in the Republic of Congo, lowland gorilla numbers dropped from around 380 individuals to fewer than 40 after a confirmed 2004 Ebola outbreak (Vogel 2006). These EBOV

epizootics resulted in infectious disease being regarded among the leading threats to gorillas (IUCN Red List) and total population recovery from them would take 75–131 years (Ryan and Walsh 2011).

Ebolavirus remains a highly significant threat to great apes in the Congo Basin region. Large areas can be affected by a single outbreak, and transmission between individuals is rapid, killing almost all affected animals as indicated by the lack of an IgG response in remaining individuals (Ryan and Walsh 2011). Environmental barriers such as rivers and forest fragmentation appear to hinder the spread of EBOV. Initiatives for vaccine development for great apes have been promising, but ethical hurdles have so far hindered further research (Walsh et al. 2017).

Ebolavirus ecology is not fully understood, but fruit bats, particularly species in the *Pteropodidae* family (discussed in section "Bats"), are suspected but not proven to be the reservoirs, maintaining asymptomatic infections in the populations (Hayman 2016). Other mammal species can be susceptible, and carcass scavenging species can be affected through feeding; even mostly frugivorous duikers (forest antelopes), such as *Cephalophus* spp., were frequently found dead during Ebola outbreaks (Rouquet et al. 2005).

Treponema: Yaws

Research indicates that bacterial *Treponema pallidum* infections, responsible for the disease known as yaws, is an emerging disease threat in wild great apes, and likely originated from humans (Sereme et al. 2024).

In great apes, yaws can lead to a range of clinical signs and pathological changes. Affected individuals often develop skin lesions, including ulcers and nodules, particularly on the face, limbs and around the mouth and nose, and persistent skin damage and prolonged infection can affect bones and joints, leading to mobility issues or difficulty moving. The presence of open lesions increases the risk of secondary infections from other bacteria or parasites, compounding the health burden on the animal, and yaws has been linked to lower reproductive success (Levréro et al. 2007).

While confirmed reports on *T. pallidium* infections are limited, evidence from neighboring regions to Congo Basin has confirmed its presence in primate populations, in nonhuman primates in Tanzania and in a wild chimpanzee in Guinea (Mubemba et al. 2020). In the Congo Basin area, reports have described yaws-like lesions in wild great apes (Levréro et al. 2007); although the specific causative agents have not been confirmed in some cases, the sightings have raised concerns for potential health and conservation implications.

Anthrax: Atypical Bacillus Species in the Congo Basin

Bacillus cereus biovar *anthracis* (Bcbva)—a typically nonpathogenic *B. cereus* associated with pathogenicity traits from the more widely understood and highly pathogenic wildlife pathogen, *B. anthracis*—is a persistent and widespread bacterial agent detected in tropical rainforest environments. Bcbva has been detected in wildlife mortalities in several species in the region, including great apes, forest elephants and duikers (Hoffmann et al. 2017).

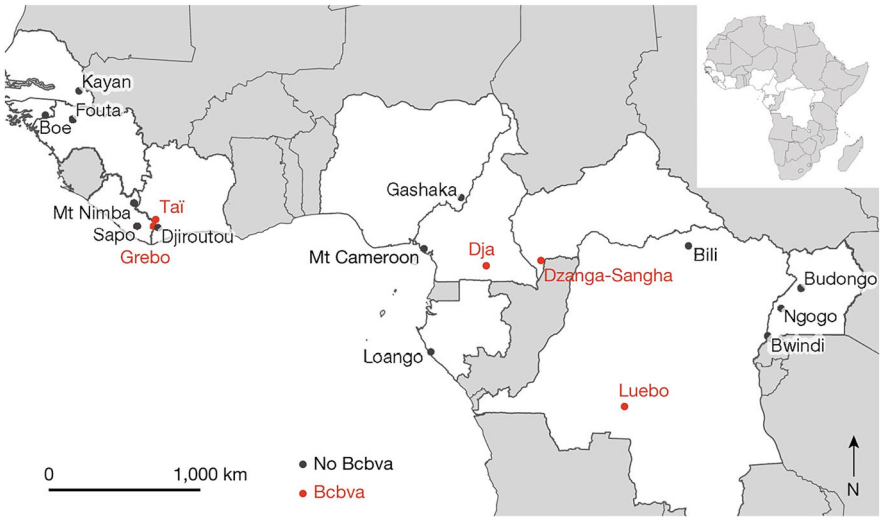

Fig. 1 Map indicating sites with known Bcbva occurrence in wildlife (indicated in red) based on Hoffmann et al. (2017) and with published locations to date. Sites where Hoffman et al. did not detect Bcbva are indicated in black (2017)

All *Bacillus* species are known for their ability to form highly resistant endospores, allowing them to survive extreme environmental conditions such as heat and drying. This makes them a long term, persistent and potentially increasing disease threat despite usually not being contagious from animal to animal (Kumar and Flora 2020), and the effects of Bcbva, especially on chimpanzee populations in Taï National Park, suggest that its effects can result in severe population declines and possible species extinctions over time (Hoffmann et al. 2017).

Evidence from human serological studies indicates that Bcbva is zoonotic, with exposure in the human population probably facilitated via wild meat contact and consumption (Dupke et al. 2020) (Fig. 1).

Bats

Bats host a wide variety of viruses often without displaying typical disease symptoms and are believed to host more pathogens than other ecologically comparable taxa, such as rodents (Guth et al. 2022; Mougari et al. 2022; Ruiz-Aravena et al. 2022). While the underlying mechanisms for this are not yet fully understood, one hypothesis attributes this to distinct features of their immune system, potentially shaped by evolutionary adaptations associated with sustained flight (Brook et al. 2020; Riesle-Sbarbaro et al. 2024). Several viruses in bats have spilled over into humans to cause zoonotic outbreaks. Egyptian fruit bats are known to be host of *Marburg virus*, a filovirus in the same family as ebolaviruses, which has caused several human outbreaks in the Congo Basin region. Phylogenetic analyses suggest that recent SARS-CoV-2 pandemic and outbreaks with more ancient origins (e.g., mumps and measles) may have originated in bats (Lau et al. 2020). Globally, bats have therefore been more intensely

researched than many other taxa. Evidence from other countries has identified thousands of bat-associated viral species from at least 28 diverse viral families (Chen et al. 2014) including many of which have not been associated with disease (Fig. 2).

In the Congo Basin region, molecular studies in bats have revealed a wide range of RNA viruses in both insectivorous and fruit bats. This includes diverse alpha- and beta-coronaviruses, including viruses most closely related to the human common cold coronaviruses 229E or NL63 (Yinda et al. 2018; Kumakamba et al. 2021; Kuchinski et al. 2022), new viruses in the family *Circoviridae* (Vidovszky et al. 2023); *Caliciviridae, Reoviridae*, *Astroviridae*, *Picobirnaviridae, Circorviridae* and *Parvoviridae*; and *Rhabdoviridae* (Cameron et al. 2021), which also includes rabies virus, hepadnavirus and dicistrovirus-, nodavirus- and tombus-like viruses with phylogenetic features suggesting arthropod origin. In addition, antibody studies have helped detect evidence of past exposure with viruses that appear difficult to capture through molecular methods, such as Ebolaviruses, Marburg virus and paramyxoviruses including Nipah and Henipa (De Nys et al. 2018; Markotter et al. 2020; Steffen et al. 2020; Seifert et al. 2022).

Bats are often consumed as wild meat and are a key source of protein for people in the region. The consumption is widespread despite the evidence that bats are an important reservoir for numerous zoonotic viruses that can cause severe disease in humans. The close interaction between bats and people, resulting from the trade and consumption in live bats or from roosting in homes or above gardens can create opportunities for a pathogen spillover from the bat host to people (Eby et al. 2023).

Fig. 2 Bats are widely consumed in the Congo Basin region. The close interaction between bats and people can create opportunities for a pathogen spillover from the bat host to people. (Brent Stirton/Getty Images)

Like many mammal species, bats host a diversity of parasites, detailed in table in https://doi.org/10.5061/dryad.8kprr4z07; however, our search found no published data on bacterial or fungal infections in bats within the region.

Other Mammalian Species and diseases affecting them.

Foot-and-Mouth Disease

Foot-and-mouth disease (FMD) is a viral disease affecting both domestic cloven-hoofed livestock and wildlife. African buffalo (*Syncerus caffer*) are the most important wildlife reservoirs, but other animals including antelope and forest duikers are susceptible.

Wild animals can transmit the virus to domestic livestock where it can cause severe harm to economies and livelihoods, and this is particularly challenging in areas with livestock-wildlife interactions, particularly where domestic cattle graze near protected areas. The paucity of research into FMDV in wildlife in the Congo Basin has prevented understanding whether FMDV is present in the local buffalo populations (Udahemuka et al. 2022), but FMD has been reported in domestic cattle through WAHIS in DRC and Rwanda in 2017, 2020 and 2023 (WOAH-WAHIS 2025).

FAO and WOAH have published guidelines on FMD vaccination and post-vaccination monitoring. These guidelines provide comprehensive information on strategies for effective vaccination campaigns in Africa that could be used in high-risk areas (FAO 2016).

African Swine Fever

African swine fever (ASF) is a viral hemorrhagic disease in pigs (suids). Both domestic and wild pigs (*Sus* spp.) are susceptible to infection, yet unlike domestic pigs many wild species do not show clinical disease when infected. Cross-border spread and cocirculation of several ASF virus strains have been widely documented in the Congo Basin region (Wade et al. 2019), and there is evidence of spread across in the African continent (Mulumba-Mfumu et al. 2019).

The virus circulates sylvatically, in native warthogs (*Phacochoerus africanus*), bushpigs (*Potamochoerus porcus*) and giant forest hogs (*Hylochoerus meinertzhageni*) of the Congo Basin, and can persist in and be vectored by African soft ticks (*Ornithodoros*) (Goatley et al. 2024).

The main impact of ASF in the region results from its effect on domestic pigs, which suffer high mortality when infected. Cases in domestic pigs have been reported through WAHIS in Central African Republic, Cameroon and Gabon (WAHIS 2025) and in DRC (Patrick et al. 2020).

Peste Des Petits Ruminants (PPR)

Peste des petits ruminants (PPR) is a viral disease of domestic small ruminants, but can also affect wild ungulates. Sharing of grazing and water sources between domestic animals and wildlife can facilitate transmission and PPR epizootics have devastated wild ungulate populations due to the high mortality rate (Aziz-ul-Rahman et al. 2018).

Several studies have reported molecular and serological evidence of PPR virus, including prolonged epizootics, in domestic sheep and goats in Burundi, DRC, Gabon

and Rwanda (Niyokwishimira et al. 2019; Mulumba-Mfumu et al. 2021). PPR is believed to have been present in domestic animals DRC since at least 2008, and neighboring countries, including Congo-Brazzaville, Gabon, Kenya and Tanzania, are also affected, with the infection considered to be endemic in some areas (FAO 2012).

A serological study reported widespread PPR virus exposure in livestock and wildlife in the Uganda-DRC border region, confirming potential for transboundary spread and transmission between farmed and wild populations (Fernandez Aguilar et al. 2020). While evidence of PPR virus infections in wildlife in the region therefore does exist, the threat to the local ungulate species is not well understood.

Rabies

Rabies, caused by rabies virus (RABV) is a serious, endemic public health problem in many parts of the Congo Basin. Rabies can circulate in domestic cycles, mainly in domestic dogs, or sylvatic cycles solely within wildlife species, including bats.

Dogs are the most abundant reservoir host species of RABV in Africa, and in the Congo Basin, stray dogs are associated with rabies infections, including reports through WAHIS in the Republic of Congo (Nakouné et al. 2012). Human cases, particularly cases in children, are common and the result of spillover from outbreaks in domestic dog populations (Thumbi et al. 2022).

To date, there are no published reports of rabies cases in wildlife in any of the Congo Basin countries, including among its diverse bat populations, but there are still conservation concerns. Serological evidence of exposure to lyssaviruses and novel rhabdoviruses (Cameron et al. 2021) (rabies virus genus and family, respectively) has been reported in bats in the region.

Rabies is a known threat to endangered canid populations elsewhere in Africa. Domestic dogs can infect wildlife, particularly in areas where human settlement encroaches into wildlife areas. The diversity of canids (family *Canidae*) in the Basin is relatively low compared to open savanna areas, but other species such as mongoose and sea mammals are susceptible (Begeman et al. 2018), as has been demonstrated by the emergence of rabies in Cape fur seals in southern Africa.

Other Microorganisms in Other Mammals

Parasites have been more widely studied in mammals in the Congo Basin—perhaps reflecting the available capacity as microscopes are affordable and widespread. Trypanosomes are protozoan parasites that infect a wide range of vertebrate hosts, including humans (e.g., human African trypanosomiasis or sleeping sickness) and nonhuman animals (e.g., animal African trypanosomiasis, or nagana in livestock). In the Congo Basin, they are primarily transmitted by tsetse flies (*Glossina* species) and are widely distributed in domestic and wildlife species.

Fish

There has been little research on fish-associated microbes in the Congo Basin. Among the few documented diseases, the most notable is epizootic ulcerative syndrome (EUS), a serious condition caused by the waterborne fungus *Aphanomyces invadans*.

EUS affects a wide range of freshwater fish species and can lead to high mortality, especially during outbreaks linked to environmental stressors such as pollution, temperature fluctuations and poor water quality (Iberahim et al. 2018). EUS poses a significant threat to wild fish populations through its potential to disrupt ecosystem health, compromise food security for local communities and undermine broader conservation efforts.

The first reported case of EUS in the Congo Basin occurred in 2017 in the Upper Congo catchment area, raising concerns about its potential spread through the Congo River system (Huchzermeyer et al. 2018). In 2020, Cameroon's national veterinary laboratory (LANAVET) confirmed the presence of the fungus in wild African sharptooth catfish (*Clarias gariepinus*), marking the first official report of EUS in the region (WAHIS 2025).

In contrast, a wide range of fish and specifically gill parasites are documented across the region (Table; https://doi.org/10.5061/dryad.8kprr4z07). Many of these parasites have species-specific relationships with their fish hosts, often coexisting without causing apparent significant harm. These host–parasite associations can provide valuable insights into biodiversity, host ecology and interactions between native and invasive fish species.

In natural environments, parasitic infections typically maintain a balanced relationship within the ecosystem and species niches they inhabit. However, environmental stressors, such as pollution, habitat degradation and climate change, can disturb this equilibrium, potentially increasing parasite loads even leading to population-level impacts (Kasembele et al. 2025).

While rare, some fish infections can also pose risks to human health. One such example is *Mycobacterium ulcerans*. This bacterium is responsible for Buruli ulcer, a neglected but emerging zoonotic disease with significant health and socioeconomic consequences. This disease is closely associated with aquatic environments, especially in swampy or seasonally flooded tropical and subtropical regions (Garchitorena et al. 2014). Aquatic organisms including fish and amphibians, as well as insects and snails, can act as reservoirs or vectors for the disease. However, limited understanding of the pathogen's ecology and transmission routes continues to hinder effective public health responses.

Birds

Wild birds in the Congo Basin face multiple threats that impact their health and conservation status. Hunting, habitat loss due to deforestation, logging and agricultural expansion are major drivers of population declines, reducing available nesting sites and food resources. Wild birds are susceptible to transmissible diseases such as avian influenza and Newcastle disease, which also have the potential to spread between wild and domestic birds and other vertebrate species.

Avian Influenza

Avian influenza viruses (AIV) are highly contagious viruses that primarily infect birds but can spread to other animals and humans. Highly pathogenic avian influenza

(HPAI) viruses are particularly concerning because they can cause severe disease and high mortality both in poultry and wild birds. AIVs can spillover to mammals including humans where they can cause disease and death or contribute to the emergence of new pandemics.

AIVs circulate in the region in a wide range of wild bird species. A 2010–2014 molecular study evaluating AIV prevalence in wild birds sampled 40,099 birds at 32 sites in Cameroon, Central African Republic, Republic of Congo and Gabon, found AIV RNA in 16.6% of songbirds (eight passerine families, $n = 1257$), 16.4% of kingfishers (family Alcedinidae, $n = 73$), 8.2% in ducks (family Anatidae, $n = 564$) but reported no associated mortalities (Fuller et al. 2015). The study did not investigate whether viruses present were highly or low pathogenic.

HPAIV H5N8 has been reported in both domestic and in wild birds in Cameroon and the DRC (Twabela et al. 2021; Wade et al. 2019). HPAIV H5N1 cases were reported through the World Organization for Animal Health's WAHIS system in poultry in Cameroon in 2006, 2016 and 2022, and in Gabon in 2016 and 2024, confirming that H5 viruses have successfully and repeatedly spread through the region (WOAH-WAHIS 2025). Studies evaluating the impact of H5 on wildlife globally have found a varying, often species-specific impact on diverse bird and mammal species ranging from minimal impact, such as reduced nesting and reproduction rates, to high levels of mortality (Mena et al. 2025). While studies specific to Congo Basin are lacking, this evidence indicates a potential threat of H5 viruses for both wildlife and wild birds in the Congo Basin.

Newcastle Disease Virus

There are no published reports of *Newcastle disease virus* (NDV), a highly contagious viral infection affecting a wide range of bird species, in wild birds in the Congo Basin area. However, NDV has been detected in over 200 bird species, demonstrating its wide adaptation to host species (WOAH 2020), and studies have reported detection of the virus, including novel virulent variants, in domestic birds in the DRC (Twabela et al. 2021) and in neighboring countries (Snoeck et al. 2009) despite vaccine efforts, and its presence presents an inherent possibility of a spillover between domestic and wild birds in the region.

Other Viral Pathogens of Birds

Few other viral pathogens have been reported in wild birds in the Congo Basin. The mosquito-borne West Nile virus (WNV), circulates in several species of birds and can infect humans. WNV originated in Africa and remains endemic across much of the continent. The virus was isolated in Central African Republic in a sample from 1967, but no recent reports exist from the region (Ergunay et al. 2015).

The psittacid herpesvirus (PsHV), primarily affects parrots (psittacine birds) causing an acute, generally fatal Pacheco's disease, but has also been found in some wild bird species. As many as five serotypes of PsHV are recognized. Studies on captive birds, some of which are wild caught, suggest that endangered African grey parrots are susceptible to the disease. It is speculated that PsHV-2 coevolved with the endangered African grey parrot in its native range, including the Congo

Basin. To date there is no adequate screening in parrots in the African region to confirm its wider prevalence (Styles et al. 2005), preventing efforts to understand its impact.

Salmonella spp. and Enterobacteria in Birds

Salmonella spp. can be pathogenic in birds. The pathogen causes mild to severe illness, with a range of symptoms, or fatal disease in both wild and domestic birds. In wild birds, salmonellosis is mostly caused by *Salmonella enterica*, and its serovar *S. typhimurium*. Wild birds can act as reservoirs, spreading Salmonella through feces, contaminating water sources and environments shared with domestic animals and humans.

One study assessed 65 village weaver birds (*Ploceus cucullatus*) in Dschang, Cameroon, and their potential to transmit bacteria to humans and animals. Bacteria from a total of nine genera of enterobacteria and two yeast species were identified in fecal samples, with high prevalence for *Salmonella* spp. (78.46%).

Protozoan Parasites in Birds

Hemoparasites are common in wild birds. Several species of vector-transmitted blood parasites have been detected in wild birds in the Congo Basin region, including potentially fatal *Plasmodium, Leucocytozoon*, *Haemoproteus* and *Trypanosoma* species.

Lack of strict host or geographic specificity for some parasites suggests extensive spread across bird species and regions. For example, *Trypanosoma everetti* and seven different *Trypanosoma avium* haplotypes were detected in 189 individuals (35%) and 42 of the 71 species (59%) across different families and geographical regions. Plasmodium parasite occurrence varied significantly across mosquito genera, species and locations (Njabo et al. 2011).

Deforestation and land-use change are linked to changes in the prevalence of disease-transmitting vectors, such as in the case of blood parasites in birds (Sehgal et al. 2005; Tchoumbou et al. 2020).

Reptiles

While many viral, bacterial, parasitic and fungal diseases have been characterized globally in reptiles, some with potential severe effects, few reports exist on infectious diseases in reptiles in the Congo Basin region. Studies that exist focus on parasites. Haemosporidian parasites have been identified in forest hinge-back tortoises (*Kinixys erosa*), mud turtles (*Pelusios castaneus*) and forest cobras (*Naja melanoleuca*) in Gabon (Boundenga et al. 2018). The order *Haemosporida* is a group of protozoan blood parasites that infect a large variety of vertebrate hosts and includes the medically important human malaria parasites. Several species of pentastomid parasites have been characterized in reptiles in the Republic of Congo. Pentastomid infections are often considered chronic rather than acutely lethal, yet can significantly impact host health depending on parasite load, host species and

environmental conditions. Snakes offered in Congolese markets are often infected with parasites like *Armillifer grandis*, posing health risks to both reptiles and humans (Hardi et al. 2017).

Research findings on ectotherms, which include reptiles, suggest they are highly susceptible to disease burden, altering the effects of climate change, partly due to the temperature-dependent nature of immune responses (Cohen et al. 2020). As top predators, reptiles are also vulnerable to pollutants and bioaccumulating toxins and heavy metals (Lemaire et al. 2024) discussed in section "Toxicity: Environmental Pollutants."

Invertebrates and Plants

Plant and invertebrate diseases play a critical role in ecosystem function, agriculture and human–wildlife interfaces. These are outside the scope of this review. However, we note that diseases in invertebrates remain severely under-researched in the Congo Basin, despite global trends highlighting the need to consider invertebrate health within a broader biodiversity and ecosystem framework. Pollinators, including bees, butterflies and some fly and beetle species, are experiencing significant population declines worldwide due to a combination of disease pressure, pesticide exposure, habitat loss and climate change. Research estimates that global insect biomass is declining by 1% to 2.5% annually (Wagner et al. 2021).

Noninfectious Diseases and Impact of Human-Driven Activities on Health

While infectious diseases often receive more attention, noninfectious diseases can be equally detrimental, influencing individual health, population dynamics and broader ecosystem stability. They can also make individuals more susceptible to infections.

Our review did not reveal extensive evidence on noninfectious diseases and their causes in the Congo Basin region, although as before, the lack of evidence may not indicate ground realities. The available information can be categorized into two key areas—toxicity and malnutrition. In addition, reduction in genetic diversity that is closely connected to increased susceptibility to disease (see Gibson 2022), and the effects of this connected to habitat fragmentation, poaching and reproductive depression are discussed in more detail in ▶ Chap. 31, "Future Risks of Disease Emergence in Humans, Wildlife, and Livestock in the Congo Basin: Predicting Outcomes Under Current Trends and Policy-Driven Solutions."

Toxicity: Environmental Pollutants

Globally, a growing body of evidence highlights multiple sources of environmental toxins impacting wildlife and ecosystems. Levels of environmental toxins are poorly

monitored and understood in the region, mining being the best documented source. Mining activities release persistent toxic substances, including mercury and other heavy metals, into the environment, where they can remain bioavailable for decades (Camizuli et al. 2018). Aquatic species are particularly susceptible to the effects and build-up of toxins, but bio-accumulation of harmful substances is enriched along the trophic food chain across taxa. In the Congo Basin, mining expansion threatens terrestrial and aquatic wildlife, particularly where protective measures are lacking ("Gold Reimagined Report," 2025). PFAS chemicals (Per- and polyfluorinated alkyl substances, often referred to as *forever chemicals*) further amplify risks due to their environmental persistence and health impacts (Aborode et al. 2025). These are discussed further in ▶ Chap. 31, "Future Risks of Disease Emergence in Humans, Wildlife, and Livestock in the Congo Basin: Predicting Outcomes Under Current Trends and Policy-Driven Solutions."

Top predators, such as reptiles and carnivores, are similarly susceptible to environmental pollutants and toxins. Hg toxicity has also been linked to neurotoxicity, impaired growth and development, reduced reproductive success and compromised immune function (Day et al. 2007).

An assessment of four African crocodile species Central African slender-snouted crocodile (*Mecistops leptorhynchus*), African dwarf crocodile (*Osteolaemus tetraspis*), West African crocodile (*Crocodylus suchus*) and Nile crocodile (*Crocodylus niloticus*) across five countries and including sites in Gabon and Uganda found that all sampled individuals were Hg-contaminated. The Central African slender-snouted crocodile (*Mecistops leptorhynchus*) exhibited the highest levels of Hg in the muscle tissue, even in remote national parks in Gabon, and surpassing safety thresholds established for human consumption (Lemaire et al. 2024), posing a health risks to the crocodiles, and concerns for human communities relying on crocodile meat as a dietary resource.

Similarly, fish are highly vulnerable to mining pollution because pollutants can enter fish through gills and diet. Bioaccumulation can lead to health problems such as impaired respiration, immune dysfunction and reproductive failure. In Gabon, Hg levels in African sharptooth catfish (*Clarias gariepinus)* exceeded safe human consumption limits (Mikala Okouyi et al. 2024). Pollutants persist in sediments and spread widely, posing long-term, ecological and health risks to fish and dependent wildlife and communities (Emon et al. 2023).

Malnutrition: Effects of Habitat Degradation

Habitat degradation alters food availability and quality for wildlife. Declining food resources and quality exacerbates nutritional deficiencies and malnutrition, reducing host's ability to withstand infections. Deforestation and land conversion reduce the diversity of plant species, leading to the depletion of essential dietary components for frugivores and herbivores (Pessoa et al. 2017). Nutritional stress affects reproductive success and weakens immune systems, thereby increasing susceptibility to disease and disease outbreaks (Eby et al. 2023; Smiley et al. 2024).

Large species such as *Loxodonta cyclotis* and *Gorilla gorilla gorilla* that are reliant on varied and seasonally energy-rich diet have been shown to experience dietary stress due to the loss of fruiting trees and browse species. Reduced protein intake in primates due to habitat disturbance can alter social behaviors and increase mortality rates within these populations. Forest elephants are more likely to inhabit areas with higher fruit availability and tree species richness, and human activities such as logging and hunting particularly affect these habitats, further reducing the availability of essential food resources and contributing to dietary stress in forest elephant populations (Djoko et al. 2022).

Studies have also indicated that the capacity of the ecosystem to support the elephant population may be further decreasing. A study monitoring fruit production over three decades in Lopé National Park protected area in Gabon revealed an 80% decline in yields across the monitored 73 plant species (Bush et al. 2020). Simultaneous observations over a decade on photographic records of forest elephants that rely on these fruiting trees as a major part of the diet indicated a substantial decline (11%) in the elephants' body condition. This reduction in fruit availability has been primarily attributed to climate change, leading to nutritional stress, and the overarching consequence of the declines in the physical condition of the elephants includes the increased susceptibility to diseases.

One Health Interactions Between Diseases and Populations

Beyond wildlife, increasing evidence shows that anthropogenic changes are driving the likelihood of human infections of zoonotic origins (Plowright et al. 2021). These effects are particularly profound in early stages of disturbance to ecological integrity (Marcolin et al. 2024) and therefore particularly important in areas such as Congo Basin where ecosystem integrity is still high.

Tropical areas including the Congo Basin have been identified as particularly high-risk zones for the emergence and spread of pathogens as human activities such as logging and expansion of agriculture disrupt ecosystems and increase contacts between humans, livestock and wildlife (Plowright et al. 2017). The dynamics of viruses are further shifted in response to climate and land-use changes, which are discussed in detail in ▶ Chap. 31, "Future Risks of Disease Emergence in Humans, Wildlife, and Livestock in the Congo Basin: Predicting Outcomes Under Current Trends and Policy-Driven Solutions." In the Congo Basin region, the recent years have seen several disease outbreaks of zoonotic origin in the human population, such as Ebola virus disease, Mpox, Marburg virus disease and trypanosomiasis. Human activities are bringing livestock in closer proximity to wildlife, increasing the likelihood of infectious disease transmission between the domestic species and wild animals (Calkins and Scasta 2020).

An important concept in understanding the dynamic balance of hosts and diseases in the environment is *ecosystem immunity, which* describes how balanced interactions between species, pathogens and environmental factors can buffer from the risk of conditions that lead to high pathogen prevalence, shedding and spillover to new

hosts. Conversely, conditions where there are intense contact between two susceptible species promote increasing pathogen spread (Plowright et al. 2021). Research supports this concept of *dilution effect*, which suggests that naturally high biodiversity can buffer disease transmission because contacts between infectious and susceptible individuals are rarer. The *loss* of this dilution effect is most evident when biodiversity is reduced due to environmental (often anthropogenic) disturbances, rather than natural gradients of reducing biodiversity, such as in mountainous environments (Halliday et al. 2020).

Disease dynamics at the wildlife–livestock–human interface are deeply intertwined with ecological integrity and anthropogenic pressures. The Congo Basin, with its still largely intact ecosystems, stands at a critical juncture where biodiversity and ecosystem function may play a crucial role in the risk of disease in both animals and humans.

Knowledge Gaps and Challenges

We still lack a thorough understanding of wildlife populations in the Congo Basin. For example, almost a fifth of frog species are unstudied, the actual number of amphibians remains unknown, and data on disease presence in and impact on even the most well-studied wildlife species in the region remains deficient. Understanding the impact of pathogens and noninfectious disease threats on wildlife will require both improvements in monitoring of wildlife populations and their ecosystems and in surveillance for diseases that affect them. Growing awareness of the influence of anthropogenic drivers of infectious disease during the last 40 years has driven increased research into this area (Plowright et al. 2021), particularly on zoonoses (Meadows et al. 2023). Despite this, the Congo Basin region remains one of the least studied areas globally. Long-term wildlife disease research in free-living wildlife hosts is scarce in the Congo Basin region despite its relevance to human, livestock and wildlife health (Barroso et al. 2021).

A UK and African Academy of Sciences workshop bringing together scientists from the African region to explore the implementation of One Health approaches in Africa identified several critical challenges and knowledge gaps that must be addressed to advance One Health in the region (AAS 2023). Future efforts, should prioritize solutions to cross-sectoral problems that improve lives and livelihoods in line with the Sustainable Development Goals (WHO, 2025). These solutions should be codeveloped with local communities to ensure they reflect local priorities and concerns and must also contribute to broader health system strengthening, including environmental health (Stephen and Walzer 2023), so that countries are better prepared to prevent, detect and respond to disease outbreaks in alignment with national, regional and global frameworks.

Gaps in leadership, communication and interministerial cooperation continue to undermine effective One Health implementation. WHO capacity assessments and discussions with national health authorities highlight the need to strengthen routine coordination and dialogue between institutions responsible for human, animal and

environmental health. The veterinary sector lacks capacity compared to the human health sector. Under-equipped laboratories' outdated documentation on animal production and health activities and inadequate continuing education in the sector are main as the main challenges and obstacles to strengthening and improving wildlife (and livestock) disease surveillance. Several systemic challenges continue to hamper disease surveillance and response capacity. These include inadequate human resources and management, limited geographic coverage, lack of infrastructure and real-time electronic surveillance systems, absence of sustained vaccination campaigns for livestock and domestic carnivores, and difficulty accessing remote or flood-prone areas. Financial support to improve these barriers remains a key challenge.

The WHO Pandemic Agreement emphasizes the need for international cooperation, respect for human rights and the One Health approach, recognizing the interconnectedness of human, animal and environmental health. It also stresses science- and evidence-based decision-making, fair access to resources and the importance of strengthening national health systems to ensure preparedness and resilience against disease emergence and future pandemics (WHO 2025). There is also a need to build a baseline, as well as adequate capacity for environmental and biodiversity research to support wildlife health monitoring and surveillance (AAS 2023). Currently, there is a lack of extensive evidence for the impact of both infectious and noninfectious diseases on wildlife in the region. One-third of One Health networks lack an environmental component, fewer than half actively perform wildlife surveillance and almost none are led by developing countries (Khan et al. 2018). Organizations like the African Union and AMCEN provide foundations for addressing pollutants. However, policies targeting specific pollutants such as PFAS that are potentially dangerous to human and animal health remain rare.

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Human Influence on Current Status of Biodiversity of the Congo Basin

22

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Abstract

The vast tropical zone of the Congo Basin was historically an intact ecosystem shaped by climatic fluctuations and gradual presence of Hominins (modern humans and close relatives) dating back at least 730,000 years BP. Early hunter–gatherers of the Late Stone Age had minimal ecological impacts. From ~40,000 years BP, the Neolithic introduced slash-and-burn agriculture and iron smelting, pottery, and polished stone tools, leading to localized forest changes during the Iron Age. The Industrial Revolution accelerated transformation with colonial exploitation of timber, ivory, rubber, and other resources, combined with increased hunting and settlement that caused widespread deforestation, biodiversity loss, and human suffering through conflicts and diseases.

Today, the Congo Basin remains a global biodiversity hotspot with over 15,000 vascular plant species, 450 mammal species, 1390 birds, diverse reptiles, amphibians, insects, and highly endemic freshwater fauna. Between 1990 and 2020, it lost roughly 8.5% of its forest cover due largely to smallholder agriculture, logging, mining, and urban expansion. These pressures have fragmented habitats, degraded water quality, and triggered Silent and Empty Forest and River Syndromes—where wildlife populations decline despite remaining forest cover. Key species, including forest elephants and gorillas, face critical threats from habitat destruction and poaching.

Despite advances in genetic and remote sensing technologies coupled with regional conservation efforts, data gaps persist, and socio-political instability and lack of finance limits research and sustainable management. Balancing ecological preservation with human development needs remains urgent to protect the Congo Basin's unparalleled biodiversity and its global climate role for future generations.

Keywords

Anthropogenic threats · Conservation · Data availability · Deforestation · Empty lake and Empty river syndrome · Large mammals · Protected areas · Silent Empty Forest syndrome

Introduction

Human Influence in the Congo Basin

The current status of biodiversity in the Congo Basin has been shaped by climatic oscillations, geological processes, and gradual human occupation (Maley 1996). Geological studies evoking paleoecological evidence suggest that African rainforests have undergone repeated contractions and expansions since the Late Cretaceous, with particularly strong effects during Quaternary glacial–interglacial cycles. Cooler, drier phases fragmented forests into refugia located in coastal Gabon, the Lower Congo, and river valleys, while savannas expanded (Maley 1996). Subsequent interglacials supported recolonization, resulting in high endemism and

phylogeographic differentiation (Maley 1996; White and Oates 1999; Malhi et al. 2013). Sediment cores and pollen records from Gabon, Cameroon, and the Democratic Republic of Congo (DRC) indicate sharp declines in rainforest taxa during arid phases, confirming the refugia hypothesis of Maley (1996). Paleo-fire records further indicate that vegetation shifts were reinforced by human activities: charcoal deposits from Gabon and Cameroon reveal recurrent burning linked to Neolithic farmers and later Iron Age communities (Oslisly et al. 2013). These fire regimes contributed to forest–savanna mosaics and favored disturbance-tolerant taxa such as the oil palm (*Elaeis guineensis*). The Congo Basin experienced late Quaternary refugial diversification but unlike the more fragmented West African forests, it retained a vast contiguous core that buffered biodiversity from extreme contraction (Malhi et al. 2013). Phylogeographic analyses confirm these hypotheses, with taxa such as *Guibourtia demeusei* and *Cercopithecus* monkeys showing genetic signatures of isolation and subsequent diversification (White 2001).

The presence of Hominins (humans and close relatives) in the Congo Basin dates between 730,000 and 620,000 years BP (Braucher et al. 2022), while the modern human settlements were recorded at least 40,000 years (Oslisly et al. 2013). The Late Stone Age hunter–gatherers used pottery and polished stone tools to hunt, fish, and gather wild plants along forest and savanna margins (White and Oates 1999). With low densities, high mobility, and subsistence strategies embedded in natural resource cycles, early foragers maintained a minimal ecological footprint in the Basin. Nevertheless, localized pressures on faunas may have occurred (Naughton-Treves and Weber 2001; White 2001).

The Neolithic Age (~3500 BP) introduced more human-transformative practices. From ~3000 BP, Bantu-speaking migrants brought horticulture, ceramics, and metallurgy (Vansina 1990; Naughton-Treves and Weber 2001). Archaeological evidence in Gabon and Cameroon shows iron slag, ceramics, and charcoal-rich soils, indicating early slash-and-burn cultivation and metalworking (Oslisly et al. 2013). Iron smelting required large quantities of charcoal which accelerated forest clearance, while farming opened new swathes of land. Palynological records thus confirm widespread anthropogenic disturbance (Maley 1996).

The Early Iron Age (c. 2500 BP) marked a turning point, as iron-smelting and more intensive slash-and-burn farming enabled broader forest clearance and soil disturbance (Oslisly et al. 2013). By the Late Iron Age, forest fragmentation became more extensive, with expanding population and agricultural villages influencing faunal communities through hunting, habitat modification, and resource competition. Nevertheless, precolonial shifting cultivation involved extended fallow periods, enabling secondary succession that secured partial biodiversity recovery. Over centuries, human activity left enduring ecological signatures, such as the dominance of useful species like *Dacryodes edulis* and *Irvingia gabonensis* (Naughton-Treves and Weber 2001).

The advent of the Industrial Revolution sparked a radical transformation in the Congo Basin, linking it to global trade and accelerating colonial exploitation. From the fifteenth century, the Congo Basin was integrated into Atlantic trade networks, serving as a source of ivory, ebony (*Diospyros crassiflora*), redwood (*Pterocarpus* spp.), rubber (*Funtumia elastica*), pepper (*Xylopia aethiopica*), and enslaved people (White and Oates 1999). Firearms increased hunting efficiency, targeting elephants

and other megafauna (Naughton-Treves and Weber 2001). By the time of the colonial regimes (late nineteenth and early twentieth centuries), traditional land-use systems collapsed. Rotational shifting cultivation with 20–50-year fallows was replaced with permanent settlements and shortened cycles (5–10 years). Soil regeneration declined, and biodiversity loss accelerated (White and Oates 1999). Simultaneously, concessionary economies mandated large-scale hardwood and rubber extraction, while forced labour, epidemic disease, and violence decimated human populations (Malhi et al. 2013; Oslisly et al. 2013). This phase of Industrial Revolution–colonial interference institutionalized extractive practices, establishing a foundation for the systemic biodiversity crises of today.

Status of Field Biological Surveys

Biodiversity research in the Congo Basin has progressed significantly in recent years through local initiatives, international collaborations, and government efforts. However, most of these efforts have focused on areas in and around protected areas (Watson et al. 2014). Protected areas (see ▶ Chap. 19, "History, Development, and Politics of Protected Areas in the Congo Basin Countries") form the backbone of biodiversity conservation across the Congo Basin; therefore, monitoring biodiversity within them is vital to global efforts aimed at sustainably managing the region's biological resources.

Fauna and Flora Projects focus on regional biodiversity, taxonomy, ecology, ethnobotany, climate change, and conservation. Institutions like African Wildlife Foundation (AWF), African Parks (AP), Kew Gardens (TIPAs), Missouri Botanical Garden (TROPICOS), Smithsonian (ForestGEO), Wildlife Conservation Society (WCS), World Wide Fund For Nature (WWF), Wetlands International, BirdLife International, Congo Basin Institute, CongoPeat, and others collaborate with local universities, national wildlife authority institutions, and scientists to advance research and conservation efforts.

Genetic research in the Congo Basin integrates DNA barcoding, eDNA, phylogenomics, and metagenomics to enhance species identification and biodiversity assessment, particularly for understudied groups (Pereyra et al. 2004; Nagy et al. 2010; Veranso-Libalah et al. 2017; Sonet et al. 2019; Venneman et al. 2019; Stoinski 2022; Roy et al. 2023). These methods reveal genetic patterns across biogeographic regions (Abeele et al. 2021) and aid species detection where morphological identification is difficult (Kress and Erickson 2012), thus leading to (re-)discovery of hundreds of new species (Thompson 2024). eDNA enables species monitoring in aquatic and remote areas (Rees et al. 2014; Marques et al. 2021), detecting rare or elusive species like amphibians and fish—an approach applied in the Yangambi Biosphere Reserve (UNESCO Courier 2023).

Remote sensing and AI-driven technologies, including camera traps, acoustic monitoring, LiDAR, drones, and satellites, are used to map vegetation, track forest

loss, and monitor biodiversity. Large-scale vegetation mapping assesses plant diversity changes from deforestation, climate change, and human activities (Bwangoy et al. 2010; Yuh et al. 2024). Acoustic monitoring offers noninvasive wildlife studies (Astaras et al. 2017; Wrege et al. 2017), while camera traps track animal populations and behavior (Bruce and Fankem 2017; Mugerwa et al. 2024). These technologies are increasingly being applied to conservation and land management, yet their mastery remains at an early stage and is only gradually advancing across the region.

Despite recent advances in biological surveys, many areas of the Congo Basin remain underexplored due to the lack of scientists and sustainable financial investment (White et al. 2021). Reptiles and amphibians are largely understudied despite new species discoveries (Thompson 2024). For example, over the last decade, 742 new species across different taxa have been discovered (Thompson 2024), yet many remain undescribed, and one-third of some major groups face potential extinction due to habitat loss (Stévart et al. 2019; Lack 2022). Political instability, difficult terrain, and limited local capacity hinder research. Expeditions by conservation nongovernmental organizations and universities aim to bridge knowledge gaps, while technology and international collaboration help overcome logistical challenges (White et al. 2021).

Assessment of Available Datasets

Data Availability

The Congo Basin remains underrepresented in biodiversity data. Most global databases lack comprehensive data from the region, focusing instead on specific taxonomic groups or individual-level data such as specimens, photographs, field observations, and genetic information (Table 1). National and regional initiatives have aimed to gather and manage biodiversity data across the basin, though quality and scope vary among nations. Biodiversity inventories and regional databases are typically maintained by environmental ministries or forestry departments as part of commitments to the UN Convention on Biological Diversity (CBD) (UNEP-WCMC 2016). These data are often stored in reports like the National Biodiversity Strategy and Action Plan (NBSAP) (UNEP-WCMC 2016).

The Central African Forests Commission (COMIFAC) coordinates sustainable forest management in the region, maintaining vital databases through the "Observatoire des Forêts d'Afrique Centrale" (OFAC[1]). These databases include data on forest species and threatened species derived from government reports, scientific studies, and field surveys (OFAC[2]; Table 1). The Congo Biodiversity Initiative (CBI[2]) also documents species with support from international conservation organizations.

[1] https://www.observatoire-comifac.net/

[2] https://congobasinscience.net/

Table 1 Global and regional databases hosting biodiversity data from the Congo Basin. Compiled using Internet Search tools

Name	Taxonomic groups included	Description	References
African Plant Database	Plants	Comprises approx. 210,000 names of African plants with their nomenclatural status	(African Plants Database (version 3.4.0) 2016)
AlgaeBase	Algae and other photosynthesizers except embryophyte land plants	Higher taxonomy, scientific names, common names, images, distribution, references	(Guiry and Guiry 2020)
Catfish Species Inventory	Catfish	Information collated by genera, including estimated numbers of species, taxonomic experts	(Sabaj et al. 2006)
AmphibiaWeb	Amphibians	Information about almost 9000 species of amphibians worldwide	(Amphibian Survival Alliance 2023)
Avibase—The World Bird Database	Birds	Information system about all birds of the world, including distribution information, taxonomy, and synonyms	(Avibase 2018)
CITES species database	All species ever listed in CITES Appendices I, II or III	Scientific names, higher taxonomy, distribution, photos, and CITES quotas	(Doellinger 2019)
Encyclopedia of Life (EOL)	All forms of life and viruses	Database with various information about known species	
FishBase	Fish	Higher taxonomy, common names, distribution, IUCN Redlist status	(Froese and Pauly 2013)
Freshwater Ecoregions of the World (FEOW)	Freshwater ecoregions	Maps of species and endemic numbers	(FEOW 2009)
Global Biodiversity Information Facility (GBIF)	All species	Map of known occurrences with data about such occurrences, taxonomy, and links to other databases	(GBIF 2004)
iNaturalist	All species	Geolocated observations, location checklists, taxonomic information, range maps	(iNaturalist 2023)
IUCN	All species	Species conservation status	(IUCN 2025)
Leipzig Catalogue of Vascular Plants (LCVP)	Plants	Standardized taxonomic reference checklist for vascular plants	(Freiberg et al. 2020)
Observatoire des Forêts d'Afrique Centrale (OFAC)	Multidimensional datasets	Species, forests, and environmental data for Central Africa	(OFAC 2025)

(continued)

Table 1 (continued)

Name	Taxonomic groups included	Description	References
Pl@ntNet	Plants identification, observation, images	Plant identification, observations, citizen science project, photographs, distribution	
Plants of the World Online (POWO)	Plants	Digitized data of the world's flora, provides taxonomic information, conservation status, distribution data	(Angelica and Hoffm 2017)
Protected Planet	Terrestrial and marine protected areas	Comprises the most comprehensive global database of terrestrial and marine protected areas, with authoritative statistics on conservation sites worldwide	(UNEP-WCMC 2023)
RAINBIO	Plants	Georeferenced records for vascular plants in continental tropical Africa, including taxonomy, distribution, habitat preferences	(Gilles et al. 2016)
Reptile Database	Reptiles	Taxonomic information, names, photos	(Uetz et al. 2023)
ScaleNet	Scale insects (superfamily Coccoidea)	Nomenclature, distribution, hosts, systematics, references	(García Morales et al. 2016)
Tropicos	Plants	Taxonomy, distribution, and specimen data of approx. 1.4 million scientific names and over 4.4 million specimens	(Tropicos.org 2022)
Wikispecies	All forms of life	Higher taxonomy, synonyms, vernacular names, references	(Wikispecies 2021)
World Checklist of Vascular Plants (WCVP)	Plants	Comprehensive list of scientifically described plant species, compiled over four decades	(Govaerts et al. 2021)
World Flora Online (WFO)	Plants	Comprehensive and authoritative list of vascular plants (flowering plants, conifers, ferns and their allies) and bryophytes (mosses, hornworts and liverworts)	(Borsch et al. 2020)
World Register of Marine Species	Marine organisms	Higher taxonomy, scientific names, synonyms, distribution, attributes, references	(WoRMS 2020)

International organizations like the IUCN through its Red List of Threatened Species and World Heritage Sites provide essential biodiversity data, documenting species distribution, population size, conservation status, and taxonomy. Data on plants, birds, and mammals are relatively abundant, but lesser-known taxa, including amphibians, invertebrates, and freshwater fish, remain underrepresented (Table 1).

The Congo Basin faces significant barriers to biodiversity data availability, including inadequate infrastructure for data collection, storage, and analysis (CBD 2014; UNEP-WCMC 2016). Field stations are often underfunded, and logistical challenges hinder research in remote areas. Existing data are often fragmented, outdated, or incomplete, with inconsistent methodologies used by different research groups (Zimmermann et al. 2014). Ongoing conflict and political instability further limit research efforts (Nackoney and Williams 2012). Herpetological datasets are sparse, though many studies from the past two decades are stored in the Herpetology Laboratory at CRSN Lwiro (DRC). Limited equipment prevents online access, though species lists are available on request, with voucher specimens housed in museums across Africa, America, and Europe.

Data Quality

Central Africa faces challenges in conserving its biodiversity, including limited data availability. Studies are often confined to specific areas, and global databases lack regional refinement. Recent improvements include a platform providing access to 168,000 herbarium specimens from six countries (Ainsa et al. 2023) and RAINBIO's 600,000 georeferenced vascular plant records (Dauby et al. 2016). ECAT offers validated distribution data for 337 endemic woody species (Tack et al. 2022).

Data on medium and large fauna, such as great apes and elephants, remain patchy and noncentralized, often with questionable quality due to inconsistent methodologies. Bird data also exhibit spatial and temporal biases, concentrated near cities, roads, and protected areas (Freeman and Peterson 2019). Citizen science platforms like eBird improve monitoring, though standardized methods and long-term studies are lacking (Bennun 2000). Taxonomic data face accuracy issues, with old voucher specimens often lacking georeferencing. Modern DNA sequencing is needed for accurate species identification, alongside extensive surveys in remote areas.

Diversity Indexes

Various diversity indices are used to quantify and compare species diversity across different forest sites, time periods, or ecological conditions in the Congo Basin (Table 2). These include species richness, Shannon diversity index, Simpson diversity index, Evenness index, Pielou's equitability, and Fisher's Alpha (Table 2).

Table 2 Diversity indices and their rationale used for taxa assessment in the Congo Basin

Taxon	Indices	Rationale	References
Plants	Shannon-Wiener, Simpson	Capture high alpha diversity and evenness in tropical rainforests	(Sosef et al. 2017)
Mammals	Shannon, Hill numbers	Compare community structure and responses to disturbance; camera trap & survey-based data	(van Vliet et al. 2011)
Birds (Avifauna)	Shannon, species accumulation curves	Assess richness and habitat turnover (beta diversity)	(Rodewald et al. 1994, Tonleu et al. 2024)
Amphibians & reptiles	Fisher's alpha, Berger-Parker	Reflect habitat specialization; identify dominant species and sensitivity to microclimatic changes	(Chifundera 2019, Smith and Lim 2025)
Invertebrates	Rarefaction, Chao1	Correct for undersampling in dense forests; estimate unseen species	(Schulze et al. 2004)
Algae & freshwater taxa	Margalef, Shannon	Evaluate ecological quality of rivers and wetlands through diversity metrics	(Taylor and Cocquyt 2015, Cocquyt et al. 2019)

Data and Research Gaps

The region remains under-researched despite its global importance for biodiversity and ecosystem services. Major data gaps exist in species distribution, genetic diversity, and forest carbon stock assessments, often due to limited field surveys, logistical challenges, and insufficient funding. Addressing these gaps with enhanced field research, capacity building (White et al. 2021), and integration of remote sensing technologies is critical to support effective conservation planning and sustainable management of this vital region. Without such efforts, informed decision-making to mitigate habitat loss, climate impacts, and biodiversity decline will remain inadequate.

Current Status of Biodiversity

Habitats and Geographical Extent

An overview of habitat types and their importance in carbon sequestration have been reviewed elsewhere in this book (e.g., ► Chap. 17, "Climate Change and Ecosystem Functions and Services in the Congo Basin"); here, we focus on their geographical extent. The Congo Basin Forest Ecosystem, as defined by the State of the Congo Basin Forests (SPCB), spans 3,462,806 km^2 and dominated by lowland wet (~28%) and dry (~16%) Guineo-Congolian rainforests. The region equally includes extensive swamp forests (13%), mangrove forests (0.3%), Afromontane forests (2.2%),

and transitional rainforest and secondary grassland mosaic (~39%) bordering the north and south of the Congo Basin (White 1983). This vast rainforest is characterized by towering canopy trees, exceptional species richness, and significant carbon storage potential. Plant species diversity ranges from single species stands, such as *Gilbertiodendron dewevrei*, to highly mixed forest assemblages (Devers and Vande Weghe 2006).

Wetlands and swamp forests, concentrated in the Cuvette Centrale region, are critical for hydrological regulation and carbon sequestration (Bwangoy et al. 2010; Tshimanga et al. 2022). These areas also include floodplains and seasonally inundated forests such as the Ngiri Swamps and Igapo forests, which provide key breeding habitats for fish and other aquatic species (Mbimbi et al. 2021). Mangrove forests, though limited to coastal Gabon, Cameroon and Congo, play an outsized ecological role by offering nursery grounds for marine species and acting as important carbon sinks (Alongi 2002; Ajonina et al. 2014).

The freshwater ecosystem which covers over 10% of the region, include lakes, swamps, and a dense network of river channels, divided into 17 ecoregions (Gumbricht et al. 2017; Hastie et al. 2021). These freshwater habitats contain one of the world's richest fish faunas, with over 1300 species, many of them endemic (Mputu et al. 2022; Deo Mushagalusa et al. 2024).

Transitional rainforest and secondary grassland mosaic, sometimes referred as savannahs, occur in northern Cameroon, southern DRC, and the Congo River periphery. Maintained by seasonal rainfall, wildfires, and herbivory, these zones form transitional zones between forest and woodland systems, supporting herbivores such as buffalo and antelopes as well as apex predators like lions (Sankaran et al. 2005; Dalimier et al. 2022). Miombo woodlands, more extensive in the southern and eastern basin, are open-canopy woodlands characterized by high faunal diversity, especially large mammals and birds (Ribeiro et al. 2013).

The Basin also contains dynamic forest-savanna ecotones, which shift in response to climate and fire, supporting species adapted to both habitats (Eba'a Atyi et al. 2022). Gallery forests line river systems, acting as ecological corridors and providing connectivity for species dispersal (de Wasseige et al. 2014).

Soils across the Congo Basin are dominated by Ferrasols and Acrisols, which are nutrient-poor but capable of supporting high biodiversity (Ngongo et al. 2014). Soil fertility is highest near volcanic regions in eastern DRC and Mount Cameroon (Inogwabini 2021). Human-driven pressures such as logging, agriculture, and mining have caused soil erosion over 32% of the basin (Mushi et al. 2019).

Flora and Fauna Diversity

The region is home to exceptional levels of amphibian, bird, fish, flora, and mammal diversity. Highlighting the dynamism of the region, at least 742 new species—including plants, animals, and fungi—were described between 2013 and 2023 (Thompson 2024), emphasizing the ongoing discoveries that enrich our

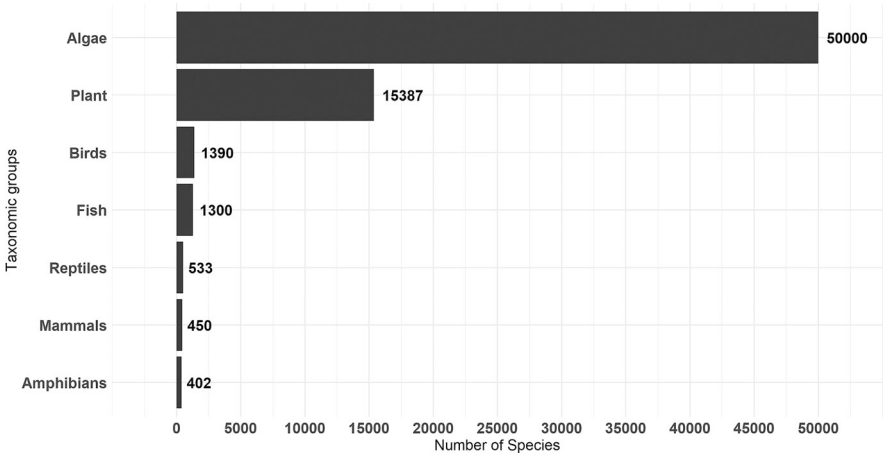

Fig. 1 Species numbers by taxonomic group (The number of amphibians comes from the compilation of data from countries with the most amphibian species: https://worldrainforests.com/03amphibian.htm)

understanding of this vital tropical biome and pointing to the critical need for sustained conservation efforts.

Vascular plants alone number approximately 15,387 species, including over 3000 tree species that account for 5–7% of tropical flora worldwide (Sosef et al. 2017; Thompson 2024). This extraordinary botanical diversity is driven by varied mid- and high-altitude landscapes, which foster speciation through spatial heterogeneity and a suitable climate (Linder 1985; Beekmann et al. 2024).

Large Mammals

The Congo Basin hosts extraordinary biodiversity yet remains one of the least-studied tropical regions on Earth. With an estimated 450 large mammal species (Thompson 2024), new discoveries continue to underscore its global importance for biodiversity conservation. While new primate species designations worldwide are often the result of splitting existing taxa or elevating subspecies, the description of an entirely new monkey species—*Cercopithecus lomamiensis* (lesula)—in 2012 was an exceptional event (Hart et al., 2012). More recently, in 2015, the "rediscovery" of Bouvier's red colobus monkey (*Piliocolobus bouvieri*), after four decades without a confirmed sighting and once thought to be extinct but long known to local communities (Thompson 2024), further highlighted the extent of our limited knowledge of the region's biodiversity.

Forest elephants, gorillas, lions, giraffes, chimpanzees, mandrills, forest buffaloes, bonobos, okapis, and giant pangolins are among the region's flagship mammals (Morgan et al. 2011; Bauer et al. 2015; IUCN 2021). The central African chimpanzee, mountain gorilla, western lowland gorilla, and forest elephant are especially at

risk, now classified as critically endangered due to habitat loss, poaching, and human-wildlife conflict (Morgan et al. 2011; Wittemyer et al. 2014; IUCN 2021). Species with restricted ranges, such as the sun-tailed monkey, okapi, and bonobo, are additionally vulnerable, often exacerbated by habitat fragmentation and hunting (Hickey et al. 2013).

In Cameroon, forest elephants and Cross River gorillas (*Gorilla gorilla diehli*) are imperiled by habitat decline and poaching, while lion (*Panthera leo*) and Kordofan giraffe (*Giraffa camelopardalis antiquorum*) populations continue to dwindle (Poulsen et al. 2017). Gabon, famously dubbed the "Last Eden," shelters forest elephants, western lowland gorillas (*Gorilla gorilla gorilla*), and chimpanzees (*Pan troglodytes*) across its extensive rainforests and 13 national parks, though poaching and habitat degradation remain significant concerns. The DRC is a critical stronghold for forest elephants, Grauer's gorillas (*Gorilla beringei graueri*), and okapis (*Okapia johnstoni*), but these species are severely threatened by poaching, deforestation, and prolonged civil conflict, with Grauer's gorilla populations plummeting by 77% since the 1990s (Walsh et al. 2003; Plumptre et al. 2016, 2021). The Central African Republic (CAR) offers refuge for forest elephants (*Loxodonta cyclotis*), western lowland gorillas, and forest buffaloes (*Syncerus caffer nanus*), but protected areas such as Dzanga-Sangha National Park continue to face pressures from illegal hunting, habitat loss, and political instability (Bouché et al. 2011). Similarly, the Congo serves as sanctuary for many of these species yet grapples with poaching, habitat conversion, and devastating disease outbreaks, notably Ebola (Maisels et al. 2013).

Population studies reveal alarming declines: forest elephants suffered a 62% reduction between 2002 and 2011 (Maisels et al. 2013). Savannah elephants in northwestern DRC followed a similar pattern, decreasing from an estimated 25,000 individuals in 1976 to around 1200 by 2005 (de Merode et al. 2005). Earlier surveys broadly categorized all gorillas in eastern DRC, Rwanda, and Uganda as mountain gorillas (Schaller 1963). However, subsequent research distinguished Grauer's gorillas (now considered a subspecies of eastern gorillas), documenting steep declines driven by conflict and insecurity, though recent surveys offer cautious optimism with localized population recoveries (Hall et al. 1998; Plumptre et al. 2016, 2021). If mountain gorilla numbers have increased, it is a testament to successful intensive conservation efforts. However, Ebola outbreaks have devastated western lowland gorillas, with mortality rates reaching 95% in certain populations (Walsh et al. 2003), exemplified by the dramatic reduction of one gorilla group in Odzala-Kokoua National Park from 380 to fewer than 40 individuals (Genton et al. 2012).

The northern white rhinoceros (*Ceratotherium simum cottoni*), once widespread across northwestern Uganda, northeastern DRC, South Sudan, Sudan, CAR, and Chad, has not been sighted in the wild since 2005, collapsing from around 500 individuals in 1976 despite considerable conservation investments (Hillman-Smith and Smith 1986, de Merode et al. 2005). Likewise, giraffe populations in the region have declined precipitously from approximately 350 individuals in 1997 to around 50 by 2005 (de Merode et al. 2005).

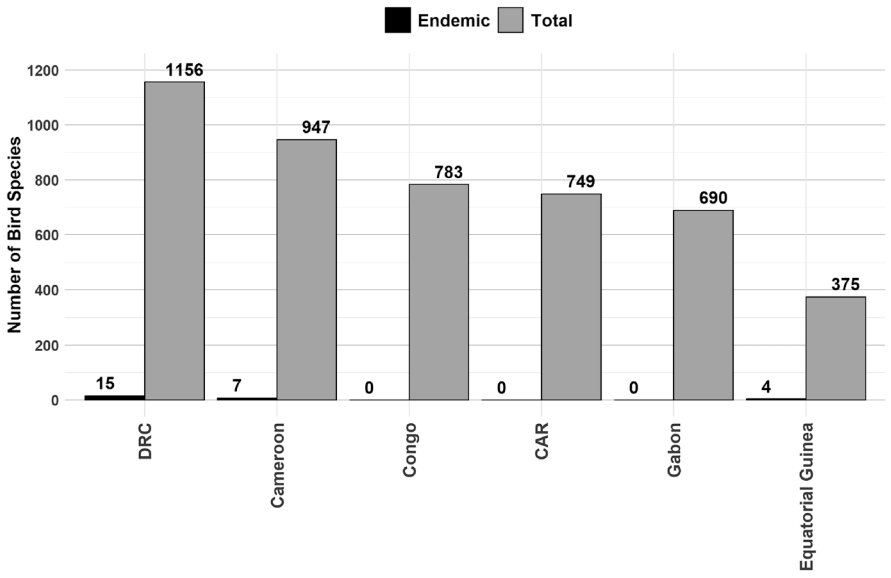

Fig. 2 Bird species and endemic species per country in the Congo Basin

Birds

Much of the region remains unsurveyed, as bird inventories are concentrated around protected areas, major roads, and accessible facilities, suggesting that actual bird diversity may exceed current estimates. Despite this, it is estimated that the region hosts approximately 1390 bird species (Borrow and Demey 2014; Fig. 2). Overall, bird populations are threatened with habitat destruction, degradation, poaching for food, body parts trade (e.g., vultures, raptors, hornbills) and live bird trade (parrots and other songbirds). Although poorly documented and not monitored, it is believed that bird trade has seriously impacted the population of many bird species, as is the case of Grey Parrot *Psittacus erithacus* (Reinhold et al. 2021).

Reptiles and Amphibians

Few surveys of amphibians and reptiles have been conducted in Cameroon, the DRC, Gabon, and Congo, leaving large portions of the Congo Basin unexplored (Jackson and Blackburn 2010; Chifundera 2019). Taxonomic knowledge is gradually improving, but species distributions remain unevenly documented, with most known species occurring in DRC and Cameroon. Many species are rare, except those in the families Hyperoliidae and Arthroleptidae. Increased scientific interest has led to the discovery of several endemic species, revealing centers of endemism and radiation (Thompson 2024). Since the late 1990s, the known species count has risen by about 20%, primarily due to intensified research and conservation efforts by

COMIFAC member states (Gonwouo et al. 2006, 2007; Thompson 2024). Between 2013 and 2023, more than 60 new amphibian and reptile species were described, further highlighting the exceptional biodiversity of the region and underscoring the urgent need for continued exploration and conservation (Thompson 2024). Bushmeat harvesting, among others, is a major threat to amphibians and reptiles especially in the DRC (Chifundera et al. 2014).

Insects

Insects also thrive in the Congo Basin (Nair 2007), but studies on them are particularly scarce (Beekmann et al. 2024). Reports show an approximate 86% reduction in average body mass of edible caterpillars—particularly *Imbrasia oyemensis*, *Pseudantheraea discrepans*, and *Imbrasia truncata*—which are now generally smaller and have shorter lifespans (Beekmann et al. 2024), thereby reducing their availability as a food source for households in the Central African Republic. This decline is paralleled by findings in central Cameroon, where (Ngute et al. 2020) documented a scarcity and decrease in caterpillar abundance—primarily attributed to logging of host trees, climate change, and slash-and-burn agriculture.

Freshwater Diversity

Freshwater ecosystems across the basin—including rivers, floodplains, swamps, and rapids—are under threat from land use changes and increased fishing pressure linked to demographic growth and economic challenges (Thieme et al. 2005; Kamdem et al. 2006). These threats parallel patterns seen in the bushmeat trade, further threatening aquatic biodiversity (Inogwabini 2013, 2025).

The Congo River boasts Africa's highest freshwater fish diversity and ranks second globally after the Amazon (Snoeks et al. 2012). The Congo Basin, including Lakes Kivu and Tanganyika, hosts approximately 1309 freshwater species across 252 genera, 46 families, and 23 orders (Froese and Pauly 2013; Fig. 1). About 75% of these species are endemic, with the highest endemism in Lake Tanganyika (71–100%) and the Kasai ecoregion (21–29%) (FEOW 2009). The Kasai ecoregion is richest with 407 species, followed by Cuvette Centrale (361), Lake Tanganyika (350), Lower Congo regions (330 combined), and Pool Malebo (317) (Froese and Pauly 2013; Mbimbi et al. 2021). However, the fish diversity is likely underestimated, with new species described annually and molecular studies revealing geographically restricted distributions (Ibala Zamba et al. 2022; Kalumba et al. 2023). Besides fish species, various aquatic plants—280 aquatic frog species, 20 aquatic snake species—have been recorded (Harrison et al. 2016).

Decline in freshwater fish abundance has been documented only in limited areas. However, fish stocks have generally declined in some parts of the basin, largely attributed to overexploitation (Brooks et al. 2011). In the DRC, declining catch per unit effort (CPUE) was reported in Lake Tanganyika fisheries, Pool Malebo and

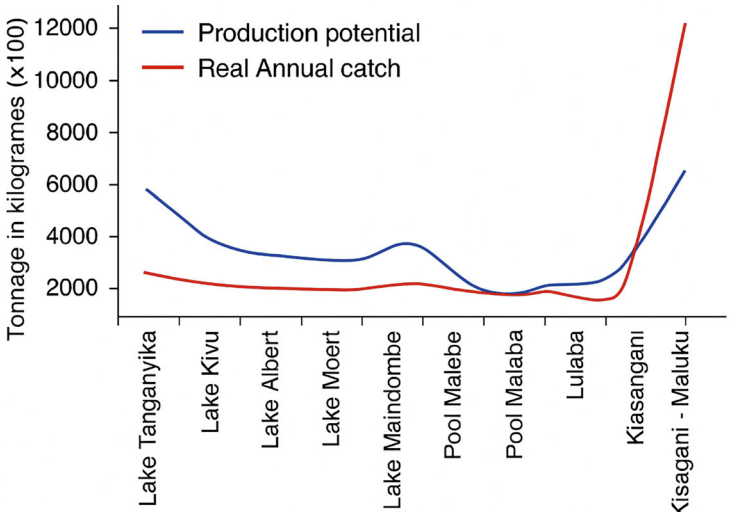

Fig. 3 Production potential and effective catch of fish by aquatic habitats of the Congo (Inogwabini 2020)

Lake Mai-Ndombe due to inappropriate fishing practices, overfishing and habitat destruction (Micha et al. 2018; Jean Métis et al. 2022). The Congo stretch between Kisangani and Maluku appears overfished (Fig. 3), whereas Lake Mai-Ndombe's fish productivity matches annual catch (Brooks et al. 2011). Some areas, including Lakes Tanganyika, Kivu, Albert, Moero, and Edward, show relatively stable fish populations, though recent trends indicate increasing juvenile catch and declined overall harvest, pointing toward unsustainable fishing practices (De Keyzer et al. 2020; Deo Mushagalusa et al. 2024).

Phytoplankton diversity studies have mostly been restricted to a few lakes. In the DRC, research in Lakes Kivu, Tanganyika, and Mweru shows Cyanophyceae dominance, notably, Microcystis flos-aquae, Planktolyngbya limnetica, and Synechococcus species, alongside Bacillariophyta (Damas 1937; Verbeke 1957; Hyangya et al. 2021). Cyanophyceae blooms, which can produce cyanotoxins, have implications for water quality and public health. In Cameroon, studies in Lake Ossa, crater lakes, and estuarine systems have documented 507 phytoplankton species, with Bacillariophyta, Chlorophyceae, and Cyanophyceae most abundant (Kemka et al. 2006; Nguetsop et al. 2008; Kueppo et al. 2023). Many of these investigations have been conducted in areas with human influence, such as municipal lakes or watersheds affected by agriculture, reflecting both the accessibility of these sites and the ecological signals of anthropogenic disturbance.

Zooplankton, like phytoplankton, is understudied. Early surveys emphasized biomass rather than species richness (Verbeke 1957). Intensive sampling since the 2000s in Cameroonian lakes revealed 212 species, dominated by Rotifers and Ciliates, with rare species such as *Mesocyclops leukarti* newly reported (Zebaze Togouet 2000; Zébazé Togouet et al. 2005). Research in estuarine zones, where

human activity such as fishing and pollution is higher, has highlighted shifts in community composition, with Copepods dominating and Rotifers and Cladocerans declining (Essomba Biloa et al. 2021; Manfothang et al. 2022).

Bacterioplankton includes pathogenic bacteria such as *Escherichia coli*, *Vibrio cholerae*, Pseudomonas, fecal coliforms, and streptococci, reflecting contamination from human activity (Nola et al. 2013; Noah Ewoti et al. 2021). Although these bacteria are not the causal agents of disease in all cases, their presence has guided monitoring efforts, particularly in human-impacted water bodies, demonstrating how anthropogenic pressure directs research focus.

Benthic macroinvertebrates are widely used as bioindicators of ecosystem quality. Surveys in tributaries of Cameroon, DRC, Gabon, and the Central African Republic reported 117 genera across five phyla (Foto Menbohan et al. 2012; Mbete et al. 2021). Decapods such as *Atyaephyra africana* occur widely and serve as sensitive indicators of ecosystem integrity (Mboye et al. 2018). Other aquatic invertebrates, including semiaquatic arthropods such as *Rhabdoblatta fotoi* and *Africalolampra camerunensis*, highlight the uncharted diversity of freshwater ecosystems and suggest that human-altered habitats may reveal previously unnoticed species (Nyame Mbia et al. 2024). The focus on sites affected by urbanization, agriculture, and resource exploitation illustrates how human influence has indirectly shaped our understanding of BMI diversity patterns.

Current Human Influence on Ecosystem Health

Availability, Continuity, and Quality of Ecosystem Services

Overall, between 1990 and 2020, the Congo Basin has lost about 8.5% of its total forest or the equivalent of 352,000 km^2 (Yuh et al. 2024). Causes of this loss include those discussed in ▶ Chaps. 10, "The Ecological Functions of Congo Basin Ecosystems and Basin-Wide Carbon Cycle," ▶ 12, "Agriculture, Ecosystem Functions, and Services in the Congo Basin," ▶ 13, "Pastoralism: Access to Land and Ecosystem Functions and Services in the Congo Basin" and ▶ 16, "Hunting, Fishing, and Ecosystem Functions and Services in the Congo Basin" describing how habitats and ecosystems of the Congo Basin are currently fragmented due to a cohort of economic and livelihood activities. Combined effects of the above drivers have made it that no ecosystem in the Congo Basin remains entirely intact, even though in relative terms such big areas as Salonga National Park (DRC), Likouala-aux-herbes and Odzala-Kokoua (DRC) and Minkebe (Gabon) have not been converted in open land yet.

Agriculture (▶ Chaps. 10, "The Ecological Functions of Congo Basin Ecosystems and Basin-Wide Carbon Cycle") practices such as shifting cultivation have been a long-standing land-use system, but rapid population growth has shortened fallow periods, undermining forest regeneration. Smallholder farming remains the dominant driver of forest loss, accounting for ~84% of deforestation (2000–2014), largely through slash-and-burn cultivation (Tyukavina et al. 2018). Expansion of cropland areas have occurred, ranging within 35,336–86,181 km^2 throughout the

Congo Basin for the period 2010–2020 (Yuh et al. 2024). For Yuh et al. (2024), between 1990 and 2000, cropland areas increased from 1834 km^2 to 32,797 km^2, totaling over 30,962 km^2 of land clearance. Between 2000 and 2010, cropland areas expanded from 32,797 km^2 to 35,336 km^2; a further expansion was observed from 35,336 km^2 (2010) to 50,845 km^2 in 2020. Yuh et al. (2024) found the largest expansions in cropland areas to occur in the DRC and Cameroon. In DRC, cropland area expanded by about 14,112 km^2 for the period 1990–2000. In the next decade, 2000–2010, the cropland expanded by about 3016 km^2, with a further expansion in the following decade (2010–2020) converting about 27,948 km^2. In Cameroon, cropland expanded by over 11,812 km^2 in the period of 1990–2000; between 2000 and 2010, about 4331 km^2 were converted into cropland expansion, which also was the case for about 6619 km^2 in the period 2010–2020. Timber extraction (▶ Chap. 12, "Agriculture, Ecosystem Functions, and Services in the Congo Basin") covers about 530 km^2 throughout the Congo Basin. Commercial forestry, both industrial and artisanal, now covers vast areas of the Congo Basin, exerting significant direct and indirect impacts. Direct impacts include the selective removal of high-value species such as Okoumé (*Aucoumea klaineana*) and African mahoganies (*Entandrophragma* spp.), while collateral damage from skidding and felling alters forest structure and architecture (White 2001). Indirect impacts often prove more severe; logging roads open access to previously remote areas, amplifying secondary pressures such as hunting, settlement expansion, fragmentation, and increased edge effects (Naughton-Treves and Weber 2001). Mining (▶ Chap. 13, "Pastoralism: Access to Land and Ecosystem Functions and Services in the Congo Basin") has been responsible for converting about 150 km^2. Gold mining introduces mercury into waterways, threatening aquatic biodiversity and human health. Coltan, cobalt, and diamond extraction cause localized deforestation and river sedimentation, often in poorly regulated contexts Mining camps intensify bushmeat hunting, while regulatory gaps fuel unmonitored exploitation and ecological degradation (Naughton-Treves and Weber 2001). In both agriculture and mining, the artisanal forms of these activities have been identified to cause more land degradation and habitat clearance than industrially organized forms.

Urbanization (▶ Chap. 16, "Hunting, Fishing, and Ecosystem Functions and Services in the Congo Basin") fragments and converts more habitats than it is conventionally believed. Indeed, just the four major towns of the Congo Basin (Bangui, Brazzaville, Yaoundé, and Kinshasa) currently occupy 10,999 km^2, with Kinshasa having the largest share (90%) of all the habitat fragmentation. Additional causes discussed by Yuh et al. (2024) include increases in human populations and climate change.

The DRC has experienced an expansion in built-up areas of approximately 7698 km 10,538 km^2 between 1990 and 2000; 2358 km^2 between 2000 and 2010; and 10,538 km^2 between 2010 and 2020. Cameroon has experienced an expansion in built-up areas of approximately 7341 km^2 between 1990 and 2000; 715 km^2 between 2000 and 2010; and 5672 between 2010 and 2020. For these two countries, Yuh et al. (2024) predicted an expansion of 21,300–29,548 km^2 and 14,395 to 16,330 km^2 respectively for the period expansion for 2020–2050. Key predictors of built-up

expansions conversions ranged from woody savannahs, grasslands, and open savannahs, as well as dense forests, to built-up areas include human population density.

Yuh et al. (2024) suggested that if current trends continue, Congo Basin could lose another 174,000–204,000 km^2 (3.7–4%) of its current forest cover by 2050; for the period 2020–2050, they project a conversion of 91,234–101,618 km^2 into cropland areas. For DRC and Cameroon, Yuh et al. (2024) project crop land areas to increase respectively by 47,683–54,759 km^2 and 17,804–21,277 km^2 respectively from 2020 to 2050.

Among the major services that ecosystems of the Congo Basin provide to its human populations, air quality and drinking water quality are negatively affected by different human activities, including mining (13) and urbanization (16). Concentrations of particles in the air and the water quality have been consistently above the norms promoted by the World Health Organization for good human health.

Silent and Empty Forest Syndrome Throughout the Congo Basin

Since the early 1960s, the metaphor of the silent spring (Carson 1962) equates silence within ecosystems to indicate spaces where no voices of wildlife are heard. The empty forest concept is used in biological assessment as an indicator of wildlife being hunted out while standing trees continued to thrive (Oates 1999). Absence of calls from guenons is particularly important because this group of species has indicated the health of the ecosystems in which they occur (e.g., (Gautier-Hion AMC et J-PG 1999)). No systematic studies of silent and empty forest syndrome have been conducted throughout the Congo Basin. The only survey to be conducted on the regional scale was the one on forest elephants in the early 2000s (Blake et al. 2007). These authors found that large, protected areas such as Salonga National Park in DRC, Dja Biosphere Reserve and Boumba-Bek (both in Cameroon) had large areas with very limited presence of large mammals and qualified as empty forest where even calls of guenons and other species were difficult to hear. Fortunately, wildlife can return to empty forests if source populations remain and better management practices are enforced, as it is currently being reported from some parts of the Salonga National Park (DRC) (Inogwabini 2025).

Empty Lake and Empty River Syndrome Throughout the Congo Basin

As with the "Empty Forest Syndrome," this also refers to the absence of wildlife in lakes and rivers due to habitat degradation and overexploitation (Antunes et al. 2016). While this syndrome has not been formally reported in the Congo River Basin, it is prevalent in small creeks in cities like Kinshasa and Brazzaville and at mining sites, where human settlements, erosion, and pollution have severely altered environmental flows and destroyed habitats (Tobit Liyandja *pers.obs.*). As human populations grow and mining expands in the Congo Basin, this phenomenon is spreading rapidly. For example, an assessment by Mputu et al. (2022) indicated that levels of fish off-takes

from Lake Tumba were exceeding thresholds of sustainability to the point that local communities refer to the lake as becoming more of an empty water body.

Competing Interest Declaration The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

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Opportunities and Potential for Sustainable Development in the Congo Basin from an Environmental Sustainability Perspective

23

Danae Maniatis and Kathryn J. Jeffery

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Abstract

The Congo Basin, comprising the world's second-largest tropical rainforest, presents both critical environmental challenges and unique opportunities for sustainable development. This chapter evaluates key pathways for environmentally sustainable development in the region, with an emphasis on extractive

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industries, renewable energy, agroforestry, biodiversity conservation, ecotourism, and climate and carbon finance. Using regional indicators such as the Fragile States Index (FSI), Human Development Index (HDI), and Environmental Performance Index (EPI), the authors highlight the structural barriers—including weak governance, institutional fragility, and extreme poverty—that constrain the region's development trajectory. Despite these challenges, the Basin's ecological wealth offers potential for transformative interventions. Strategies such as Reduced-Impact Logging for Climate (RIL-C), sustainable mining practices, decentralized renewable energy systems, and integrated agroforestry models are analyzed for their capacity to reduce emissions, protect biodiversity, and enhance local livelihoods. The chapter further explores the potential of REDD+ and emerging carbon market frameworks to finance conservation and climate mitigation efforts. Emphasizing the role of participatory governance, indigenous knowledge systems, and scientific innovation, the chapter underscores the necessity of context-specific, cross-sectoral approaches to operationalize sustainability in one of the planet's most ecologically and geopolitically complex regions.

Keywords

Sustainable development · Congo Basin forests · Environmental policy and governance · Climate and carbon finance · Agroforestry systems · Reduced-impact logging

Introduction

The previous chapters have highlighted the critical value of the Congo Basin, emphasizing its vast ecosystem services, exceptional biodiversity, essential role in global climate regulation, rich cultural diversity, and the extensive historical and growing modern impacts of human activity on its ecosystems. Building on this foundation, the present chapter aims to explore the key opportunities and potential pathways for sustainable development across the Congo Basin.

The key components of sustainable development are typically grouped into three core pillars, often referred to as the "triple bottom line," with several cross-cutting principles and concepts that run through all pillars (e.g., governance, resilience, etc.):

1. Environmental sustainability: preserving the planet's ecosystems and natural resources for future generations
2. Social sustainability: ensuring social equity, inclusion, and community well-being
3. Economic sustainability: promoting economic growth that is inclusive and long-lasting

Treating all three pillars of sustainability is beyond the scope of this chapter, which will focus on key environmental sustainability elements.

To properly assess these opportunities, it is crucial to understand the current situation and evaluate how realistic it is to implement sustainable change at scale and at an appropriate pace within each country.

This can be approached in many ways; here, we look at the Fragile States Index (FSI), the Human Development Index (HDI), and the Environmental Performance Index (EPI).

The FSI, produced annually by the Fund for Peace, offers a snapshot of a country's resilience or vulnerability, allowing for comparisons over time. The relative "fragility" of the region's nation-states, as fragility directly influences essential pillars of development, such as national economies, political stability, social cohesion, and security. According to the 2024 Fragile States Index, several Congo Basin countries are among the most fragile in the world: the Democratic Republic of Congo (DRC) ranks 5th, Central African Republic (CAR) 7th, Cameroon 20th, the Republic of Congo (RoC) 29th, and Equatorial Guinea 42nd (Fig. 1). Despite the recent military coup, Gabon is not considered a fragile state, ranking 79th on the list. Nevertheless, the region as a whole faces major structural challenges, notably widespread corruption, weak governance, and fragile institutional frameworks. These issues significantly hamper the creation of a transparent and stable environment for sustainable development policies, private investment, and donor engagement.

The Human Development Index (HDI) provides another lens through which to assess the prospects for sustainable development. Compiled by the United Nations Development Programme (UNDP), the HDI measures three core dimensions: health (life expectancy), education (mean and expected years of schooling), and standard of

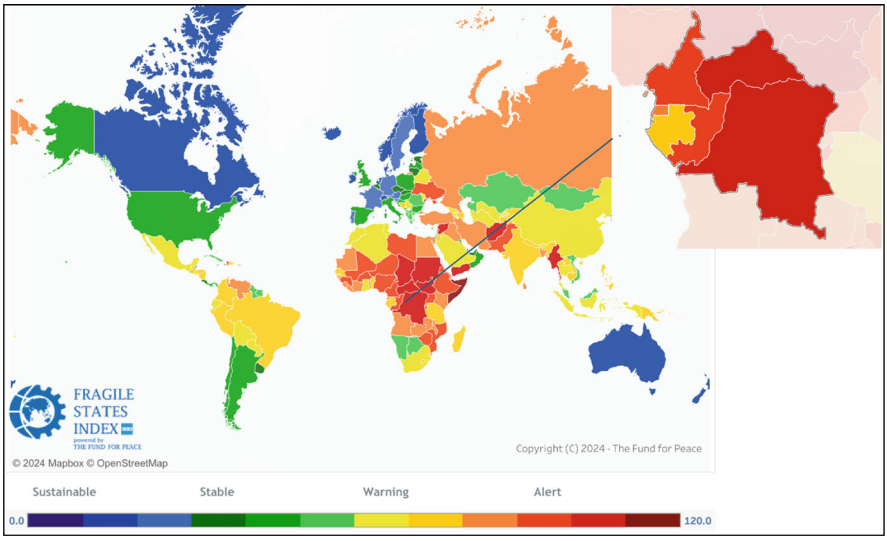

Fig. 1 Fragile States Index Heat Map, with zoom-in to Congo Basin countries. (Source: Fragile States Index)

living (gross national income per capita). It reflects the overall well-being and capabilities of a country's population rather than its vulnerability to conflict or collapse.

The EPI provides a data-driven summary of the state of sustainability around the world using 58 performance indicators across 11 issue categories. It ranks 180 countries on climate change performance, environmental health, and ecosystem vitality (Fig. 2). None of the Congo Basin countries rank highly on the EPI: Gabon 44th, Equatorial Guinea 114th, Republic of Congo 116th, Democratic Republic of Congo 128th, Central African Republic 132nd, and Cameroon 136th.

When comparing the indices, a clear pattern emerges: countries with high fragility scores in the Congo Basin also consistently rank low in human development and environmental performance. Out of 191 countries, DRC ranks 179th on the HDI, CAR 188th, RoC 153rd, and Equatorial Guinea 145th. Gabon stands out again, with a relatively higher HDI rank of 112th, reflecting better health, education, and income levels compared to its neighbors.

The combination of high fragility and low human development impacts environmental performance and highlights the profound challenges facing the region. Weak governance, low-income levels, limited access to quality education and healthcare, and a lack of economic diversification all hinder sustainable development efforts.

Moreover, these difficulties are exacerbated by broader regional trends. Central Africa exhibits the highest extreme poverty rate on the continent, with 54.8% of the population living in extreme poverty (Institute for Security Studies 2022). Rapid population growth compounds these challenges, as the Congo Basin's population is expected to double by 2050 (see ▶ Chap. 18, "Urbanization, Biodiversity, Ecosystem Functions and Services in the Congo Basin"), significantly increasing pressure on natural resources, infrastructure, and social services.

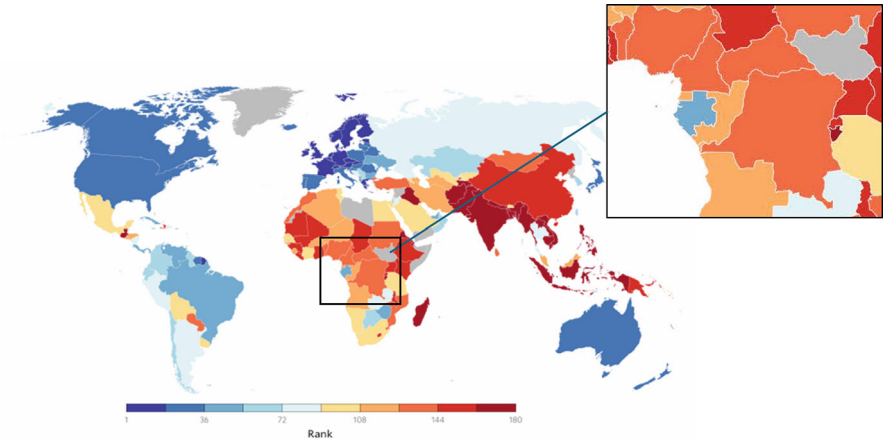

Fig. 2 Rankings in the Environmental Performance Index, with zoom-in to Congo Basin countries. (Source: Environmental Performance Index)

Thus, any realistic discussion of sustainable development opportunities in the Congo Basin must be framed within this challenging socio-economic and political context. Recognizing both the significant barriers and the immense potential of the region is critical for designing strategies that are not only ambitious but also feasible and context sensitive.

Sustainable Development from an Environmental Sustainability Perspective in the Congo Basin

Sustainable development seeks to balance the current needs of economic growth, environmental protection, and social well-being without compromising the ability of future generations to meet their own needs.

In the context of this report and building on the previous chapters, we identify key categories of opportunities for sustainable development from an environmental sustainability perspective in the Congo Basin:

1. Improved practices in the extractive industries, including forest management and mining
2. Transitioning to renewable energy
3. Agroforestry and sustainable agriculture
4. Protected areas and biodiversity management and ecotourism
5. Climate and carbon finance mechanisms

This section provides a brief overview of each of these opportunities, outlining their potential contributions to a more sustainable future for the Congo Basin.

Improved Extractive Industry Practices

Extractive industries, including oil and minerals, are crucial drivers of economic activity and development in the Congo Basin, providing significant revenue and employment opportunities, yet their extraction also presents substantial environmental and social challenges. Mineral wealth, particularly copper and cobalt in the DRC, and oil reserves in countries like Gabon and Equatorial Guinea, are major contributors to national economies through exports and potential for growth.

Improved extractive industry practices, particularly in logging and mining, have the potential to generate significant socio-economic and environmental benefits for the Congo Basin. Sustainable logging practices, such as Reduced-Impact Logging for Climate (RIL-C), offer a promising pathway to balancing timber production with environmental conservation. Sustainable development related to extractive industry practices must simultaneously seek to maximize jobs and benefit to Congo Basin country economies while minimizing environmental impacts, both linked to pollution from the mining process and deforestation.

Sustainable Logging and Forest Management Plans

Approximately one-third of the Congo Basin forests are managed as productive logging concessions with mandatory Forest Management Plans (Tritsch et al. 2020). However, this proportion varies greatly between countries: Equatorial Guinea (~78%), Republic of Congo (~74%), and Gabon (~64%) have the highest proportions of forests under logging concessions, while Cameroon manages roughly one-third of its forests under this system (Central African Forest Initiative 2024; Corbier-Barthaux 2012; Forest Trend 2024). By contrast, in the Democratic Republic of Congo (DRC), only about 10–12% of forests are formally managed in this way—here, most forest use is artisanal or nonindustrial (Central African Forest Initiative 2024).

While logging does contribute to deforestation in the Congo Basin, logging for timber export has a significantly lower impact compared to other forms of logging. There is a strong inverse relationship between timber exports and deforestation rates. Between 2010 and 2020, countries with the highest timber export values and processing rates—such as Gabon (0.02%) and Cameroon (0.04%)—had the lowest national deforestation rates. Conversely, countries with the lowest export values and minimal processing—like the DRC (0.46%) and the CAR (0.27%)—experienced the highest rates of deforestation (Eba'a Atyi et al. 2022).

Selective logging in the Congo Basin is a significant source of greenhouse gas emissions—potentially accounting for up to ~40% of the region's combined emissions from deforestation and degradation (Ellis et al. 2019; Umunay et al. 2019). However, when conducted under mandatory Forest Management Plans and sustainable practices, logging can also act as a land-use strategy that helps maintain forest cover and reduce large-scale deforestation, thereby potentially lowering net emissions over time (Tritsch et al. 2020).

RIL-C practices offer an innovative solution to mitigate the environmental impact of logging by lowering greenhouse gas emissions and preserving the forest's capacity to sequester carbon. RIL-C techniques, which include constructing fewer and narrower access roads, meticulous tree selection, mapping of skid routes, and the use of specialized forestry equipment, have been shown to reduce forest damage while maintaining timber production (Ellis et al. 2019). In the Congo Basin, Umunay et al. (2019) estimate that adopting best-practice RIL-C methods across Forest Management Enterprises (FMEs) could avoid nearly 50% of logging-related emissions. Beyond emission reductions, sustainable forest management approaches like RIL-C also help maintain more intact canopy structure, larger residual tree populations, and healthier forest regeneration, which together enhance the forest's ongoing carbon sequestration potential and long-term storage capacity (Ellis et al. 2019). Thus, widespread adoption of RIL-C can contribute to significant climate benefits by simultaneously reducing emissions from degradation and sustaining the carbon sink function of tropical forests.

Scaling up RIL-C in the Congo Basin presents important opportunities, though several challenges must first be addressed. These include limited technical capacity among logging companies, high initial costs for training and specialized equipment, weak enforcement of existing forest management standards, and the absence of strong economic incentives or policy frameworks that prioritize reduced-impact

practices. Nevertheless, the region offers strong potential for RIL-C rollout due to its extensive area of active logging concessions, many of which already operate under Forest Management Plans that could integrate RIL-C practices. Growing international demand for deforestation-free products, opportunities in climate finance and carbon market mechanisms, and existing support from NGOs and pilot projects further strengthen the case for RIL-C adoption.

Additionally, RIL-C can reduce operational costs for companies by minimizing forest damage and improving timber recovery, making it both an environmentally and economically viable pathway for more sustainable forest management in the region. The transformation of raw timber within the region—adding economic value through local processing and manufacturing, which can generate jobs, increase exports, and contribute to GDP growth. This shift from exporting raw logs to producing higher-value wood products not only promotes economic development but also reduces pressure on forests by incentivizing sustainable harvesting practices. Such approaches align with recent policy measures like Gabon's log export ban and initiatives in special economic zones such as GSEZ, which have successfully fostered local timber transformation and created positive economic outcomes.

Opportunities for Sustainable Mining Development in the Congo Basin

Extractive mining plays a crucial economic role in the Congo Basin, particularly in the DRC, which holds vast mineral wealth. However, mineral extraction also poses serious risks to vulnerable ecosystems, including deforestation, biodiversity loss, environmental pollution, and social instability (Luckeneder et al. 2021; Murguía et al. 2016). Historically, land-use planning and zoning efforts in the region have focused largely on the forestry sector, with limited integration of mining development. More recently, forest atlases have been developed in several countries in the region with support from the World Resources Institute (WRI) that are available through Global Forest Watch: Cameroon, CAR, DRC, Equatorial Guinea, Gabon and RoC. Building a sustainable mining sector thus presents a major opportunity to drive economic growth while mitigating environmental and social risks.

Early and integrated planning for mining projects—including infrastructure development such as roads, railways, and energy systems—can significantly reduce environmental impacts and avoid uncontrolled expansion into sensitive areas (PROFOR 2024). Strategic land-use planning that incorporates environmental safeguards, biodiversity corridors, and no-go zones can help preserve intact ecosystems while enabling responsible resource extraction.

Technological advances, such as remote sensing and spatial analysis, offer new tools to strengthen environmental monitoring of mining operations. These technologies can track land-use changes, detect illegal mining activities, and ensure better waste management practices during exploration and hydrometallurgical ore treatment phases (Mufungizi 2024). Harnessing these tools can reduce deforestation and pollution, increase transparency, and improve regulatory oversight.

The discovery of valuable minerals in eastern DRC has spurred significant migration into remote forest areas, causing widespread indirect deforestation through expanded farming and settlement. Recent research shows that these indirect impacts can be up to 28 times greater than the direct clearing for mining itself (Ladewig et al. 2024). Addressing this challenge presents an opportunity to promote sustainable agricultural practices and rural development programs that reduce the pressure to clear forests, while investing in alternative livelihoods that support forest conservation.

The artisanal and small-scale mining sector, particularly for diamonds and gold, provides critical income opportunities for many communities but often contributes to severe environmental degradation and unsafe working conditions (Galli et al. 2022). Formalizing and professionalizing the artisanal and small-scale mining operations—through licensing schemes, technical training, health and safety standards, and environmental restoration requirements—could transform the sector into a driver of sustainable rural development. In the Republic of Congo, for example, a USD 10.5 million project launched by the Global Environment Facility (GEF) in 2022 seeks to reduce mercury use in gold mining by promoting mercury-free technologies, improving miners' access to markets and finance, and supporting sustainable landscape management practices (Global Environment Facility 2022).

Artisanal cobalt mining is another example that provides many challenges but also opportunities for improvements in the sector by identifying key monitoring points. Recent research (Gulley 2023) found that between 2000 and 2020, global demand for cobalt, primarily for battery production, increased 26-fold, with 82% of that growth occurring in China. During this period, China's cobalt refining capacity expanded 78-fold. Due to reduced industrial cobalt output in the early 2000s, many Chinese firms began sourcing cobalt from artisanal miners in the DRC, where child labour has been widely reported. While DRC's total cobalt production rose from 11,000 to 98,000 metric tons (t) over these two decades, artisanal mining contributed 1000–2000 t in 2000 and 9000–11,000 t in 2020 (Gulley 2023), peaking at 17,000–21,000 t in 2018. Artisanal mining's share of global and DRC cobalt output peaked around 2008, then declined to 6–8% globally and 9–11% nationally by 2020. Most artisanal cobalt is either exported to China or processed in the DRC by Chinese companies, accounting for an estimated 72–79% between 2016 and 2020 (Gulley 2023). These processing sites represent key monitoring points that could support responsible sourcing and efforts to address human rights abuses in the artisanal cobalt sector.

Optimizing mineral use in the Congo Basin through local processing, whether partial or full, presents an important potential pathway toward sustainable development. While full processing offers greater value addition and economic benefits, it also carries higher environmental and social risks. Partial processing, on the other hand, can offer a more balanced approach, mitigating some risks while still contributing to economic development. A key aspect of optimizing mineral use is integrating spatial planning, participatory resource management, and robust environmental regulations to ensure that mining activities contribute to sustainable development rather than undermining it (PROFOR 2024; World Bank 2016). However, the

experience of artisanal cobalt mining (Gulley 2023) illustrates the substantial challenges involved in developing a local processing industry (in this case mostly by Chinese companies in the DRC) that is economically, socially and environmentally viable.

Finally, improving governance across the mining sector—including stricter enforcement of environmental regulations, participatory land-use planning, community consultation, and benefit-sharing mechanisms—can ensure that mining revenues contribute to local development, strengthen land rights, and reduce conflicts linked to resource exploitation.

Improved governance should also tackle illegal mining (e.g., gold, diamond, etc.) and trafficking in the Congo Basin. In the case of coltan, Ojewale (2022) found a network of organized crime involved in the production and supply chain of coltan and connections to legitimate businesses in advanced economies. The research identified seven key elements of transnational organized crime and the networks of actors involved in illicit activities. These include illegal mining, corruption, counterfeiting, fronting, and collusion—primarily carried out by local Congolese actors—as well as smuggling and resource predation, which involve cross-border operations. Among these, illegal mining and smuggling have the most significant impact on organized crime (Ojewale 2022).

Together, these strategies offer a major opportunity to transform mining in the Congo Basin into a sector that not only powers national economies but also safeguards forests, protects biodiversity, and enhances the well-being of local communities.

Although this section does not cover the oil industry, it is important to note that it is a major contributor to several Congo Basin economies, especially the DRC, Gabon and the RoC. As world economies attempt to shift away from hydrocarbon energy systems, this is inevitably going to decline, necessitating strategies for posthydrocarbon economic development.

Transitioning to Renewable Energy

For decades, countries have relied heavily on fossil fuels – such as coal, oil, and natural gas – to meet a wide range of energy needs. This dependence has caused substantial environmental damage, contributing to climate change and broader environmental degradation (Massonini Ngoma et al. 2024). In contrast to fossil fuels, renewable energy sources are exceptional because they can be generated from limitless resources.

The Congo Basin holds vast renewable energy potential, with abundant sunlight, hydroelectric resources, and biomass feedstock including forest residues and agricultural by-product (Dalder et al. 2024). Despite having abundant renewable resources, the Congo Basin struggles with a significant energy deficit, which hampers sustainable development by affecting health, education, and economic opportunities (Aquilas and Atemnkeng 2022). The reliance on traditional biomass (fuelwood and charcoal) for energy further exacerbates deforestation and its related

climate and ecological impacts. Despite these challenges, there are opportunities for transformative change.

Considerable investment is needed in renewable energy infrastructure and technology, complemented by government policies that support rural electrification and the promotion of sustainable energy practices. Investing in decentralized renewable energy solutions like solar panels, micro-hydro systems, and biomass technologies allows rural communities to bypass the limitations of conventional grid infrastructure, opening up new opportunities for development (Bishoge et al. 2020).

Awazi (2025) provides a detailed overview of the challenges and prospects of meeting the energy needs of the urban and rural poor in the Congo Basin through renewables. Key possibilities highlighted for the renewables transition include: biomass, solar, hydroelectric power, wind, tidal and geothermal energy. As this section is unable to provide an in-depth analysis of these possibilities, we refer to Awazi (2025) and present some illustrative examples here.

The transition to renewable energy in the Congo Basin presents a critical opportunity to reduce deforestation and forest degradation, primarily driven by the demand for fuelwood and charcoal. Initiatives such as the PREFOREST CONGO project, led by the Food and Agriculture Organization (FAO) of the United Nations, aim to shift subsistence farmers away from more destructive slash-and-burn practices toward agroforestry systems. These systems integrate tree management with crop production, offering environmental and economic benefits, while also supporting sustainable livelihoods by restoring degraded forests and improving market access for smallholder farmers.

In the Yangambi landscape of Tshopo Province, the Center for International Forestry Research (CIFOR) and World Agroforestry (ICRAF) are supporting local communities by establishing agroforestry woodlots. These woodlots not only provide a renewable source of wood for charcoal but also include fruit and caterpillar-bearing trees, helping diversify income and strengthen economic resilience while contributing to environmental sustainability (Ngunyam 2024).

In parallel, regional research and capacity-building networks such as the Réseau de Recherche sur la Transition Énergétique en Afrique Centrale (ReTEAC) provide an important platform for accelerating renewable energy transitions in the Congo Basin. Through its network of demonstration sites, training programs, and applied research initiatives, ReTEAC supports the testing and scaling of context-appropriate renewable energy solutions. Facilities such as the Centre d'Excellence d'Oyo in the Republic of Congo offer a concrete opportunity to pilot decentralized energy technologies, build local technical expertise, and foster collaboration between researchers, policymakers, and practitioners. By linking scientific research with on-the-ground implementation, these sites can help bridge the gap between renewable energy potential and practical, locally viable energy solutions.

Hydropower represents a significant renewable energy opportunity in the Congo Basin, with the region's vast river systems offering considerable potential for clean energy production. However, progress has been hindered by high initial investment costs and the complexity of developing large-scale energy infrastructure, as highlighted by Awazi (2025). To overcome these barriers, the region could leverage

international financial support, public–private partnerships, and regional cooperation to share infrastructure costs and improve project feasibility. Furthermore, strengthening local technical expertise and providing training in hydropower technology can help ensure the long-term sustainability and maintenance of these projects.

In addition to hydropower, the integration of other renewable energy solutions, such as solar ovens for fish drying, improved charcoal production from wood residues, and fuelwood plantations within agroforestry systems, can contribute to both energy access and environmental conservation. These solutions can reduce reliance on traditional biomass fuels, promote sustainable forest management, and improve local livelihoods by providing cleaner, more efficient energy alternatives.

The transition to renewable energy in the region faces several challenges, thereby limiting their exploitation. These include limited access to capital, inadequate infrastructure, insufficient technical, financial, and human resources, weak institutional and regulatory frameworks, and sociopolitical obstacles and the lack of technical expertise to implement and maintain renewable energy systems (Awazi 2025; Bishoge et al. 2020). Moreover, the local population's dependence on traditional biomass fuels remains deeply embedded, making the transition slow. Additionally, remote rural communities face barriers in accessing renewable technologies, and policy frameworks are often fragmented and underfunded. To overcome these obstacles, it is essential to create supportive policies, build technical capacity, and ensure the active participation of local communities in decision-making processes.

By fostering a holistic approach that combines renewable energy, agroforestry, and capacity-building efforts, the Congo Basin can create a more sustainable and climate-resilient future, addressing both energy needs and environmental challenges while strengthening the economic resilience of local communities.

Agroforestry and Sustainable Agriculture

Agroforestry

In the Congo Basin, small-scale slash-and-burn agriculture remains the dominant driver of forest disturbance, with far-reaching consequences for freshwater systems, biodiversity loss, and the bushmeat trade (Shapiro et al. 2023). While historically viable for low-density populations, this form of agriculture is no longer sustainable in the face of rapid demographic growth. It leads to soil degradation, short-term yields, and a constant need for new forest clearance, placing increasing pressure on intact ecosystems.

Industrial agriculture in the Congo Basin is increasingly characterized by large-scale monocultures—particularly oil palm, rubber, and sugar—which introduce a range of environmental and social challenges (Feintrenie 2014). These systems often depend heavily on agrochemicals, contributing to soil degradation, pollution of water bodies, and biodiversity loss over time (Meena et al. 2020; Tao and Liu 2024; Ukwu 2024). Despite these limitations, agriculture is a key livelihood sector

and, if properly transformed, holds enormous potential to contribute to sustainable development in the region.

One pathway to realizing this potential is agroforestry, which integrates trees with crops and/or livestock to deliver both productive and ecological benefits. Agroforestry has been shown to reduce deforestation and forest degradation (Teo et al. 2025), combat soil erosion and improve soil health (Hasanuzzaman et al. 2025; Muchane et al. 2020), support biodiversity (Fahad et al. 2022), and sequester carbon (Kay et al. 2019). For example, in the DRC, coffee agroforestry systems were found to be as productive as monocultures, while supporting 19 times greater biodiversity and sequestering twice as much carbon (Broeckhoven et al. 2024).

Experiences from other tropical regions demonstrate that modern, intensively managed agroforestry systems can enable farmers to transition from shifting cultivation to permanent land use, stabilizing their livelihoods while sustaining high productivity (Mathur and Bhattacharya 2022). These systems offer a promising model for the Congo Basin, particularly where they are supported by secure tenure, market access, and policy incentives.

However, the adoption of agroforestry in Central Africa has remained limited to date, despite the proliferation of donor-supported agroforestry initiatives (Kaua 2020; Nkamleu and Manyong 2005). Systemic challenges—such as pests and disease, suboptimal agroecological conditions, insecure land tenure, limited knowledge, inadequate capital, and poor access to improved tree germplasm—continue to hinder widespread agroforestry adoption in the Congo Basin (Bekele et al. 2023; Houndjo Kpoviwanou et al. 2024).

Overcoming these barriers requires targeted, context-sensitive interventions: robust training programs, accessible financing, participatory land tenure reforms, and supportive policy environments. The International Fund for Agricultural Development (IFAD 2024) stresses that successful agroforestry systems depend on local adaptation, market access, and inclusive governance frameworks.

However, scaling such systems in the Congo Basin will require confronting entrenched structural constraints—particularly insecure land tenure, the slow uptake of new agricultural practices, and a chronic lack of investment at the scale required. Ultimately, understanding the motivations and barriers that shape farmers' land-use decisions is essential. Research from the Yangambi Biosphere Reserve illustrates that while many farmers value the long-term benefits of tree integration—such as improved soil fertility—others remain hesitant due to perceived risks to yields or land security (Katayi et al. 2023).

With strategic investment, enabling land-use policy, and institutional reform, agroforestry could play a central role in unlocking the Congo Basin's immense agricultural potential—offering a path to food security, forest conservation, and climate-resilient livelihoods across both smallholder and commercial scales.

Biochar

An emerging technique with promising applications in the Congo Basin is biochar—a stable, carbon-rich material derived from organic biomass. While still

underexplored in the region, biochar has shown potential as an improvement to conventional practices such as fallowing, slash-and-burn, and mineral fertilizer application particularly on the nutrient-poor and heavily weathered soils common throughout the Basin (Koutika 2025).

Biochar can augment traditional composting and mulching methods by increasing soil organic carbon more permanently, improving cation exchange capacity, and enhancing nutrient and water retention. Unlike many organic amendments that decompose rapidly in tropical climates, biochar's chemical stability allows it to persist in soils for decades to centuries, acting as a long-term soil conditioner (Eykelbosh et al. 2014; Lehmann 2007).

Several studies have demonstrated that integrating biochar with existing techniques—such as composting or mineral fertilizers—can amplify their effectiveness. In low-input farming systems, biochar reduces the need for chemical fertilizers, helping to lower input costs while maintaining or improving yields—up to 25% in the tropics (Jeffery et al. 2017).

When coapplied with compost or manure, biochar enhances soil carbon stocks by boosting microbial activity, nutrient availability, and soil structure, locking carbon in the soil for centuries (Adekiya et al. 2023; Lehmann 2007).

Trials in sub-Saharan Africa have shown biochar-enhanced soils can support more consistent crop performance under drought stress, especially when combined with mulch or agroforestry (Neogi et al. 2022).

In this sense, biochar should not be viewed as a silver bullet but rather as a value-adding amendment that can strengthen the sustainability and productivity of existing land-use practices. For example, combining biochar with agroforestry—such as applying it in tree-crop interspaces—can further enhance soil fertility, support tree survival, and buffer crops against climate extremes, thereby improving the resilience of both smallholder and commercial farming systems. Nevertheless, the successful adoption of biochar in the Congo Basin will depend on locally adapted approaches, farmer training, and long-term evaluation of biochar's performance under Congo Basin conditions.

International Regulations Related to Agricultural Commodities

At the international level, new regulations are being introduced to decouple commodities such as coffee and cocoa from deforestation, while promoting biodiversity enhancement. Key regulatory frameworks impacting supplying countries, including those in the Congo Basin, are the European Union's Regulation on Deforestation-Free Products (EUDR) (EU 2023), the European Union's Corporate Sustainability Due Diligence Directive (CSDDD) (EU 2024), and the United Kingdom's Due Diligence Law (UK Government 2021). These regulations aim to prevent products linked to deforestation and ecosystem degradation from entering EU and UK markets. The implementation of such international regulations offers an opportunity to reduce deforestation and forest degradation in the Congo Basin, while also fostering collaboration between Congo Basin countries and the private sector to ensure these regulations are effectively executed in ways that benefit local economies and livelihoods.

These regulations can be seen as an opportunity rather than a punishment or threat in several important ways:

- *Market access for sustainable producers*: these regulations could create a competitive advantage for producers in the Congo Basin who adopt sustainable practices;
- *Incentivizing sustainable land use*: the regulations can stimulate investment in sustainable agriculture and forestry, including agroforestry, attract green finance and sustainability-linked investment from buyers and financial institutions seeking compliant supply chains and promote diversification and resilience in rural economies;
- *Institutional and private sector collaboration*: encourage stronger partnerships between governments, local communities, and the private sector by creating an imperative for joint capacity building, infrastructure upgrades (e.g., traceability systems), and knowledge sharing, fostering dialogue and support mechanisms (e.g., technical assistance from EU/UK stakeholders) to meet compliance goals, potentially leading to public–private investment platforms in supply chain traceability, farmer training, and certification
- *Improved governance and transparency*: implementing these regulations supports improvements in land tenure security (as clearer land ownership and usage rights are needed for compliance), transparency and accountability in commodity value chains and monitoring and enforcement capacity, which also benefits domestic forest policies.

A recent literature review on cocoa, livelihoods, and deforestation in the Tridom landscape of the Congo Basin suggests that economic development, especially through improved market access and reduced self-consumption (the portion of goods or resources consumed directly by producers rather than traded or sold), could have a positive influence on reducing deforestation (Ngouhouo-Poufoun et al. 2024). However, the same review indicates that without effective land-use planning, zoning, and appropriate incentives, promoting sustainable agriculture practices such as complex cocoa agroforestry systems may inadvertently contribute to forest degradation and deforestation. Developing robust land-use planning and zoning programs in the fragile states of the Congo Basin may prove challenging.

Further research on the impact of the EUDR on cocoa and timber supply chains in Cameroon concluded that the regulation is likely to have only a limited impact on deforestation within these supply chains (Tankam and Lescuyer 2024). The limited impact is attributed to factors such as the specific characteristics of the products, sector dynamics—particularly the relative importance of European markets versus domestic, regional, and Asian markets—and certain aspects of the regulations themselves (Tankam and Lescuyer 2024).

Although the regulations are still being clarified and may be initially complex to implement, the EUDR, the EU CSDDD and the United Kingdom's Due Diligence Law offer opportunities for the Congo Basin to promote sustainable forest management, reduce deforestation, and ensure responsible business practices within the

region (EU Directorate-General for Environment 2023). If implemented effectively, these international regulations offer a pathway to reducing deforestation and forest degradation in the Congo Basin while enhancing biodiversity and creating economic opportunities that benefit local communities and producers alike.

Protected Areas, Biodiversity Management, and Ecotourism

Protected Area Governance, Effectiveness and Community Participation

Protected areas (PAs) are critical tools for conserving the Congo Basin's exceptional biodiversity, yet they face serious and persistent challenges. Threats such as illegal wildlife trade, deforestation from agriculture and infrastructure development, extractive industries, invasive species spread, climate change, and rapid population growth exert growing pressure on ecosystems. Despite a relatively strong formal commitment to protection—about 22.6 million hectares, or 14% of Central Africa's rainforest, are under protected status (Doumenge et al. 2021), PA management across the region remains severely underfunded, understaffed, and undermined by weak governance structures (Coad et al. 2019; WWF 2023).

Current models of PA management are often ineffective because they inadequately address the needs and rights of local communities. Many PAs suffer from unresolved land conflicts, erosion of customary land rights, limited local livelihood alternatives, and persistent poaching (Pyhälä et al. 2016; Walters and Wardell 2023). Studies, such as recent research on the Kiziba-Baluba hunting domain in the DRC (Muteya et al. 2024), reveal that PA designation alone has minimal impact on halting deforestation, unless it is accompanied by participatory boundary setting, improved enforcement, and meaningful community involvement.

Nonetheless, it is important to note that "paper parks" do better than unprotected areas generally (Brodie et al. 2023; Li et al. 2024). A global study (Li et al. 2024) found that from 2003 to 2019, 73% of protected areas experienced habitat loss—totaling 1.14 million km^2, equivalent to three times the size of Japan—mainly due to urban expansion, agriculture, and deforestation. Larger and stricter protected areas saw less loss, and while most halted urban growth, they were less effective against deforestation and farmland expansion. Protected areas were 33% more effective than unprotected areas in reducing habitat loss, but their ability to buffer nearby human pressures varied. The study highlights the urgent need to improve the management of existing protected areas to meet global biodiversity goals.

Recognizing the need to increase effectiveness, new approaches are emerging. Inclusive conservation models, including devolving management authority to Indigenous Peoples and local communities (Walters and Wardell 2023), offer promising alternatives by fostering equitable governance and enhancing conservation outcomes. The Lomami National Park in the DRC is one such example. Its creation in 2016 involved extensive consultation with seven ethnic groups (Mbole, Lengola, Mituku, Langa, Ngengele, Arabisées, and Tetela) who were all involved in the

founding process of the national park together with the Congolese Institute for the Conservation of Nature (ICCN) (Walters and Wardell 2023). Community forestry legislation provides a way that communities can work with ICCN to gain greater control over the use and management of their forest resources if they can demonstrate changes that lead to long-term forest sustainability and hunting viability.

In parallel, initiatives led by the International Union for Conservation of Nature (IUCN), the Biodiversity and Protected Areas Management (BIOPAMA) Programme, and others have developed frameworks to assess Protected Area Management Effectiveness, providing critical tools to measure progress, identify gaps, and guide adaptive management strategies across the region (BIOPAMA n.d.). For example, the BIOPAMA programme assists African, Caribbean, and Pacific countries to address their priorities for effective conservation and sustainable use of natural resources by providing tools, services, and financial support in the Congo Basin region. BIOPAMA provides services such as hosting and data information through a Reference Information System and assessment tools such as the Integrated Management Effectiveness Tool to support better protected area planning and decision making. In the Congo Basin, it does this through working with the Observatory for Central African Forests (COMIFAC OFAC) as well as national counterparts. Deploying the BIOPAMA Integrated Management Effectiveness Tool over five consecutive years in the BCB Yamoussa Binational Complex, spanning Cameroon and Chad, enabled more effective planning and the design of tailored interventions. This was achieved through a participatory, inclusive process that integrated evaluation, planning, and monitoring (BIOPAMA n.d.).

The global momentum generated by the Kunming-Montreal Global Biodiversity Framework, particularly the 30 × 30 target, provides new opportunities to strengthen PA management, enhance biodiversity resilience, and support sustainable livelihoods. This initiative aims to protect 30% of the world's terrestrial and marine ecosystems by 2030, reflecting a critical shift in international conservation policy, endorsed by the Convention on Biological Diversity (CBD) (Hughes and Grumbine 2023; Günther and Ekardt 2023). In the context of the Congo Basin, these opportunities could encompass strategies such as expanding community-managed conservation areas, reinforcing comanagement agreements between governments and local communities, and securing long-term financing for PAs through biodiversity credits, climate finance, and ecotourism revenues.

Strengthening local scientific capacity through the training of researchers, technicians, and research assistants is critical for generating robust, context-specific data that directly informs protected area management and biodiversity conservation. Locally produced data enhances the responsiveness and relevance of management decisions by reflecting ecological dynamics and conservation needs as observed on the ground. When grounded in regional expertise, such information contributes to more adaptive, evidence-based management practices and helps align conservation actions with ecological priorities (Danielsen et al. 2005). Furthermore, the development of local scientific infrastructure and expertise supports improved governance of research—ensuring that data collection and analysis are responsive to park management objectives, rather than externally driven agendas. Emerging platforms such as

the Congo Basin Science Initiative, the One Forest Vision, and the Central Africa Forest Initiative (CAFI) Science & Innovation grant funding are fostering this shift by funding research as well as research training programs designed to strengthen scientific leadership and research governance in the region. These investments ultimately help bridge the gap between science and policy, reinforcing both the legitimacy and effectiveness of biodiversity governance.

Empowering Indigenous Peoples and local communities through the recognition of customary land rights and participatory management frameworks can be effective in enhancing biodiversity stewardship and reducing conflict (Andrade and Rhodes 2012; Gatiso et al. 2022). Involving communities in decision-making fosters ownership and compliance, leading to more adaptive and culturally appropriate conservation outcomes.

In the Republic of Congo, the Lac Télé Community Reserve illustrates this approach (Rainey and Twagirashyaka 2010). Since the early 2000s, communities—supported by WCS and local authorities—have contributed to wildlife monitoring using both traditional knowledge and scientific methods, improving tracking of forest elephants and great apes and reinforcing local engagement.

Similarly, in the DRC's Yangambi Biosphere Reserve, participatory forest monitoring—facilitated by CIFOR, local universities, and community-based organizations—has generated valuable data for land-use planning while advancing environmental education (Van Vliet et al. 2023). However, research has also revealed that community participation in Yangambi often remains superficial, driven by externally funded projects with limited long-term community influence or ownership (Koy et al. 2019).

These examples highlight both the promise and pitfalls of community-based conservation in the Congo Basin. While participatory models can be effective, they often fall short due to insecure land tenure, dependence on short-term funding, and a lack of integration with local livelihoods and cultural norms (Endamana et al. 2010; Larson et al. 2010). Moving beyond tokenistic involvement demands sustained investment, long-term institutional commitment, and the establishment of clear legal frameworks that formally recognize customary rights and position communities as active comanagers—not merely beneficiaries—of conservation efforts. Moreover, policies must be more nuanced, tailored to local contexts, aimed at strengthening local governance capacity, ensuring equitable participation among all stakeholders, and addressing the broader socio-political dynamics that influence tenure reform (Andrade and Rhodes 2012; Larson et al. 2010).

Ecosystem Services and Ecotourism as Pathways to Sustainable Development

Protected areas are vital to sustainable development, safeguarding ecosystem services that underpin local and regional economies. The Monts de Cristal watershed, for instance, supplies water to three hydroelectric dams, generating renewable energy and delivering significant economic value. Although exact figures are not

yet available, the development of a payment for watershed services (PWS) scheme reflects recognition of this value—utilities are willing to invest in maintaining the park's ecological functions (Emerton and Nlom 2011). This example highlights how well-managed protected areas can directly support biodiversity conservation while strengthening livelihoods and economic resilience.

Ecotourism in the Congo Basin holds promise as a strategy to align biodiversity conservation with economic development. However, its growth faces significant structural barriers compared to other African regions. These include limited transportation infrastructure, an underdeveloped hospitality sector, complex and costly visa procedures, and generally higher travel costs (Doumenge et al. 2021), as well as political instability. Additionally, the dense rainforest makes wildlife viewing more difficult than in open savanna ecosystems, reducing the immediate appeal for some tourists. These factors collectively constrain the region's competitiveness in the African ecotourism market. Ecotourism is defined as "*responsible travel to natural areas that conserves the environment, sustains the well-being of the local people, and involves interpretation and education*" (The International Ecotourism Society 2015). Despite the challenges, examples such as Odzala-Kokoua National Park in the Republic of Congo illustrate the potential for sustainable ecotourism. The park offers opportunities to see lowland gorillas, forest elephants, and a variety of bird species while generating income and employment for surrounding communities. Similarly, the Dzanga-Sangha Protected Areas Complex (CAR) and Nouabalé-Ndoki National Park (RoC) have garnered international attention through successful gorilla habituation tourism programs that contribute to conservation funding. However, large investments would need to be made (e.g., through public–private partnerships) to make these ecotourism activities profit making.

Insights can also be gained from neighboring Rwanda, which has developed a successful mountain gorilla ecotourism model. The substantial revenue generated from mountain gorilla tourism has motivated the Rwandan government to adopt strict protectionist conservation measures. However, despite this approach, ongoing human–wildlife conflicts among communities living near the parks have continued, and threats to wildlife, such as poaching, have not significantly decreased. Research finds that limited access to tourism benefits including revenue sharing, high costs of living adjacent to the park, lack of community involvement and participation in the park management and decision-making process limit the opportunities of the mountain gorilla tourism to reduce wildlife threats and generate support for conservation (Sabuhoro et al. 2021). It will be important to take such lessons into account to further sustainable development while developing this sector in the Congo Basin.

Yet, these initiatives are not without their difficulties. Disease transmission is a major concern in gorilla tourism, as habituated great apes are particularly vulnerable to human-borne illnesses like influenza and SARS-CoV-2. Although protocols such as mask use and distancing exist, their enforcement is often inconsistent, particularly in remote or underfunded regions. Poorly managed ecotourism can also lead to environmental degradation, such as trail erosion, habitat disruption, and stress among wildlife due to human proximity (Consolee et al. 2024; Patil and Pattanshetti 2024).

Another challenge is the cultural commodification that can arise when local traditions are reshaped to suit tourist expectations, potentially undermining cultural integrity (Carr et al. 2016). Social inequity also emerges as a concern, with tourism revenues frequently benefiting external operators rather than the communities who bear the cost of conservation restrictions. In places like Virunga National Park in the DRC, unequal benefit distribution and disputes over land rights have sparked tensions (Marijnen and Verweijen 2016). Moreover, the sustainability of ecotourism remains vulnerable to external shocks such as political instability, armed conflict, and global health crises, which can abruptly disrupt visitor flows and conservation financing.

Despite these setbacks, ecotourism remains a promising avenue for integrated conservation and development in the Congo Basin. Strengthening community participation and ensuring transparent benefit-sharing can help mitigate social tensions and promote inclusive governance (Azevedo et al. 2024; Christian and Kasumi 2016; Snyman and Bricker 2019). Investments in infrastructure—paired with strict environmental and health safeguards—can make tourism more sustainable while improving visitor experiences. Enhanced screening measures and visitor guidelines can help protect wildlife, while also attracting ethically minded travellers (Sak et al. 2013). Diversifying tourism products is another key strategy. Examples of additional activities to gorilla viewing that leverage the region's natural and cultural richness are birdwatching, guided forest walks, and community-led cultural experiences (Mohammed 2022; Snyman 2014). For instance, Hausmann et al. (2017) found that tourists in sub-Saharan Africa increasingly value both recreational and cultural components of nature-based tourism, pointing to the potential of broader ecotourism models to distribute benefits more widely and foster deeper local engagement. Finally, investing in long-term capacity building and adaptive strategies (such as promoting year-round tourism or diversifying income sources) and strengthening partnerships among governments, conservation organizations, and private sector actors can consolidate a more sustainable, scalable ecotourism model in the region (Dibie et al. 2018; Muzirambi and Mearns 2018).

If successfully implemented, particularly as stability and governance improve, these strategies could contribute to improved PA management and ecotourism playing an important role in sustainable development by conserving biodiversity and improving local livelihoods throughout the Congo Basin.

Climate and Carbon Finance

It is important to clearly distinguish between *climate finance* and *carbon finance*, terms often mistakenly used interchangeably. Climate finance refers broadly to the funds required to address climate change mitigation and adaptation, sourced from public, private, or alternative mechanisms, across local, national, or transnational levels (Gupta 2016). This can include results-based payments (RBPs) for verified outcomes. In contrast, *carbon finance* specifically refers to revenue generated from the sale of carbon credits earned through verified emissions reductions or removals (Gupta 2016).

One of the key opportunities for Congo Basin countries to access climate and carbon finance lies in the framework of *REDD+*—Reducing Emissions from Deforestation and forest Degradation, and promoting conservation, sustainable forest management, and enhancement of carbon stocks in developing countries. REDD+ was established under the United Nations Framework Convention on Climate Change (UNFCCC) in 2009 and was subsequently anchored in the Paris Agreement under Article 5 (UNFCCC 2015, 2024). Although there are several climate and carbon finance opportunities, this section will focus on REDD+.

In terms of forest-related climate and carbon finance, two different approaches exist, which can be complementary if there is a strategy for integration (e.g., nesting): jurisdictional and project-based. Jurisdictional approaches work at a larger scale, such as national or subnational levels (e.g., a state, province, or country) and is typically led by governments and integrated into broader land-use planning and climate policies. Project-based approaches operate at a local or site-specific level (e.g., a single forest area or community), are usually implemented by NGOs, private companies, or local governments and often have limited or informal coordination with national governments. Further differences between the two approaches also existing in terms of accounting and monitoring: project-based approaches use their own baseline and monitoring system (depending on the standard and methodology they are using), which may not always align with national systems and have a risk of leakage (emissions shifting outside the project area), while jurisdictional approaches use a centralized accounting system consistent with national forest monitoring and greenhouse gas inventories and are designed to reduce leakage and double counting by covering larger areas. At both scales, private sector engagement—often through public–private partnerships—is essential to mobilize investment and implement programs at scale. Grouping project developers can create the scale and predictability needed to attract medium-to-long-term private finance.

At the jurisdictional level, Central African countries remain under-represented in REDD+ results-based payments (RBPs). To date, Gabon's payment under the Central African Forest Initiative (CAFI) (UNDP 2021) remains the region's only major RBP example, despite over a decade of REDD+ readiness activities. Under this agreement, Gabon received $17 million US dollars for emissions reductions of 3,382,204 tCO_2 (at $5 per tCO_2) made in 2016 and 2017, compared to annual emission levels from 2006 to 2015 (NICFI 2021). While the Green Climate Fund pilot delivered USD 500 million to six countries (mostly in Latin America and Indonesia) (Green Climate Fund 2021), no African countries were "ready" to access these funds. However, the Congo Basin is progressing: the DRC and the RoC have advanced carbon finance programs through the World Bank's Forest Carbon Partnership Facility (FCPF) Carbon Fund. Having started work through the FCPF readiness program in 2008 and the carbon fund in 2014, DRC received the first payment of $19.47 million in June 2025 for reducing 3.89 million tons of carbon emissions through efforts to protect and restore forests in the Mai-Ndombe province (World Bank 2025). This timeline is consistent with experiences elsewhere, reflecting the complexity and slow pace of building REDD+ frameworks.

Developing jurisdictional REDD+ programs involves significant challenges, including creating comprehensive greenhouse gas (GHG) accounting frameworks, aligning policies and incentives, and establishing credible systems for claims to emission reductions and access to finance. Crucially, REDD+ must be embedded into national policy and governance structures through inclusive consultations with government, private sector, and civil society actors. The success of REDD+ in the Congo Basin ultimately depends on sustained stakeholder engagement, institutional strengthening, transparent governance, and long-term financing mechanisms.

Different types of climate and/or carbon finance can be accessed at a jurisdictional level. These are, for example:

(a) results-based finance (e.g., Green Climate Fund REDD+ pilot, Gabon-Norway agreement),
(b) mixed results-based finance and carbon finance (e.g., World Bank Forest Carbon Partnership Facility Carbon Fund Tranche A and Tranche B),
(c) carbon finance including both the voluntary carbon market (VCM) and the compliance carbon market (e.g., Architecture for REDD+ Transactions (ART) The REDD+ Environmental Excellence Standard (TREES) credits, Verra Verified Carbon Standard (VCS) Jurisdictional and Nested REDD+ Framework).

Currently, only the DRC, RoC, and Gabon have accessed REDD+ RBPs, with no jurisdictional-level carbon credit transactions yet completed. However, Gabon and DRC's Tshuapa province have submitted concept notes to ART, indicating growing readiness.

At the project level, several REDD+ projects exist in the Congo Basin. However, recent years have been turbulent for the voluntary carbon market (VCM). Public and investor confidence has been shaken by political, technical, and scientific controversies around the social and environmental integrity of carbon projects, with media coverage highlighting cases of overstated benefits or weak governance (Balmford et al. 2023; Greenfield 2024; Trencher et al. 2024). In particular, studies claimed that baselines for many REDD+ projects were significantly overinflated (Jones and Lewis 2023; West et al. 2023), though these findings have been contested on the basis of methodological flaws (Mitchard et al. 2023; eLetters responses to West et al. 2023). Despite the introduction of a new consolidated REDD+ methodology by Verra (2023) and moves toward higher integrity standards, debate continues around baseline setting and the estimation of greenhouse gas (GHG) mitigation and removal benefits (Ecosystems Marketplace 2024).

Reflecting these dynamics, the VCM, and especially project based REDD+, has experienced a significant contraction in 2023, with transaction volumes declining sharply across most regions except North America, particularly impacting REDD+ projects in Asia, Latin America, and the Caribbean (Ecosystems Marketplace 2024).

In response to concerns around integrity, multiple initiatives—such as the Integrity Council for the Voluntary Carbon Market (ICVCM), the Voluntary Carbon Markets Integrity Initiative (VCMI), and the Science-Based Targets Initiative (SBTi)—have introduced new or updated guidance to strengthen standards for

carbon credits. Additionally, the adoption of Article 6 rules at COP29 (UNFCCC 4/CMA.6, 5/CMA.6, 6/CMA.6, 7/CMA.6) provides new pathways for voluntary international cooperation in achieving countries' Nationally Determined Contributions (NDCs) through market-based and nonmarket mechanisms, opening further opportunities for Congo Basin countries.

The big push for integrity in the carbon markets has also impacted jurisdictional REDD+. The jurisdictional ART initiative with its TREES standard (The REDD+ Environmental Excellence Standard) has received the ICVCM Core Carbon Principles (CCP) label for the main methodology, with the High Forest Low Deforestation (HFLD) module under review. Two key Verra VCS methodologies have also received the ICVCM CCP label, at the jurisdictional level VCS JNR and at the project level VM00048 on reducing emissions from deforestation and forest degradation.

Furthermore, the ART TREES methodology is also CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) compliant. CORSIA is the International Civil Aviation Organization's (ICAO) global market-based measure designed to stabilize net CO_2 emissions from international aviation at 2020 levels and beyond, achieving carbon neutral growth for the sector. It achieves this by requiring aircraft operators to offset their emissions growth through the acquisition and cancellation of emissions units from the global carbon market. Recently, Guyana was the first country to sell its ART TREES credits to airlines in the CORSIA compliance market through the CORSIA measure for $22.25 per ton (Xpansiv 2025).

The integrity recognition of both jurisdictional and project level REDD+ programs and methodologies by the ICVCM provides an important market signal. Globally, the VCM is valued at approximately USD 2 billion and has the potential to grow 5- to 50-fold by 2030. The upcoming compliance market through CORSIA also offers potential, with estimates for Phase I (2024–2026) ranging from 100 to 150 million tons of CO_2 equivalent ($MtCO_2e$) and Phase II (2027–2035) potentially reaching between 502 and 1299 $MtCO_2e$ (Carbon Pulse 2025). These figures highlight CORSIA's role as a potential major driver of global carbon credit transactions that Congo Basin countries could access through standards such as ART-TREES for example. High-integrity carbon markets could therefore deliver significant benefits for African communities and become an important contribution to sustainable finance for the Congo Basin (Africa Carbon Markets Initiative 2024).

At the project level, finance opportunities include not only REDD+ but also activities such as reduced-impact logging (RIL-C) and improved cookstove initiatives (Kahlenberg et al. 2021). However, carbon finance flows into the Congo Basin remain limited compared to other regions, constrained by fragile governance, political risks, and institutional weaknesses.

Nevertheless, with growing global attention on forest conservation and climate action, the Congo Basin holds considerable untapped potential to access and leverage climate and carbon finance, provided that efforts focus on building high-integrity, inclusive, and transparent mechanisms for project and jurisdictional implementation.

Synthesis

The aim of this chapter was to highlight the diverse opportunities for sustainable development across key sectors in the Congo Basin. Protected area management and biodiversity conservation, inclusive governance, community participation, and strengthened local scientific capacity can enhance both ecological outcomes and social equity. Ecotourism offers a sustainable economic alternative that supports conservation while generating income for local communities. Agroforestry practices contribute to food security, restore degraded land, and help maintain biodiversity through integrated land-use systems. In the extractive industries, the adoption of RIL-C and responsible mining standards can reduce environmental degradation while supporting economic development. Expanding renewable energy sources can reduce reliance on wood fuel, lower emissions, and improve energy access in remote areas. Additionally, climate and carbon finance mechanisms, including REDD+ and biodiversity credits, offer crucial funding to protect forests, support emission reductions, and strengthen community resilience and livelihoods.

Each of these opportunities comes with its own challenges and needs to be further explored and designed within a national and local context. Further research and modelling need to happen together with national institutions and the private sector to better understand how to implement these opportunities in the most effective way while taking into considerations national priorities, climate change, and the rights of indigenous peoples and local communities.

But the opportunities do not stop there. The Congo Basin is not only a critical ecological region but also a unique and underexploited laboratory for the creation of new knowledge and innovation. Its vast tropical forests, which host over 10,000 species of plants and countless endemic animal species, provide invaluable opportunities for biological, ecological, and pharmacological research. For instance, the study of forest-based medicinal plants, long used by indigenous communities for healing, could lead to the discovery of new treatments and bio-based pharmaceuticals. Additionally, the region offers a living context in which to explore sustainable land-use models, particularly through the co-development of agroecological techniques that merge indigenous farming practices with modern agro-technologies such as precision agriculture or biochar application to improve soil fertility.

Moreover, the Congo Basin presents a powerful case for innovation in climate monitoring and carbon accounting. Community-based forest monitoring, combined with remote sensing and satellite data, could generate robust, low-cost methodologies for tracking forest cover and carbon sequestration—methods that are critical to the success of REDD+ initiatives. In the energy sector, the region's abundant rivers offer possibilities for decentralized hydropower projects, which can be co-designed with local communities to meet energy needs without compromising environmental integrity.

Critically, innovation in the Congo Basin need not, and should not, replicate models from the Global North. The integration of indigenous ecological knowledge with digital tools and green technologies could be harnessed to produce hybrid systems of innovation that are context-specific and resilient. In this sense, the

Congo Basin represents a rare opportunity to pioneer a new development paradigm: one that is rooted in equity, ecological stewardship, and bottom-up knowledge production. Indeed, the green revolution may find its most authentic and transformative expression in regions like the Congo Basin, where development pathways are still in flux and more open to systemic change than in industrialized countries bound by existing infrastructure and socio-economic inertia.

By harnessing its rich natural resources, empowering local communities, and embracing innovative, inclusive approaches, the Congo Basin has the potential to become a global model for sustainable development—demonstrating how ecological conservation, economic growth, and social equity can go hand in hand.

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Section III

Prospective Biodiversity, Ecosystems, and Climate of the Congo Basin

The Future of Biodiversity in the Congo Basin

24

Katharine Abernethy, Emmanuel Abwe, Etienne François Akomo Okoue, Fidèle Evouna Ondo, Loïc Makaga, and Donald Midoko Iponga

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Abstract

The biodiversity of the Congo Basin is currently highly threatened. Climate change is driving fundamental functional change in forest and aquatic ecosystems. Forest loss, driven by fire, agricultural expansion, logging, and fuelwood collection, drives further climate change and directly threatens forest species. In addition, overconsumption by human populations is challenging fish, bird, and mammal survival, and pollution from cities, industries, and agriculture particularly affects insects and aquatic biodiversity.

But there are solutions to counter this bleak outlook. Sustainable use of renewable natural resources is possible alongside economic growth and biodiversity preservation, as the implementation of sustainable logging policies has shown. Sustainable subsistence hunting is possible for engaged communities, willing to monitor and regulate their hunting and enabled to adapt traditional management systems to present-day contexts. Governments are supported by their own laws and international conventions to enact strong regulation of pollutants from the mining sector, urban waste, and infrastructural development, if they have the courage, transparency, and budgets to do that. The most difficult challenge will be the restructuring of economies to move away from raw natural resource exports toward manufacturing and services that will allow wealth to alleviate pressure on biodiversity, rather than increase it.

Keywords

Biogeography · Climate change · Protected areas · Sustainable use · Endangered species · Habitat loss

Introduction

The Congo Basin is home to immense diversity in its geology, physical environment, ecosystems, habitats, and species. Within each species lies vast genetic diversity, selected over evolutionary time to adapt each organism to the particular conditions of its life, and all species interact with each other and their environment. Together, all these sources of biological variation, living and mineral, make up "biodiversity." The complexity and constant variation in the earth's biodiversity is so overwhelming that humanity has yet to come up with adequate ways of fully describing it, let alone robust metrics to allow its quantification (Butchart et al. 2010). Nonetheless, the importance of biodiversity for the survival of humanity is abundantly clear. Many millions of rural people still depend on directly harvesting food, water, fuel, and shelter from natural sources, and for these people, the link between biodiversity and

survival is evident. Even for urban communities, food is an existential need fundamentally reliant on biodiversity. Naturally occurring biological compounds underpin around half or more of modern medicines and almost all traditional medicines including making significant contributions to tackling globally challenging diseases, such as cancer (Newman et al. 2008). Biotechnology is a multi-billion dollar and fast-growing industry using biological processes to produce new foods and raw materials and to treat waste (Voigt 2020). Biomimetics mimic the functioning of natural organisms to find solutions in medicine and prosthetics. Biological processes such as neural networks inspire engineering solutions, data processing techniques, and the AI revolution. Ecosystem services, such as water or air purification provided by natural biomes, are worth billions of dollars every year (Díaz et al. 2018), and in addition, access to natural, biodiverse environments has been shown to be closely linked to human health and well-being (Xian et al. 2024).

What Do We Know About Biodiversity in the Congo Basin?

Globally, species diversity tends to be naturally higher nearer the equator, in areas of high rainfall, and in places where biomes have remained stable over millennial timescales (Rolland et al. 2014). These global patterns in terrestrial species biodiversity show broad similarities across both the plant and animal kingdoms. But nowadays, the underlying evolutionary pattern has been eroded by human activity, lowering species diversity in areas of high human occupation and infrastructure.

The Congo Basin, which is equatorial with high rainfall, areas of ancient biomes, and a low human footprint (Potapov et al. 2017; Venter et al. 2016a), may be home to a million different biological species. It is known to be particularly rich in trees and mammals (Mittermeier et al. 2003); however some taxa, such as mollusks, annelids, crustacea, fungi or algae, are less studied and it is possible that less than 1% of their diversity is documented (Cowie et al. 2022). The Congo River has the highest species diversity of any freshwater system in Africa and is second in species richness globally, after the Amazon (Snoeks et al. 2011). For the better studied taxa, species richness estimates for the Congo Basin are not exhaustive, but range around 8–11,000 plant species, 275–480 mammals, 700–1000 birds, 140–200 reptiles, 200–320 amphibians, and 700–2000 fish (Mittermeier et al. 2003; WWF International 2024). However, even the high end of these estimates are minimum numbers, with almost a thousand additional species, from all the classes above, described between 2013 and 2023 (WWF International 2024) and known low proportions of species described for some hyperdiverse phyla, such as arthropods or mollusks (Cowie et al. 2022; Boyle et al. 2024). Aside from its species diversity, the Congo Basin is also known for its high rate of endemism in several taxonomic groups. For plants, 3000 species, (or ~30%), are endemic to the Congo Basin (WWF International 2024), and for fish, nearly 937 species (or 75%), and this does not include more than 250 endemic species of Lake Tanganyika (Snoeks et al. 2011). Around 10% of all the amphibian, reptile, bird, and mammal species found here are endemic to the region.

The Congo Basin contains 2 of the 36 areas on Earth considered as global biodiversity hotspots. Biodiversity hotspots are areas of exceptionally high species

richness. Overall, the 36 biodiversity hotspots of the world cover just 1.4% of the Earth's land area yet contain nearly 44% of known species (Mittermeier et al. 2011). At the extreme east edge of the Basin lies the *Eastern Afromontane* biodiversity hotspot and at the west edge *the Guinean forests of west Africa* biodiversity hotspot. The Eastern Afromontane hotspot hosts nearly 11,000 known plant and animal species, 3000 of them endemic to only that region. The Guinean forests harbor just over 11,000 species, of which around 2200 are endemic.

Akin to the data deficiencies in the description of Congo Basin species, there is also debate on the description of habitats and ecosystems. Frank White's (1983) map and accompanying description of the vegetation of Africa is still the most widely accepted description of the diversity and composition of structural habitats across the Congo Basin. However, several other biogeographical classifications of the region have since been proposed, taking into account factors that refine species patterns, such as elevation, temperature, rainfall, light, soil type, and history as well as habitat function and quality (Fayolle et al. 2014; Fonteyn et al. 2023; Olson et al. 2001; Philippon et al. 2019; Shapiro et al. 2021). These are useful when considering terrestrial habitats, but take far less account of the patterns in freshwater systems, which are defined by the Basin's hydrology, coastal ecology, and rainfall. Currently, 18 of the 86 known freshwater ecoregions in Africa are in the Congo Basin (Thieme et al. 2005; Abell et al. 2008). These ecoregions are delimited using the distributions and compositions of freshwater fish species and incorporate major ecological and evolutionary patterns (Abell et al. 2008). There is no general consensus on which of any of these is the better representation of the biological composition of the region, which attests to the complexity of robustly quantifying biodiversity and epitomises one of the challenges for future evaluation of conservation success. What is agreed upon is that the Congo Basin encompasses a complex mosaic of coexisting biomes, constantly shifting their boundaries, but allowing distinct communities to coexist and interact along their borders.

Biogeographical maps derived from remote sensing tools are becoming ever more sophisticated and are now able to map the structure of the Congo Basin forests with astonishing accuracy and make data widely available (i.e., https://ctrees.org and https://www.globalforestwatch.org). Terrestrial LiDAR scanning is less widely available, but can provide assessment of forest structure to a precision of centimeters (Maeda et al. 2025). Open-source data projects like the upcoming MapBiomas DRC collaboration will map and classify land use across the country in 30 cm^2 pixels, allowing, over time, a deep understanding of land use trajectories. Using raster (pixel)-based visualizations of the data, rather than polygons, these maps allow more flexible combinations of data from different taxa (for instance, combining tree structure with mammal abundances) and are powerful tools for understanding patterns in biodiversity at multiple scales. However, in 2025, remote sensing is still unreliable at designating the species of a tree it can structurally map. Likewise, remote sensing is not able to see fungal networks, birds, insects, or animal species under the canopy, inside trees, underwater, or underground, and so the mapping of biodiversity below the habitat level is still the work of field biologists.

Finally, we should consider what is known of genetic diversity in the Congo Basin. Perhaps counterintuitively, high genetic variability *within* a species is not necessarily

found in the areas of high species diversity. In areas of high species diversity, animals may have evolved to coexist by exploiting very specialized niches, with variability between individuals reducing over time. An alternative evolutionary strategy is to become a generalist, able to exist in a wide range of conditions and for some individuals to always have the traits to survive, even if conditions change between generations. Such species need to retain genetic variability, with different genotypes gaining advantage in different areas or generations, as habitat conditions vary. The Congo Basin is a mosaic of refugial forest and peatland habitats that have stayed environmentally stable for tens of thousands of years allowing species to specialize (Maley 1996; Sosef et al. 2004) and younger forest habitats that have expanded from these refugia under the forest-favorable climatic conditions since the Holocene (Lebamba et al. 2009; Reynaud and Maley 1994) with species adapting to new conditions. Much of the basin has then been additionally modified by human activity (Morin-Rivat et al. 2014, 2017), complicating the selection pressures on its species.

Phylogeographical studies that consider the distribution of genetic variation across and within the species of the Basin have been relatively rare, due to the costs, technical skills, and laboratory infrastructure needed. The discipline is gaining traction as labs able to process genetic samples become more accessible within the region, but our understanding of the distribution of genetic diversity remains fairly rudimentary (Beekmann et al. 2024).

Why Is Congo Basin Biodiversity Important?

Ecosystems are maintained through a complex network of species interactions and the loss of any species will provoke changes in the biome. Many species share functional roles, such as seed dispersal, meaning that the system is somewhat resilient to the loss of one. However, altering the populations of keystone species, species, which have a disproportionately important effect on their habitat in a role that is not shared across other species, such as elephants (Blake et al. 2009) or apex predators, can result in profound cascading changes and ultimately in transformation of the biome to a different type of habitat (Terborgh and Estes 2010). Wildlife-depleted "empty" forests (Redford 1992) may eventually stop regenerating and, when also under pressure from human land uses, shift to open forests or even grasslands (Dirzo et al. 2014). Freshwater systems that lose keystone species will also enter altered states; they will remain "empty" waterbodies. The functional consequences of this are not yet well understood. Ultimately, the climate services that the Congo Basin provides to the planet by producing and propagating rainfall across the continent (Nyasulu et al. 2024) and the ecosystem services the forests provide to millions of people within the Congo Basin (Brandon 2014) depend on the survival of the region's species, and through them, the diversity of its habitats.

The survival of viable populations of large wildlife is becoming increasingly rare in the overcrowded lands of the twenty-first century (Ripple et al. 2016). That areas of the remaining Congo Basin forests retain their top predators as well as their largest

species of herbivore, frugivore, and insectivore in all of the mammal, bird, fish, amphibian, reptile, and invertebrate guilds is a testament to the stewardship of these forests over the past centuries. They now represent the world's last chance to preserve some of the most globally iconic African species such as the great apes, forest elephants, and grey parrots, animals that have inspired people across the world for centuries. Their survival is of a cultural significance way beyond the borders of the Congo Basin.

Beyond the intrinsic value of the Congo Basin's biodiversity, the region relies economically on its biota. Most of the region's population do not have access to national grid supplied energy and they use wood and charcoal as their primary source of energy (Balume et al. 2025). Direct harvesting of wildlife and fish for food and income still underpins the rural food system across the basin (Ingram et al. 2025) and both forests and savannas provide materials for rural construction. In the absence of widespread access to healthcare, medicines are sourced from natural habitats. Forest products are harvested alongside agricultural production and underpin a significant portion of rural incomes (Iponga et al. 2018). In the Congo Basin, people rely directly on freshwater for drinking, washing, agriculture, transportation, and industrial processes, including the generation of electrical energy. Freshwater ecosystems provide humans with fish and to a lesser extent, turtles, frogs, snails, and crayfishes are harvested. Fisheries and aquaculture of fishes are an essential part of the economy of rural population of the region and are a major source of protein for millions of people (Brooks et al. 2011). Were forest ecosystems to fail and change to grasslands, or grasslands degrade to deserts, lakes, and rivers turn into empty waterbodies; the economic cost of the lost ecosystem services would measure in billions of dollars each year (Díaz et al. 2018).

What Are the Drivers of Change in Biodiversity?

Globally, species and habitat diversities have been vastly eroded by human activity over the Anthropocene, pushing us toward the sixth mass extinction event. Land conversion from natural habitats to agricultural, industrial, and urban areas is the strongest driver of diversity loss at the ecosystem scale. Even before habitat conversion happens, forests are vulnerable to degradation while retaining tree cover (Haurez et al. 2017) and savannahs are increasingly vulnerable to overuse of fires. The situation is much more serious for freshwater species, which are generally more threatened than terrestrial species (IUCN 2011). In addition to the threats mentioned above, freshwater species are also threatened by pollution, flow modification, introduction of invasive alien species, and overharvesting (Brummett et al. 2011). The Global Wildfire Information System (https://gwis.jrc.ec.europa.eu) shows that around 45 million ha in DRC are currently burned each year, including use of fire for clearing forests. CAR burns around 18 million ha annually, Cameroon and Congo between 2 and 3 million ha each, and Gabon and Equatorial Guinea 200–300,000 ha each. Fire frequency is increasing, as ecosystems become drier and human populations more dense.

Species loss follows habitat loss, particularly for low-mobility organisms, such as plants or mollusks, but species loss can also be driven within a persisting habitat, by excessive targeted consumption (i.e., hunting, fishing, or plant collecting). All fauna are susceptible to pollutants and emerging diseases, and the increase in both of these threats has increased overall vulnerability. Recent pandemics in avian influenzas and amphibian fungal infections have seriously impacted wildlife survival globally, even in areas otherwise relatively unaffected by human pressures. Climate change is affecting the productivity of vegetation systems, with knock-on effects for the trophic webs that depend on them (Butt et al. 2015). It is also raising land, freshwater, and sea temperatures, potentially with rapidly ensuing and catastrophic effects on amphibians, reptiles, fish, and insects that require specific oxygen levels in water and will be increasingly affected by changes in temperature, precipitation, and the extraction of water by human communities (Barbarossa et al. 2021; Ficke et al. 2007). The IUCN Red List indicates where human activities are responsible for the species' endangerment. If human-driven climate change is included in the anthropogenic pressures, over 90% of current species endangerment is caused by human factors. If we included non-native species introductions and the spread of disease within the anthropogenic responsibilities, which in most cases it would be fair to do, then close to all species endangerment is due to human activity.

How Are These Drivers of Biodiversity Loss Affecting Species and Habitats in the Congo Basin?

Within the Congo Basin, the modern human footprint is still lower than across most of the world and the region was considered one of the last great wildernesses at the start of the millennium (Mittermeier et al. 2003). However, only around 20% of the land area is still considered to be in an intact state (Mu et al. 2022; Watson et al. 2016). Over the past 25 years, overall human density and infrastructure have expanded relatively slowly compared to human pressure on the tropical forests of Asia or the Amazon (Williams et al. 2020), although estimates of intact forest loss vary considerably, dependent on the criteria for "intactness" (Haurez et al. 2017; Williams et al. 2020). Worryingly, most increase in human activity has been on the eastern (Albertine Rift) and western (Nigeria) boundaries of the Basin, where species diversity is exceptionally high (Venter et al. 2016b). Over the last 15 years, cities and road infrastructure have seen the largest increases in human activity, but where rural populations are at high density, particularly in Cameroon, DRC, and Equatorial Guinea, deforestation and land conversion rates are also high, driving loss of habitat diversity and threatening species (Mu et al. 2022; Williams et al. 2020). Even in low-income countries, city dwellers are typically wealthier than rural populations and consume more natural resources per capita. As urbanization increases across the Congo Basin, cities are increasing their catchments for natural resources, affecting species harvests and land conversion for hundreds of kilometers around them (Ahrends et al. 2010). The core six countries of the Congo basin have very different

human geographies and demographics, which will heavily influence the overall human impacts on their biodiversity in the future, with absolute rural population density likely to be more influential on biodiversity outcomes than the relative degree of urbanization (Abernethy et al. 2016).

Agricultural practices are varied across the Basin due to both variations in rural population characteristics and differing policy approaches to agro-industry, and this drives divergence in biodiversity outcomes. Cameroon, DRC, and Equatorial Guinea all have areas of dense rural populations, which drive faster conversion of forest than in the low rural density countries of Gabon, Congo, and CAR. Congo Basin forest systems hosting over eight persons per km^2 have been shown to have little chance of recovery from human conversion, with smallholder agriculture rapidly becoming permanent (Mayaux et al. 2013). In Gabon, Congo, eastern CAR, and central DRC, rural populations are very low density, but in other areas of DRC, southern Cameroon and much of Equatorial Guinea rural populations are already far beyond the key density of eight persons/km^2 and continue to rise (UN Division of Economic and Social Affairs 2024). In these latter areas, forest losses to smallholder agriculture are likely to be permanent and future forest preservation will be determined by whether food systems and energy systems can change, to alleviate pressure on forest resources. Yet, intensification through agro-industry can have disproportionate effects on biodiversity, through rapid conversion of large areas disrupting connectivity, creation of effluent pollution, and facilitation of new human population centers. Agro-industry is increasingly appealing for the region challenged by the high cost of food imports and a rising population, but it will need to be managed carefully to avoid high biodiversity costs (see "Agriculture and the Future of the Congo Basin").

Subsistence hunting, where it supplies *only* local needs, targets mainly animals $<$20 kg, which are resilient to some offtake and traditional management practices can underpin sustainable offtakes (Wilkie et al. 2016). However, frugivorous species are highly important in the subsistence offtake (Abernethy et al. 2013) and are also more central to the trophic webs that support the Congo Basin forests (Durand-Bessart et al. 2022), than in other tropical forest regions, making the Congo Basin forests particularly vulnerable to functional disruption if the seed-dispersing animals are removed (Effiom et al. 2013; Vanthomme et al. 2010). Thus even slow declines in the species targeted by subsistence hunting may initiate greater system changes over time. Declines in availability of animals can also drive increased use of fish, so as overhunting leads to wildlife depletion, pressure will fall on fish stocks, eventually depleting these too (Brashares et al. 2004).

The need for income in areas of low economic development and where food systems are inadequate is driving rural hunters to use an increasing part of their catch for commerce (Coad et al. 2019). Commercial trade disproportionately affects larger mammals, because income-driven hunters target them preferentially (Kuehl et al. 2009), because they are slow to regenerate populations and, for carnivores, because hunting can also eradicate their prey base (Henschel et al. 2011). In addition to the transition of village-based hunters from purely household to partly trade motives, professional hunters, exclusively supplying illegal international trafficking,

represent a significant threat to species in the Congo Basin. Beyond the mainly regional demand for meat, intercontinental demands for ivory and pangolin scales (Challender and Hywood 2012; Thouless et al. 2016) have pushed forest elephants and giant pangolins close to local extinction in some parts of the basin, despite both national and international bans on their trade. African grey parrots are also known to be heavily affected by capture for the pet trade and are thought to be locally extinct in parts of their west African range (IUCN 2020). Poorly studied groups, particularly reptiles, may be under more hunting pressure than has yet been properly evidenced (Morton et al. 2021).

Protected areas have to some extent been successful at conserving species from the direct threats of human expansion and consumption (Laurance et al. 2012) and Other Effective Area-based Conservation Measures (OECM), such as certified logging concessions or community forests, extend that conserved land. However, they are not effective for freshwater biodiversity because, with the exception of Ramsar sites identified under the Convention on Wetlands, these ecosystems are often not taken into account in the delimitation and management of most protected areas (Hermoso et al. 2016). In addition, they are not effective against disease and climate change. The Congo Basin outbreaks of Ebola viruses in the past 40 years have devasted ape populations, even in protected area strongholds (Bermejo et al. 2006). Climate change has raised the mean minimum temperature of the Basin by around 1 °C in the last 40 years and altered local rainfall patterns (Bush et al. 2020a; Kasongo Yakusu et al. 2023) impacting the region's forests. Although there is much variation in species responses and across geographies and biomes (Adamescu et al. 2018), within local tree communities a decline in fruiting behavior can be intense, leading to measurable negative effects on the health of frugivore populations (Bush et al. 2020b).

What Are Likely Scenarios for Biodiversity Under Business as Usual, with Human Population Doubling, Economic Growth, and a Temperature Increase of 3 Degrees by 2100?

Where Will Human Populations Exert Most Future Pressure?

Most of the region is already highly urbanized. Although CAR and DRC are still majority rural smallholder populations, more typical of the rest of the continent, population growth trajectories predict these countries to pass 50% urbanization in the next 2–12 years, with DRC reaching 50% urbanization nearly a decade faster than was predicted in 2014 (UN Division of Economic and Social Affairs 2024). The growth of towns into cities will lead to the large peri-urban areas that have already suffered considerable degradation being unlikely to recover even a small proportion of their original biodiversity. The amount of land affected by city haloes in Africa has increased 700-fold since the turn of the century (UN-Habitat and HIS-Erasmus University Rotterdam 2018). Importantly, three-quarters of the recent growth has been in smaller cities (<1 million people), which often lack adequate supply systems

for basic needs, such as food, health, and construction, but cannot attract the investment or government budgets of major cities. They may also have weaker governance, for similar reasons. Citizens then turn to the "open-access" resources of the peri-urban land, degrading it rapidly to the point of no-return.

Despite urbanization, absolute densities of rural populations are also expected to grow in all countries except Gabon, increasing human pressure on currently intact forests and biodiversity hotspots. Gabon has a rural density of 0.8 persons/km^2, only 10% of the forest-critical eight persons/km^2 threshold (UN Division of Economic and Social Affairs 2024). However, the rural populations of Congo and CAR are now at a mean of seven persons per km^2 and could soon reach a tipping point to permanent ecosystem damage in some areas. The biodiversity hotspots in the eastern montane and west African forest regions are particularly at risk as smallholder populations are rising steeply and the depletion haloes from megacities also extend into these areas (Ginzky et al. 2021).

How Might Economic Growth Affect Consumption of Biodiversity?

As the biodiversity crisis has grown, predicting how economic growth will affect human choices has become important in forecasting human pressure.

Large cities are motors of economic growth and the region's economies have all been growing 2–3% per year over the past 5 years (Factors of the Economic forecasts for the Congo Basin). Wealth is a significant driver of consumption in all societies, and even though the region's cities have a high proportion of urban poor (around 60% of the region's urban population are below the poverty line; Anderson et al. 2013), they are still on average richer than their rural compatriots. This, together with the sheer number of city dwellers, will drive the aggregate consumption of cities to be a huge pressure on the relatively small amount of land around them. Frail transport infrastructure around cities intensifies the peri-urban damage, as transport costs to move goods in from a wider catchment become prohibitively high.

However, although initially economic growth increases impacts on biodiversity, analyzing biodiversity consumption in Asia and Europe in the same way as other commodities has been insightful. An environmental Kuznets curve analysis for Asia's emerging economies shows that as GDP grew, the consumption of biodiversity reached a high, but then began to decline as dense populations realized the value of nature and ecosystem services and had the means to purchase less environmentally demanding goods (Yiew et al. 2025). A similar analysis for the Congo Basin shows that when considering agricultural output as the expression of economic performance, growth continues to degrade the environment, but when considering manufacturing as the expression of economic performance, biodiversity consumption also showed a decline as the economy grew. The authors conclude that "a structural transformation of the economy from the agricultural to the manufacturing sectors, while strengthening governance, will curtail deforestation and pave the way for sustainable exploitation of forest resources" (Aquilas et al. 2022) and this is echoed in the analysis in Factors of the Economic forecasts for the Congo Basin.

To date, economic growth in the Congo Basin has largely been driven by foreign direct investments (FDI). Access to natural resource deals is increasingly used to attract FDI, particularly from China (UN-Habitat and IHS-Erasmus University Rotterdam 2018). While FDI brings welcome solutions to infrastructural challenges, it can be very difficult to plan and regulate the natural resource concessions issued in counterpart to these investments. Regulation of the FDI sector to respect higher environmental standards, rather than regulation of the resource concessions, may yield better outcomes.

Where and How Will Climate Change Effects Be Critical for Biodiversity?

Climate change has already made measurable differences to the weather experienced in the Congo Basin; however a dire lack of weather reporting across the region has undermined robust climate modeling and impeded adaptation efforts (Niang et al. 2014, Climate of the Congo Basin). We know that the region has warmed by around 1 °C over the past 40 years (Bush et al. 2020a; Kasongo Yakusu et al. 2023) and this rate of warming is likely to increase. Rainfall changes are less predictable, with some regions drying significantly and losing seasonality, while others are getting wetter, with more extreme seasonal or erratic events. Importantly, dry season cloud cover in the western Congo Basin system is weakening (Philippon et al. 2019). This is potentially a huge hazard for the Basin, leaving the western forests vulnerable to drying and fire, which would in turn weaken or stop rainfall propagation eastwards, transferring the vulnerability across the Basin (Nyasulu et al. 2024).

Yet even preceding the existential threat to the forests, climate change is provoking functional changes within ecosystems that already pose threats to individual species or groups. Beekmann et al. (2024) reviewed 104 papers and report assessing the effect of climate change on biodiversity in the Congo Basin. They found empirical evidence of changes underway in eight different ecological processes; perhaps most worryingly, ecosystem shifts to alternate states, such as forest replacement by grassland habitats or the inverse. Predictions of the speed and geography of ecosystem change are difficult, as there are complex and poorly understood feedback loops between land use change and climate (The Climate and Land-Use Change Feedback), and, crucially, we do not understand the mechanisms by which tipping points may be reached Sanders D, Frago E (2024).

In the past decade, research has revealed devastating impacts of climate change on tropical insects (Janzen and Hallwachs 2021). In central America, tropical forest insects have declined to a quarter or less of their abundance in the 1970s, with correlated declines in the insectivorous lizards, birds, and frogs that rely on them (Lister and Garcia 2018). In the Congo Basin, there are, as yet, no studies on change in insect abundances; however, the changes seen in the Americas are also seen in Asian tropical forests and are very likely to be happening in the Congo Basin too (Sharp et al. 2025). Climate-driven declines affect larger insects more, with declines in beetles already affecting the rate of litter decomposition and the cycling of key nutrients in American tropical forests (Boyle et al. 2024; Sharp et al. 2025). This is

the beginning of a fundamental change in tropical forest function, the consequences of which are hard to predict and should be a global research priority to understand. In addition, the extent of agricultural land in a landscape is a major determinant of the rate of insect declines, accelerating climate change effects with the input of pesticides and hotter temperatures at the local scale (Outhwaite et al. 2022). As agriculture extends across the Basin, pollinator loss will accelerate, reducing yields. If the response to this is to add further pesticides and fertilizers and cultivate more land, pollinator loss will accelerate further, in a spiral toward ever-decreasing diversity and lower-yield lands.

Freshwater biodiversity, at both species and habitat levels, is highly vulnerable to changes in precipitation, temperature, and seasonality, which will change water levels and chemistry. Indeed, global climate change will alter water temperature, as well as the timing and amount of rainfall, directly affecting the flow of the major rivers and their tributaries. Many freshwater species are highly dependent on water temperature and specific flow rates and particular signals from seasonal variations in these flows for their reproductive, feeding, and migration cycles (Brummett et al. 2011; Knouft and Ficklin 2017). The hydrological systems of the Basin are already undergoing significant change (The Hydrology of the Congo Basin) with consequences for biodiversity unclear, but likely to be negative. Fish stocks of many species are steeply declining in the Congo River, mostly due to overfishing, but climate change is exacerbating the problem (Castello et al. 2023). These losses will also undoubtedly be affecting species from other taxonomic groups dependent on fish, such as African fish eagles (*Haliaeetus vocifer*), the near-threatened Congo clawless otter (*Aonyx congicus*), and the critically endangered slender-snouted crocodile (*Mecistops cataphractus*). There is an urgent need to better understand the diversity, functional ecology, and threats to aquatic systems. They remain an understudied part of the Congo Basin system, despite the paramount importance of unpolluted freshwater, for health and food security across the Basin.

Is Congo Basin Biodiversity Currently Protected Sufficiently?

At a global scale, the Congo Basin remains a haven of biodiversity in an increasingly nature-impoverished world, but protecting this treasure trove for the future is a critical challenge, given the rising human pressure.

The IUCN Red List of Threatened Species (https://www.iucnredlist.org) is the leading information source on the status of the world's species and assesses past and future trends, although many of the Congo Basin's species are not well enough studied for assessments to be made, which is worrisome. The status of keystone species, often the larger species, can be used as indicators of the general health of faunal communities, and in the Congo Basin, all the largest species are considered endangered to some degree. The apex mammal predators, lion (*Panthera leo*), leopard (*P. pardus*), and golden cat (*Caracal aurata*), are all assessed as Vulnerable. The largest raptor, the crowned hawk-eagle (*Stephanoaetus coronatus*), is also Vulnerable. Of the large herbivores, hippopotamus (*Hippopotamus amphibius*), are

Vulnerable; Okapi (*Okapia johnstoni*) are Endangered and the forest elephant (*Loxodonta cyclotis*) is Critically Endangered. The forest buffalo (*Syncerus caffer nanus*) has not been assessed. Within the great apes species, icons of the Congo Basin, chimpanzees (*Pan troglodytes*) and bonobos (*P. paniscus*), have Endangered status and both western gorillas (*Gorilla gorilla*) and eastern gorillas (*G. beringeii*) are Critically Endangered. In freshwater biodiversity, the analysis by Snoeks et al. (2011) of the conservation status of fish in Central Africa (Congo Basin and Lower Guinea) revealed that 62% of fish species were of Least Concern and only 15% were threatened with extinction. Within this latter category, the majority of species were Vulnerable (8%) or Near Threatened (5%), and only 2% were Critically Endangered.

In estuarine and lagoon habitats of the west coast, predatory large-toothed sawfish (*Pristis pristis*) are thought to be extinct and the large herbivorous African manatees (*Trichechus senegalensis*) are considered Vulnerable. The endangerment of these key species will be leading to functional changes in their habitats and a research priority for the future is to understand how ecosystems are responding to keystone species loss and improve predictions for when tipping points may be reached.

The most influential global target for habitat protection is proving to be "30 by 30," the ambition to protect and effectively manage 30% of each habitat in each country, by 2030. This was agreed by 196 countries at the Convention on Biodiversity (CBD)'s Conference of Parties in 2022, as Target 3 of the Kunming Montreal Global Biodiversity Framework (GBF). Since the CBD implemented its 10-year Strategic Plan in 2011, then setting Aichi Target 11 to protect 17% of habitats, the Congo Basin countries have become leaders in implementing formal habitat protection and continue on this path (Trends in the context of 30 × 30 Congo Basin Engagements).

Table 1 shows the countries' terrestrial protected area status in May 2021 (updated to 2025 for DRC and CAR), with details of the degree to which the

Table 1 The degree of habitat protection in force in the six core Congo Basin countries, in respect of total land area, Ecoregions, Key Biodiversity Areas and national carbon stocks

Countries	Total Terrestrial Protected Area		Ecoregions		Terrestrial Key Biodiversity Areas		National Carbon Stocks protected (%)		
	km^2	%	N	Mean % Ecoregion protected (N with no protection)	N	Mean % of KBA protected (N with no protection)	Above ground biomass	Below ground biomass	Soil organic carbon
DRC *(Jan 2025)	864,290	37	19	31 (4)	24	60 (8)	27	35	20
Congo	126,472	37	4	39 (0)	10	73 (1)	43	41	48
Gabon	59,708	22	4	20 (0)	8	62 (1)	23	22	26
CAR *(July 2021)	132,078	21	6	16 (2)	8	75 (2)	23	20	18
Equatorial Guinea	5,228	19	5	54 (0)	5	100 (0)	20	19	20
Cameroon	51,538	11	13	23 (1)	37	36 (20)	15	13	11

Data are from the May 2021 CBD and UNDP Aichi Biodiversity Target 11 Country Dossiers available at https://www.cbd.int/pa/doc/dossiers/*country*-abt11-country-dossier2021.pdf.
*Data for CAR and DRC have been updated to include major protected areas gazetted since May 2021. NB for DRC the overlay of around 71% of the 2025 Kivu-Kinshasa Green Corridor with industrial oil blocks means that estimating the real proportion of protected national carbon stocks and KBA is complex (Earth Insights 2025)

ecoregions, key biodiversity areas, and carbon stocks of the countries are afforded protection by the national PA and OECM networks (CBD and UNDP 2021; Earth Insights 2025). In 2021, all countries had already protected at least 10% of their land area, although DRC and Cameroon had less effective protection of their highly biodiverse landscapes, with one-third of KBA's in DRC and over half in Cameroon unprotected. Congo had already exceeded Global Biodiversity Framework targets, years before they came into force, and Gabon is close to meeting them. DRC has now gazetted a new protected area, the 544,270 km^2 Kivu-Kinshasa Green Corridor, which also brings it above the 30% GBF target well before 2030. Equatorial Guinea and Cameroon are only halfway, or less, to meeting the GBF targets on land and, with their high-density rural populations, may struggle to find land unoccupied and suitable to be set aside. For these countries, OECM could provide the remaining land to meet the GBF 30% target, but implementing effective conservation in OECM will require improvements in governance and monitoring. Insufficient funding, training, personnel, and infrastructure, as well as often a lack of local support for protected areas, have hampered their ability to truly protect wildlife. Key species targeted by lucrative international wildlife markets, particularly elephants, have declined in every country except Gabon, with protected areas offering only slight sanctuary (Laguardia et al. 2021; Maisels et al. 2013). In addition, smaller species targeted by the wildmeat trade have also declined across the basin, with proximity to cities being a major determinant of their status (Ingram et al. 2025).

What Could Mitigate Biodiversity Loss in the Future?

There are solutions within reach to put the Congo Basin on the path to a more biodiverse future than Business As Usual will bring. There is optimism in the extent of the intact forests and wildlife communities that still remain. Nature is resilient and the archaeology of the Basin shows that forest ecosystems have recovered from intense human pressure and climate changes in the past (Morin-Rivat et al. 2014; Ngomanda et al. 2007). They may do so again, if human societies can support them. However, the "bottom-up" trophic cascades provoked by the changing climate and the knock-on declines in the productivity of plants and the abundance of insects and fish are altering ecosystems profoundly, in ways that are hard to understand or predict. Our lack of natural history knowledge of the Congo Basin species and systems is a further obstacle to predictive power. Exhaustive collections of tropical beetles and experimental tests on their ability to adapt to climate change indicated that almost 80% of the tropical forest beetle species alive today are unnamed for science and unstudied. Furthermore, the unnamed species were less able to adapt to climate change when challenged (Boyle et al. 2024), implying that the most sensitive species may be gone already, before their unique contributions to ecosystem survival were ever known. Insect loss has only been measured for the past 50 years, yet climate change has been in progress far longer. It is possible that the insects left today are only a subset of the original trophic web supporting tropical forests, whose functions and genes are already lost. With so much unknown, policy and actions to

mitigate biodiversity loss will need to remain agile and responsive to new knowledge to be effective.

Governments are the main authorities that determine outcomes for biodiversity and could make significant change, if nature becomes more important in the political agenda. The greatest power available to the Congo Basin countries right now may be to become a stronger voice in the international arena, advocating for the biodiversity of the Congo Basin, continuing to implement world-leading environmental policies at home, and insisting more forcefully that other countries respect the commitments made to the UN Conventions. As the region becomes economically stronger and less structured around natural resource exploitation, this may be easier for governments to deliver. But they can also work immediately within their current budgets and by leveraging the private sector, to deliver biodiversity-positive economies and societies. Focusing on a green energy transition in rural areas, as well as within cities, proper regulation of freshwater pollution and overharvesting, boundaries for ensuring national investments are not environmentally damaging; increased environmental impact control on foreign investments; support for better environmental science and evidence-based policy-making; improved planning and regulation of urbanization; and design of trade policy to promote sustainable domestic food systems would all deliver substantial gains for biodiversity.

At the private sector level, OECM lands, often under concessionary management, are recognized as significant in extending the area where biodiversity can flourish, beyond formal protected areas that are costly to the State and often contested by local populations. The Congo Basin countries, as well as the international community, funders of and clients for the resources and products from Congo Basin land concessions, can promote OECM land to be an integral part of sustainable land management, as is already the case for FSC certified logging, or Roundtable on Sustainable Palm Oil (RSPO) accredited palm oil production. Were other agriculture and mineral concessions to be managed in a similar way, biodiversity gains would be substantial.

Private sector actors can also self-regulate, even if governments are weak, and they can be driven to act by civil society. Consumer action has driven major industries that highly impacted biodiversity in other parts of the world to change their practices, for example, the North American fur trade, or the Chinese ivory trade. Public outcry over tropical deforestation has led to the establishment of consumer demand for deforestation-free products in many countries outside the basin; however within the region, poverty is a significant limitor of consumer choice and it is unlikely that local consumer pressure will be a force until living standards become much higher. The private sector is more agile than government, and significant societal change has been driven by business approaches. It remains to be seen whether the current digital revolution will play out for biodiversity in the Congo Basin—will the need for data centers drive up emissions and drive further climate change, or will the greater dissemination of information result in higher bioliteracy and increased constituency for nature-positive solutions?

Families, individuals, and civil society organizations are also important actors for, or against, biodiversity. Deforestation and biodiversity loss in the high rural density

areas are still mainly driven by smallholder individuals, but new paradigms are emerging for sustainable energy, agriculture, and forest and wildlife management at the community level. These are showing positive results at very local scales and could enable and empower people to live more in harmony with nature (Agriculture and the Future of the Congo Basin & Hunting, Fishing and the Future of the Congo Basin). Rural families and communities need help, training, and economic support to invest in better systems for agro-ecological production, solar or small-scale hydro rather than wood-driven energy systems, and domestic livestock production that can reduce hunting to sustainable offtake levels.

Urban families also drive biodiversity loss through demand for wild resources from around their city and their decisions on disposal of polluting waste. With high urbanization, urban dwellers have a disproportionate voice in the electorate and can demand national investments in clean energy systems, sustainable domestic food systems, effective waste management, and better urban planning for city growth, which would yield biodiversity rewards in even the short term.

Ways Forward

Chapman et al. (2022) consider the future of biodiversity in the whole of sub-Saharan Africa and show that the funds needed for more effective protected area conservation are considerable (estimates range from $USD 10 to 76 billion annually for the whole continent), but are a tiny fraction of Africa's total GDP and a microscopic part of global GDP, certainly within reach of a willing population at either level. Chapman et al. then contemplate how to engender the will within society to preserve Africa's biodiversity. They find that efforts to achieve development through conservation, i.e., (and most familiarly) by revenue-sharing from ecotourism, have in fact very little evidence of success. When populations are at high densities, revenues must be shared so widely that individuals see little direct benefits. This is likely to hold true for areas of high human density in the Congo Basin; however, in low rural density areas, such projects could be much more successful in engaging constituencies for biodiversity benefits. In high-density areas, the greatest success in achieving local community support for conservation has come from projects that deliver tangible health benefits linked to wildlife protection, in a One Health approach. Scaling of these community initiatives is likely to be a better strategy in such areas, than direct revenue-sharing.

Direct payment for biodiversity-positive performance is likely to become a reality for Africa in the next decade. Based on the trials and tribulations of the carbon markets, the key to making this approach work for the Congo Basin will be in establishing an authority for biodiversity within the Basin, using transparent and standardized monitoring and biodiversity metrics that are easily understood and accepted to be of value. Avoiding international negotiations on biodiversity value being driven from outside the Basin will be important. The valuation of the Congo basin's biodiversity must be made inside the region, by the governments, societies, cultures, and families who will live with whatever species and habitats persist in the

future. There are choices still for the Congo Basin, but there will be a high cost to the inertia of allowing the Business As Usual practices currently in place to go on.

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What Might Influence Economic Forecasts for the Congo Basin?

25

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Abstract

While the Congo Basin remains an important repository for biodiversity, the economies of the basin rely on primary commodity exploitation and trade. Renewable and exhaustible commodities such as timber, minerals, and hydrocarbon are major sources of income flow. This chapter addresses the current and future economic landscape of the Congo Basin. The demand for more agricultural land to meet the food needs of the growing population and addressing the raw material needs of the industrial sector, wood fuel consumption, and expansion of road infrastructure as well as trade and foreign direct investment would determine

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the growth and stability of countries in the basin. It is established that meeting the international demand for biofuel and natural resources of renewables and exhaustible resources would combine to shape the trajectory of future roles of the Basin in both the regional and global economy. There is need for a new economic model for countries in the region, in which priority is given to processing and value addition to the primary commodities that dominate trade, which balances the need for economic growth with environmental preservation, while addressing poverty, inequality, and governance challenges. Within the region itself, increased economic integration would be the platform to promote political and socioeconomic stability and development, particularly through increases in regional trade, cooperation, and levels of self-reliance.

Keywords

Growing populations · Investments · Infrastructure · Renewable resources · Economic growth · Environmental preservation

Introduction

The economies of countries in the Congo Basin hinge on the trade of natural resources and the majority of countries participate in global policy processes to protect the environment (Lernborg and Atallah 2025; Trefon 2017). However, with a business-as-usual scenario, negative trends in the state of nature and its contributions to people are projected to worsen in the coming decades, albeit unevenly between different countries (IPBES 2024; Díaz et al. 2020). The direct drivers of nature's degradation are reinforced by a multitude of societally mediated indirect drivers such as economy and trade, culture, demography, institutions, and governance systems (IPBES 2024; Díaz et al. 2020).

The Congo Basin will remain an important repository of biodiversity in the foreseeable future; however, degradation is evident in all the realms (terrestrial, freshwater, and marine) (Beekmann et al. 2024; Shapiro et al. 2021; Inogwabini 2020; Bele et al. 2015). Biodiversity decline is projected to continue, without transformational change in the regional and global socioeconomy (IPBES 2024; Díaz et al. 2020). Therefore, understanding the role and influence of nature on the economy provides useful insights into what is needed to ensure future resilience.

The Basin's economic future centers on balancing its resource-driven growth with sustainable practices. However, the present economic structure stands in sharp contrast to these aspirations. The region continues to be heavily dependent on extractive sectors, which account for more than 70% of all exports. This reliance on finite oil, gas, and mineral resources exposes national economies to a high degree of uncertainty and vulnerability. Its future economic outlook requires diversification to move beyond reliance on natural resources toward manufacturing, services, and technology sectors, which could foster resilience and job creation (Atyi et al. 2022).

Distributing and marketing primary commodities continue to debase the value of the economy in the basin. Since commodity value addition is a cornerstone of sustainable economic development, countries in the basin require structural transformation from a raw material-based economy to a more industrial and knowledge-driven one. Innovations in green technologies and renewable energy may open new economic possibilities (World Bank 2024a), but these hinge on improved energy access, and digital connectivity, which are expected to boost trade and facilitate economic diversification (AfDB 2024; World Bank 2024b). As the population expands, the growing demand for wood and minerals, especially those that are critical for renewable energy (e.g., cobalt), will continue to drive extraction, although this raises concerns over environmental and social impacts. Being signatories to multilateral conventions and policies promoting sustainability could influence the Congo Basin countries' adoption of new resource extraction policies, although translating these commitments into new and responsible resource-extraction practices remains an ongoing challenge. Long-term success will inevitably depend on effective governance, regional collaboration, environmental stewardship, and investment in human capital.

Status and Trends of the Economy in the Congo Basin

The Congo Basin countries have constituted some of the oldest regional agreements in Africa, both the Economic Community of Central African States (ECCAS) and the *Communauté Économique et Monétaire de l'Afrique Centrale* (CEMAC), with objectives to strengthen cooperation and economic development (Ofori-Amoah 2024; Iloh and Ojukwu 2021; Diaw and Lessoua 2013). All countries in the Basin are classified as low- or middle-income developing countries (World Bank 2025b). Economic integration in the region is seen as a platform for political and socioeconomic stability and development, through regional trade, cooperation, and self-reliance.

Natural resources account regionally for three-quarters of total exports and 40% of government revenues (AfDB 2024; World Bank 2024a). However, agriculture remains vital as the basin's largest employer (Sassen 2025; Atyi et al. 2022) and a significant contributor to GDP (AfDB 2024). Smallholder agriculture provides for the subsistence and livelihood of millions (Molua et al. 2023). Despite its importance for food security, employment, and rural development in the Congo Basin, agriculture is hindered by restricted market access resulting from inadequate infrastructure, including roads and storage facilities.

The basin's vast forests uphold timber as an important sector in the economy, worth around 6% of GDP in some countries. However, insufficient government capacity and poor enforcement of logging regulations have driven unsustainable practices, further exacerbated by corruption (▶ Chap. 12, "Agriculture, Ecosystem Functions, and Services in the Congo Basin"). The illegal logging and trade of timber products deprives governments of revenue (Piabuo et al. 2021), as well as frequently exacerbating corruption and criminal networks (Cerutti et al. 2013).

The extraction of nonrenewable mineral resources similarly continues to be a significant component of the basin's economic framework (Mufungizi 2025).[1] A recent mining boom has attracted billions of dollars in foreign direct investments (FDI) (Gulley 2023; Tetzlaff 2022; Rubbers 2020), particularly in DRC, but Cameroon and Gabon also have huge unexploited mineral resource potentials. Gabon has almost 25% of the world's manganese reserves, yet the mining sector currently contributes only around 6% of GDP. Cameroon's geological diversity predisposes the country to a wide range of mineral deposits, among which are gold, copper, zinc, lead industrial minerals, diamonds, and other gemstones (World Bank 2024b).

Each of the countries espouses a long-term development agenda anchored around industrialization. The region presents significant opportunities for hydropower development, as well as potential advancements in solar and biomass energy, indicating a potentially promising future for renewable energy growth. However, accessing an *existing* reliable energy supply impedes the industrialization aspirations. Enhancing access to electricity through renewable energy would facilitate economic activity, thereby fostering regional development and alleviating poverty. Hydropower emerges as the most promising renewable energy source in the basin, due to the extensive river systems. The Congo River offers opportunities for large-scale hydroelectric initiatives that hold the potential to generate very significant quantities of clean energy. Nevertheless, nations in the region have not fully harnessed these potentials due to political instability, infrastructural deficits, financial investment challenges, and environmental constraints.

The volatility of key export commodity prices has meant significant fluctuations in incomes for the Congo Basin bloc and attendant fiscal challenges exacerbated by external borrowing. According to the IMF (2025), "persistent and significant fiscal slippages have intensified pressures on regional government debt markets, leaving many countries struggling to secure financing amid tightening financial conditions reflecting growing investors' concerns. These tensions in the regional issuance market have spilled over to the banking system, triggering a significant tightening in the money market. As a result, financial stability risks have risen, and the broad-based tightening of financing conditions is likely to dampen economic activity. Without decisive corrective measures to address the persistent fiscal imbalances across many countries, external imbalances could worsen significantly over the medium term, threatening the monetary union's external stability."

There are varied economic performances for the different countries in the basin. The AfDB (2024), World Bank (2024a, b), and IMF (2025) in their periodic African economic reviews captured the similarities and divergent performances of the Congo Basin countries.

[1] The basin contains a range of valuable minerals, including cobalt, copper, gold, and coltan, essential for the electronics and renewable energy industries. DRC is recognized as the foremost global producer of both cobalt, crucial for batteries in electronics and electric vehicles, and coltan, utilized in electronic components. Gold and diamonds are obtained from alluvial and hard rock deposits throughout the basin. Additional minerals of economic significance include copper, tin, tungsten, iron ore, uranium, and rare earth elements.

- ***Cameroon***: Economic growth of around 3.7% in 2022 and 2023 due to the good performance of the forestry and services sectors (AfDB 2024). Growth was driven mainly by private investment. Inflation stood at 6.3% in 2022 and 7.4% in 2023, driven by food prices, which rose by 11.1%. GDP growth was 4.1% in 2024 and 4.4% in 2025 thanks to a gradual increase in domestic gas production and higher world commodity prices. Inflation of about 6.3% in 2024 dropped to about 4.3% in 2025 due to the continued tightening of monetary policy by the Bank of Central African States (BEAC). Among the economically active population, 23% were living under the $2.15 a day poverty rate in 2023, and the unemployment rate was 3.7%. Between 2014 and 2021, the number of urban poor more than doubled, reshaping the poverty landscape.
- ***The Central African Republic***: Though steeped in civil war in recent times (Mandon et al. 2024; Stapleton 2019), economic growth picked up slightly, from 0.5% in 2022 to 1% in 2023 (AfDB 2024), driven by improvements in the agriculture sector. The industrial sector recorded growth of 0.5%, up from a decline of −0.8% in 2022, and the services sector a growth of 0.7%, up from 0.6%. Poverty remains widespread, with 68% of the population (or 4.2 million people) living below the national poverty line. Unemployment stands at 28% for men and 42.5% for women, and the Gini coefficient for inequality remains high. Postwar economic recovery has an estimated economic growth of 2.3% in 2024 and 3.1% in 2025 and inflation of 4.1% in 2024 and 3.4% in 2025. Tailwinds for this better outlook include consolidation of peace and internal security, improvements in energy and fuel supplies, and acceleration of development of the road infrastructure related to the Pointe-Noire–Bangui Corridor. Agriculture employs 70% of the workforce, and services employ 22%. Agricultural contribution to GDP averaged 42% over 2001–2010 and 35% over 2011–2020, while that of the services sector rose from 33% to 40% and that of the industrial sector remained mostly stable at 25% and 22%.
- ***The Republic of the Congo***: Economic growth was 3.9% in 2023, up from 1.7% in 2022, driven by the oil sector and food crops. Economic growth is estimated at 4.3% in 2024 and 4.4% in 2025 driven by increased oil production, investments in the gas sector, and paying down of the domestic debt to national economic operators. However, economic performance remains precarious subject to persistent civil insecurity, rising food import prices and volatile oil production and prices. Services, at 47.1% of GDP, and industry, at 45.3%, dominate the economy, with agriculture accounting for just 7.6% of GDP. The main obstacles to economic transformation in Congo are dependence on oil, weak human capital, poor governance, and an unattractive business environment.
- ***The Democratic Republic of the Congo***: Economic growth rate declined from 8.8% in 2022 to 7.5% in 2023, due to underperformance in extractive industries. Growth in non-extractive sectors rose from 3.1% in 2022 to 3.6% in 2023. Economic growth remained favorable, at 5.7% in 2024 and 5.6% in 2025, driven largely by the mining sector, construction and public works, and trade. Over the period 2005–2020, agriculture's share of employment dropped from 71.1% to 60%, while industry's share rose from 7% to 10.7%. Services' share climbed,

from 22% to 29.3%. Employment in DRC is gradually shifting from agriculture to industry and services due to the low productivity of agricultural jobs, a large informal sector, and the dominance of the capital-intensive mining sector. The poverty rate is almost 56%, and unemployment was 15.1% in 2020. Constraints to structural transformation in DRC include border insecurity, infrastructure challenges, an unattractive business environment, and weaknesses in human capital, institutions, governance, and financing.

- ***Equatorial Guinea***: In recent years, hydrocarbons dominated the economy, estimated at 42% of GDP, 95% of exports, and 90% of total revenue. However, Equatorial Guinea's economy has contracted over the past decade amid a shrinking hydrocarbon sector, declining investment, and a series of external and domestic shocks. Between 2013 and 2023, economic activity contracted by 4.1% per year on average. Gross national income per capita was estimated at $5240 in 2023, a 58% decrease from its peak in 2008. The economy experienced a recession in 2023, with real GDP contracting, due to oil and hydrocarbon production shrinking to 12.8% of GDP in 2023. However, the development of new gas wells boosted gas production in 2025. The main challenges to structural transformation are a downward trend in labor productivity in the industrial sector, weak development of value chains, and low mobilization of internal resources in the non-oil sector. The secular decline in hydrocarbon reserves indicates the need for Equatorial Guinea to adopt a new growth model and better leverage the remaining hydrocarbon resources to unlock alternative sources of growth.
- ***Gabon***: Gabon similarly has an extractive resource-dependent economy. Oil accounts for about 40% of the country's GDP and 80% of export earnings. In 2022, top exports were crude petroleum ($4.88 bn) and manganese ore ($1.83 bn) (AfDB 2024; World Bank 2024a). Real GDP grew 3.0% in 2022, up from 1.5% in 2021, due to the healthy state of both the oil sector (which grew 7.1%) and the non-oil sector (which grew 2.3%). Growth in the oil sector was driven by the 45.3% rise in oil price associated with the 6.1% increase in oil production in 2022, and growth in the non-oil sector was driven by agriculture (which grew 4.9%), forestry (which grew 6.5%), and transportation (which grew 4.2%). Although Gabon has achieved higher exports of processed wood products by combining a log export ban with incentives for local wood production, the log industry has struggled to move up in the value chains. Hence, despite natural resources wealth and a relative high GDP per capita ($8017 in 2020), social indicators remain poor, with poverty estimated above 30% and unemployment estimated above 28% in 2021. Real GDP growth is estimated to continue at 2.7% in 2023 and 2.8% in 2024, due to high demand for export products (oil, manganese, wood, palm oil). Gabon has one of the highest urbanization rates in Africa, with more than 80% of its population living in urban areas. Half the population is under 20 years old, and fertility rates are significantly higher in rural areas (estimated at six children per woman), compared to urban areas (four children per woman). Since regime change in 2023, Gabon has experienced changes in economic policies, including the adoption of more expansionary fiscal policies, increased efforts to support business and job creation across various sectors, and improvements in the quality and accessibility of infrastructure and public services.

Drivers of the Bioeconomy in the Congo Basin

Within the Congo Basin, forestry and agriculture and hunting/fishing have been identified as the prominent drivers of biodiversity loss (IPBES 2018, 2024; Atyi et al. 2022). As the demand for food, industrial raw materials, and profits increases, the effects of these drivers also increase. The Congo Basin countries face difficult trade-offs between preserving nature and pursuing economic activities that may hinder nature's sustainability.

Synopsis of Direct Drivers

Conversion for Agriculture

The need to increase yields (in order to provide food to a growing population) by irrigation, mineral fertilization, the use of agro-chemicals, and rise in unsustainable practices is resulting to an agricultural system detrimental to the environment. This is increasingly associated with deforestation, land degradation, and depletion and contamination of freshwater. Intensification of agriculture can mitigate the rate of forest conversion. Precision agriculture and soil conservation could intensify yields and reduce post-harvest losses. Additional factors, such as engagement with training, continue to increase household incomes without agricultural extension (Ndona et al. 2024; Chap. 31, "What Might Influence Economic Forecasts for the Congo Basin?").

Climate Change

Climate change effects within the basin are highly location specific, with some regions experiencing drier conditions and others wetter, or more extreme seasonality. All regions are warming. The economic losses driven by climate change include dramatic flooding or drought, declines in reproductive viability of crops, plant disease dynamics, and fluctuations in agricultural output. These lead to insecurity and declines in rural incomes and an increase in poverty.

Forest Degradation and Pollution

Forest degradation and pollution remain pervasive affecting Indigenous and traditional groups, as well as having transboundary effects. Forest degradation releases stored carbon, contributing ultimately to the future costs of mitigating climate change. Deforestation also diminishes the region's resilience to climate change impacts like altered rainfall patterns and increased temperatures. Pollution from uncontrolled agricultural inputs and mineral exploitation are local as well as having transboundary effects on human and ecosystem health (Balasha and Peša 2023; Mwanamoki et al. 2014).

Invasive Species

Invasive alien species have negative impacts in the basin (Beekmann et al. 2024; Chen et al. 2023; Mikissa et al. 2021). Aliens reduce the resilience of natural habitats

and agricultural systems and thus compromise environmental strategies (IPBES 2024). For instance, on the Congo River, the invasion by alien water plants is a growing threat to the delivery of both economic (transport, water use) and ecosystem services.

Synopsis of Indirect Drivers

Salient Economic Factors

Countries within the Congo Basin continue to make economic progress, achieving growth primarily by exploitation of natural assets (Ngoma and Yang 2024; Putzel et al. 2011). Rural populations rely disproportionally on direct resource extraction for their livelihoods (Nteranya 2024; Chia et al. 2016; Bele et al. 2015; Ijang and Ndikumagenge 2013). The informal economy related to small-scale logging, subsistence agriculture, artisanal mining, fishing, hunting, charcoal production, and non-timber forest products is both a lifeline for millions and a hidden engine of economic activity in the Basin, but does not contribute to government revenues. Conversely, informal natural resource use may stimulate localized economic dynamism through trade and income generation at the household level. Trade is strongly correlated with GDP growth (Tameko 2024; Megevand and Mosnier 2013) and both are key factors for increasing prosperity although inequality, governance, and education also play decisive roles (Tchatchou et al. 2015; Mosnier et al. 2014). Overexploitation reduces the availability of natural resources for trade both now and even more intensely for future generations, threatening intergenerational welfare. In the long term, unsustainable resource depletion will undermine economic growth and resilience, hence harnessing the benefits of resource use, while minimizing its risks requires policies that strike a balance between the rate of formalization, the adoption of sustainable management, and the promotion of inclusive development.

Demographic Bulge

Population growth in the Congo Basin remains among the highest in the world. More than 60% of the population is under 25. Urbanization is increasing with almost 60% of the population now urbanized (Tyukavina et al. 2018), but rural population densities around biodiversity hotspots will also grow (▶ Chap. 23, "Opportunities and Potential for Sustainable Development in the Congo Basin from an Environmental Sustainability Perspective"). Extractive industries are not labor-intensive and tend not to create sufficient jobs for the region's young population. However, in a value-added and service-driven economy, the Congo Basin's youthful population could become an engine of growth as a labor supply.

Institutional and Cultural Factors

Local culture and environmental knowledge can be an important component of sustainable use by providing knowledge on the consequences of over-use (Boyette et al. 2022; Cuni-Sanchez et al. 2019; Bele et al. 2015). Literacy and information exchange have increased over last decades, but this has not, as yet, translated to slow

biodiversity-related challenges in the basin (Bele et al. 2015). Literacy raises awareness but does not remove the structural drivers of deforestation, e.g., poverty and livelihood dependence, weak governance, limited access to energy, as well as political pressures.

Technological Developments

Technology is an important indirect driver that supports development in the region (Atyi et al. 2022; Tyukavina et al. 2018). Technologies that improve energy access, information flow, transparency, efficiency, safety, or reduce waste could generate a wide range of economic benefits across all sectors. New technologies have created opportunities in eco-tourism, e-commerce, and digital finance (mobile money, fintech, online services) that expands employment especially for youth and women. Technology thus remains an important aspect for solving sustainability challenges (Piabuo et al. 2021; Enongene and Fobissie 2016; Gillet et al. 2016; Megevand and Mosnier 2013).

The Peculiarity of War on the Bioeconomy of the Congo Basin

The Congo Basin countries have witnessed significant civil strife and armed conflicts since the 1960s (Kelly et al. 2022; Stearns 2022; Nagabhatla et al. 2021; Turner 2007; Weiss 2000). Between 1996 and 2003, the DRC experienced two devastating wars that collapsed its formal economy and caused social unrest and poverty (Nackoney et al. 2014). The wars in DRC increased the number of people that rely on wood for fuel and bushmeat for protein, and the presence of soldiers and refugees aggravated this pressure (Draulans and Van Krunkelsven 2002). During violent conflicts forest cover loss increased (Butsic et al. 2015). In addition, wildlife poaching was especially severe during the DRC wars. The sale of protected species as bushmeat in urban markets in northeastern DRC increased by 23% during the war (De Merode and Cowlishaw 2006) and forest elephant densities in eastern DRC decreased by half (Beyers et al. 2011). War heightens pollution, resource exploitation, and long-term environmental degradation, impeding progress toward environmental goals (Wirtu and Abdela 2025; Draulans and Van Krunkelsven 2002). In addition, war in forested areas often exacts a disproportionate toll on IPLCs, with militarization efforts often coordinated from remote protected areas.

Conjecture on the Future Economy of the Congo Basin

Determinants of Congo Basin's Future Economy

A moot question in policy circles relates to what the economic landscape of the Congo Basin will look like in the near and mid-term futures if current trends persist over time. Internally, the demand for more agricultural land and forest products and externally the international demand for natural resources will combine to shape the

trajectory of the basin in the global economy. These factors shall themselves be shaped by a combination of environmental, technological, and policy variables. The development of the basin hinges on its supply and management of renewable resources, the extent of renewable energy production, the modernization of its agriculture, the efficiency in utilizing minerals and natural resources within the region, the advancement of its digital and physical infrastructure, exploiting the demographic labor dividend, as well as its collaboration with other nations and regions (FAO 2024; AfDB 2024; IMF 2025; World Bank 2024b; Atyi et al. 2022).

Natural Resource Exploitation and Supply

Both artisanal and industrial logging will continue to account for extensive land use, if business continues as usual. While the forestry sector's contribution to the economy has remained below potential over the years, revolutionizing this will require reengineering the forestry economy and strengthening the implementation of Sustainable Forest Management (SFM) principles (Brandt et al. 2016; Bele et al. 2015). A development agenda to eradicate illegal logging and promote value addition along the secondary and tertiary stages could generate significant employment and optimize economic gains from existing forest resources (▶ Chap. 12, "Agriculture, Ecosystem Functions, and Services in the Congo Basin").

Although mineral resources are exhaustible, technological progress and socioeconomic factors are likely to make mining natural resources feasible for a longer period. The mining sector is currently positioned in most national economic development plans as the engine of growth in the region (Mballa 2025; Mufungizi 2025; Nteranya 2024; Murhula and Achiza 2021). With improvements in public and private infrastructure and the business climate, countries are now expecting to develop other extractive industries (e.g., copper, cobalt, tin, uranium, iron, titanium, coltan, niobium, and manganese) and non-metals (e.g., precious stones, phosphates and coal). The estimated global growth in the technology, transportation, and construction sectors will likely fuel greater minerals demand in the future (Yager 2017). However, with growing global awareness of environmental and human rights, there is increased pressure to adopt improved mining practices.

Sustainable Forest Management for a Greener Economy

The region's forests can generate about US$7.8 billion annually, comparable to 6.3% of regional GDP (Mitchell and Pleeck 2022); thus sustainable management of the forest resources remains a primary foundation of a future green economy. The vast rainforest could provide for sustainable forestry, ecotourism, and conservation efforts that can balance economic growth with environmental preservation (Molua et al. 2023; Diaw and Lessoua 2013).

However, expanding investments to improve forest conservation and governance in the Congo Basin requires including technological innovations, robust policy frameworks, international collaboration, and cost-effective sustainable management practices (Nago and Ongolo 2021; Piabuo et al. 2021; Mahonghol and Keong 2018; Trefon 2017). Financially empowering institutions to monitor sustainability, alongside the adoption of innovative monitoring technology, will be required to

significantly enhance forest governance. The strengthening of governance and policy frameworks shall be essential, and this includes implementing legal and technical reforms that promote transparency and accountability, including within community-based management, and empowerment of IPLCs via legal recognition and participatory governance (IPBES 2024).

Energy Demand and Renewable Energy Expansion

Demand for energy is correlated with population growth and economic development (Olson and Omoyajowo 2025; Gottschalk 2016; Showers 2010). The future urban lifestyle is likely to be yet more energy intensive (Awazi 2025; Gottschalk 2016). The material needs of economic growth in the basin will require significant investments to rapidly achieve an efficient energy mix and a renewable energy transition. If investments are not properly planned and managed, there is risk that economic progress will stall, or come at the expense of excavating more forest land and hydrocarbons, with attendant threats on ecological balance and biodiversity health (Deng et al. 2020; Oyewo et al. 2018; Winemiller et al. 2016).

Yet, an efficient renewable energy supply would transform the economies of the basin. The expansion of infrastructure for renewable energy presents a strategic opportunity to enhance industrial growth and improve public electricity access. The basin possesses major rivers that present substantial opportunities for hydroelectric power (Kenfack et al. 2021; Tshimanga and Hughes 2012). The Congo River possesses an estimated hydropower potential of over 100,000 megawatts, although only a small portion has been harnessed so far. The Inga III or Grand Inga Dam complex in the DRC is a significant project, with objectives to generate up to 39,000 MW, potentially making it the largest hydroelectric power plant globally. However its predecessors, Inga I and Inga II, operate at only 80% capacity and there has been considerable investor reticence for Grand Inga, despite the potential, including fears that power will be exported from the region and fail to drive local economic growth (Showers 2010). Cameroon's hydropower potential is estimated at approximately 115,000 GWh per year, with around 4% being exploited. The country's objective is to achieve an energy production capacity of 5000 MW by 2035 (Kenfack et al. 2021). The Nachtigal dam will have a capacity of 420 MW and is anticipated to fulfill around 30% of Cameroon's energy requirements by 2026.

Solar, wind, or "run of river" microturbine renewable energy generation remain small markets. Although solar panels for domestic use are now widespread, scaling the production to meaningful quantities at the national scale remains largely unexplored. These are all potentially large markets, but as yet remain dormant. There is no nuclear power capacity in the region.

Food Demand and Agricultural Modernization

Structural transformation from traditional to modern economies requires first the modernization of agriculture, as the agricultural economy of the basin remains crucial for regional food security. Countries in the basin are signatory to the Comprehensive African Agriculture Development Programme (CAADP) of the African Union Agenda 2063, which is currently the cornerstone of Africa's

agricultural transformation (African Union 2025). With projected population expansion driving demand, agriculture will increase in importance in the years ahead, potentially attracting investments in the basin (Badibanga and Ulimwengu 2020; Kalala et al. 2020; Molua et al. 2014). Achieving national balance of payments and curtailing budget deficits will require lowering food import bills and switching to more domestically produced food.

Agricultural development faces challenges, including limited access to inputs; increasingly diverse consumer demand for quality, safety, and nutrition; and exogenous challenges driven by climate change (Chia et al. 2016; Tshimanga and Hughes 2012). Agriculture in the future should embrace sustainable technology innovations, data-driven practices, and industrial transformation (Chap. 31, "What Might Influence Economic Forecasts for the Congo Basin?"). Agriculture could be economically promising, if intensive agriculture increases productivity rather than land conversion and if it drives rural development and effectively links farmers to markets (Shapiro et al. 2023; Tyukavina et al. 2018; Ickowitz et al. 2015; Chap. 31, "What Might Influence Economic Forecasts for the Congo Basin?").

Economic Growth and Stability

Future economic growth in the basin is critical for the region's sustainable development, environmental conservation, and the well-being of its diverse populations. Despite the challenges from low growth, high and persistent poverty, and a strong dependence on volatile natural commodity markets, there is room to increase government revenues and promote sustainable commodity supply through fiscal reforms. Well-designed fiscal policies, complemented by increased natural commodity processing, can help build a sustainable regional economy while preserving the vast natural wealth of the Congo Basin. The economic paradigm should internalize promoting responsible forestry practices, reducing illegal logging, and expanding eco-forestry that can generate revenue while conserving biodiversity.

Transportation Infrastructure and Digital Development

Countries in the basin have espoused development plans in which infrastructural development is at the center of projected economic progress (Foster et al. 2023). Proper road infrastructure will open the landlocked economies of Chad, Central African Republic, and DRC to improve trade opportunities. Similarly, developing digital infrastructures would facilitate access to markets enabling the growth of technology startups and innovation-driven industries (Foster et al. 2023; Kaiser and Barstow 2022). Rural productivity and market access can be enhanced by digital resource management and environmental monitoring. In general, infrastructure development that involves improving transportation, communication, and trade links within the Congo Basin and enhancing the connectivity with neighboring regions can open markets for diversified products and services.

Carbon Markets

There is consensus that the carbon market could continue to grow (World Bank 2025c; Mitchell and Pleeck 2022). About 28% of global GHG emissions are covered

by a direct carbon price, and jurisdictions representing two-thirds of global GDP have adopted carbon taxes or emissions trading systems. Carbon pricing mobilized over $100 billion for public budgets in 2024 (World Bank 2025c). The global carbon market is large, with the value of traded CO_2 permits attaining a record 881 billion euros (US$ 948.75 billion) in 2023 (Twidale 2024). In 2023, the European Union's Emission Trading System (ETS) was valued at over 770 billion euros, while the North American markets collectively amounted to 71.4 billion euros, and the Chinese market was valued at 2.3 billion euros. In 2023, the price of carbon allowances in the EU ETS reached an unprecedented high above 100 euros per ton (Twidale 2024). In North America, prices reached $39 per ton in the Western Climate Initiative and exceeded $15 per ton in the Regional Greenhouse Gas Initiative. In 2023, prices in China's national ETS attained $11.19 per ton (Twidale 2024). Many countries and regions continue to incentivize corporations to invest in low-carbon technologies to achieve climate objectives. However, carbon credit supply continue to outstrip demand, moving the global pool of unretired credits to almost 1 billion tons in 2024. Carbon pricing, nonetheless, remains an important tool to mobilize finance and secure development outcomes (World Bank 2025c).

The Congo Basin peatlands are home to about 30 billion metric tons of stored carbon—the equivalent of 3 years of global fossil fuel emissions (World Bank 2025c). The other soils store yet more carbon and the forests themselves store around 20–30 billion tons in their wood—another 3 years of global emissions. This positions the Congo Basin to tap into the growing carbon market and exploit its sequestration potential. The annual carbon sequestration value of the Congo Basin rainforests is estimated to be worth $55 billion or more than a third of the region's GDP (World Bank 2025c). This potential is being enhanced through programs like REDD+, which incentivizes local communities, governments, and organizations to protect and manage forests in a way that is good for the environment and linked to community development (Enongene and Fobissie 2016). Several REDD+ projects are operational or in development across the Congo Basin due to increasing interest from international organizations and governments to expand carbon market activities. In addition to REDD+, Voluntary Carbon Markets (VCMs) and, very limitedly, Compliance Carbon Markets operate in the basin. Many reforestation, forest conservation, and sustainable land management projects could generate voluntary credits by avoiding deforestation and promoting forest restoration (World Bank 2025c).

For the carbon markets to better incentivize forest conservation, reduce emissions, and support sustainable development in the basin, they must be supported by bilateral and multilateral initiatives and emerging market platforms, implemented via development agencies or international climate finance (e.g., Green Climate Fund) (World Bank 2025c; Mitchell and Pleeck 2022). However, the implementation of these carbon credit schemes has been challenged by unclear land tenure and governance issues, as well as accurate measurement and reporting of carbon sequestration. Hence, data acquisition remains crucial, particularly collecting data at scale with emerging solutions such as satellite technology and blockchain, which enhance the transparency, reliability, and integrity of carbon credits. The numerous challenges

notwithstanding, the future of carbon markets in the Congo Basin offers significant opportunities for environmental conservation and sustainable development.

Foreign Direct Investments

FDI, which plays a pivotal role in the regional economy by channeling capital, technology, and expertise, continues to influence Congo Basin's infrastructural development, resource extraction, and economic growth. With rising demand and high prices, mineral reserves that used to be considered financially unviable are now receiving much attention from foreign investors (Morgan et al. 2022; UNCTAD 2021). Land and non-timber forest resources are also attracting interest. Though FDI reached 2% of GDP in 2023, it was still lower than the average 5.3% from 2010 to 2016 (World Bank 2024a, b). While overall FDI flows to Africa reached US$83 billion, accounting for 5.2% of global FDI, flows in the Central Africa subregion were only US$9.4 billion. FDI to some countries experienced a surge, such as to DRC, which rose by 14% to $1.9 billion, due to oil fields and mining; however flows to Congo fell by 8%, to US$3.7 billion (World Bank 2024a). European investors remained by far the largest holders of foreign assets in the Congo Basin.

Policy decisions to intensify FDI are increasing within the basin countries (Morgan et al. 2022; UNCTAD 2021). This is because of increased awareness that FDI is significant in infrastructure development and industries. In the mining sector, substantial investments are likely to be directed toward the extraction of cobalt, copper, gold, and coltan, particularly in the DRC. Oil and gas reserves in Gabon and Congo draw the interest of multinational oil corporations. Investments in infrastructure development have mostly focused on transportation, energy, and logistics to enhance resource export and promote regional integration. The influx of foreign direct investment in timber extraction generates economic benefits but also raises significant concerns over sustainability and the potential for deforestation, resulting in a complex scenario (▶ Chap. 12, "Agriculture, Ecosystem Functions, and Services in the Congo Basin"). Guarantees to sustainable development require proper land use management for the protection and conservation of biodiversity (Brabant et al. 2025).

Due to the confluence of global aid, technical advancements, and local engagement, the Congo Basin is experiencing a rise in opportunities for green and sustainable investments. There is optimism that, although at a very small scale as yet, investing in biodiversity and ecotourism, together with the necessary infrastructure, is attracting international tourists, generating cash, and bolstering conservation initiatives while promoting economic growth. This trajectory indicates a dual focus on socioeconomic development aligning with the global climate objectives established in international accords like the Paris Agreement and biodiversity treaties.

While FDI creates jobs and accelerates productivity improvements, its potential to transfer environmentally friendly technologies and superior safety standards is also important for sustainable development. Despite the current efforts being inadequate, the increasing global emphasis on climate change and the necessity of conservation of the Congo Basin may yield transformative outcomes.

Trade

The trade of countries in the Congo Basin is primarily characterized by the export of natural resources, particularly timber and minerals, with food and beverage constituting the primary components of intra-regional trade. Timber is destined for the United States, EU, and China, but China is emerging the predominant market (Gulley 2023; Ren and Zhang 2021; Diaw and Lessoua 2013). China is now the largest trade partner of African countries, with the trade value of about US$ 204.19 billion, of which US$ 104.91 billion is imported from China and US$ 99.28 billion is exported to China (Ren and Zhang 2021). The six Congo Basin countries contribute 11.8% of the total value of China-Africa trade. The value of exports to China from these countries represents 16.9% of the total export value, whereas the value of imports into the region from China is 6.2% of the total import value.

Countries within the basin are poised to take advantage of initiatives such as the African Continental Free Trade Area (AfCFTA) to strengthen regional cooperation and reduce trade barriers, thereby leveraging new opportunities and unlocking the economic potential of the basin. Under the AfCFTA imports and exports among member countries are facilitated with reduced or zero tariffs, free market access and market information, and the elimination of trade barriers (Morgan et al. 2022; Songwe et al. 2021). Investment in agro-processing industries has the potential to enhance value and boost regional trade, as agricultural growth is anticipated to create opportunities for increased exports of coffee, cocoa, and other commodities. Enhancing the roads, railroads, and ports infrastructure could further facilitate the movement of goods across borders, thereby reducing costs and increasing trade volumes within the basin and with international markets.

However, more efforts should be directed toward maintaining green trade. Combatting corruption on illegal resource-related trade, promoting traceability,[2] and encouraging the effective implementation of certification programs like the Forest Stewardship Council (FSC) shall ensure the ongoing health and productivity of forests. The development of markets for sustainably produced products, including non-timber forest products (e.g., medicinal plants, nuts, and fruits) and organic agricultural goods, can also diversify income sources and contribute to ecosystem preservation. Utilizing digital technology in monitoring trade practices would improve transparency, traceability, and sustainability.

Geopolitics, Regional Integration, and Environmental Cooperation

While the contemporary geopolitical situation of the Congo Basin is defined (and complicated) by historical legacies and international economic interests, the interplay

[2] Multiple countries in the Congo Basin have established forest observation systems to enhance transparency in accordance with the Forest Law Enforcement, Governance and Trade Voluntary Partnership Agreements (FLEGT VPAs) signed with the EU, aimed at reducing the flow of illegal and unsustainable timber to Europe (Mbzibain et al. 2024). Notwithstanding these agreements, numerous nations in the Congo Basin still lack functional traceability systems. Primary challenges encompass the procurement and installation of essential equipment, the training of stakeholders, and addressing the opposition from timber operators over supplementary expenses.

of resource access, regional security, environmental concerns, and international diplomacy will shape the future geopolitics of the region. The international discourse surrounding environmental diplomacy has elevated the basin's importance due to its critical role in carbon sequestration and the regulation of global climate systems; however, its abundant natural resources continue to attract both domestic and international actors seeking access and control. Regional dynamics are further shaped by nations with a stake in both resource extraction and global geopolitical influence, such as the United States, China, and France. The interplay of foreign interests has implied both economic opportunities and challenges associated with biodiversity and natural resources management. Considering that control over resources affects regional power, conflict over valuable minerals may continue to rage in mineral-rich areas, particularly in the DRC. International and regional powers are likely to continue to invest in resource extraction, infrastructure, and development projects. However, for the basin to sustain supplies, diplomatic relations will have to focus on stability, sustainability, and balancing influence among competing global interests.

Trade, infrastructure development, and collective economic resilience can all be facilitated by fortifying regional collaboration through institutions such as ECCAS. International collaborations would facilitate investments and capacity building and promote technology transfer. The key aspects of environmental cooperation in the Basin should be anchored around transboundary protected areas, and regional partnerships combatting illegal activities, as well as in research and monitoring. This requires reinforcing support for reserves that cross borders, such as the Sangha Tri-national Conservation Area shared by Cameroon, Central African Republic, and Republic of the Congo (Goué and Kana 2023).

New Economic Model for the Congo Basin

Previous governance effort has not achieved the desired outcomes with respect to human and economic development for countries in the basin. There is need to modify the paradigm through which natural capital significantly contributes to socioeconomic development. The new economic paradigm for the basin should be one that ensures resource potential effectively be at the center of regional development (social, environmental, and economic). Unlike the recent past where the marketing and trade of unprocessed natural commodities has been the *modus operandi* of post-independence economies, countries require a new model in which value addition to natural commodities and the ensuing income from their trade forms the basis of national and regional economies. Aligned with the UN SDGs, the Congo Basin's future economy should hinge on balancing resource utilization with environmental sustainability, fostering regional cooperation, and investing in infrastructure and human capital. If managed effectively, the region could become a key player in Africa's green economy and a hub for natural resource-based industries. In fact, unfolding new economic structure should be one which fosters the agenda of green growth via ecological-driven industrialization for inclusive sustainable development.

The principal actors in the Congo Basin remain *households* that supply labor, *firms* that exploit labor to generate goods and services, responsive *governments* that internalize diverse policy decisions and a *foreign sector* that forms not only the basis of external cooperation but whose market potentials seek to be served with the region's goods. Stability of the economy as shown in Fig. 1 rests on the interaction of several core actors, inherently requiring that the economic forces relating to households' supply of labor and their consumption decisions (including the selection, use, and disposal of goods and services, and payment of taxes), the firms' responsibilities of taxes to government and wages to labour, as well as government's macroeconomic responsibility should be balanced with external trade relations and international cooperation that accounts for fair trade rules.

As shown in the model, markets are important for synchronizing the core sectors of the economy. To optimize gains, the natural commodity markets must work better to reduce costs, risks, and uncertainty of supply. By effectively linking producers to consumer-markets, marketing systems transmit signals on new market opportunities

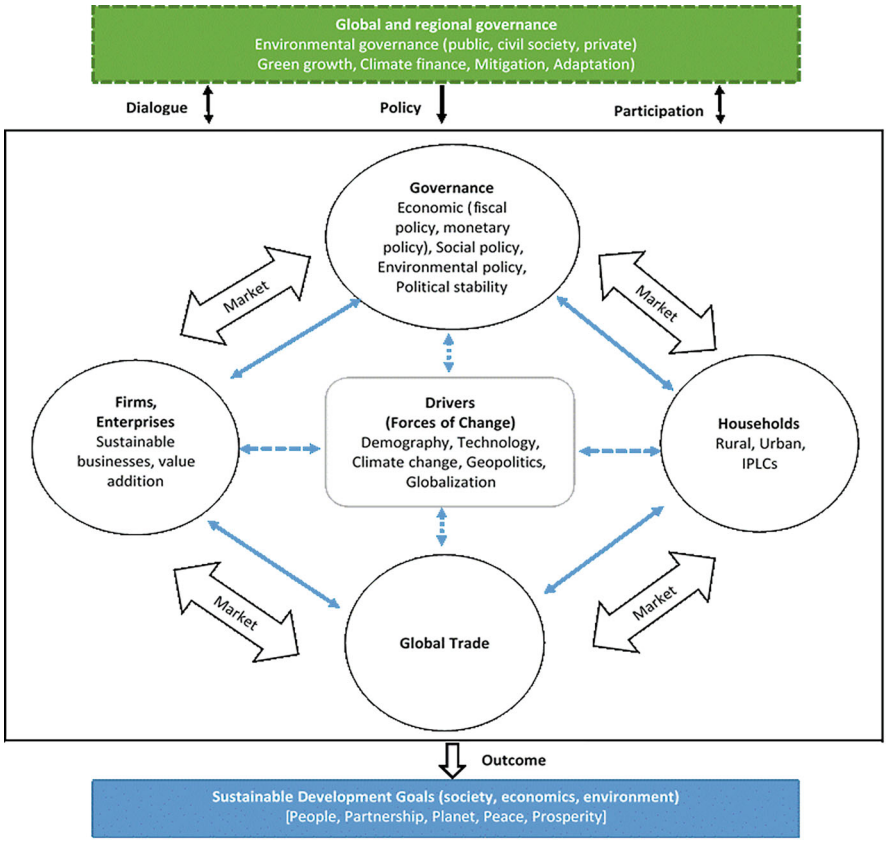

Fig. 1 Bioeconomic model for Congo Basin

and guide suppliers to meet changing consumer preferences for quantity and quality. Thus, improving market performance will require investments in infrastructure, market information systems, and managing price volatility. However, efficient markets alone, without good governance and effective public policy, do not promote equitable outcomes.

A strong governance framework is also crucial for the successful execution of tax policies and for promoting the collaboration and transparency required for sustainable natural resource management. There is room to increase government revenues and promote sustainable production through fiscal reforms. One option is to calibrate tax rates to the environmental impact of industry activities, in order to incentivize firms to adopt sustainable practices. Furthermore, strengthening regional collaboration via harmonized regulations, enhanced law enforcement, and improved alignment of forestry and mineral extraction policies will better enable the Congo Basin countries to tackle cross-border challenges, augment institutional capacities, and attract increased international funding. Governance measures must further address contemporary challenges of circularity (reducing waste and reusing materials to create a closed-loop system), inclusivity (reducing inequality by promoting equitable access to resources and opportunities), technological change, and sustainability (environmental stewardship and resource management to ensure long-term viability) in a digital economy where technology enhances productivity and creates new markets.

Overall, the economic framework for the basin needs to be part of a broader approach, as outlined in Box 1. Given the diminishing oil reserves and income, it is imperative for countries in the basin to use income from the extractive sectors now, to invest in human and physical capital in order to develop diversified, resilient, and inclusive economies.

Box 1 Principal Sectors for a New Economic Model for the Congo Basin
Priority areas for a bioeconomic model for the Congo Basin

1. Diversification of Economy and Leveraging Natural Resources
2. Agriculture and Food Security
3. Manufacturing and Processing
4. Infrastructure and Technology Development
5. Transition to Green Energy
6. Governance, Institutional Reform, and Education
7. Climate Change Adaptation and Biodiversity Preservation
8. Private Sector Development
9. Regional Integration and Trade

Agriculture remains paramount for food security; however, the Basin's agriculture must move away from unsustainable slash-and-burn practices toward techniques such as agroforestry, which could help restore soil health and enhance food security. Strengthening local food systems is critical to reduce the dependence

on imported food. This can be done by supporting smallholder farmers with technical knowledge and access to finance, as well as embarking on agricultural modernization.

Industrialization associated with manufacturing will have to be prioritized, to promote processing of timber, minerals, and agricultural products. This not only reduces post-harvest losses but also enhances export competitiveness, supports rural development, and enhances domestic value chains and ultimately GDP.

Linking the different sectors of the economy requires robust infrastructure. Investment in regional transport corridors and information networks would facilitate trade and regional cooperation. Further, a continental approach connecting Congo Basin countries to neighboring regions could unlock economic synergies. However, building infrastructure requires significant upfront investment and substantial external support or internal revenue reforms.

Guaranteed access to energy supply is paramount for economic development but increased energy demand from a burgeoning economy will pressure existing supply. An energy mix and gradual transition to green energy will support the demand and rapidly deliver local off-grid energy needs (i.e., through solar). With high insolation and vast river networks, countries in the basin could invest in hydropower and solar to supply both domestic and regional needs, reducing obsolete reliance on fossil fuels. In expanding urban centers, there is an opportunity to design new spaces with sustainable infrastructure, focusing on green spaces, waste management, and zero-energy buildings (▶ Chap. 29, "Mining Influence on the Future of the Congo Basin").

Catalyzing the dynamic interaction of the different subsectors is the role of governance, institutional reform, and education, especially with respect to anti-corruption measures and transparent governance. Effective and transparent institutions are crucial to implementing a new economic paradigm for the basin. Strengthening democratic governance and tackling corruption through digital solutions, accountability mechanisms, and civil society participation will be essential. Involving local communities in decision-making processes shall ensure that growth is inclusive. Social and environmental justice should be part of the economic equation. Investing in education and skill-building particularly for youth would provide a foundation for long-term growth.

Prioritizing resilience via climate change adaptation and biodiversity preservation to internalize mitigation is a high priority for countries in the basin. Protecting the Congo Basin forests with mechanisms for compensation, e.g., carbon credits, for the countries that bear the economic cost of conserving this resource is therefore also a priority. There is potential for a win-win outcome from the integration of conservation efforts into economic planning, to protect future ecosystem services, climate resilience, human health, and well-being and sustain natural resource assets for the future.

The private sector is the dynamo of an economy. However, the private sector requires a conducive investment climate through incentives and streamlined processes. A growing private sector encourages the rise of local startups that can help diversify economies. Public-private partnerships can foster innovation, while FDI

can bring in the capital needed for large-scale projects. Supporting social entrepreneurship through financial incentives and infrastructure can support community-driven development.

Trade and markets shall remain the fulcrum of the Basin's economy. Regional economic cooperation under the CEMAC and ECCAS currently facilitates intra-regional trade and boosts international trade. However, lowering the barriers in the central African regional trade agreements, to be in line with the African Continental Free Trade Area (AfCFTA), would not only increase economic activity but also reduce reliance on external actors. Boosting regional trade would lower vulnerability to external shocks. Joint investments in cross-border infrastructure and shared resources (such as trans-boundary water management) can promote peace and economic interdependence.

Conclusion

A new economic model for the Congo Basin countries must be founded on principles of sustainability, inclusivity, and resilience. By leveraging the region's rich natural resources now, while focusing on long-term growth strategies that protect its environment and foster equitable social development, these nations can chart a path toward prosperity that is both global in its engagement and local in its empowerment. The future of economic diversification in the Congo Basin hinges on strategic investments, sustainable practices, and regional cooperation. It will require cooperation between governments, international partners, the private sector, and local communities committed to long-term sustainability. If these strategies are effectively implemented, the Congo Basin would boast of a thriving green economy, contributing to regional development and global climate change mitigation and biodiversity conservation.

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How Could Agricultural Policies and Practices Influence the Future of the Congo Basin's Biodiversity and Ecosystems?

26

Lucie Félicité Temgoua and Nyong Princely Awazi

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Abstract

This chapter explores how agricultural policies and practices shape biodiversity outcomes and ecosystem health in the Congo Basin. It highlights the dual role of agriculture as both a driver of biodiversity loss and a sector dependent on ecosystem services like pollination and water regulation. Shifting cultivation, expanding commercial plantations, and land tenure insecurity are contributing to deforestation, soil degradation, and exacerbating climate vulnerability. Yet, promising practices such as agroforestry, ecological intensification, and agroecological zoning offer integrated approaches to enhance productivity while preserving biodiversity. The chapter emphasizes the need for effective land-use planning, capacity building, and tailored policies that align agricultural development with climate mitigation and conservation goals. By comparing the Congo Basin with experiences from Southeast Asia and Latin America, the authors stress the

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urgency of transitioning away from slash-and-burn agriculture. Precision agriculture, investment in data infrastructure, and stakeholder-inclusive planning are essential to restore degraded lands and secure food systems. Financial mechanisms like green bonds are proposed to support agroecological transitions. Ultimately, sustainable agriculture must be positioned as both a development and a conservation tool, ensuring that rural livelihoods and global biodiversity targets are mutually reinforcing.

Keywords

Agricultural policy · Land use · Soil degradation · Ecosystem service · Precision agriculture · Agroforestry

Introduction

The Congo Basin, often referred to as the "lungs of Africa," is a vast and ecologically significant region in central Africa, with the Democratic Republic of the Congo (DRC) at its core. This tropical rainforest harbors one of the most biodiverse ecosystems on Earth, home to countless species of flora and fauna, many of which are endemic and endangered (Tari et al. 2024). In addition to its ecological importance, the Congo Basin plays a crucial role in the global climate system, acting as a major carbon sink and influencing global weather patterns (Raghavendra et al. 2020). However, this remarkable natural resource is increasingly under threat from human activities, especially agricultural expansion. Agriculture in the Congo Basin is primarily subsistence-based, particularly in the DRC, Republic of Congo, and Central African Republic, while Cameroon and Gabon are increasingly moving toward cash crops and industrial crops, respectively. Smallholder farmers rely on shifting cultivation, mixed cropping, and livestock farming for their livelihoods. However, the region is also experiencing increasing pressures from commercial agriculture, including large-scale oil palm plantations. The demand for land to meet the growing food needs of an expanding population, combined with international investment in cash crops, poses a significant challenge to the preservation of the region's natural ecosystems. In recent decades, the economic importance of agriculture in the Congo Basin has surged, particularly due to the expansion of palm oil, rubber, and cocoa production (Ngouhouo-Poufoun et al. 2024). These changes are driven not only by domestic needs but also by global markets, as multinational corporations seek new sources of raw materials. This has led to the conversion of large tracts of forest (11%) into agricultural land, a trend that threatens the region's biodiversity by fragmenting habitats and altering the landscape (Forest Declaration Assessment 2022). As the demand for agricultural products increases, understanding how agricultural practices interact with biodiversity becomes vital for ensuring that future policies do not lead to irreversible ecological damage.

The influence of agricultural policies on the Congo Basin's biodiversity is multifaceted. National and regional policies, whether aimed at boosting food

production or encouraging export-driven agricultural growth, directly affect how land is utilized and how ecosystems are managed. For instance, policies that promote the intensification of agriculture can reduce the pressure on forests by increasing yield per hectare, but they may also lead to the overuse of chemicals such as fertilizers and pesticides, which can degrade soil quality and water resources (Tshimanga et al. 2021). On the other hand, policies that favor the expansion of commercial agriculture without adequate environmental safeguards can result in widespread deforestation and ecosystem degradation as has been the case in large parts of South America and Southeast Asia. Agricultural subsidies, land tenure reforms, and infrastructure development policies play significant roles in shaping land-use decisions. In some cases, the promotion of large-scale, monoculture plantations (such as those for oil palm or rubber) has led to the loss of biodiverse forests (Bokanga 2024). This type of land use does not only reduce biodiversity by clearing forests but can also disrupt important ecosystem services such as water regulation, pollination, and carbon sequestration. Deforestation in the Congo Basin, if unchecked, will contribute to the destabilization of the climate and the displacement of countless species, many of which are already vulnerable to extinction. On the other hand, policies that prioritize agroforestry, sustainable land management practices, and conservation incentives can help preserve biodiversity while also supporting agricultural productivity. For example, agroforestry systems, which integrate trees with crops or livestock, can help maintain forest cover and improve soil fertility and water availability while providing economic benefits to local communities (Koutika et al. 2021; Chuma et al. 2021). Similarly, promoting sustainable agricultural practices that limit the use of harmful chemicals and encourage crop diversity can mitigate some of the negative impacts of farming on biodiversity.

Effective governance and land-use planning are central to managing the complex interactions between agriculture and biodiversity in the Congo Basin. Clear land tenure rights and policies that involve local communities in decision-making are critical for ensuring that both conservation and development goals are met (Molua et al. 2023). In the absence of strong governance, land use in the Congo Basin is often characterized by illegal logging, land grabbing, and weak enforcement of environmental regulations, leading to unsustainable agricultural practices and significant biodiversity loss (Ken et al. 2020). The complexity of land ownership in the region, often involving competing interests between indigenous populations, government authorities, and multinational corporations, further complicates efforts to implement sustainable agricultural policies. One solution proposed by researchers is the adoption of a "landscape approach," which integrates agricultural development, conservation, and local community participation into a cohesive strategy (Inogwabini 2020). This approach focuses on managing land at a broader scale, considering the full range of ecological, economic, and social factors, and can help to identify win-win scenarios where agriculture and biodiversity conservation can coexist.

As the pressures on the Congo Basin's ecosystems continue to grow, the future of its biodiversity will depend to a great extent on the evolution of agricultural policies and practices. A shift toward sustainable, climate-smart agriculture (characterized by

practices that enhance productivity while reducing environmental impacts) will be essential to balancing development with conservation and other land uses. Governments, international organizations, and civil society must work together to ensure that agricultural policies not only foster economic growth but also protect the integrity of the region's ecosystems. There are promising initiatives that highlight the potential for sustainable agriculture to contribute to biodiversity conservation in the Congo Basin. For example, the Central African Forest Initiative (CAFI), a partnership between the governments of Central Africa and international donors, supports forest preservation through sustainable land-use practices and climate finance mechanisms (Eba'a Atyi 2022). These efforts focus on reducing emissions from deforestation and degradation while promoting sustainable agriculture, providing a model for how agricultural policies can be harmonized with conservation goals. In light of the foregoing, this chapter examines how agricultural policies and practices influence the future of the Congo Basin's biodiversity and ecosystems.

Agricultural productivity in the Congo Basin is closely tied to forest-derived ecosystem services, particularly water regulation and pollination (Harrison and Chepstow-Lusty 2024). Forests in the basin play a crucial role in maintaining local and regional hydrological cycles (Chapters 4 and 5). Through evapotranspiration and canopy interception, they influence rainfall patterns, soil moisture retention, and groundwater recharge (Barimalala et al. 2023). These processes are vital for sustaining both rain-fed and irrigated agriculture, especially in rural areas where infrastructure is limited and farming depends heavily on natural precipitation cycles. In addition, forests are habitats for a wide range of pollinators that are essential for the productivity of crops. A decline in pollinator populations, which often accompanies deforestation, leads to reduced yields and lower crop quality (Besisa Nguba et al. 2025). This interdependence between agriculture and biodiversity underscores the ecological balance maintained by intact forest ecosystems. Excessive deforestation, driven by logging, mining, and agricultural expansion, disrupts this balance. Loss of forest cover alters local climates, reduces rainfall, and increases temperatures, exacerbating the impacts of global climate change (Yuh et al. 2024; Cook et al. 2025). These changes reduce arable land viability and can eventually render agriculture unsustainable in parts of the basin, especially for smallholder and subsistence farmers who lack adaptive resources. The interdependence between agriculture and forests is thus both intricate and fragile. While agriculture drives much deforestation, it is also highly dependent on the very ecosystems being degraded. Sustainable land-use strategies that integrate forest conservation with agricultural development (such as agroforestry and buffer zone management) are critical for preserving ecosystem services and ensuring long-term food security in the Congo Basin.

Agricultural Land Assessment

The region has historically been sparsely populated, but with increasing pressures from population growth and economic development, there has been growing interest in the conversion of land for agricultural use. The Congo Basin's agricultural

potential is immense, with areas of fertile soils, high rainfall, and an equatorial climate that supports diverse crops such as cassava, plantains, yams, oil palm, maize, rice and cocoa. However, agricultural practices in the region have traditionally been small-scale and subsistence-based, relying on shifting cultivation or agroforestry systems. Shifting cultivation, also known as slash-and-burn agriculture, is a traditional farming system practiced widely in the Congo Basin. It originated approximately 2500 years ago with Bantu-speaking agriculturalists who migrated across Central Africa (Boyette et al. 2022). This technique involves clearing forest land, burning vegetation to enrich the soil with ash, cultivating for a few years, and then abandoning the land to fallow while moving to a new plot. While this method was sustainable when populations were low and land was abundant, it has changed little over time and is increasingly unsuited to current demographic and environmental pressures. In contrast, other tropical regions have adopted modern, more sustainable techniques. In parts of Southeast Asia and Latin America, farmers use permanent raised beds, integrated soil fertility management, and agroecological approaches that maintain soil productivity without the need for constant land rotation (Alexandre et al. 2021; Blundo-Canto et al. 2025). These methods help prevent soil degradation and reduce deforestation by eliminating the need to continuously clear new forest areas. In the Congo Basin, the persistence of traditional shifting cultivation under rising population density and land scarcity threatens both ecological integrity and long-term food security.

Several factors complicate the assessment of agricultural land suitability in the Congo Basin. These include ecological and environmental constraints, land tenure systems, as well as climate change and environmental degradation (Table 1). The Congo Basin is largely covered by dense tropical rainforests, and its soils are often acidic and low in nutrients, which can limit the viability of agricultural expansion (Agegnehu et al. 2021; Mulimbi et al. 2023). Furthermore, the region is characterized by high biodiversity and sensitive ecosystems that must be preserved while considering the needs of agriculture. Wetland ecosystems, for instance, are highly productive but also fragile (Chapter 19). The assessment of agricultural land suitability must thus consider factors like soil fertility, topography, climate, and the potential for soil degradation, pollution, or erosion. Land tenure in the Congo Basin is complex and varies widely across different countries and even regions within countries. In many cases, land is communally owned or subject to informal tenure arrangements, which can complicate land-use planning and the implementation of large-scale agricultural projects (Shapiro et al. 2023). The absence of clear legal frameworks or effective governance mechanisms can lead to land conflicts, which further complicate the development of agricultural policies. The Congo Basin is not immune to the effects of climate change, which include shifts in rainfall patterns, increased frequency of droughts, and temperature fluctuations. These changes have profound implications for agricultural productivity, as crops may become less suited to the changing climate, particularly in the already fragile soils of the region (Vinke et al. 2023). Land assessment must therefore incorporate climate models and forecasts to predict future agricultural viability.

Table 1 Factors complicating the assessment of agricultural land in the Congo Basin

Factor	Description	Affected countries	Relevant sources
Limited land tenure security	Unclear land ownership or tenure rights can create disputes and undermine investment in agriculture.	All Congo Basin countries	Inogwabini (2020), van Leeuwen et al. (2022) Bahati Shamamba et al. (2023)
Deforestation and land degradation	High rates of deforestation, land conversion for agriculture, and soil erosion make land assessments difficult.	Cameroon, DRC, CAR,	Adams and Garcia-Carreras (2023), Aquilas et al. (2022), Shapiro et al. (2023)
Limited data availability	Lack of reliable, up-to-date, and detailed land-use data hinders the accurate assessment of agricultural potential.	All Congo Basin countries	Christensen and Jokar Arsanjani (2020), Shapiro et al. (2021)
Smallholder dominance	The prevalence of smallholder farms, often with informal and fragmented land-use patterns, complicates mapping and assessments.	All Congo Basin countries	Chuma et al. (2022a), Shapiro et al. (2023), Molua et al. (2023), Mulimbi et al. (2023), Drake et al. (2024)
Climate variability and change	Erratic rainfall, unpredictable weather patterns, and long-term climate change affect agricultural productivity and land assessment.	All Congo Basin countries (future)	Sonwa et al. (2020), Cook and Vizy (2022), Tshimanga et al. (2022), Karam et al. (2023), IPCC (2023)
Conflict and political instability	Ongoing conflicts, particularly in the CAR and DRC, disrupt land use, agricultural activities, and data collection.	CAR, DRC, Republic of the Congo	Tshimanga et al. (2021), Nagabhatla et al. (2021), Kormoh (2021), Tongele (2021)
Inadequate land-use planning	Weak land-use policies and a lack of comprehensive land planning result in poor agricultural resource allocation.	All Congo Basin countries	Inogwabini (2020), Chishugi et al. (2021), Chuma et al. (2022b)
Biodiversity and conservation priorities	High biodiversity and conservation priorities may limit agricultural expansion and complicate land assessments.	Gabon, Republic of the Congo, Cameroon	Huge et al. (2020), Shapiro et al. (2021), Kamath et al. (2024), Beekmann et al. (2024)
Infrastructure limitations	Poor infrastructure (e.g., roads, mapping technologies) hinders the ability to assess and manage agricultural land.	All Congo Basin countries	Coffin et al. (2021), Schouten et al. (2022)
Land conflicts with indigenous peoples	Land conflicts between indigenous populations and settlers or commercial interests complicate land assessment.	DRC, Cameroon, Republic of the Congo	Domínguez and Luoma (2020), Claessens et al. (2021)

(continued)

Table 1 (continued)

Factor	Description	Affected countries	Relevant sources
Lack of good soil maps/ crop suitability analysis	Lack of detailed soil maps and crop suitability analysis hinders informed agricultural planning and sustainable land-use decisions.	All Congo Basin countries	Kulimushi et al. (2021), Mondo et al. (2024a)

A range of methodologies is employed in the assessment of agricultural land in the Congo Basin, including traditional field-based surveys, remote sensing technologies, and combining data layers in geographic information systems (GIS). The integration of these tools allows for a more comprehensive and detailed understanding of land suitability and potential productivity. Satellite imagery and GIS tools have revolutionized land assessment by allowing for the monitoring of land use and land cover changes over time (Brown et al. 2022). In the Congo Basin, remote sensing data is invaluable for mapping forest cover, identifying areas of deforestation, mapping of soil moisture, and assessing the spatial distribution of agricultural potential. Studies have shown that integrating remote sensing with GIS can help identify areas most suitable for agricultural expansion while minimizing environmental damage. Soil surveys remain essential for understanding the physical characteristics of land in the Congo Basin. Many soil types in the region are poorly suited for intensive agriculture, but detailed soil mapping helps to identify areas where soil amendment strategies or agroforestry practices could improve productivity. Field surveys also provide data on crop yields, farming practices, and local agricultural knowledge, which are necessary to contextualize remote sensing data. Several models have been developed to assess the suitability of land for various crops. These models can be adapted to the specific conditions of the Congo Basin and used to predict crop performance under different management scenarios.

Adapting existing crop suitability models to the Congo Basin is technically feasible, but several challenges must be addressed for successful implementation. Models such as FAO's agroecological zoning (AEZ), EcoCrop, and DSSAT (Decision Support System for Agrotechnology Transfer) have been effectively used in other tropical regions and can be calibrated to reflect the Basin's unique biophysical and socioeconomic conditions. These models require reliable datasets on soil characteristics, climate variables, topography, and crop parameters, data that are often sparse or outdated in the Congo Basin. There are no significant intellectual property (IP) constraints for the most widely used models, as many are open-source or accessible through institutional partnerships (FAO or CGIAR platforms). However, practical barriers exist: financial resources are needed for ground-truthing data, purchasing high-resolution satellite imagery, and acquiring computing infrastructure. Additionally, specialist training is essential. Running and interpreting these models requires cross-disciplinary expertise in agronomy, geospatial analysis, and climate science, skills that may be limited in national research institutions or

extension systems. Therefore, support from Agricultural Research (AR) initiatives and development donors could play a catalytic role. With the right support, these tools can transition from being technically promising to practically transformative.

As agricultural activity in the Congo Basin expands, there is increasing recognition of the need to balance economic development with environmental conservation (Chapter 24). Unsustainable agricultural practices, such as large-scale monoculture plantations and slash-and-burn farming, have led to deforestation and degradation of valuable ecosystems. Sustainable land assessment in the region must therefore incorporate environmental considerations alongside economic ones with particular focus on agroforestry, ecological intensification, maintenance of ecosystem services, and agroecological zoning. Agroforestry, or the integration of trees with agricultural crops, is seen as a promising solution for promoting sustainable land use in the Congo Basin (Katayi et al. 2023). This system helps to preserve soil fertility, reduce erosion, and maintain biodiversity while also improving agricultural yields. It also improves water penetration/replenishment in topsoil, creates local cooling, contributing to drought and extreme temperature mitigation and flood control, and if done on a larger scale increases rainfall (Ellison et al. 2024). Many land assessments now include agroforestry systems as part of land-use planning to ensure long-term sustainability. Rather than expanding agriculture into new forested areas, ecological intensification seeks to increase agricultural productivity on existing farmland while minimizing environmental impacts (Molua et al. 2023). This approach is particularly relevant in the Congo Basin, where expanding agriculture into forests could lead to irreversible damage. Land assessments that prioritize ecological intensification emphasize the use of organic farming practices, integrated pest management, and the restoration of degraded lands. Agroecological zoning (AEZ) is another tool used to assess land suitability, taking into account ecological, social, and economic factors to determine the most appropriate land uses. AEZ is used to identify regions where agriculture can be expanded without compromising the region's ecological integrity (Mondo et al. 2024b). In the Congo Basin, AEZ is crucial for guiding land-use decisions and ensuring that agricultural expansion does not encroach on high-conservation-value ecosystems.

Soil Fertility and Degradation

Soil fertility refers to the ability of the soil to supply essential nutrients to plants for growth. Soil fertility is influenced by factors like rainfall, temperature, soil texture, and organic matter. However, tropical soils often present unique challenges due to high levels of weathering, leaching, and erosion. The soils of the Congo Basin, predominantly Oxisols and Acrisols, are typically acidic and nutrient-poor, characterized by low concentrations of essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K). The soil's low base saturation and high acidity further reduce its fertility (Bauters et al. 2021). The fertility of soils in the Congo Basin is highly dependent on organic matter, which comes from the dense vegetation cover and decomposition of plant material. Tropical rainforests like those in the Congo Basin

have a high rate of nutrient cycling, where nutrients are rapidly absorbed by plants and returned to the soil through litter fall and decomposition. This creates a fragile equilibrium where soils are initially fertile but quickly lose nutrients under intensive land use. The role of forest ecosystems in maintaining soil fertility is emphasized in studies by Baumgartner (2022), who highlights the essential services provided by the rainforest's canopy in protecting the soil from erosion and promoting nutrient cycling. However, the introduction of large-scale agriculture, logging, and other human activities in the Congo Basin has strained this fragile fertility balance. As populations grow and demand for land increases, agricultural practices often fail to replenish the nutrients being extracted from the soil, leading to declines in soil quality and fertility.

Soil degradation refers to the decline in the quality and productivity of soil, often due to human activities. In the Congo Basin, soil degradation is a critical concern, particularly in areas where traditional agricultural practices have been intensified or where deforestation and land conversion have occurred. The main drivers of soil degradation in the Congo Basin are deforestation and loss of soil cover, nutrient depletion from agriculture, erosion, and water runoff. The most significant driver is deforestation, often linked to logging, slash-and-burn agriculture, and the expansion of subsistence farming. Deforestation removes the protective forest canopy, leaving the soil exposed to erosion by wind and water. Without the buffering effect of trees, which help retain moisture and prevent soil erosion, the exposed soils quickly lose structure and fertility. According to studies by Potapov et al. (2012), Barthel et al. (2022), and Shapiro et al. (2023), deforestation rates in the Congo Basin have escalated over the past few decades, leading to the degradation of vast areas of soil. The removal of forest cover not only depletes soil nutrients but also disrupts the hydrological cycle, exacerbating water runoff and further contributing to soil erosion (Mushi et al. 2019). In many parts of the Congo Basin, agricultural practices are not aligned with sustainable soil management principles. Slash-and-burn agriculture leads to temporary soil fertility boosts through the burning of biomass but is ultimately unsustainable in the long term. After several cycles of cropping, soils become depleted of nutrients and organic matter, leading to reduced agricultural yields. This process is well documented in a study by Syauswa Musondoli (2020), who noted that continuous cropping without adequate fallow periods or soil fertility replenishment leads to a depletion of vital nutrients such as phosphorus, nitrogen, and potassium. Moreover, the limited use of organic or synthetic fertilizers exacerbates the problem, as farmers lack access to the means to maintain soil fertility. Without external inputs or effective crop rotation systems, soils in these regions experience rapid degradation. For example, a study by Drake et al. (2024) found that soil organic carbon stocks in degraded agricultural land in the Congo Basin were significantly lower than in nearby natural forests, indicating a loss of fertility and overall degradation.

The degradation of soils in the Congo Basin has profound implications for both the environment and the livelihoods of local communities. In the short term, soil degradation leads to decreased agricultural productivity, which threatens food security in an already vulnerable region. Smallholder farmers, who rely on rainfed

agriculture for subsistence, are the most affected by declining soil fertility and the resulting decrease in crop yields. As soil degradation progresses, many farmers are forced to abandon their land and move to more fertile areas, contributing to the expansion of deforestation and land conversion. In the long term, soil degradation also poses a threat to the broader ecological functions of the region. The Congo Basin's forests and soils are essential for carbon storage (8% of global forest-based carbon reserves, i.e., a net carbon sink of ~0.61 Gt CO_2e/year), and soil degradation could potentially exacerbate climate change by releasing stored carbon into the atmosphere (Dargie et al. 2017; Baumgartner 2022; UNEP 2023). The loss of biodiversity, which is closely linked to soil health, also becomes a concern as degraded soils cannot support the same diverse soil flora and fauna or plant and animal species found in healthy ecosystems.

Efforts to combat soil degradation in the Congo Basin focus on improving agricultural practices and promoting sustainable land management. Key approaches include agroforestry, soil conservation techniques, and sustainable land-use planning. By integrating trees into agricultural systems, agroforestry helps improve soil fertility, prevents erosion, and enhances biodiversity. Studies by Koutika et al. (2021), Fahad et al. (2022), Singh et al. (2024), and Awazi et al. (2025) have shown that agroforestry systems, such as the cultivation of nitrogen-fixing trees alongside crops, can improve soil quality and increase agricultural productivity. Furthermore, agroforestry helps farmers diversify their income sources, providing resilience against fluctuating agricultural yields and market prices. Soil conservation practices such as terracing, contour farming, and mulching are being promoted as part of sustainable agriculture programs. These techniques help prevent erosion, increase water retention, and improve nutrient cycling. Several NGOs and research organizations are working with local communities to implement these techniques, although their widespread adoption remains limited by financial constraints and knowledge gaps. National and international efforts to combat soil degradation in the Congo Basin include both policy and research initiatives aimed at sustainable land-use management. Governments and regional organizations have been working on reforestation projects, land restoration programs, and better land-use planning. Research by Mangaza et al. (2021) highlights the importance of policy frameworks that integrate soil conservation into agricultural development plans, recognizing the long-term benefits of soil health for food security and climate change mitigation.

Policy-Driven Precision Agriculture

Precision agriculture (PA) refers to the use of advanced technologies to optimize agricultural practices, minimize resource use, and maximize crop productivity. In the context of the Congo Basin, PA presents a transformative opportunity to address the twin challenges of food security and environmental sustainability, but while PA has been rapidly adopted in various parts of the world, its application in the Congo Basin

is still in its nascent stages. This is largely due to the region's complex socioeconomic, ecological, and policy challenges. However, with the support of targeted policies, PA could significantly enhance agricultural productivity while preserving the region's fragile ecosystems.

Precision agriculture relies on technologies such as Geographic Information Systems (GIS), remote sensing, drones, soil sensors, and climate forecasting tools. These technologies help farmers monitor and manage their crops more efficiently by providing data on soil health, moisture levels, pest infestations, and weather patterns. The adoption of these technologies in the Congo Basin could revolutionize agriculture by improving crop choices for suitable land, and improving yields, thereby improving food security and protecting the region's rich natural resources. Policy-driven PA initiatives in the Congo Basin need to address several key areas including infrastructure development, training and capacity building, access to finance, sustainability and environmental conservation, climate adaptation, as well as regional cooperation and policy coordination.

One of the main barriers to the adoption of precision agriculture in the Congo Basin is inadequate infrastructure. Poor road networks, unreliable electricity, and limited Internet access hinder the distribution of technology and limit farmers' ability to use digital tools. According to a report by the Food and Agriculture Organization (FAO) and the International Fund for Agricultural Development (IFAD), investments in rural infrastructure are critical for scaling up PA in the region (IFAD 2016; FAO 2021). Effective policies should focus on improving access to these technologies by investing in digital infrastructure, electricity supply, and rural connectivity. Even if the technologies are available, farmers in the Congo Basin must be trained to use them effectively. Many farmers in the region are not familiar with the tools and techniques of precision agriculture. In a study by Nsele et al. (2022), the authors noted that the lack of education and extension services in rural areas is a significant barrier to adopting modern agricultural technologies in the Congo Basin. Policies aimed at improving agricultural education and creating extension programs could play a vital role in equipping farmers with the knowledge and skills they need to use PA tools. The capital required to implement precision agriculture technologies can be prohibitive for smallholder farmers in the Congo Basin. Traditional financial systems are often inaccessible to rural farmers due to a lack of collateral, high interest rates, and limited financial literacy. Policy interventions that facilitate access to credit and financial services, such as microfinance and low-interest loans, can help farmers invest in PA technologies. Public-private partnerships could also be leveraged to lower the costs of implementing PA systems in the region. Policy frameworks should integrate PA into broader climate change adaptation strategies. The Congo Basin spans multiple countries, each with its own agricultural policies and regulatory frameworks. For PA to be effective at a regional level, there needs to be coordination among governments and regional organizations. Policies should promote cross-border collaboration in research, data-sharing, and technology transfer. The Central African Forest Commission (COMIFAC), for example, could play a crucial role in harmonizing policies related to sustainable agriculture and land use in the Congo Basin.

Possible Future Soil Fertility and Land Degradation Effects on the Congo Basin's Biodiversity

The region is endowed with significant mineral resources, and mining activities (especially for copper, gold, and diamonds) have expanded notably over recent decades (Chapters 24 and 28). Although the total surface area directly affected by mining is relatively limited compared to agriculture (estimated at tens of thousands of hectares across the region), the environmental impacts can be severe and localized. Mining operations, both industrial and artisanal, strip away vegetation, compact soils, and intensify erosion processes. Artisanal mining in countries like the Democratic Republic of Congo has led to soil contamination through the use of toxic substances such as mercury and cyanide, with serious long-term consequences for land fertility and surrounding ecosystems (Tongele 2021). The combined pressures from mining and slash-and-burn agriculture, even if differing in scale, contribute to the progressive degradation of land and ecosystems throughout the Congo Basin. As soil fertility declines, the forest ecosystem becomes less able to support the biodiversity that has evolved in this region. Deforestation and land degradation not only reduce the area of intact forest but also fragment remaining habitats, making it harder for species to migrate or find food. Species that rely on specific forest types, such as the endangered Okapi, may be pushed to the brink of extinction if their habitats degrade. Soil degradation also disrupts critical ecosystem services, such as water filtration, carbon sequestration, and soil stabilization. The Congo Basin is one of the largest carbon sinks in the world, storing enormous amounts of carbon in its soil (Dargie et al. 2017) and vegetation (Hubau et al. 2020). As soils degrade and forests are cleared, this carbon is released into the atmosphere, exacerbating climate change. The degradation of soils impairs the ability of the ecosystem to regulate water cycles, leading to altered rainfall patterns, reduced soil moisture, and increased vulnerability to floods and droughts (Karam 2024).

If current trends continue, soil degradation will likely worsen, leading to more severe consequences for biodiversity. However, there is still an opportunity to mitigate some of these effects through proactive soil conservation and sustainable land management strategies. Implementing sustainable agricultural practices, such as agroforestry, permaculture, and conservation tillage, would help mitigate soil degradation while still supporting local farmers. By integrating trees and other perennial plants into agricultural systems, farmers can enhance soil fertility, reduce erosion, and create more resilient ecosystems (Awazi and Tchamba 2019). Additionally, agroecological practices can reduce the need for chemical fertilizers and pesticides, which often degrade the soil and harm nontarget species. Reforesting areas that have been cleared or degraded, particularly using native species, can help restore soil fertility, improve water retention, and reintroduce biodiversity. Efforts such as the Great Green Wall initiative in Africa, which aims to combat desertification by restoring ecosystems, can serve as an inspiration for restoration in the Congo Basin (Ejim-Eze 2025). The future of soil fertility and land degradation in the Congo Basin is inextricably linked to the health of its biodiversity. As soil fertility declines, the effects on the region's plant and animal life will be devastating, with

long-lasting consequences for both local and global ecosystems. However, through sustainable land management, restoration of degraded lands, and concerted conservation efforts, it is possible to reverse some of the damage and preserve the incredible biodiversity of the Congo Basin for future generations.

One such tangible example is Gabon's Oil Palm Policy, formally adopted by its Land use Planning Commission and Government, which only allows for oil palm and other industrial agriculture in highly degraded forests and savannas, minimizing carbon emissions and biodiversity impacts, could serve as a model for other countries to follow. In Gabon, the government provides guidelines to comply with throughout the three phases of oil palm development: (i) site selection, (ii) environmental and social impact studies (EIES), and (iii) monitoring and evaluation. For environmental, social, and societal protections, Gabon requires, at minimum, compliance with the national interpretation of Roundtable for Sustainable Palm Oil (RSPO) principles and criteria for certification. All companies invested in this sector must comply OLAM Palm in Gabon is the only example of a greenfield investment in palm oil, which is 100% RSPO certified. It had a comprehensive EIES, did Free Prior and Informed Consent (FPIC) in all communities, and was guided by Gabon's land-use plan; plantation was located in highly degraded forests and low species diversity grasslands (avoiding high conservation value savannas and marshes). It includes about 50% conservation set aside of natural forests (where carbon was above the threshold in the national guidelines). The study by Burton et al. (2017) shows that OLAM oil Palm plantation in Gabon was carbon neutral and this study illustrates that comprehensive land-use planning at both the national and site levels can facilitate low-emissions agricultural development in tropical forest landscapes.

Discussion

The Congo Basin hosts one of the world's largest tropical rainforests. This forest ecosystem provides a vital carbon sink, mitigating climate change by absorbing large amounts of CO_2 (Dargie et al. 2017; Hubau et al. 2020). Given this immense biological wealth, the Basin's ecosystems contribute significantly to global biodiversity conservation and climate regulation (Chapters 23 and 31). However, the future of these ecosystems is uncertain with agriculture being one of the most significant pressures. Over the past several decades, agriculture has expanded into previously untouched forests, driven by both national and international economic pressures. The demand for palm oil, cocoa, timber, and other resources has led to deforestation, habitat fragmentation, and degradation of critical ecosystems.

Agricultural policies in the Congo Basin are shaped by both national governments and international institutions, often reflecting economic priorities over ecological preservation. These policies are varied, but key trends include promoting commercial agriculture, increasing mechanization, and encouraging export-oriented production of crops such as palm oil, rubber, cocoa, and cassava. Governments in the region, under the pressure of global trade dynamics and international development

organizations, tend to prioritize agricultural growth as a key strategy for poverty alleviation and economic development (Yufenyuy et al. 2024). At the international level, organizations such as the World Bank and the International Monetary Fund have often promoted agricultural intensification to generate income and reduce poverty. These policies, however, frequently overlook the long-term ecological costs associated with such growth, which can be costly later on; for example, large-scale agriculture often leads to land-use changes that negatively affect ecosystem services, such as clean water or pollination. The conversion of forests to agricultural land reduces habitat for many species, some of which are endemic to the Congo Basin and highly vulnerable to extinction. One of the most prominent agricultural policies in the Congo Basin is the promotion of palm oil cultivation. Palm oil, a highly profitable crop, is in demand worldwide for use in food, cosmetics, and biofuels. As the price of palm oil increases, it creates strong incentives for governments and private enterprises to clear forests for cultivation. The Democratic Republic of Congo (DRC) and Cameroon are both seeking to increase palm oil production to meet global demand, which is contributing to deforestation (Gunarso et al. 2013; Eba'a Atyi 2022). However, while these policies may provide short-term economic benefits, they are often at odds with biodiversity conservation goals. Nevertheless, certification programs such as the RSPO (2016) and land-use planning represent progress in taking biodiversity into account.

Agricultural expansion often leads to the establishment of monoculture (large areas of land devoted to a single crop). While monoculture farming can be economically efficient in the short term, it comes at the expense of biodiversity, clearing diverse ecosystems to create vast, uniform plantations that support very few species. This form of farming leads to a decline in both plant and animal diversity, as only a limited range of species is suited to survive in these artificial environments. Monoculture farming also reduces genetic diversity within crops, making them more susceptible to pests and diseases, which can lead to crop failure and further environmental degradation. The heavy reliance on a few economically important crops like palm oil or cocoa diminishes the ecological variety that these landscapes once supported, reducing the resilience of the entire ecosystem to environmental changes.

Another agricultural practice that poses a significant threat to the Congo Basin's biodiversity is the use of agrochemicals, such as fertilizers, pesticides, and herbicides. The widespread use of these chemicals in large-scale farming operations has led to pollution of water systems, which in turn affects aquatic biodiversity (Tsufac et al. 2021). The rivers and streams of the Congo Basin are home to unique species of fish and amphibians, many of which are already endangered due to habitat loss and overfishing. Pesticides and fertilizers, when washed into water systems, can cause eutrophication, a process in which excessive nutrients promote the growth of algae, depleting oxygen levels and killing aquatic life (Ncheuveu et al. 2021). Moreover, the indiscriminate use of pesticides has been linked to declines in pollinators, such as bees and butterflies, which are vital for the reproduction of many plant species in the region. The loss of pollinators further exacerbates the decline of biodiversity, affecting not only crops but also native flora and fauna that depend on these plants.

While the environmental impacts of agriculture in the Congo Basin are undeniable, it is also crucial to consider the socioeconomic factors driving agricultural expansion as well as the need for a comprehensive ESIAs and RPIC processes. For rural communities in the Congo Basin, agriculture represents a vital livelihood, and expanding agricultural production is often seen as a way to meet the growing demand for food and jobs. The challenge, however, is to balance agricultural development with the need for conservation. Policies that promote agricultural intensification without adequate environmental safeguards are likely to cause long-term damage to the region's ecosystems and as a result negatively impact critical ecosystem services. One example of this is the Green Revolution, which has been implemented in various parts of Africa to boost food production through technological innovations and chemical inputs (Effa et al. 2025). While these methods have increased yields in some areas, they have also led to environmental degradation, including soil erosion, water pollution, and loss of biodiversity. To address these issues, scholars argue that agricultural policies in the Congo Basin must be reoriented toward more sustainable practices (Awazi et al. 2025). Agroforestry, for example, is one such alternative that integrates tree cover with agricultural crops, providing ecological benefits like soil fertility and erosion control while also maintaining biodiversity (Chuma et al. 2021; Kumar et al. 2025). Additionally, policies that incentivize sustainable land management practices and promote the restoration of degraded land can help mitigate the negative impacts of agriculture.

International trade policies play a significant role in shaping agricultural practices in the Congo Basin. The demand for commodities drives land-use change in the region, as multinational corporations seek to capitalize on lucrative markets. The EU's zero deforestation commodities policy aims to curb global forest loss by banning imports of products like cocoa, coffee, palm oil, and timber unless they are proven to be deforestation-free. While this promotes global climate goals, it poses serious challenges for farmers in the Congo Basin. Most smallholder farmers lack the resources, infrastructure, and knowledge to meet the EU's traceability and certification standards. This could exclude them from valuable European markets, reducing their income and deepening poverty in already vulnerable communities. According to Jeary et al. (2022), the international market for agricultural products is not aligned with environmental sustainability goals, creating a disconnect between economic incentives and ecological preservation. In response to these challenges, scholars such as Jeary et al. (2022) advocate for the incorporation of environmental criteria into international trade agreements. This could involve enforcing stricter environmental standards for agricultural production and requiring businesses to source raw materials from sustainable sources. Certification programs like the RSPO and Fair Trade are steps in this direction, but critics argue that they are often insufficient in preventing deforestation and ensuring genuine sustainability (Reyniers 2021). Thus, agricultural policies and practices in the Congo Basin have profound implications for the region's biodiversity and ecosystems. While agriculture plays an important role in the region's economy, the environmental costs associated with unsustainable practices are increasingly apparent. To ensure the long-term preservation of the Congo Basin's biodiversity, it is essential to integrate

ecological concerns into agricultural policies and practices. This requires a shift toward more sustainable, inclusive, and ecosystem-friendly agricultural strategies that prioritize both economic development and environmental conservation. Only through such a balanced approach can the Congo Basin continue to provide its vital ecological services to the planet and future generations.

Synthesis

Agricultural policies and practices play a critical role in shaping the future of the Congo Basin's biodiversity and ecosystems, which are among the world's most vital and diverse. The Congo Basin faces increasing pressures from agricultural expansion driven by policies that encourage the conversion of forested land into agricultural areas in the form of industrial-scale monocultures, logging, and smallholder farming. However, agricultural policies can also be designed to promote conservation. Implementing sustainable farming techniques, such as agroforestry, intercropping, and organic agriculture, can mitigate environmental damage and enhance biodiversity. Policies that incentivize the restoration of degraded lands and the protection of forested areas, along with the promotion of community-based conservation efforts, have the potential to reconcile agricultural development with biodiversity conservation. The future of the Congo Basin's biodiversity therefore hinges on a careful balance between agricultural growth and environmental protection. Integrating conservation goals into agricultural policy and practice is essential to ensure the long-term sustainability of the region's ecosystems.

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How Could Logging Policies and Practices Influence the Future of the Congo Basin Biodiversity and Ecosystems?

27

Lee J. T. White, Ghislain Moussavou, David Ingueza, Le Bienfaiteur Sagang, Jean-Louis Doucet, and Kumar Mohan

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Abstract

The Congo Basin forests are currently undervalued. Economic and social returns from forestry and timber processing are relatively low compared to some nations outside Africa. Furthermore, the ecosystem services provided by the forests, such as the net absorption and storage of atmospheric carbon, continue to be considered by the international community as a free commodity. We propose an economic model involving maximizing the proportion of third-level timber processing and planting new forests that can increase forest economies and job creation by an order of magnitude. We argue that only by making forests valuable to the people and nations of the Congo Basin will we be able to avoid the large-scale deforestation that has occurred in West Africa and in other tropical forest regions, where the economic and social benefits of conversion were higher than those linked to preservation and sustainable harvest. We discuss knowledge gaps that need to be filled, possible technological solutions and policy reforms, and fiscal incentives needed to implement our model across the Congo Basin.

Keywords

Sustainable forestry · Timber processing · Economic model · Corruption · Fiscal incentive

Introduction

Ebony (*Diospyros crassiflora*), rubber (*Funtumia elastica*), and "redwood" (*Pterocarpus soyauxii*—whose powdered wood was used to make a red pigment) were among the earliest products traded out of the west coast of the Congo Basin, starting in the fifteenth and sixteenth centuries, along with ivory. It is testament to the rapacious nature of this commerce that very few ebony trees exist in Gabon, even today. The first export of logs from French Equatorial Africa was in 1889, when okoumé trees (*Aucoumea klaineana*) were exported from Libreville to Berlin. Due to okoumé wood's excellent suitability for making plywood (today it constitutes the

world's best quality marine plywood), it was soon the subject of a thriving trade from coastal Gabon and Congo to France, Germany, and other European nations.

The economic model during the colonial period was to extract raw timber as logs, to be shipped to Europe for processing. Upwards of 90% of the economic value and jobs (see below) were thereby realized off the African continent, a model repeated in other sectors and that has seen the rest of the world develop on the back of cheap raw materials extracted from Africa. Today this model continues in all Congo Basin countries other than Gabon, which banned export of unprocessed timber in 2010, by decision of the Conseil des Ministres confirmed by order n°008/PR/2010 of the President of the Republic signed on February 25, 2010. Both Cameroon and Republic of Congo have announced similar bans, but they are yet to come into full effect.

Today Malaysia, with just over 18 million ha of forest area, has an annual forest and timber processing economy of just over $6.5 billion and wood exports of $4.8 billion. The value of timber exports in Cameroon (20 million ha of forest), Republic of Congo (22 million ha), and DRC (152 million ha) are currently about $440 million, $380 million, and $140 million, respectively, or between 10% to 0.5% of their potential value, based on the Malaysian model. In Gabon (almost 24 million ha), the value of timber exports has increased steadily from less than $200 million, since the government made in-country wood processing compulsory before export in 2010, reaching $1 billion in 2022. The huge gap in the value of forestry and timber processing between Malaysia (despite its smaller forest area) and the Congo Basin countries is a result of the following: (1) biologically Malaysian "Dipterocarp" forests have higher volumes of commercial species, resulting in larger per hectare harvest intensity and profitability (but perhaps lower sustainability); (2) its highly developed wood processing industry; (3) its development of extensive plantation forests; and (4) Malaysia supplementing its timber production through imports, including large quantities of logs from the Congo Basin. Malaysia also has tenfold more jobs in its forestry and timber sectors than the Congo Basin countries.

Looking to West Africa, industrial forestry operations in Nigeria, Ghana, and Côte d'Ivoire were a precursor to extensive deforestation by subsistence slash and burn and small-scale cocoa farmers. Many of the foresters who had been active in the forestry industry in Ivory Coast moved to Gabon and Congo in the 1980s, and for a while, it seemed likely that the same pattern would repeat itself, until these countries strengthened forestry legislation and forest conservation policies in the 1990s and 2000s, made easier by their relatively lower human population density. This has resulted in sustained low deforestation rates, although it is currently uncertain if this can be maintained in the face of growing competition for land. Deforestation rates in the more highly populated Cameroon and DRC are much higher and are currently increasing rapidly. As populations increase across the region, forestry can only hope to continue to cover large areas if it is sufficiently profitable to compete with other possible land uses and creates sufficient jobs to be socially viable.

For the Congo Basin's forests to remain standing into the next century and continue to supply the critical ecosystem services they provide to the Congo Basin and the world at large, they need to be more valuable alive than dead. For a while

there was an expectation that the UNFCCC REDD+ process, agreed under Article 5 of the Paris agreement, would provide a strong mechanism to contribute to this. However, this process has largely failed; just $36.9 million of results-based payments ($17.4 million under a bilateral agreement between Gabon and Norway and $19.5 million to DRC through the World Bank's Forest Carbon Partnership Facility for the Mai-Ndombe province) have been dispersed to the region since REDD+ was agreed in Paris in 2015. With payments averaging $5/ton of CO_2e, this will barely cover the protection and management costs to the Congo Basin governments.

With young, rapidly growing populations and weak economies, Congo basin nations need forests to contribute in a meaningful way to sustainable development and GDP. Unfortunately, typically representing less than 5% of GDP, forests are currently underperforming in terms of direct economic benefits, while covering at least 50% and up to 88% of land in each country, with over 100 million people directly living there and depending on forest resources at large. If this is to change, then either mechanisms to effectively integrate the ecosystem services the forests provide onto the balance sheet of the Congo basin countries need to become effective or the forest economies need to increase in order to provide an economic incentive to preserve the forests. It is difficult to envisage that the Congo Basin will avoid the large-scale deforestation that has been experienced in West Africa, the Amazon, and SE Asia through agriculture if forestry revenues and jobs are not competitive with other land uses.

In this chapter we will assess the potential of forests to sustainably contribute in a more meaningful manner to economies and job creation in the Congo Basin countries, examining the co-benefits this would provide in terms of climate change mitigation and biodiversity, as well as the threats that might derail the best laid plans. We use the economic experiment undertaken by Gabon when the decision was made to ban the export of unprocessed timber as an alternative to the business as usual scenario in which the Congo Basin countries continue to export unprocessed logs, which almost inevitably will lead to the Côte d'Ivoire or Ghanaian pattern of forest loss.

The Economic Potential of the Forestry and Timber Processing Industries in the Congo Basin

The striking difference in the forest and timber economies of the Congo Basin countries and Malaysia offers an indication of the potential economic and social gains that could be achieved through intensifying and increasing the sophistication of timber processing in the Congo Basin. Based on real costs and benefits of investment in forestry and different forms of timber processing from experience with companies owned and operated by the Gabon Special Economic Zone (GSEZ), a public-private partnership with the Government of Gabon owning 40% of the company, the authors constructed an economic model of the implications of shifting from a forest economy based on log export to third-level processing based on predicted costs and production (Table 1). This model was used by GSEZ to make

Table 1 Economics of a forest exploitation company

Area (ha)	100,000
Annual cut (ha)	5000
Average yield (m^3/ha)	8
Annual production (m^3)	40,00
Production cost (cost of road building, felling, extraction, etc. averaged/m^3 ($USD)	$60
Average sales price (m^3) *N.B. price will be higher in FSC certified concessions.* *This is the price at the forest park. This price can range upto $180/200 USD if the quality of logs is good and fresh.*	$90
Capital expenditure. *Management Plan, Bulls, Excavator, Trucks, Pickup, Camp* etc.	$6,000,000
Jobs created	150
Profits (before tax). *Assuming sale of 70% for peeling and 30% to sawmills near the concession.*	$1.200,000
Tax on profits (20%)	$240,000
Salaries and contributions	$1,260,000
Other costs *Of "other costs", only 30% is spent in Gabon, the rest is on equipment purchased outside Gabon and therefore only 30% contributes directly to the Gabonese economy*	$1,140,000
Return on investment	7.7 years

investment decisions in Gabon and is therefore a real-world example tested by the private sector, although not all operators may agree the assumptions are realistic.

The model runs from an average concession covering 100.000 ha, based on a 20-year sustainable management plan, exploiting approximately 2 trees/ha/rotation above 70 cm dbh and using a conservative figure for the average timber per tree. Numbers are converted from Central African francs at a rate of 500 FCFA: 1$ for ease of calculation. Many permits in Central Africa use a rotation of up to 30 years, but would expect to harvest more cubic meters per hectare than in our model.

The forests potential, harvesting rules, stakeholders, and costs in other Congo Basin countries are sufficiently similar that it should be possible to construct similar models for each country, although the rotation period, average yield per hectare, cost of wages, transport, and capital investment costs, would need to be adjusted for each country. Sale prices on the international timber markets are notoriously fickle and can vary significantly from 1 year to another, potentially making our model unrealistic during periods of downturn.

The economics of a forestry operation in a concession covering 100,000 ha are presented in Tables 1 and 2.

In Gabon all timber has to undergo at least first level processing, into veneer or sawn timber (Tables 3 and 4).

In these two cases, if we add all the taxes due to government, including the surface area tax and the export tax, if these products are exported at this stage, the Gabonese government receives a total of $11.3 and $9.2/ha in taxes and the economy

Table 2 Economics of a timber transport company

Average transport price (per m^3)	$50
Average transport cost (per m^3)	$41
Capital expenditure *Estimate = 7 trucks*	$1,330,000
Jobs created	28
Profits	$360,000
Taxation	$108,000
Salaries and contributions	$504,000
Other costs. *Of "other costs" only 30% in Gabon and contributing to the local economy*	$1,137,000
Return on investment	5.7 years

Table 3 Economics of a first transformation company—veneer

Plant capacity (m^3)	40,000
Capital expenditure *30% invested in country, 70% outside*	$6,000,000
Average cost of logs (per m^3)	$150
Average production efficiency	50%
Total production (m^3)	20,000
Total waste (m^3) *This is a big asset loss to the country, which could be recovered.*	20,000
Total Ex Factory cost	$470
Handling costs (per m^3)	$67.5
Av. Sales price (per m^3)	$588
Profitability (per m^3)	$50
Jobs created	400
Taxes	$287,850
Salaries and contributions	$3,840,000
Other costs *Of "other costs" only 30% in Gabon and contributing to the local economy*	$6,910,000
Benefit to owner	$1,010,000
Return on investment	6.25 years

as a whole receives a total of $135/ha and $85/ha from veneer production and sawn wood production, respectively.

Were the logs to be exported unprocessed, if we apply current taxes, the government would receive about $8.4/ha in total revenues and the economy would benefit to the tune of only $47/ha, or 30–50% of the revenues to be made from keeping first transformation in the country.

Moving to a second transformation and at the same time investing in recovering some of the waste wood from the first transformation (focusing on plywood for simplicity—results from sawn wood show the same tendency but are slightly lower), the numbers look like this (Table 5):

Table 4 Economics of a first transformation company—sawn wood

Plant capacity (m^3)	40,000
Capital expenditure *30% invested in country, 70% outside*	$4 million
Average cost of logs (per m^3)	$120
Average production efficiency	45%
Total production (m^3)	18,000
Total waste (m^3) *This is a big asset loss to the country, which could be recovered.*	22,000
Total Ex Factory cost	$317
Handling costs (per m^3)	$67.5
Av. Sales price (per m^3)	$420
Profitability (per m^3)	$36
Jobs created	200
Taxes	$183,825
Salaries and contributions	$1,440,000
Other costs *Of "other costs" only 30% in Gabon and contributing to the local economy*	$5,474,000
Benefit to owner	$612,750
Return on investment	6.5 years

Table 5 Economics of a second transformation company

Plant capacity (m^3)	20,000
Recovery of waste	8000
Total output:	28,000
Capital expenditure *30% invested in country, 70% outside*	$6 million
Average cost of veneer (per m^3)	$240
Average production efficiency	80%
Total production (m^3)	22,400
Total Ex Factory cost (m^3)	$470
Handling costs (m^3)	$67.5
Av. Sales price (m^3)	$588
Profitability (per m^3)	$50.5
Jobs created	600
Taxes	$441,000
Salaries and contributions	$5,760,000
Other costs *Of "other costs" only 30% in Gabon and contributing to the local economy*	$6,280,000 (only 30% in Gabon)
Benefit to owner	$1,075,000
Return on investment	5.6 years

This results in an additional revenue of $3.3/ha for the government and a further $102/ha injected into the economy. Finally, if there is investment in third transformation factories to transform the plywood/sawn timber into furniture, the numbers are as follows (Table 6):

In this case the Gabonese government receives a further $8.1/ha and an additional $206.3/ha is added to the economy.

In summary, taking the plywood model, assuming 15 million hectares of active concessions in Gabon (there are just over 16 million ha allocated but not all are currently active), theoretical government revenues, GDP contribution, and jobs created are presented in Table 7.

These figures can be further improved by investing in industries that use waste from first level transformation, such as the production of activated charcoal, biochar or

Table 6 Economics of a third transformation company, furniture

Plant capacity (m^3)	22,400
Capital expenditure *30% invested in country, 70% outside*	$12 million
Average production efficiency	90%
Total export (m^3)	20,160
Average cost of veneer (per m^3)	$520
Total production (m^3)	22,400
Total Ex Factory cost	$920
Handling costs (m^3)	$67.5
Average Sales price (m^3)	$1600
Profitability (per m^3)	$610
Jobs created	1000
Av taxes	$3,690,960
Salaries and contributions	$9,600,000
Other costs *Of "other costs" only 30% in Gabon and contributing to the local economy*	$12,303,200
Benefit to owner	$11,688,040
Return on investment	1.03 years

Table 7 Projected government revenues, GDP contributions, and direct job creation if all of Gabon's timber concessions are harvested sustainably and timber undergoes first-, second-, or third-level transformation

	Gvt. revenues	GDP contribution	Direct Jobs[a]
Log exports	$126 million	$705 million	26,700
1st Transformation	$165.5 million	$2025 million	86,700
2nd Transformation	$215 million	$3555 million	176,700
3rd Transformation	$336.5 million	$6650million[b]	326,700

[a]There will be at least as many indirect jobs created

[b]In 2023 Gabon's oil sector contributed $7.7 billion, representing 40% of GDP. The exact number of jobs in the oil sector is not clearly defined in the available official sources but it is thought to be well below 10,000

particle board, or at the very least the use of waste biomass in wood dryers and for electricity generation or to make charcoal. Wood waste should also be used to support and develop a more efficient local cottage industry led by smallholders and communities to generate more added value in terms of yield, employment, and income through mentoring mechanisms involving large companies and the government.

Learning from Malaysia, if Gabon was to also plant 100,000 ha of plantations of fast growing trees (e.g., *Eucalyptus* spp, *Acacia* spp), production figures, investment, and revenues would look something like this (Table 8):

One investment (or a series of smaller investments) in 100,000 ha of plantations would almost double the sustainable wood harvest in Gabon from 6 million to 11 million m^3/yr. While the plantation wood would be made into lower-quality (value) products, it would still result in comparable profits and job numbers and would potentially allow more stringent sustainability rules and lower harvest intensity to be implemented in natural forests. Plantations of native species would be up to five times less productive and take longer to mature, making them a lot less profitable (De Wasseige et al. 2014; ▶ Chap. 12, "Agriculture, Ecosystem Functions, and Services in the Congo Basin") although Doucet et al. (2016) suggest that Ayous may be an exception. They would however be more ecologically valuable and

Table 8 Plantation establishment and production costs and profitability

Planted area (ha)	100,000
Annual rotation	6 years
Annual area harvested (ha)	16,667
Average Yield/ha/rotation (m^3) *= 50 times natural forest—this is an ambitious but conservative figure, based on yields achieved in Brazil and India, that can reach 500m^3 using new clones* (de Assis et al. 2004; Dhiman and Gandhi 2022) *and similar yields obtained in Kenya* (e.g., Oeba et al. 2009). *The decision by GSEZ to invest in plantations in Gabon was taken based on a projected yield of 330m^3/rotation, confirmed by experimental plantings*	300
Average production (m^3) *(from year 7 onwards)*	5000,000
Average Production cost:	$30
Average Sale price:	$44
Profitability/m^3:	$14
Annual profits from year 7:	$70,000,000
Investment in forest:	$360,000,000
Jobs created:	12,000
Average Taxation from year 7:	$14,000,000
Salaries and contributions	$100,800,000
Other costs *Of "other costs" only 30% in Gabon and contributing to the local economy*	$99,200,000
Benefit to owner *(from year 7 onwards)*	$56,000,000
Return on investment (interest rates on loans will influence the return time)	c.15 years

climatically resilient. Before taking the decision to invest massively in plantations of exotic species, a clear understanding of the value of lost ecosystem services and the potential costs is necessary. Typically non-native fast-growing plantation trees can be very ecologically damaging and use large quantities of water. Some species also become invasive, which may entail control costs in future years, but *A. auriculiformis*, for example, is not invasive in Africa, indicating that species choice is critical. Given the comparatively low productivity of plantations of native species, their economic viability is considered low given the cost of borrowing in the region (e.g., ONFI 2005). Such investments may only be viable if the negative costs of exotics are factored in through taxes, or the carbon and biodiversity benefits of natural plantations are realized through carbon and biodiversity credits, which is not currently the case.

The figures emerging from this model are consistent with the statement in ANRC (2021) that "adding value to primary processed products before export could generate additional margins of between 350% and 1000% and a multiple of 4-12 times more jobs." However, comparing the modelled economic impacts of forestry with those currently achieved by the Congo Basin countries (see above and ► Chap. 13, "Pastoralism: Access to Land and Ecosystem Functions and Services in the Congo Basin"), it is apparent that with the possible exception of Cameroon, Congo Basin countries are not currently seeing even the minimum projected revenues appearing on their balance sheets. For example, in 2023 the contribution of the forestry sector in Gabon to government revenues and GDP were estimated at $ 70 million and $ 642 million, respectively, a factor of 2–3 times less than predicted just for first-level transformation at optimal forest productivity.

In 2023, with production of round logs estimated at 3.58 million m^3, Gabon's projected forest economy with first-level transformation would have been c. $1.2 billion, yet the declared revenues were only around half that amount. Is the model overestimating the potential of forestry and timber processing to contribute to the economy, or are there factors that result in leakage? The 2019 report, Toxic Trade: Forest Crime in Gabon and the Republic of Congo and Contamination of the US Market (EIA 2019) documented many cases of serious fraud and illegal forestry activities, including almost systematic tax evasion through false declarations of profitability and corruption. For example, many companies investigated admitted to keeping two sets of accounting, one for government authorities demonstrating +/− 0% profits while in reality they were achieving profits of 30–40%, up to twofold higher than predicted by our model, through a combination of illegal activities, including overharvesting, stealing wood either from outside authorized areas inside their concession or outside their concessions, or underreporting harvest volumes and mis-reporting species harvested, including unauthorized species, in favor of less valuable timber both in harvest logs, transportation, processing, and export paperwork. In addition, there are inefficiencies in revenue billing by Ministry of Economy staff and in labeling of certain in-country spending as being related to the forestry sector.

This under-declaration is confirmed by the doubling of the annual timber production figures between 2019 and 2022, when the forestry ministry tightened up

reporting significantly, going from less than 2000,000 m^3 in 2019 to more than 4,000,000 m^3 in 2022. Considering this period corresponds to the decrease in economic activities during the COVID-19 pandemic, the recorded doubling of annual harvested logs was due to improved law enforcement and statistics, rather than a growth of logging activities.

All told, it seems highly likely that our numbers, based on commercial activity by GSEZ companies in Gabon, are relatively close to reality and that a mix of government inefficiency and corruption, as well as active tax evasion by some companies, is the cause in the gap between our model and reality on the ground.

This model, based on today's costs and prices, demonstrates clearly (1) that the forestry and timber processing sectors have the potential both to make a significant (>30%) contribution to GDP across the Congo Basin and to grow to be the major employer, a critical consideration for nations where over 50% of the population are less than 18 years old and unemployment is already in double digits and where significant of populations live in forest and directly depend on forest resources (▶ Chap. 7, "Central African Rainforest Archaeology"). Indeed, Gabon's national vision for the development of the sector, adopted in Cabinet in 2022, aimed to achieve full third-level transformation by 2030 based on this model (MINEF 2021).

The next question is to ask whether there is sufficient affordable capital and interested investors to lead the transition to third-level processing and whether the Congo Basin governments see this as a priority. When Gabon announced its ban on the export of unprocessed timber it was not met with applause in the halls of power in Europe and Asia and all Congo basin countries kept doubting and hesitating, waiting to see the results in Gabon before considering following suit. The biggest challenge for the Gabonese government trying to attract investment was not a lack of interested parties (60 companies invested in timber mills in the Special Economic Zone after the log export ban): but rather the lack of affordable financing from commercial banks and multi-lateral institutions.

If we consider retrofitting our model to investigate how Congo Basin countries' economies might have benefitted from retaining the transformation of their resources from the moment of their Independence in 1960 (rather than continuing to export logs for transformation in Europe and elsewhere in the world), assuming compound interest at 10% for the period 1960–2009, Gabon's economy could have been $439 billion richer today. Currently its GDP is about $21 billion and its debt burden is about $14 billion. If a more conservative interest rate is applied, using 7% as the average cost of Gabon's sovereign debt, the figure reduces to $182 billion, but if we use the average cost of private sector debt across the region, estimated at 18% compound interest rate, it rises to $6.10 trillion.

The strategy for management and development of the forestry and timber sectors in Congo basin is based on current understanding of maximum sustainable harvests. It is founded on the principal of implementing a sustainable harvest of a renewable resource, a very different approach to that of the oil and mining sectors that currently dominate the economies of most Congo Basin nations. Our model suggests that by transitioning to second- and third-level transformation, forestry provides an attractive combination of economic returns and jobs for Congo Basin countries. Having

answered the question about the economic and social potential of forestry and timber processing, before recommending the "in-country transformation model" as a silver bullet for forest management across the Congo Basin, we must consider possible weaknesses or knowledge gaps that might undermine the strategy.

Key Questions Still To Be Answered?

Sustainability?

The long-term sustainability of extracting timber selectively from natural forests will depend on the ability of target species to grow and regenerate after logging or on the possibility that species not exploited today can become commercially viable in the future. For long-lived species, some of which grow to be 1000 years old or more, and do not necessarily regenerate in the conditions that exist today, this may prove problematic. Important commercial species such as Okoumé (*Aucoumea klaineana*), Sipo and Kosipo (both Mahoganies: *Entrandophragma utile* and *E. candollei*), Ayous (*Triplochiton scleroxylon*), Azobe (*Lophira alata*), and Moabi (Baillonella toxisperma) all regenerate in large open areas following slash and burn farming or are otherwise dependent on human activities (Biwol et al. 2015; Fay 1997; Morin-Rivat et al. 2017; White and Oates 1999). In the case of Okoumé, which only live up to about 150–200 years, their presence is an indication of relatively recent human farming activity, while the mahoganies can live for almost 1000 years and are the result of farming up to a millenium ago. Moabi (*Baillonella toxisperma*) regenerates almost exclusively in old hill-top village sites, subsequently living for up to 1000 years (Oslisly et al. 2000). Village sites were located systematically on hill tops and ridges, which is exactly where the majority of Moabi trees are found and were the only places where the seeds would have been protected from seed predators such as red river hogs and porcupines and avoid the predatory browsing by elephants, who consume saplings whole and push over young trees.

Sustainable harvest of species with this type of life history is almost impossible, certainly on the "short" 20–25-year rotations practiced today, and inevitably they will be treated as being analogous to mineral resources, even if active promotion of regeneration through replanting can ensure the species will be available for near-future generations. In forests where these are the dominant species, such as for the mahoganies in Northern Congo, sustainable harvests will have to be measured in terms of timber volumes rather than volumes of specific species, at least for this life-history group. Even with the relatively short-lived Okoumé, there are important questions about regeneration that need to be answered, given that most of the trees being logged today were established during the 1930–1960 period, when the colonial authorities forcibly moved all Gabonese villages out to the forest and relocated them along roads, leaving Okoumé trees to regenerate in their abandoned fields (CNC 2021; Hymas 2015). As the species that makes the best quality marine plywood, there is a strong economic argument for promoting the regeneration of Okoumé and as a relatively fast-growing species, able to reach up to 70 cm dbh in

just 40 years (Nestor Laurier Engone Obiang et al. 2013), but this species highlights the problems that exist when planning for long-term sustainability rather than just one or two rotations. There is an extreme lack of data on the life histories, ecology, and regeneration of even the most important commercial species.

The question of how to deal with species that regenerated massively in the past open conditions but do not regenerate under a closed forest canopy, such as Okoumé, Ayous, Azobé, and the Mahoganies is an important one. Recently, the EU proposed adding Okoumé to Annex 2 of CITES on the basis that forestry represents a threat to its commercial sustainability. Okoumé is a wind-dispersed species that specializes in colonizing open ground but cannot regenerate under the forest canopy. It is an early succession species that naturally dies out over a period of about 150 years as the forest develops (e.g., White et al. 2000). As such, it can occur at huge densities in early successional stages of forest establishment in old farms or savannas, often exceeding 10,000 stems per hectare (1 million stems per km^2!—see Guidosse et al. 2022) but is absent from the lower size-classes in closed-canopy forests. It is illogical to apply sustainability criteria to the exploitation of such r-selected species and highlights the overly simplistic view that non-specialists have of tropical rain forests, as stable habitats that have always had the same species composition as we see today. We simply cannot judge a species with a 1000-year life strategy that includes periods of rapid expansion and periods of relative stasis in this way.

This begs the question, because there is no in situ regeneration, should we ban the exploitation of these types of species because it is not locally sustainable? If we do not log, the species is likely to disappear naturally even if forests persist, but for the forest to be economically viable and thereby resist deforestation, we need to log these species. There is a need for a much more sophisticated approach to these questions, based on better understanding of the life strategies and ecology of the Congo Basin trees. In the case of Okoumé, it is relatively easy to promote regeneration through active interventions (Doucet 2003).

The issue of regeneration and sustainability across rotations has been the subject of much applied, but unpublished research and regeneration models for all commercial species are included in forestry management plans. However, we are just seeing the first companies coming to the end of their first logging cycles (e.g., Precious Woods in Gabon in 2026) and beginning to undertake the inventory work to update their management plans, and this will provide the data to assess the reliability of the models used. This is a critical field for future applied research in the Congo Basin if the Congo Basin countries and their private sector partners are to have the confidence they need to make the long-term investments in timber processing that we are proposing. There is research to suggest that improving regeneration through assisted or artificial methods is relatively easy (e.g., Doucet et al. 2016), but for this to become a widespread management strategy reform in the politics of allocation of forestry, concessions will be needed. Companies are unlikely to make significant investment in silvicultural techniques to promote regeneration of even the fastest-growing species that will not reach harvestable dimensions before 30–40 years, in areas where their concession is only valid for half that period. For slower-growing hardwood species even longer forest stewardship will be required.

Impacts of International Policies on Deforestation

The EU's Regulation on Deforestation-Free Products (EUDR—formally known as Regulation (EU) 2023/115) aims to prevent certain products, including wood, entering the EU common market that have contributed to deforestation globally. To define imported deforestation, one first needs to define what a forest is. Generally, international agreements and regulations refer to the FAO definition that states that a forest is an area of at least 0.5 ha with a canopy cover of 10–30% (countries decide which is most appropriate to their forests) of trees with the potential to exceed 5 m in height. This UN definition adopted by consensus was crafted to allow all countries to be able to say that they possess forests, but it is not adapted to the Congo Basin ecosystem where a "forest," in the sense of most traditional communities in the region, is a "mature forest," with close to 100% canopy cover and trees above 40 m. By the FAO definition, many Congo Basin savannas qualify as "forests" and it would be impossible for a forestry company to establish a camp or log-loading area of more than 0.5 ha in their concession without being accused of deforestation, even though their economic activity is the reason the forest will survive in the medium term.

If this regulation is applied appropriately, it might result in a price increment for sustainably harvested tropical timber in the same way as FSC certification and be positive, but if applied "*bêtement*," without economic incentive mechanisms, there is significant risk of perverse effects. Indeed, in its UNFCCC NDC, the Gabonese Government went as far as to make its emission reduction and forest preservation commitments conditional on continued access of its certified sustainable wood products to international markets (CNC 2022), on the basis that its economic model involves using sustainable forestry as a mechanism to maintain forests, which in Gabon's case net absorb about 100 million tons of CO_2 annually.

Furthermore, decisions by CITES to place species of African timber that scientists do not consider threatened (such as *Afzelia* and *Pterocarpus*)—e.g., Nkenne Tikeng (2025) under CITES Appendix II on the basis of proposals submitted by the EU, imposes enormous constraints on producer countries and forestry companies. This results in export blockages, particularly due to the slowness of permit issuance within the EU. Even FSC- or PEFC-certified timber ends up being held for months and deteriorating in EU ports. The attitude of several EU Member States amounts to a kind of unacknowledged boycott of tropical timber, stemming from a lack of understanding of the reality of African forests.

Human Population Increase and Competing Land Uses?

As described in ▶ Chap. 17, "Climate Change and Ecosystem Functions and Services in the Congo Basin," human populations are increasing rapidly in all of the Congo Basin countries and are predicted to reach 261.7 million by 2050 (e.g., de Wasseige et al. 2012). In both DRC and Cameroun, this is resulting in increased deforestation rates, as people turn to forested areas as the only land available for subsistence agriculture (eg. Shapiro et al. 2023). There is a risk that the scenario that played out

in West Africa and resulted in the loss of almost all the forest in, for example, Ghana and Ivory Coast, is beginning to occur in the Congo Basin. Loss of humid primary forest in DRC has increased over the last 25 years from 169,000 ha in 2000 (0.16%) to 590,000 ha (0.56%) in 2024, while tree cover loss increased from 456,000 ha (0.23%) to 1,380,000 ha (0.69%) in the same period (data on Global Forest Watch; see ▶ Chap. 21, "Effects of Diseases on Wildlife Species in the Congo Basin").

Agriculture is critical to the well-being, nutrition, and food security of the people of the Congo Basin (cf. ▶ Chap. 11, "Global, Regional, and National Economic Drivers of Deforestation and Forest Degradation in the Congo Basin") but so too are the ecological services provided by the forests. Indeed, the rainfall generated through evapotranspiration over the forest is critical to sustaining agriculture (cf. ▶ Chap. 19, "History, Development, and Politics of Protected Areas in the Congo Basin Countries"), particularly in light of the generalized climate change-induced drying of the region seen in ground observations (cf. ▶ Chap. 2, "Geology and Geodynamics Evolution of the Congo Basin"). Transitioning from relatively unproductive agricultural techniques that date from the beginning of the Iron Age (see ▶ Chap. 7, "Central African Rainforest Archaeology") to modern tropical agriculture and agroforestry is a critical component to preservation of the forests, although some argue that improved productivity and stabilizing farmers on the same piece of land through soil improvement techniques is no guarantee of forest preservation, given the enormous agricultural potential of the region and the growing global human population (e.g., Hourticq and Megevand 2013). Moreover, as long as small farmers or local communities don't receive better financial benefits from their commitment and efforts to conserve a piece of forest land rather than shifting it to crops, no policy will be able to guarantee forest preservation.

For the forest to survive, it needs to be seen to be playing an equally important role in the economies of the Congo Basin Nations and the lives of its peoples in order to be able to resist the pressures of competing land uses. Table 1, which summarizes the potential of the forest to contribute to the economic and social development of Gabon, and by analogy the other Congo Basin countries, by making a similar contribution to GDP as oil, while employing over 700,000 (direct and indirect employment). This economic benefit will probably be enough to protect areas that are producing less direct economic gains and jobs (e.g., protected areas) but which provide enormous ecosystem benefits to the basin and the world at large. Given the failure of processes such as REDD+ and the carbon market to reward ecosystem services that are easily quantifiable, it seems unlikely that payment for these services will be an alternative to forestry and timber transformation in the short to medium term.

Impacts of Climate Change?

In Gabon's revised NDC, the second qualifier of its commitment to remain carbon neutral forever was that it would be powerless to act and could not be held responsible if climate change caused by global emissions of CO_2 and other

greenhouse gases, to which the Congo Basin has made no net contribution (the entire region continues to be a net sink of CO_2), becomes so severe that the forest begins to die faster than it is growing. Currently the Congo Basin forests are proving to be more resilient to the effects of climate change than the Amazon (Hubau et al. 2020; Sullivan et al. 2020), but the evidence of massive forest fires and replacement of forests by savannas and degraded forests during a dry climatic phase between 2500 and 2000 years ago (Maley 1992; Peyrot et al. 2003; White 2001) suggests that as temperature increases toward the +3 °C increase that seems currently to be the trend, (perhaps large) parts of the Congo Basin will no longer be able to support humid tropical rain forests. Rainfall models tend to predict slight increases in overall but more seasonal rainfall and more extreme storm events, but ground measurements seem to show the opposite, with progressive drying recorded in both Yangambe (DRC) and Lopé (Gabon) (Bush et al. 2020a; Kasongo Yakusu et al. 2023). Bush et al. (2020b) demonstrated a catastrophic reduction in fruit availability in Lopé, Central Gabon over a 30-year study with corresponding loss of body condition of forest elephants. This is the first sign of dramatic impacts of climate change on Congo Basin forests and suggests possible direct (reduced seed availability for regeneration) and indirect (reduced seed disperser availability) impacts on forest regeneration, including after logging. In the Republic of Congo, similar observations have been noted by some foresters (Ifo, S. A., pers. comm.).

The possible implications of climate change for humans and biodiversity are severe (e.g., Beekmann et al. 2024) and the biggest contribution the Congo Basin countries can make to mitigating the worst impacts is to preserve the forest ecosystems, including the vast peatland wetlands in Congo and DRC.

Concession Allocation and Forest Management Policies and Laws in Congo Basin Countries

A key feature of Central African forests is that they belong to the state, which retain management rights but grant harvesting rights to private companies for periods covering one rotation, generally around 25 years. As noted above, this is considered by forestry companies too short a time period to justify investment in silvicultural methods that will produce harvestable trees a further two rotations later. Renewal of forestry concessions is not guaranteed in current legislation and until operators have a longer-term vision, or there is stricter, more hands-on management by forestry authorities to ensure forestry practices promote regeneration of commercial species, sustainability of timber yields across multiple rotations is unlikely. Currently, all too often, concession holders are expected to assume all responsibilities, including those that are the responsibility of the state, to make up for shortcomings, such as the lack of transport and unfair competition from illegal timber, among others.

Another key management issue is the control of hunting in forestry permits, which is key to maintaining healthy populations of animal seed dispersers, which are vital for healthy regeneration of logged forests (e.g., Daïnou et al. 2021). This nature-based solution to replanting in disturbed areas is easily interrupted in forestry

permits, where poaching is prevalent and government wildlife managers are not present. The debate about whether the private sector permit holder or the government should foot the bill for wildlife management is ongoing, but some companies do share the costs of government wildlife brigades in their concessions.

Co-benefits of Implementing Sustainable Forestry at a Large Scale Across the Congo Basin: Carbon and Biodiversity

In Central Africa, tall forests with the highest densities of large trees have historically been targeted for commercial forest concessions. Well-managed forestry as practiced in the Congo Basin involves the sustainable selective harvest of 1–3 trees per hectare on a 20–30-year rotation (e.g., Medjibe et al. 2013; Umunay et al. 2019; White 1994) typically results in the loss of about 10% of standing biomass, most of which is released as carbon emissions. However, the resulting opening up of the canopy causes increased growth of surviving trees, resulting in accelerated carbon uptake, which makes logging neutral or even positive in carbon across the rotation (CNC 2021; Gourlet-Fleury et al. 2013). As such, sustainably managed forestry concessions in the Congo Basin are an effective way of maintaining or even enhancing forest carbon stocks (CNC 2021; Poulsen et al. 2020; Sagang et al. 2024; in prep).

However, when timber harvesting occurs in uncertified logging concessions, with no effective oversight by government, illegal practices often result in higher harvesting intensity and damage rates. Figure 1 maps aboveground carbon measurements across the Congo Basin and presents measurements of average carbon stocks in old growth forests, in certified and uncertified timber concessions, and in areas with active slash and burn farming. Areas where forestry is underway, particularly when it is certified, consistently have higher carbon stocks than unlogged old growth forests.

The map also clearly demonstrates that slash and burn agriculture, which is increasing in extent outside logging concessions, is a significant threat to carbon stocks and environmental services generally.

The physical damage caused by felling and extraction (skidder trails, roads, log loading areas) of trees results in more light penetrating into the forest understory, increasing temperature and reducing humidity, resulting in the loss of more sensitive components of the biodiversity. However, wildlife management in these concessions is undertaken more and more systematically, with active participation in prevention of poaching and in promoting sustainable subsistence hunting (e.g., Zwerts et al. 2024). As a result, they act as a sanctuary for healthy populations of medium- and large-sized mammals, which are susceptible to hunting, including elephants and apes (Laguardia et al. 2021; Morgan et al. 2018; White 1994b; Zwerts et al. 2024), although certified concessions tend to perform better than non-certified (Zwerts et al. 2024).

As such, sustainable forestry concessions are an effective means of managing Congo Basin forests both for economic plus social returns and ecological services such as carbon and biodiversity. Indeed, given that they exist on government-owned

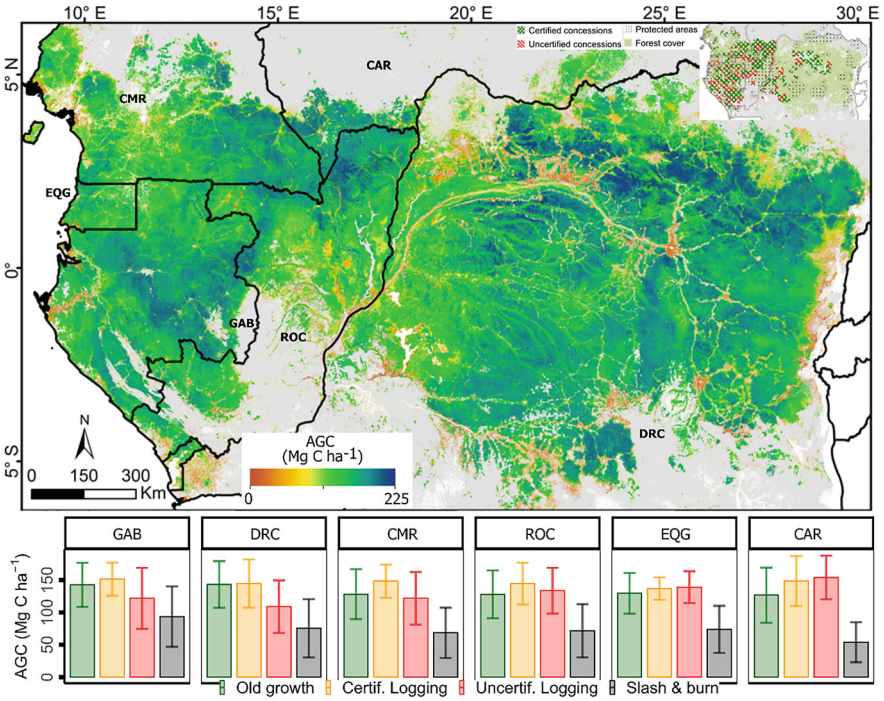

Fig. 1 Aboveground carbon (AGC, Mg C ha-1) density in the Congo Basin rainforest for the year circa 2020 (a) with the distribution across land-use disturbances including certified and uncertified logging as well as slash-and-burn (Sagang et al., in prep. GAB—Gabon, DRC—Democratic Republic of Congo, CMR—Cameroon, ROC—Republic of Congo, EQG—Equatorial Guinea, CAR—Central African Republic)

land and are subject to legally binding management plans, they are almost equivalent to the "National Forests" in the USA, which are considered IUCN Category VI protected areas. As in the US system, some parts of the concessions, e.g., protected, river protection and community zones, would qualify as higher category protected areas. Applying these criteria to Gabon's forests, for example, would raise the % of terrestrial areas under protection to about 80–85% of the territory.

What Investments in Skills Will It Take to Get the Basin onto a Sustainably Logged Future?

In order for the vision for sustainable harvest and in-country/regional processing of timber to become a reality, a number of investments in capacity and law enforcement and certification are required:

Law Enforcement and Certification

Law enforcement and certification go hand in hand. Perhaps the greatest threat to the creation of a sustainable timber economy is the pervasive presence of illegality in the industry and corruption in the administration. The EIA Toxic Trade report (EIA 2019) resulted in the US wood market being closed for Gabonese timber products for several years. More and more the international market expects the legality of natural resource extraction to be guaranteed. This will require a significant, ongoing investment in legal framework improvement, law enforcement, and forest concession auditing to be undertaken throughout the Congo Basin and will require training of staff, enhancing of operations capacities, and implementation of anticorruption measures in forestry, customs, and the judiciary. Achieving this also includes investing in digitization of systems of authorizations and controls to facilitate real-time verification by international markets and improve confident in legality and traceability.

Certification of legality and environmental sustainability is gradually becoming a requirement rather than a premium. Indeed, in 2018, in response to the preliminary findings of the EIA investigation, Gabon announced the requirement for all forestry concessions and factories to be FSC certified by the end of 2022 (informally extended to 2025 post-COVID). This is complex because, in some systems, e.g., FSC, governments have no formal influence or ability to make input on the adoption of norms and rules, creating a parallel governance structure that forestry companies need to conform with. In July 2021 the French government announced that no tropical timber would be used in the construction of venues for the 2024 Olympic Games. This restriction was lifted in in June 2022 for FSC certified "tali," used to make outdoor decking and barriers. In the context of the implementation of Regulation (EU) 2023/115 and China's new forestry law that lays the foundation for prosecution of Chinese companies and individuals found guilty of illegal forestry practices anywhere in the world, certification is likely to become more and more widespread.

Capacity Building

Implementation of government sustainability legislation and norms of certification, both in forestry operations and timber processing factories, require a high level of qualified personnel. Today we often still lack even the basic knowledge of the ecology of target species, their life history characteristics, phenology, growth rates, seed dispersers, and pollinators. As such, there is a need for increased investment in applied forestry research. There is also a lack on management capacity within government departments, whose ability to intervene on the ground is limited because of lack of budgets and equipment and absence of modern traceability software. As such, inventories generally do not exist before concessions are allocated and monitoring and auditing of commercial forestry operations is often inadequate. There is also a distinct lack of capacity in wood processing, especially third-level

transformation (e.g., manufacture of furniture and housing). There is an urgent need for the development of targeted professional training programs as well as fiscal incentives designed to help private sector companies undertake extensive on-the-job training.

Remote sensing (RS) could be a game changer in the future both for inventory, management planning, and monitoring felling and illegal exploitation. Laser technology mounted on aerial and satellite systems generates a three-dimentional view of the forest, measuring precise details about the tree density, height, shape and even the forest floor, all of which are essential for sound management. Coupled with multispectral optical imagery and artificial intelligence to identify tree species, RS will help to optimize forest inventories, including biomass mapping and monitoring of canopy disturbances at relevant frequency and scale, allowing forest administrations to effectively channel management and law enforcement measures. Unless governments invest in managing their forests and controlling illegal activities, the optimal model we present here will not be achieved.

What Economic, Fiscal, and Policy Levers Are Needed to Help the Rollout of Such a Program?

While our model demonstrates that return on investment is relatively rapid, averaging about 6 years in much of the sector in an ideal situation, even this is considered a blockage for many investors, nervous about the business climate, including corruption, political stability, and risk in the Congo basin countries, in addition to unpredictable changes in demand from the international markets. There is a need for the provision of relatively long-term capital at affordable cost if the private sector is to make the investments needed to realize the potential of the sector. Bilateral and multilateral banks and partners need to prioritize making debt affordable and putting in place political risk insurance and sovereign guarantees for investors willing to make the large investments needed. Obviously, the Congo Basin governments have a critical role to play in this, putting in place favorable fiscal regimes and good governance in order to promote strategic investments and investing in the infrastructure (road, rail, and ports) needed to support this logistic-heavy industry. That also includes a strategy for optimizing forest permits allocation in favour to long-term investments that require large concessions to guarantee sustainable projects with healthy economic, social, environmental, biodiversity, carbon, and other ecosystem services returns.

Fiscal incentives are a good way to reward early movers during the transition to increased transformation within the region. For example, Karsenty and Salau (2023) describe the Gabonese Governments use of a differential surface area tax involving lower annual per hectare surface area taxes for companies with forest management ($0.5/ha) or legality ($1/ha) certification compared to uncertified companies ($1.35/ha). A similar scheme is applied to export taxes, which are progressively higher from third- to second- to first-level transformation products.

There will always be a friction between private sector investors seeking to maximize returns on investment and governments, seeking to maximize fiscal revenues and local development. The extremes, characteristic of the colonial model of exporting 100% of raw materials to maximize offshore value-added, which was replicated by many companies operating illegally in Gabon and Congo, who maximize short-term profitability to the detriment of sustainability, using corruption to bypass laws and fiscal frameworks (EIA 2019) result in minimal revenues, jobs, and development for the Congo Basin nations while also undermining the long-term viability of the forest.

The other extreme, with full third-level transformation and investment in regeneration and plantations, requires higher levels of capital expenditure and longer-term economic models. This seems to have been most successful in the public-private partnership (PPP) model developed in the Gabon Special Economic Zone and since replicated in DRC and Congo, where government is a shareholder, has full visibility on investment and financial returns, and actively supports the commercial success of the investment through policy reforms. In an industry that has long thrived in the shadows of the forest, transparency is perhaps key to creating a healthy dynamic between governments and private sector partners (EIA 2019). Use of modern traceability systems to track production, transport, and processing of timber can greatly help ensure this transparency while improving efficiency, reducing corruption, and guaranteeing payment of appropriate taxes.

Principals of Sound Forestry

The DYNAFAC consortium brings together institutions from both the Global South and North and published a series of sound recommendations to improve sustainability (DYNAFAC 2023).

- Tailor management to the region's ten major forest types rather than using one-size-fits-all.
- Set a standard 30-year rotations as a best compromise to balance stock recovery and sustainability.
- Aim to restore harvested stocks to 100% for the commercial species group and at least 50% for each individual species by the end of each rotation.
- Revise and harmonize minimum harvest diameters (DME) region-wide based on biology, so enough seed trees remain.
- Install forest monitoring plots/transects in every large concession (≥50,000 ha) and partner with national research bodies to improve knowledge on the natural history and regeneration of commercial species, so these parameters can be fed directly into management plans.
- Actively encourage natural regeneration (including enrichment planting with native timber species) and protection/restoration of wildlife, considering that many tree species ~70–90% depending on forest type—rely on animals for seed dispersal.

How Does the Vision Presented in This Chapter Differ from the Business-as-Usual Scenario?

The business-as-usual scenario for the forestry and timber industries is one in which almost all round logs or mostly only first level transformed wood is exported from the Congo Basin to other countries. In this scenario, <10% of the forest economy and jobs are generated locally, to the detriment of the Congo basin countries. It is also one scenario in which all added value is generated from natural forests, without investment in planted trees to increase the volume of harvested wood while reducing pressure on natural forests. In this scenario the sector will remain insignificant in terms of economic impact and social returns and other more favorable land uses will be sought by governments desperate to grow their economies and provide jobs for their people. This will result in a scenario similar to that observed in Ivory Coast and Ghana, where forests have dwindled to <5% of their previous extent and agriculture has replaced forestry as the primary land use.

In this scenario, the Congo Basin will become a net contributor to global carbon emissions and both the region and the world at large will lose the priceless ecosystem services currently provided free by the basin's forests. For example, the rains in the Sahel and the Ethiopian Highlands are likely to dwindle as the forests are cut, weakening agricultural productivity in these regions and further exacerbating the already consequential effects of climate change.

We believe our model provides a viable solution to this disastrous scenario and would result in the survival of the majority of the Congo basin forests. It should be noted that our model does not rely on payments for carbon or other ecosystem services in order to be viable and of great interest to the Congo basin nations. If carbon credits, biodiversity certificates, and other mechanisms for recognition and payment for ecosystem services become effective, our economic model will be enhanced.

While the numbers we present are specific to the forestry and wood processing sectors, similar benefits would accrue from the transformation of non-timber forest products and mineral resources, although preconditions, such as the need for cheap, reliable sources of energy, are likely to be more acute for some sectors. In a continent and a subregion blessed with exceptional natural resources and a growing young population, we consider in situ transformation not only to be the only development pathway that guarantees sustainable exploitation of renewable resources and optimized use of non-renewables, but that it is critical to the future stability and economic prosperity of all who live in the Congo Basin and more widely in Africa.

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How Could Hunting and Fishing Policies and Practices Influence the Future of the Congo Basin Biodiversity and Ecosystems?

28

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Abstract

Terrestrial and freshwater wildlife in the Congo Basin provide crucial ecosystem services, food, medicine, and income, for millions of rural and urban communities. However, unsustainable hunting and fishing have caused significant ecological disruptions, including population declines and altered species composition, threatening biodiversity and livelihoods. Despite political and scientific efforts, overharvesting continues, driven largely by persistent poverty, limited protein and income alternatives, and rising demand fueled by population growth, urbanization, and migration. Modern technology and improved transport have shifted practices from subsistence to commercial exploitation, increasing pressure on wildlife. Traditional resource governance, weakened since colonial times, struggles to regulate use, while conflicts exacerbate wildlife exploitation through displacement and increased firearm availability. Meanwhile, deforestation, habitat fragmentation, and mining pollution further degrade ecosystems and complicate sustainable management.

In response, Congo Basin countries have made strides toward more sustainable wildlife management. There is a clear shift from exclusionary, militarized conservation to community-based wildlife management (CBWM), empowering Indigenous Peoples and local communities by integrating traditional knowledge with modern practices. Efforts have evolved from expert-driven solutions to community-focused, nature-based businesses, alongside campaigns to reduce wildmeat consumption in urban areas. National recognition of hunting and fisheries' roles in poverty alleviation has increased, prompting policy reforms to formalize these sectors and improve regulation under initiatives such as the

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Sustainable Wildlife Management program and the Central African Regional Program for the Environment. Additionally, countries are adopting biodiversity-positive practices in logging and mining sectors through certification schemes and legal reforms, though challenges remain in scaling these measures.

Financially, although some steps have been taken recently, there is a need for a more meaningful transition toward innovative finance mechanisms to support sustainable wildlife management and to explore the development of wildlife-based economies. Initiatives such as the BIOFIN program, the Central Africa Forest Initiative, and the High Integrity Forest Finance Initiative are fostering investment, policy dialogue, and sustainable funding models to ensure wildlife and community well-being in the Congo Basin's future.

Keywords

Drivers of unsustainable use · Community-based wildlife management · Alternative livelihood projects · Behavior change · Enabling policy frameworks · Sustainable finance

Introduction

Terrestrial and freshwater wildlife in the Congo Basin provide essential ecosystem services, including food, medicine, and income for both rural and urban populations. These resources are fundamental to the livelihoods, culture, and well-being of millions of people. However, the unsustainable exploitation of wildlife has already triggered significant ecological shifts, leading to changes in species composition, declines in population sizes, localized depletions, and alterations in population traits in both aquatic and terrestrial ecosystems (Wilkie et al. 2019). Such disruptions have cascading effects, threatening biodiversity, destabilizing ecosystems, and undermining the livelihoods of those who depend on these resources (Abernethy et al. 2013). In the Congo Basin, despite political statements and scientific efforts to address wildlife overharvesting, hunting and fishing continue to drive biodiversity loss and undermine the livelihoods of dependent communities, exacerbating the ongoing biodiversity crisis in tropical regions (Coad et al. 2019).

The main drivers of unsustainable use have not changed significantly since the early 2000s (Ingram et al. 2021). Communities in the Congo Basin rely heavily on wildmeat and fish for food and income due to poverty, few alternatives, and the high cost of other protein sources. Rising demand for wild protein, advances in hunting and fishing technology, along with better preservation and transportation, have transformed these activities from small-scale subsistence to widespread commercial exploitation, increasing pressure on wildlife. Traditional resource management systems struggle to regulate use effectively. Conflicts worsen the situation by causing displacement, insecurity, and wider access to firearms, with some armed groups exploiting wildlife for profit. Meanwhile, deforestation, habitat loss, and pollution, especially from mining, damage ecosystems and threaten biodiversity and human health, making sustainable management even more challenging.

Despite these challenges, governments are increasingly pressured to provide innovative solutions that can trigger transformative change to balance conservation and human needs, particularly in view of the objectives set aside by the Global Biodiversity Framework from the Convention of Biological Diversity. Over the past two decades, Congo Basin countries have taken significant steps to mitigate unsustainable hunting and fishing through a range of initiatives. These include efforts to officially recognize these informal sectors and build resilient policies that account for the important role that communities and the private sector can play in conservation, the promotion of community-based conservation approaches, and efforts to scale alternative livelihoods for wildlife-dependent communities while promoting more culturally respectful behavior changes (FAO 2021; Coad et al. 2019). Despite these efforts, challenges remain in ensuring effective implementation and long-term success.

This chapter examines the drivers of unsustainable hunting and fishing, explores the obstacles to creating an enabling environment for sustainability, and discusses how existing initiatives can be expanded and integrated into broader conservation and development frameworks. By addressing these issues, we aim to highlight pathways toward a transformational change in hunting and fishing in the Congo Basin for a future where both wildlife and people can thrive sustainably.

Barriers and Challenges to Sustainable Hunting/Fishing

Lack of Alternatives and Poverty

Due to a lack of viable food and income alternatives, communities and wildmeat/fish traders in the Congo Basin are often trapped in a cycle of overhunting and overfishing, driven by the increasing number of actors involved in the trade and the expansion of wildmeat and fish markets at regional and national levels (Coad et al. 2019). Wildmeat and fish trade is primarily fueled by poor socioeconomic conditions, limited employment opportunities, and the high cost of producing alternative protein sources (Nasi et al. 2011). For many rural communities and wildmeat traders, hunting and fishing remain essential for both food and cash income (Abernethy et al. 2016). Wildmeat and fish also serve as critical safety nets during times of crisis, helping households cope with economic shocks, unexpected cash needs, or income shortfalls (Ogunjinmi et al. 2022; Namwira et al. 2024; Emogor et al. 2024). In Cameroon, educators have turned to wildmeat trading to supplement their salaries when teaching wages are delayed, demonstrating the role of this trade in stabilizing household incomes (Randolph et al. 2022). In remote areas where alternative income sources and food supplies are scarce, the sale of hunting and fishing products provides access to essential goods and services, including medicine, energy, and education (Abernethy et al. 2016). In Kisangani, wildmeat was the most affordable and widely consumed source of animal protein during the 2002 conflict. However, as peace was restored and households were able to invest in livestock production, domestic meats became more available, cheaper, and consequently more commonly

consumed (van Vliet et al. 2014, 2017c). This shift demonstrates that improved market access and safer conditions for domestic meat production can reduce reliance on wildmeat by encouraging the transition to alternative protein sources.

Increased Efficiency of Hunting and Fishing Gears

Over historical times, traditional communities have developed diverse hunting practices to meet their nutritional needs, including capturing small and medium-sized mammals for self-consumption (Fargeot 2013; Duda et al. 2017, 2018; Coad et al. 2019; Fongnzossie et al. 2023). Traditional Baaka hunters still use various techniques such as spear hunting, crossbows, traps, and over 176 plant species in hunting practices (Duda et al. 2017; Coad et al. 2019; Fa et al. 2021, 2022; Fongnzossie et al. 2023). In farming communities, hunting methods continue to include collective hunting with spears, dogs, net hunting, and trapping with organic materials (Walters et al. 2015; Dounias 2016; Coad et al. 2019; Fa et al. 2022). However, over the past 40 years, a drastic shift from subsistence to commercial hunting in the Congo Basin has taken place, leading to the specialization of hunting and changes to more efficient hunting gears (Walters et al. 2015; Ziegler et al. 2016; Ichikawa et al. 2017; Van Gils et al. 2019; Martin et al. 2020; Fongnzossie et al. 2023; Taylor et al. 2015; Abernethy et al. 2016; Coad et al. 2019; Fa et al. 2022; Fa and Funk 2024; Kwidja et al. 2023; Ingram et al. 2025). Rural populations, including the Baaka, have adopted modern techniques like wire traps, head lamps, and firearms, leading to the proliferation of night hunting, losses due to the large number of traps set without regular visits, and the possibility to better target arboreal animals (Dounias 2016; Duda et al. 2017; Martin et al. 2020; Fa et al. 2022). Changes to more commercial hunting have also implied the development of more efficient and diversified preservation methods through salting, smoking, and freezing as well as motorized transportation means (outboard canoes, motorbikes, etc.), which provide easier access to remote forests and facilitate loading larger quantities of biomass back to the markets.

A similar trend has been observed in inland fisheries. Traditional fishing practices included weir, poison, net, line, hook, and bail fishing (Gallois and Duda 2016; Fongnzossie et al. 2023). However, most traditional practices have been declining over the last 40 years in favor of individual and industrial methods (hooks, nylon line fishing, cotton, or nylon netting) (Comptour et al. 2016). Currently, most communities practice a variety of fishing methods, adapted to seasonality, including pond, weir, bait, poison, net, barrier, basket trap (woven with rattan vines and raffia palm stems), line, longline, and harpoon fishing (De Graaf and Garibaldi 2015; Comptour et al. 2016). In the DRC, fishermen commonly use mosquito nets, which capture very small fish and pose an immediate threat to population replenishment at spawning grounds along the Congo River and various lakes (Namwira et al. 2024).

Human Population Trends

The Congo Basin is one of the fastest-growing regions in Africa, experiencing significant population expansion (Ongolo and Karsenty 2011; Leridon 2015). For example, the Democratic Republic of Congo (DRC), home to 100 million people, has a fertility rate of six children per woman, with a similar rate recorded in Cameroon (4.8 children per woman) (Véron 2022). At the same time, the region has the world's highest urbanization rate (Megevand 2013), with new urban spaces emerging at an unprecedented pace and scale (Magrin and Ninot 2021). Between 1950 and 2015, Africa's urban population—particularly in sub-Saharan Africa—increased by 2000% (Didier and Simonneau 2022). In the Congo Basin, urban expansion is driven by economic activities, energy, rural exodus, and population growth. In the DRC, armed conflicts and insecurity in rural areas have further accelerated migration to cities (Jacobs and Kyamusugulwa 2018). This rapid urbanization has profound implications for wildlife. Cities are major consumption hubs for fish and game, with urban markets and restaurants offering wildmeat in high volumes (Igugu and Boutinot 2023; Wright et al. 2022; Simo et al. 2024; Fargeot et al. 2017; Mitchell et al. 2025; Bachand et al. 2015). Although per capita consumption of wildmeat may decline in urban areas, the sheer size of the population means overall demand continues to rise (Bauld et al. 2026). This growing demand fuels the overexploitation of wildlife, with wildmeat trade in major city markets reaching hundreds, if not thousands, of tons (Medzey Me Sima et al. 2024). As a result, hunters are increasingly driven to supply urban markets, intensifying hunting pressure on already vulnerable species (Ingram et al. 2025).

Another factor intensifying pressure on wildlife is migration into rural areas in search of better livelihoods. Climate change impacts in Sahelian countries have driven herders to migrate into the Congo Basin (Gemenne et al. 2017), increasing threats to lions and leopards as transhumant Mbororo herders kill them to protect their livestock, often using firearms and fire (Abossolo and Nkans 2022; Binot et al. 2006). Additionally, the movement and settlement of cattle in protected areas, such as the Bili-Uéré Hunting Reserve in the DRC, heightens competition with wild herbivores (Kiéma 2007). Migration linked to industrial activities also contributes to wildlife depletion. The influx of workers, jobseekers, and their families into logging concessions increases pressure on wildlife, as these newly established populations often have limited alternative food sources (Poulsen et al. 2009). Roads built and maintained by logging companies further intensify wildmeat hunting by providing hunters with greater access to previously unexploited wildlife populations and lowering the costs of transporting wildmeat to markets (Wilkie et al. 2008). Similarly, mining areas in the DRC and CAR attract migrants seeking to exploit gold and diamond deposits (Spira et al. 2019). Once settled, these migrants create conditions that facilitate hunting and the wildmeat trade. Beyond mineral resources, wildlife—particularly elephants and rhinoceroses—also attracts poachers and armed groups that take advantage of porous borders to conduct illegal activities (Funk et al. 2022).

Disruption of Customary Governance Systems Perpetuated Since Colonial Times

Historically, interactions between different civilizations have led to a variety of factors that have disrupted customary systems in the Congo Basin (Verweijen and Van Bockhaven 2020). The arrival of Europeans, with their religious influence, forced displacement policies and centralized authority is cited among the most prominent factors having reshaped local governance systems in Central Africa (Ocheni and Nwankwo 2012). Their monotheistic Western religion weakened and altered cosmologies and traditional practices related to resource management (Hickey 2007). This significantly contributed to the desacralization of customary practices in hunting, agriculture, and fishing (Baco et al. 2007; Savadogo et al. 2011; Juhé-Beaulaton and Roussel 2003). In the Bateke region (Gabon), among the Pouvi, before colonial time, the forest surrounding the villages was divided into named hunting zones, belonging to individual lineages and within a lineage they were divided by households. In these zones only members of the household had exclusive access and resource extraction and management rights, and the ownership of these forest zones was strictly enforced (Walters et al. 2015). However, the colonial resettlement that occurred between 1910 and the 1960s forced some ethnic groups to migrate into the customary lands of other groups, causing resource-use conflicts and concomitantly, laws continually evolved, reducing customary controls over time, and centralizing hunting authority at the state level (Walters et al. 2015). Based on evidence from the Republic of Congo, Mavah et al. (2022) argue that outdated institutions and historical exclusionary conservation since colonial times have led to the disempowerment of local people ("empty laws" open-access syndrome) in which neither national nor local controls are working.

Persistence of Conflict

Another significant factor affecting wildlife populations is conflict (Beyers et al. 2011). The accumulated evidence suggests that war in the Congo Basin has exacerbated both intensive hunting and habitat conversion resulting in an increase in forest cover loss (Butsic et al. 2015) and is detrimental for wildlife (Daskin and Pringle 2022). The region has been plagued by different armed groups, from rebel militias controlling lucrative mineral resources to ethnic factions, perpetuating a state of violence and engendering a climate of fear, instability, and uncertainty for civilian populations. The displacement of populations exacerbates poverty and food insecurity (Brinkman and Hendrix 2010). In Lake Tanganyika (DRC), Namwira et al. (2024) showed that the unpredictable nature of the violence in DRC generates insecurity, loss of equipment, and increase in fishing pressure associated with newcomers, who turn to fishing as a safety net. During conflict, firearms and cartridges become more available, which increases the efficiency and scale of hunting (Braga-Pereira et al. 2020). Smallholders fear to invest in livestock and prefer to rely on hunting for primates, rodents, and ungulates for food and income

(van Vliet et al. 2017c). Certain species are exploited by militia for the lucrative international trade in tusks, horns, skins, and other body parts (Pires and Moreto 2016). Retaliatory killing of wildlife species has also been observed in contexts of food insecurity and war, with increased local resentments toward land-grabbing by authorities contributing to the willingness of local people to engage in illegal exploitation of wildlife resources (Yamagiwa 2003).

Deforestation, Forest Degradation, Fragmentation, and Pollution

Historically, deforestation in the region has been relatively low (Megevand 2013). However, while situations vary from country to country, the Congo Basin is generally under increasing pressure particularly from smallholder forest clearing for agriculture both for subsistence and commercial crop farming (such as for cocoa and oil palm) (Kamath et al. 2024; Zeppetello et al. 2020; Molinario et al. 2020; Tyukavina et al. 2018). In 2019, it was estimated that about 30–40% of tropical moist forests in the region were degraded (Vancutsem et al. 2021). Deforestation also affects some protected areas, such as inside the Yangambi Biosphere Reserve, which presents similar degradation rates inside as outside its boundaries (Kipute et al. 2023). Deforestation is also observed in the miombo forests of DRC, inside the Kiziba-Baluba Hunting Domain (KBHD), where forest loss and fragmentation is progressing at fast pace due to charcoal production and agricultural expansion (Muteya et al. 2024). Given projected increased global demand for food products and regional policy objectives to boost agricultural production, the current rate of disturbances is likely to continue over the next decade. In the business-as-usual scenario, the DRC will have lost 22% of its humid forests by 2050 and 33% of its undisturbed rainforests (Eba'a Atyi et al. 2022). Regions that are most at risk of losing wildlife through deforestation in the next decades are west Cameroon and northeastern and eastern edges of DRC, where cocoa expansion is pushing into biodiversity-rich forests (Kamath et al. 2024). In the Congo Basin, unpaved logging roads used by timber firms, as well as paved and unpaved public roads, have expanded by 50% inside logging concessions since 2003 and by 40% outside logging concessions. Logging activities open up remote forest areas by building roads and establishing permanent camps that not only make these regions more accessible to hunters (Wilkie and Carpenter 1999; Kleinschroth et al. 2019; van Vliet and Nasi 2008) but also facilitate the establishment of new agricultural frontiers, except along abandoned unpaved roads inside certified forest concessions (Kleinschroth et al. 2019).

A major factor affecting aquatic wildlife in the Congo Basin is pollution associated to mining activities. Various processes, including deforestation, soil degradation, chemical contamination of aquatic and terrestrial systems, and changes to the turbidity of watercourses, largely affect wildlife, particularly amphibians and freshwater fish (Schure et al. 2011; Dossou Etui et al. 2024). In Lubumbashi (DRC), mining activities for the hydrometallurgical extraction of copper and cobalt have resulted in toxic metal liberation and contamination of the surrounding soil and the

near to surface waters endangering wildlife and human health (Ramazani et al. 2022). Coltan mining and the illicit trade generate major environmental impacts, including on sites of historical heritage and indigenous lands (Ojewale 2022). In Lake Tshangalele, which receives effluents from metallurgical and mining plants in Likasi, high concentrations of cobalt, copper, iron, manganese, zinc, and aluminum were found in fish collected closest to the copper mining plant. Metal contamination from mining activity is of great concern because of potential health risks to the local inhabitants due to the consumption of heavily contaminated fish (Squadrone et al. 2016).

Transformational Changes for Sustainable Wildmeat and Inland Fisheries Sectors in the Congo Basin

From Expert-Driven Alternatives to Bottom-Up Solutions for Livelihood Diversification Among Hunters and Wildmeat Traders

In the Congo Basin, expanding access to alternatives to wildmeat is essential for reducing pressure on wildlife while ensuring food security. Early interventions in the 2000s explored various alternatives, including sustainable agricultural and forestry practices, domestication of wild species, livestock rearing, and aquaculture (van Vliet et al. 2016). Since then, many initiatives have focused on promoting terrestrial animal farming, particularly pig, snail, and cane rat rearing (Willis et al. 2022). However, these projects often lacked the necessary enforcement, long-term monitoring, and impact evaluations, limiting their effectiveness (Wicander and Coad 2018).

Building on past lessons, the CARPE alternative livelihood projects have emphasized the importance of a people-centered approach and the involvement of rural development experts to ensure successful integration within conservation landscapes (Yanggen 2010). Crucially, shifting reliance away from wildmeat and fish requires new food and income sources that offer greater benefits than the environmentally harmful activities they seek to replace (Brown and Williams 2003). In the Democratic Republic of Congo (DRC), research by Nyumu et al. (in press) demonstrated that higher-income alternatives, such as pig farming, can significantly contribute to wildlife conservation, as observed in the Yangambi landscape. Properly designed farm subsidies have the potential to reduce hunting frequency and, thus, volume of wildmeat taken out of forests and to bring down the costs of domestic meat compared to bushmeat in rural areas (Nana et al. 2022). To be effective, alternative livelihoods must be embedded within broader land-use or resource management plans and developed through participatory approaches that strengthen local capacity. Community-based strategies that involve local populations in planning and implementation have been particularly effective in aligning conservation objectives with local needs and cultural values.

Fish farming has long been recognized as a potential solution to food insecurity and the overexploitation of fish resources (Micha 2013). The first aquaculture efforts

in the Congo Basin began in 1946 in Lubumbashi, DRC, with the introduction of tilapia species from Lake Moëro. Initially promising, these efforts expanded under colonial rule but declined following independence due to a lack of public sector support. Today, fish farming in the region remains underdeveloped. Rural fish production is minimal due to poor pond management practices, inadequate access to quality fish feed and seeds, a shortage of training programs for young farmers, and low market integration (Micha 2013). More advanced semi-intensive and intensive fish farming systems are virtually absent, except for a few projects such as the Fish Culture Project in Katanga. The development of aquaculture is hindered by weak policies, uncoordinated interventions by NGOs and international organizations, and the predominance of subsistence-level projects that fail to transition into viable commercial enterprises (Chan et al. 2021). Other major barriers include the lack of fish-feed industries, limited access to capital, and poor control over production technologies (Thiao and Bunting 2022). Without a shift toward viewing aquaculture as a business opportunity rather than a subsistence activity, its full potential will remain unrealized. Policy interventions should promote value-added processing initiatives to prevent post-harvest losses, maintain market value, and improve the profitability and sustainability of fish farming.

From Criminalization to Sustainable Consumption Choices

Efforts to increase the availability of alternative food sources must be accompanied by strategies to shift consumption patterns, particularly regarding wildmeat. Behavior change campaigns aimed at reducing wildmeat demand in urban areas are an emerging field in the Congo Basin, focusing on altering consumer preferences and promoting sustainable alternatives. Effective interventions address both the supply and demand sides by shifting social norms and consumer behavior. Research has shown that wildmeat consumption is driven by accessibility, cultural preferences, and the lack of affordable alternatives (van Vliet and Mbazza 2011). In Brazzaville, Chausson et al. (2019) found that wildmeat is perceived as natural, tasty, and healthy, with cost and availability being the primary barriers to purchase. While locally produced fish, meat, and poultry are generally viewed positively, imported frozen animal proteins are often considered unhealthy and of poor quality. Understanding these socioeconomic and cultural factors is essential for designing successful behavior change campaigns that promote sustainable food choices (van Vliet et al. 2017b). Research has highlighted the importance of audience-specific communication strategies, using messages that resonate emotionally and culturally with local populations. In Southern Cameroon, Simo et al. (2024) found that the lack of awareness regarding health risks associated with wildmeat consumption was a key barrier to shifting consumer behavior, particularly regarding endangered pangolin species. Similarly, Marracoli et al. (2019) suggested that hunter self-monitoring in the Republic of Congo could be a valuable tool for initiating behavior change and tracking resource trends among hunters. A useful framework developed by the Wildlife Conservation Society (WCS) was initially designed for major urban centers

in the Congo Basin and later adapted to rural, protein-poor towns. This approach addressed the entire wildmeat value chain, offering consumers sustainable legal alternatives while engaging stakeholders in other economic activities (Wieland et al. 2022).

However, evidence on the effectiveness of such interventions remains mixed. Some studies have shown positive trends but lacked statistical significance, suggesting the need for caution when scaling these strategies (Chaves et al. 2017; Veríssimo et al. 2018). Moreover, while behavior change approaches can contribute to a more sustainable wildmeat sector, ethical concerns must also be considered to ensure that they are compatible with the values of resource users (Nana et al. 2022). Indeed, interventions must take into consideration the multiple intrinsic (e.g., attitude, moral obligation, perceived legitimacy of rules) and extrinsic (e.g., social pressure, customary laws) social incentives that interact to influence attitudes and the decision to enter and remain in wildmeat trade or consumption (Nana et al. 2022). Guidelines should be established to assess potential risks and ensure that interventions do not disproportionately affect vulnerable communities (van Vliet et al. 2022). Ultimately, behavior change strategies must be part of a broader system that includes community participation, equitable access to conservation benefits, land rights, and viable alternative livelihoods. Addressing wildmeat consumption effectively requires integrated approaches that tackle its multiple drivers, from market dynamics to cultural preferences and economic incentives (Thomas-Walters et al. 2020; van Vliet et al. 2022).

From Exclusionary Conservation to Community-Based Wildlife Management

In the 1990s, conservation models in the Congo Basin largely based on militarized conservation, overlooked the complex values wildlife holds for local people, focusing instead on Western-oriented approaches, which have been described as a form of "cultural imperialism" in addressing the unsustainable uses of wildlife (van Vliet 2018). The limits of fortress conservation in the Congo Basin have become increasingly evident in the twenty-first century, with the realization that highly militarized, top-down approaches cannot sustain long-term conservation goals at scale (Wellsmith 2011; Bennett 2011; Challender and McMillan 2014; Cooney et al. 2017). These approaches have sparked a "cultural backlash," which not only undermines conservation efforts but also exacerbates local conflicts and negatively impacts livelihoods. Anti-poaching units have faced criticism for human rights violations (Pihälä et al. 2016), failing to build institutional capacity within governments (White et al. 2023), and even fueling conflicts rather than resolving them (van Vliet et al. 2017c). Historically, the establishment of protected areas has often meant the forcible displacement of local populations who relied on forests for their livelihoods, creating lasting resentment and conflict (Walters and Wardell 2023). In Virunga National Park, law enforcement efforts have failed to stop poaching, instead fueling armed mobilization and resistance poaching (Marijnen and Verweijen 2016;

Verweijen and Marijnen 2018). Extreme law enforcement tactics can criminalize rural and Indigenous communities, trapping them in cycles of illegality and unsustainable practices that lead to both ecological and cultural losses.

In response, there is now growing recognition that empowering local communities in wildlife management presents a more effective alternative to fortress conservation (Challender and Mc Millan 2014; Inogwabini 2014; Mavah 2015). In Central Africa, Community-based Wildlife Management (CBWM) remained limited until the 1990s, primarily driven by short-term projects with minimal empowerment of local decision-makers (Roe et al. 2000). For decades, CBWM was also hindered by conflicts between customary and national land tenure systems, which disempowered local communities (Tchigio 2007; Walters et al. 2015). However, in recent decades, CBWM has gained new momentum, largely due to the recognition of Indigenous Peoples and Local Communities' (IPLCs) rights to manage the resources they depend on. Programs like the Sustainable Wildlife Management (SWM) initiative, which operates in several Congo Basin countries since 2017, define CBWM as a collaborative process in which rights holders manage wildlife sustainably (FAO 2021). CBWM not only integrates traditional knowledge with modern conservation practices (Pollock and Whitelaw 2005) but also acknowledges the utilitarian relationships rural populations, especially poorer households and women, have with wildlife, often driven by the need to mitigate risks like crop raiding (Rickenbach et al. 2017). Additionally, CBWM recognizes the cultural and spiritual connections to wildlife, such as wildmeat and fish consumption during ceremonies or hunting and fishing as symbols of prestige (van Vliet and Mbazza 2011; Dounias and Ichikawa 2017). Moreover, CBWM addresses the costs of living alongside wildlife, including agricultural damage and livestock loss, which have often been neglected in previous conservation models (Gomez et al. 2022) and empower communities to engage in wildlife monitoring to improve decision-making and enable local populations to benefit from wildlife management (Froese et al. 2022). At the core of CBWM is the promotion of social cohesion and human rights principles such as free, prior, and informed consent (FPIC), equitable benefit-sharing, and conflict resolution (FAO 2021). In this context, community-based monitoring systems present a cost-effective and empowering approach to wildlife data collection. By involving local communities in monitoring wildlife populations, habitat health, and resource use, these systems not only generate valuable ecological data but also strengthen local stewardship and build technical capacities, integrating traditional ecological knowledge (TEK) with modern scientific methods (van Vliet et al. 2017a).

However, CBWM still faces significant challenges in the Congo Basin, including the low capacity of local communities to self-regulate and to exclude outsiders (Ingram et al. 2021). Recent initiatives emphasize the importance of creating policy environments that recognize community rights and ensure decision-making processes are community-driven. At the community level, wildlife management institutions are scarce at present; communal rights to wildlife do not extend to management, ownership, or exclusion; and communities are excluded from formal co-management (Mavah 2015). Laws that disregard customary practices are ineffective because they exclude local populations from decision-making on traditional lands and restrict their ability to regulate wildlife offtakes and benefit from them

(Nana et al. 2022). These legal frameworks often impose complex licensing procedures that exceed the administrative and financial capacities of local communities (van Vliet 2018) and result in tensions between local communities and their governments, exacerbating conservation conflicts (Egbe 2001; Nana et al. 2022). For CBWM to succeed, it must involve substantial power transfers to ensure communities directly benefit from wildlife management and actively participate in decision-making (DeGeorges and Reilly 2009). Addressing these challenges will be key to ensuring the long-term success of community-based approaches to wildlife conservation in the Congo Basin.

From Invisible Sectors to Improved Statutory Recognition and Attention

Hunting and freshwater fisheries form a vital part of the informal economy in the Congo Basin, providing essential food and income for poor communities, thereby contributing to poverty reduction and lowering inequality. Despite their significance, these sectors have not been adequately recognized in formal policy frameworks (Enns et al. 2023). Hunting for wildmeat is often indiscriminately labeled as "illegal," failing to distinguish between subsistence hunting, which definition in legal texts is often blurred and more harmful illegal practices like organized wildlife trafficking (Ingram et al. 2021; Enns et al. 2023). This generalized stigmatization complicates efforts to create clear, fair regulations. National food security databases rarely capture the economic contributions of wild foods like wildmeat or freshwater fish, with even major databases like FAOSTAT failing to fully reflect their role in regional food security (Ziegler 2016). A significant barrier to effective wildlife and fishery management has been the lack of formal policies that reflect the collective views and values of local communities regarding wildlife. The lack of clear regulations around inland fisheries and hunting limits innovation in promoting sustainable practices while also preventing countries from fully adhering to international biodiversity commitments, such as Target 9 of the Convention on Biological Diversity (CBD), which encourages the sustainable use of wildlife. The legal ambiguity and outdated laws across much of Central Africa contribute to confusion and insecurity for subsistence hunters and fishers. These gaps fuel underground markets that are difficult to regulate and dilute accountability for sustainability (van Vliet 2018). In many Central African countries, wildlife laws are outdated and fragmented, creating contradictions and inconsistencies across various legal sectors (Mavah et al. 2022). Key concerns include the unclear recognition of hunting and fishing rights for subsistence or trade, insufficient regulatory tools to implement laws (such as permits and certificates), and the imposition of constraints that are unrealistic given local customs.

While some Congo Basin countries had developed national wildmeat strategies in the early 2000s, these efforts were largely driven by international NGOs with minimal involvement from national governments or local communities. These strategies seldom received official validation from government authorities. Similarly,

while countries like the DRC and the Republic of Congo (RoC) have developed inland fisheries strategies, most countries in the region do not have a specific inland fisheries strategy. Besides, where inland fisheries strategies exist, their implementation is hindered by insufficient infrastructure, lack of expertise, and political instability. Another challenge is the absence of financial mechanisms to support these strategies, which prevents timely mobilization of resources for effective implementation. For instance, a financial plan identifying domestic and international funding needs is often missing, making it difficult to gather necessary resources for implementation.

Nevertheless, over the past decade, Gabon has developed and updated its bushmeat strategy and the DRC is engaged into a similar process. A positive shift is emerging in the region, driven by the need to implement the Kunming-Montreal Global Biodiversity Framework (KM-GBF), adopted at the fifteenth Conference of Parties to the Convention on Biological Diversity (CBD COP 15). Target 5 of the KM-GBF urges countries to ensure that the use, harvesting, and trade of wild species are sustainable, safe, and legal, to prevent overexploitation while target 9 emphasizes sustainable management and use of wild species to provide social, economic, and environmental benefits. This aligns with the ongoing updates to National Biodiversity and Action Plans, a key tool for KM-GBF implementation at the national level. Also, countries in the Congo Basin are increasingly adopting the One Health framework to align conservation and resource management with public health and food security. Given the close links between wildlife, fisheries, and human populations, unsustainable resource use can lead to biodiversity loss, disease spillover, and ecosystem degradation. National strategies for sustainable wildlife management are now integrating this approach, recognizing the interconnectedness of human, animal, and environmental health. As part of these efforts, the multi-year INFORBIO program (INtact and effectively managed FORests and BIOdiversity) aims to implement an early warning system to prevent the spread of infectious diseases. For example, sustainable fisheries management should incorporate disease surveillance in fish populations to prevent outbreaks that could threaten both wildlife and human communities. Similarly, regulating bushmeat trade and promoting alternative protein sources can reduce the risk of zoonotic diseases while ensuring food security. Collaborative efforts between conservationists, public health experts, veterinarians, and policymakers are essential to implementing One Health strategies effectively. By integrating ecosystem health considerations into conservation policies, Central African countries can create resilient management systems that benefit both people and nature.

National efforts to strengthen legal frameworks for wildlife protection are crucial in curbing unsustainable hunting. Recently, Congo Basin countries have updated and enacted new wildlife conservation laws to increase penalties for illegal hunting and trade. For instance, all countries except the Republic of the Congo have passed legislation on community forestry, granting forest management decision-making rights to local communities (Trefon 2017). In Cameroon, securing tenure rights for local communities has also improved compliance with wildlife and forest regulations (Tegegne et al. 2022). The DRC and Gabon have introduced stricter penalties for

poaching and illegal wildlife trade and updated their protected species lists, which has led to a reduction in illegal activities (Nasi et al. 2021). These countries are also enhancing wildlife management laws, recognizing the rights of Indigenous peoples and local communities, incorporating gender considerations, and addressing conflicts. The DRC, for example, recently enacted a law to protect the rights of Indigenous Pygmy Peoples though outcomes are yet to be experienced. Regional initiatives have supported legal reforms and enforcement. Programs such as the Central African Regional Program for the Environment (CARPE) and the Congo Basin Forest Partnership (CBFP) have fostered cross-border collaboration, resource-sharing, and intelligence exchange. Regional capacity building for law enforcement has also been a priority, with initiatives like the Monitoring of Illegal Killing of Elephants (MIKE) program, which trains law enforcement personnel and gathers data on illegal activities to inform decision-making (Mubalama and Bashige 2006). These efforts have enhanced enforcement capabilities and helped combat poaching networks (Van Doormaal et al. 2022). Nevertheless, research has shown the need to further improve public awareness, the surveillance and investigative capabilities of frontline officers, and education of judicial actors on wildlife laws to strengthen the criminal enforcement system (Ntungfor and Atanga 2017; Cox et al. 2006). More recently, efforts from different donors (EU, USFW, GEF, etc.) have developed into long-term programs (e.g., FAO Gestion durable de la faune, Sustainable Wildlife Management, etc.) generating momentum for sustainable use in the Congo Basin. These large programs have contributed to enhance governmental capacities to improve policies for sustainable wildlife use. The CBFP's 2023 report highlights the success of a Ba'ka project in promoting gender equity and forest conservation in Cameroon. In the Central African Republic, efforts have focused on managing transhumance. Additionally, the Sustainable Wildlife Management Program (SWM), implemented since 2018 in DRC, Republic of Congo, Cameroon, and Gabon, aims to strengthen legal frameworks for sustainable exploitation of wildmeat and fish (SWM Report 2021). Legal hubs have been established to analyze policies and provide recommendations to improve national wildlife management, aiming to ensure these resources contribute to the food security and well-being of Indigenous Peoples and Local Communities (IPs and LCs), for whom forests are vital cultural and natural resources.

From Mitigation of Impacts to Biodiversity-Positive Measures in Logging and Mining Concessions

Logging is one of the most extensive extractive activities across Central Africa's remaining forests, where 30–40% of forests fall within commercial logging concessions (Laporte et al. 2007). The conservation value of degraded forests depends on how logging affects biodiversity, either directly, through forest structure alteration and fragmentation, or indirectly, through increased hunting, disease transmission, and deforestation for agriculture (Clark et al. 2009). Logging often leads to road building, more job seekers moving in, and a rise in commercial hunting and wildlife

trade (Wilkie et al. 2000; Fa et al. 2005). These indirect impacts affect wildlife more significantly than the extraction of timber itself (Milner-Gulland and Bennett 2003). Given the large tracks of selectively logged forests they manage, private logging concessions expand conservation areas in Central Africa by maintaining viable large mammal populations (Clark et al. 2009). Research from certified concessions in countries like the Republic of Congo and Gabon indicates that these areas support healthy wildlife populations, comparable to those in national parks (Poulsen and Clark 2010; Yoh et al. 2024). While forest elephants face increasing constraints from roads across the Congo Basin (Blake et al. 2008), logging roads do not act as barriers to them. Scalbert et al. (2023) found that secondary logging roads and skid trails are not avoided by large mammals—forest buffalos prefer secondary roads, while gorillas and chimpanzees use a mix of secondary roads, skid trails, and elephant paths.

As such, when integrated with proper management strategies, certified logging concessions can contribute to wildlife conservation. Until now, certification schemes, such as those from the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC), have mostly focused on reducing the negative impacts of logging operations on wildlife. These certifications promote responsible logging by enforcing environmental, legal, and social standards (ATIBT 2023). While FSC operates based on global principles, PEFC supports national schemes. Both seek to minimize logging's negative impacts on wildlife by addressing poaching and wildmeat consumption through hunting management strategies (Haurez et al. 2020). FSC emphasizes documenting and regulating hunting, whereas PEFC requires comprehensive wildlife management plans and designated legal hunting zones. Effective interventions within certified forests include optimal road network planning, providing alternative protein sources for staff, managing community-based hunting to benefit local livelihoods (e.g., CIB concession in the Republic of Congo), controlling external access, and preserving high-biodiversity ecosystems within concessions (van Vliet and Nasi 2008; Nasi et al. 2012; Poulsen and Clark 2010; Clark et al. 2009). However, these effective and positive actions toward biodiversity in logging concessions have a cost for the private sector, which they can't bear, even less so with the increased competition from non-certified logging companies. Until now, most support to implement these positive measures has come from projects that have tested these measures at site level. Bringing those measures at scale and mainstreaming them across all logging concessions will require new legal provisions, the renewal of management plans, and sustainable financial resources to support the logging sector in better contributing to the 30*30 agenda.

While certification in logging concessions has made significant steps in addressing wildlife conservation, certification in the mining sector in the Congo Basin was driven by the urgent need to address human rights abuses, promoting gender equality, eradicating child labor, improving worker safety, and ensuring fair wages, with less emphasis on mitigating environmental impacts. A recent study by the World-Wide Fund for Nature (WWF) provides recommendations for reconciling mining and biodiversity conservation in the Congo Basin. These include improving

governance in the mining sector, enforcing bans on mining exploration and activities in protected areas, and developing a common policy and strategy for the sector's sustainable growth, but no mention is made about the need to address the impacts of mining on wildlife (WWF 2017). Much could be learned from the forestry sector in that respect, specially with the expected growth of mining activities in the Congo Basin.

From Project-Driven Wildlife Management to Sustainable Finance for Permanence

Most wildlife conservation and management initiatives in the Congo Basin over the past 40 years have been largely driven by official development assistance (ODA) and through project cycles. While these efforts have certainly provided the possibility to test meaningful conservation models at site or landscape scales, there is a growing interest in ensuring efforts on the ground can be sustained for permanence through sustainable financial mechanisms. Broadly speaking, countries are transitioning from public finance for nature to private financial streams (Piemonte et al. 2019). The recent collapse of USAID and the stagnation of ODA funds (except for refugee costs and humanitarian aid) (OECD, https://www.oecd.org/en/topics/oda-trends-and-statistics.html) urges governments in the Congo Basin to explore innovative solutions for the long-term sustainability of biodiversity conservation, including wildlife conservation and management. Most donors are transitioning from grant-based processes to blended finance as mechanisms that can leverage the financial flows necessary to cover the biodiversity funding gap.

Wildlife is an economic asset by nature, as it can generate a diverse range of wildlife economies. Wildlife economies are businesses and economic activities that either directly depend on wildlife or contribute to wildlife conservation through their activities (Snyman and Bricker 2021). Wildlife economies in Central Africa focus on five categories of activities: ecotourism, trophy hunting and fishing, game meat hunting, artisanal and small-scale fishing, and wildlife ranching. In wildlife economies, the use of wildlife generates enough income to manage the resource in a sustainable manner while providing meaningful revenues for people. However, as opposed to Eastern and Southern Africa, the Congo Basin hasn't yet explored its full potential in developing wildlife-based economies, and there is scope for innovation in the development of wildlife economies that can benefit local communities and sustain stewardship for wildlife.

However, given the financial gap to conserve wildlife in Central Africa, there is a clear need to expand financial flows for the long-term permanence of wildlife conservation and management initiatives. There is now a global surge in the practice of valuing nature in the global economy through the development of "nature markets" (Nature Finance 2024). The biodiversity finance landscape is changing, with both domestic and international financial flows growing and the range of financing instruments significantly wider than ever before, including debt-for-nature swaps, corporate funding, biodiversity and carbon markets, payments for ecosystem

services, and bonds (BIOFIN 2024). Central African countries have not yet explored the full potential for developing innovative funding mechanisms to benefit wildlife conservation and management. A fundamental challenge for Central African governments is understanding how various financial flows are, or can be, better leveraged to fund the biodiversity gap (BIOFIN 2024).

CAFI (Central Africa Forest Initiative) was established in 2015 for six partner countries (Central African Republic, the Democratic Republic of the Congo (DRC), the Republic of Cameroon, the Republic of Congo, the Republic of Equatorial Guinea, and the Republic of Gabon) as a trust fund supporting direct investments on the ground and a political negotiation platform that aims to drive high-level policy dialogue for forests and biodiversity conservation. More recently, the High Integrity Forest Finance Initiative (HIFFI) was launched to reshape conservation finance by ensuring long-term, high-integrity funding for tropical forests. Led by COMIFAC (Central African Forest Commission) and supported by WWF, the HIFFI demonstrates that conservation is not just about protecting species; it is about creating economic models that incentivize governments, businesses, and communities to prioritize nature-based solutions.

Conclusions

Sustainable hunting and fishing in the Congo Basin face multiple, interconnected challenges. Poverty, limited alternatives, and high costs of other protein sources keep communities reliant on wildmeat and fish for food and income, especially during crises. Modern hunting and fishing gear, improved preservation, and better transport have shifted practices from subsistence to large-scale commercial exploitation, increasing efficiency and pressure on wildlife. Rapid population growth, urbanization, and migration, driven by conflict, climate change, and industrial expansion, boost demand for wild protein, while infrastructure like logging roads facilitates access to remote areas. Colonial-era erosion of customary governance weakens traditional resource controls, and conflict exacerbates hunting through displacement, insecurity, and greater firearm availability, with some armed groups exploiting wildlife for trade. Additionally, deforestation, habitat fragmentation, and pollution, particularly from mining, degrade ecosystems and threaten biodiversity and human health, complicating sustainable resource management.

To address these challenges, Congo Basin countries have made significant efforts to address the drivers of unsustainable hunting and fishing. First, there has been a shift from exclusionary, militarized conservation to community-based wildlife management (CBWM), which empowers Indigenous Peoples and local communities (IPLCs) to combine traditional knowledge with modern conservation, addressing ecological, cultural, spiritual, and livelihood concerns. Efforts to reduce wildlife pressure and enhance food security have evolved from expert-driven solutions, like sustainable agriculture, livestock, and aquaculture, which struggled with

enforcement, to community-centered approaches that promote nature-based business opportunities. Emerging campaigns aim to reduce wildmeat consumption by shifting behavior in urban and rural areas, though cultural and socioeconomic factors remain challenging. A comprehensive strategy combining behavior change, community engagement, and nature-positive economies is critical for lasting impact.

Second, there is growing recognition of hunting and inland fisheries at the national level. Despite their key role in poverty reduction, these sectors are often stigmatized or labeled "illegal," complicating regulation and sustainability. Legal ambiguities have fostered underground markets, but recent policy reforms and initiatives, such as those promoted by the Sustainable Wildlife Management (SWM) program and the Central African Regional Program for the Environment (CARPE), are strengthening legal frameworks and aligning with global biodiversity goals. Countries are also adopting the One Health framework, recognizing the link between human, animal, and environmental health.

Furthermore, Congo Basin nations increasingly see potential to move from mitigating logging and mining impacts to adopting biodiversity-positive measures. Certification schemes like the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC) promote responsible logging practices, including hunting management and road planning. However, scaling these across concessions is challenged by financial burdens and competition from non-certified companies. New legal frameworks, updated management plans, and sustainable financing are needed to support the logging sector's role in the 30 × 30 conservation agenda. The mining sector has been slower to implement wildlife conservation measures, focusing more on human rights and worker safety. While governance has improved, comprehensive strategies to reduce mining's wildlife impact are still lacking. Lessons from forestry could guide biodiversity-friendly mining, especially as mining expands.

Finally, wildlife management is shifting from donor-driven projects to sustainable financial mechanisms for long-term biodiversity protection. Declining official development assistance (ODA) and short-term funding have pushed Congo Basin governments to explore innovative finance models such as blended finance, debt-for-nature swaps, and biodiversity markets. These tools can help close the funding gap and foster wildlife-based economies, including ecotourism, that generate sustainable income for local communities while supporting conservation. Though promising, these opportunities remain underdeveloped, and governments face challenges in mobilizing long-term financial flows. Initiatives like the Central Africa Forest Initiative (CAFI) and the High Integrity Forest Finance Initiative (HIFFI) are reshaping conservation finance by promoting nature-based economic models, encouraging investment, enabling policy dialogue, and developing mechanisms to sustain wildlife management over time.

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Mining Influence on the Future of the Congo Basin

29

Pascal Mambwe, Bila-Isia Inogwabini, Kumar Mohan, I. Ichikowitz, and Lee J. T. White

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Abstract

The Congo Basin in central Africa is well known for its ecosystem complexity and biodiversity, which are closely linked to its geological history and diversity. High mineral resource potential and the development of the mining sector, principally oil and gas, and base, critical and precious metals, play an important role in the economy in the region. Negative environmental practices linked both to industrial and artisanal mining are common. Strict application of environment regulations, modern best practices, and good governance are critical if this sector is to fulfil its potential in the region without doing irreparable damage to both human and environmental health. Looking to the future, it is essential that an increased share of the jobs and economic benefits from the use of the Congo Basin's rich mineral resources remain in the region, rather than developing economies predominantly outside Africa. This may require policies to restrict and even ban the export of unprocessed ores and crude oil in favor of the development of local transformation industries.

Keywords

Biodiversity · Hydrocarbons · Mineral ore · Pollution · Socioeconomic development · Congo Basin

Introduction

The Congo Basin in the central part of Africa is the second largest river basin after the Amazon in south America, with a succession of Phanerozoic sedimentary rocks (Kadima et al. 2011, ▶ Chap. 1, "Introduction: Congo Basin Resilience and Sustainability: From Past to Future"). High hydrocarbon and mineral resource potential has been demonstrated in the Congo Basin, through the development of the mining sector, which boosts the economies of Angola, Cameroon, Equatorial Guinea, Gabon, Central African Republic, Republic of Congo, and the Democratic Republic of Congo (Table 1).

The mining sector in the Congo Basin can be divided into two sub-sectors. The first is oil and gas production, which today is partially impacted by the low-carbon energy challenge, as well as social and environmental risks due to the pollution, and price drops and deficits in reserves (Ackah-Baidoo 2012; Adeola et al. 2022; Lapeyronie and Szedlacsek 2025). The second is non-oil mineral production, mainly for base and critical metals (e.g., copper, cobalt, tin, tantalum) and diamond and gold (▶ Chaps. 1, "Introduction: Congo Basin Resilience and Sustainability: From Past to Future," and ▶ 14, "Timber Production and Ecosystem Functions and Services in the Congo Basin"). The global demand for these crucial metals is increasing, occasioning extensive mineral exploration using advanced techniques, that has resulted in the discovery of new deposits and increased production over the last decade (Broughton and Rogers 2010; Mambwe et al. 2024a, b; Gatsé Ebotehouna et al. 2021; Benson et al. 2025).

Table 1 Macroeconomic contribution of oil and gas and non-oil mining in the six principal Congo Basin countries

Country		GDP share (%)	Export share (%)	Gov. revenue (%)	Key commodities
Cameroon[a]	Oil and gas	6.3	41.1	25.5	Oil, gas
	Mines	<0.1	0.1	<0.1	Ciment
CAR[b]	Oil and gas	0	0	0	
	Mines	1.1	46.5	1.6	Diamonds, gold
DRC[c]	Oil and gas	0.6	2.7	1.1	Oil, ags
	Mines	22.5	96.5	38.9	Copper, cobalt, gold
Eq. Guinea[d]	Oil and gas	27	91	>80	Oil, gas
	Mines	0	0	0	
Gabon[e]	Oil and gas	27.4	72.9	63.3	Oil, gas
	Mines	2.9	22.4	4.7	Manganese, gold
ROC[f]	Oil and gas	57.2	94.4	68.2	Oil, gas
	Mines	0.8	1.3	0.6	Copper, zinc

Sources
[a]République du Cameroun (2025)
[b]Central African Republic (2024)
[c]DRC (2024)
[d]World Bank (2024)
[e]République Gabonaise (2024)
[f]Republic of Congo (2024)

This chapter highlights the current economic contribution of the mining sector to the Congo Basin nations, highlights the environmental and social challenges it creates, and charts a possible way forwards that will optimize the contribution of the sector to sustainable development while managing its environmental impacts.

Oil and Gas Production

The majority of known and exploited oil and gas deposits occur offshore in the Gulf of Guinea, outside the limits of the Congo Basin as defined in this report, although there are significant oil-producing areas onshore in Angola, Cameroon, Equatorial Guinea, Gabon, and Republic of Congo. Furthermore, offshore oil production has had significant impact on the economies of these countries, influencing other land uses such as agriculture and forestry through a phenomenon often referred to as the "Dutch disease" (e.g., Benjamin et al. 1989; ▶ Chap. 24, "The Future of Biodiversity in the Congo Basin", Table 1). In 2022 Equatorial Guinea, Republic of Congo, and

Gabon's oil revenues constituted >80%, 68.2%, and 63.3% of government revenues with export values of $billion 6.6, 9.3, and 6.8, respectively. Adeola et al. (2022) review oil production in Africa, including the Congo Basin, and discuss its economic, social, and environmental impacts. Edwards et al. (2014) reviewed the environmental threats from African mining development, including habitat alteration, infrastructure expansion, human migration, bushmeat hunting, corruption, and weak governance.

The main oil and gas fields lie offshore in the Gulf of Guinea, extending from Guinea Bissau to Angola, but there are also onshore deposits in the lowlands of the coastal sedimentary basin in Cameroon, Gabon, Republic of Congo, DRC, and Angola; the Eastern DRC Lowlands; and the Albertine Rift Mountains along the East African Rift System, which include important gas reserves in lake Kivu (Fig. 1; see also Taylor et al. 2009; Bolson et al. 2021; Najoui et al. 2022; Rainforest Foundation 2022; Sadeghi and Hassan 2025). The Rainforest Foundation (2022) reports that currently 150 existing or designated oil and gas blocks cover over 35% of the Congo Basin forests (64 million hectares—Fig. 1), including the majority of the largest peat forest on earth and parts or all of 13 protected areas. However, only the Gulf of Guinea and Western Congo Basin sedimentary basin fields are currently

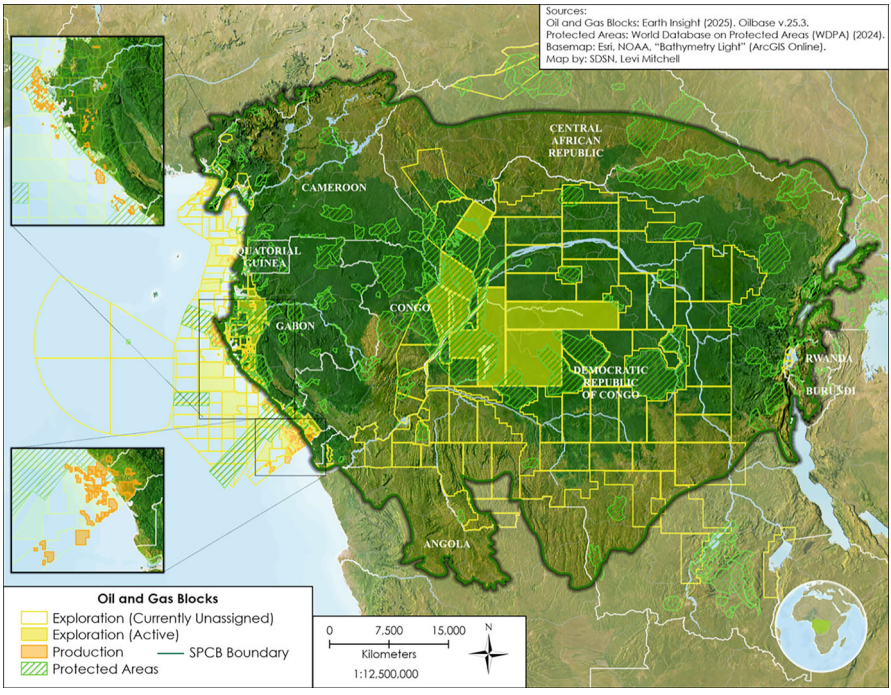

Fig. 1 Location of key oil and gas basins in the Congo Basin, including Cameroon-Gabon, the central Congo-DRC peat swamps and Eastern DRC/Albertine Rift. (Source Rainforest Foundation 2022)

producing oil and gas. Exploration and possible future development of fields in the central Congo Basin and Albertine Rift are still underway.

Oil production in the Western Congo Basin/Gulf of Guinea during the last decade has fluctuated and is generally in decline, although in Gabon there has been a steady increase in production from a low in 2019 (Fig. 2a). In Equatorial Guinea and Angola, oil production has decreased steadily from 2017 onward and in the Republic of Congo, production peaked between 2018 and 2019 and has rather gradually decreased since then. Angola's production is around seven times more than each of the other countries; thus trends in Angola dominate regional performance. Despite this negative trend in oil and gas production during the last decade, exploration and production will continue to be important in the Congo Basin, either until reserves are depleted or until the global community has transitioned away from hydrocarbons.

Non-oil Mineral Production

While production in the active oil fields in the Congo Basin is in decline, barring substantial discoveries in the central basin, non-oil minerals are likely to become more important in coming decades, both in terms of the economic value and their environmental impact in the Congo Basin. Non-oil mineral production in the Congo Basin, as in other countries in Africa, is both through large-scale (industrial) mining (LSM) and artisanal and small-scale mining (ASM). Taylor et al. (2009) mapped the known mineral deposits of all African nations and demonstrate that 30% of the world's minerals occur in Africa, although currently only 5% of exploitation is on the continent. However, in much of the Congo Basin region, artisanal mining, which is often linked to higher levels of illegality, social injustice, and environmental degradation (e.g., Megevand et al. 2013; Mambwe et al. 2024c) currently often dominates, as is evident in Fig. 2.

In the Mining Contribution Index (Ericsson and Olof 2019; ICMM 2022) report, which evaluates the significance of the (non-oil) mining sector's contribution to domestic economies, DRC was listed in 12th position, down from 2nd in the previous assessment. DRC's mineral exports in 2022 (DRC 2024—see Table 1) included twenty billion US dollars of copper (10% of global supply), six billion of cobalt (74% of global supply), and 1.1 billion of gold, as well as smaller amounts of tin, tantalum, tungsten, zinc, and diamonds, and accounted for 19.4% of employment (DRC 2024; USGS 2025). In 2024, the Kamoa (0.44 Mt) and Tenke Fungurume mines (0.41 Mt) made DRC the first producer of copper in Africa (Sillitoe 2025). Furthermore, lithium production is due to begin in 2026 at the exceptional Manono-Kitotolo Li-Sn-Ta pegmatite deposit in DRC (AVZ 2024; Rodriguez-Ardila et al. 2025; Goodenough et al. 2025).

There is likely to be increasing global demand for minerals, such as lithium, whose international market demand is rapidly increasing to accommodate new technological developments to transition away from the fossil fuel economy. This demand will result in pressure on DRC to increase exports, reducing the duration of extraction estimated in Table 2. Figure 3 shows a general trend for exports of key minerals from DRC to increase, with the exception of zinc.

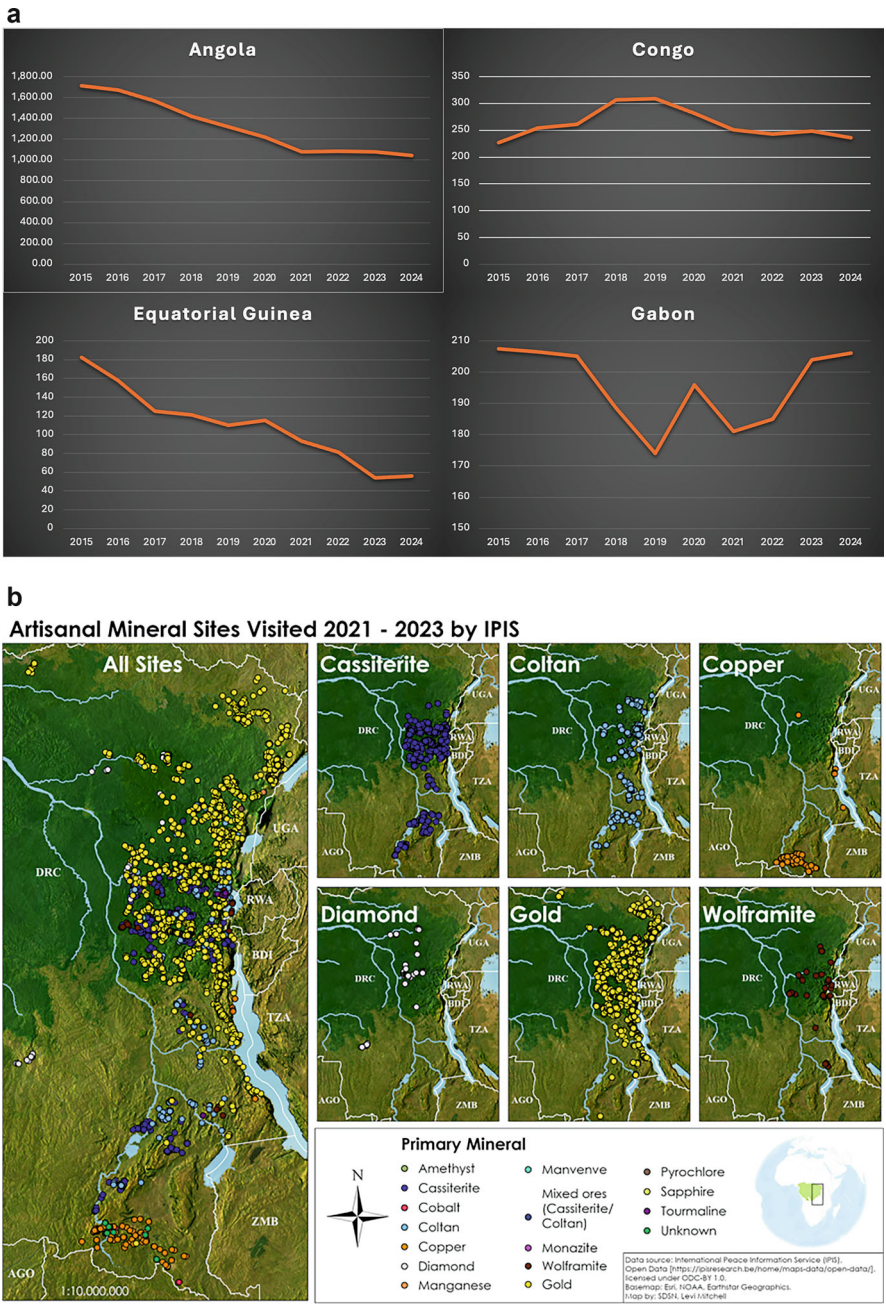

Fig. 2 (**a**) Crude oil production in thousands of barrels per day (1000b/d), 2015–2025) in Angola, Equatorial Guinea, Republic of Congo and Gabon. Compiled from OPEC's Annual Statistical Bulletin country-level "World crude oil exports by country." 2010–2014: ASB 2015, Table 5.3; 2015–2019: ASB 2020, Table 5.2; 2020–2024: ASB 2025, Table 5.2; (**b**) distribution of artisanal mining sites in eastern DRC

Table 2 Simple projections of the lifetime for some minerals in the Congo Basin

Country	Mineral	Lower reserve (t)	Export (t/Year)	Years to go (A)	Years to go (B)
Cameroon	Bauxite	700,000,000	20,000,000	35	
DRC	Bauxite	150,000,000			
	Cobalt	4,500,000	82,500	55	40
	Copper	75,000,000	1,100,000	68	37
	Lithium	400,000,000	4,000,000	100	43
	Zinc	7,000,000	250,671	28	
Gabon	Manganese	150,000,000	3,500,000	43	30
	Phosphate	140,000,000			

Sources: Mineral reserves come from Pitte et al. (2021); current exports were collated using Pitte et al. (2021) for all other countries and Trade Map (2024) for DRC. Years to go (A) = Constant rate; B = adjusted to global demand

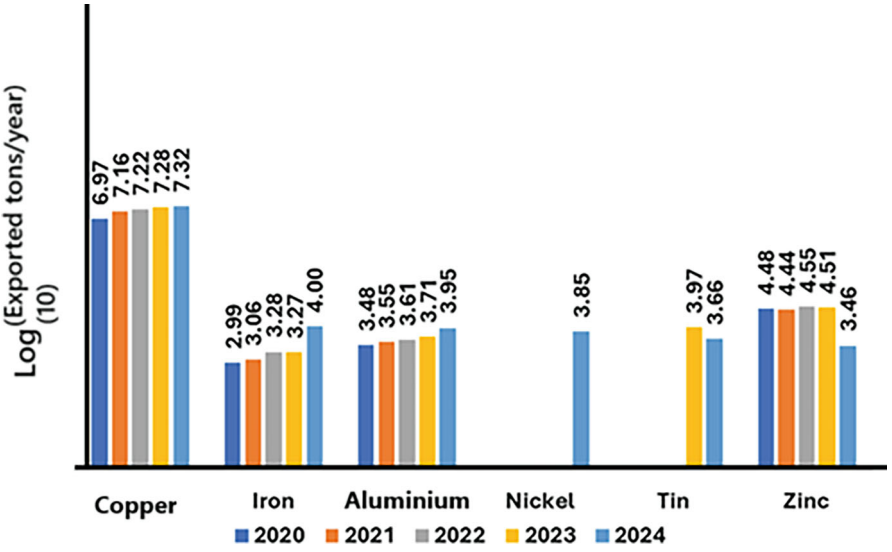

Fig. 3 Trends in Export of several minerals from DRC. (Raw data used to create the figure are from Trade Map (2024))

Graham et al. (2021), Tuomela et al. (2021), and Soares et al. (2025) have all suggested that the demand for cobalt, copper, lithium, and nickel will continue to increase as part of the growth in the global demand to meet the needs for batteries in plug-in electric vehicles and grid-scale energy storage, essential in the ecological transition toward a globally decarbonated economy. For example, Graham et al. (Graham et al. 2021) calculated the world demand for lithium will rise from 429 kt (2020) to 1000 kt or even 2500 kt (2030) depending on the path the global economy takes. If the countries of the Congo Basin respond by supplying the equivalent of the market demand, DRC will have only about 17–43 years of proven lithium reserves. Likewise, Jenns (2025) calculated that the global demand in cobalt will increase

from 300 kt in 2024 to 410.9 kt in 2030, which suggests DRC's known cobalt reserves will be depleted within 40 years. Klose and Pauliuk (2023) estimated that the global demand in copper will rise from 24 Mt in 2015 to 44 Mt by 2050, a rate of increase of about 1.8. Applying the same logic as above, this means that DRC will extract and export all of its copper over the next 37 years.

Gabon has the second-largest proven manganese reserve (around 250 million metric tons of reserves) and is currently the second manganese producer in the world, with 4.6 million metric tons (23% of global supply) in 2024 (USGS 2025). However, with global demand in manganese expected to jump from 27.4 kt in 2023 to 39.3 kt in 2030 (Sokolova et al. 2025), Gabon might deplete its reserves in just 30 years.

With the planned production of iron at the Baniaka and Belinga deposits in 2026, mining of minerals will take on growing importance in Gabon's economy, reducing oil dependency (Table 1). In Republic of Congo, the Mayoko iron deposit, with an estimated 150 million tons of ore, began production in 2024. Another new giant iron ore deposit that could soon be supplying the international market is located across Cameroon and Republic of Congo at Nabeba (Gatsé Ebotehouna et al. 2021). There are also several iron deposits (e.g., Mbarga) in Cameroun and Equatorial Guinea, with potential to make a significant contribution to base metal supply chains (Ngiamte et al. 2024). Figure 4 shows the distribution of key mineral deposits in the Congo Basin and their proximity to protected areas (Fig. 5).

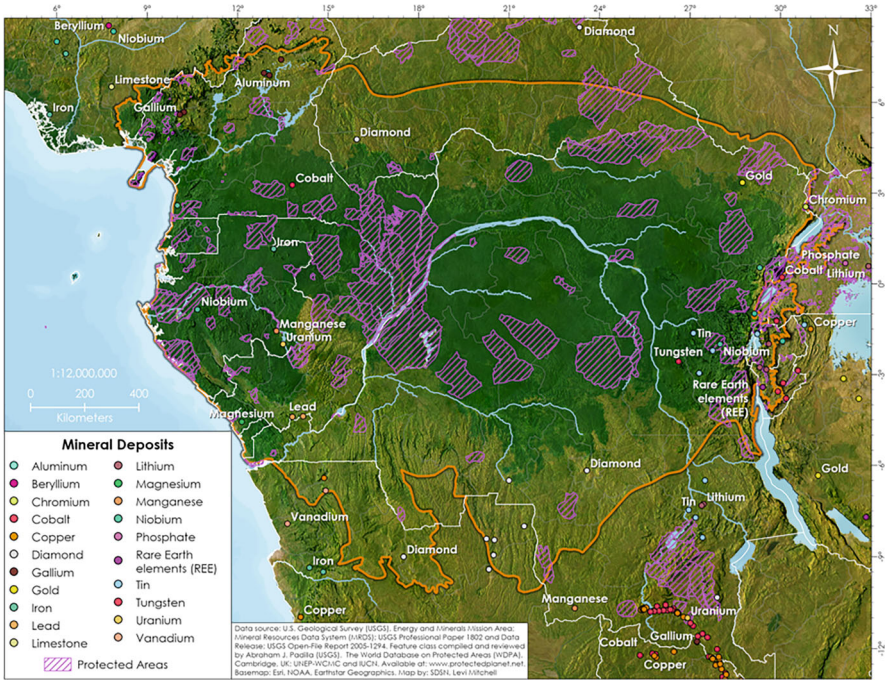

Fig. 4 Distribution of key mineral deposits in the Congo Basin, shown in relation to protected areas (see Durán et al. 2013)

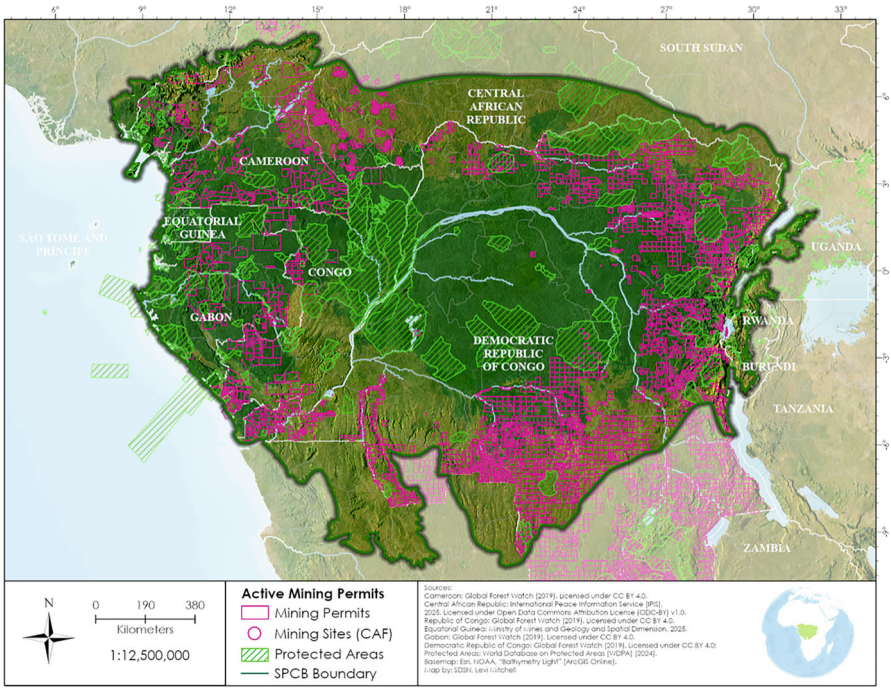

Fig. 5 The mining permits and sites in the Congo Basin

Table 2 shows that mining will remain active in the Congo Basin at least for the next century, if the current rates of extraction and exports remain constant. As illustrated, Cameroon could continue to extract and export its bauxite over the next 35 years; DRC could continue to extract its copper for the next 65–100 years, and Gabon may have another half century of manganese reserves. Noting that the reserve data in Statista (2024) give much higher estimates of Cobalt (6 million tons) and copper (120 million tons) for DRC, the extraction's lifetime could be significantly lengthened.

When projecting the importance of minerals in the Congo Basin economies in the future, it is important to consider that projected increases in the global demand suggest that no single mineral presented in Table 2 will last for two human generations. This poses a serious question about the economic sustainability of naturally mineral-rich yet poorly industrialized and internationally politically powerless countries of the Congo Basin.

Vedrine (2021) suggested that access to cobalt, copper, lithium, nickel, and rare earths will be the new battleground that will determine the balance of power between nations and their economies. The geopolitical stakes are high. Countries where these minerals are found are likely to become a battleground between competing global political powers, particularly between China and the USA. China currently processes 67% of global lithium hydroxide from hard rock-mined sources, 73% of global

cobalt, and 95% of global manganese (Graham et al. 2021; Sharma 2024). With the heightened frictions due to protective measures on trade at the forefront of the global geopolitics, the Congo Basin nations will take on increased global significance and are likely to become one of battlegrounds foreseen by Vedrine (2021).

Managing the Environmental and Social Impacts of Mining

The negative environmental and social impacts of mining are described in Edwards et al. (2014), in Abernethy et al. (2016), and in ▶ Chaps. 14, "Timber Production and Ecosystem Functions and Services in the Congo Basin," ▶ 21, "Effects of Diseases on Wildlife Species in the Congo Basin," and ▶ 23, "Opportunities and Potential for Sustainable Development in the Congo Basin from an Environmental Sustainability Perspective." Megevand et al. (2013) argue that there are well-established means of mitigating the environmental impacts of mining (including oil and gas) in the Congo Basin, through (1) undertaking thorough environmental and social impact assessments for all stages of mining operations (from exploration to mine closure) with clear management plans that are regularly monitored; (2) learning from international best practices and fostering risk mitigation through an "Avoid – Minimize – Restore - Compensate" approach; (3) upgrading the ASM sector, using the Alliance for Responsible Mining certification system for ASM cooperatives as a model to integrate environmental and social standards into this form of mining, which often remains under the radar; and (4) promoting innovative mechanisms to offset negative impacts of mining operations, such as biodiversity offsets or financial guarantees to ensure mine reclamation and restoration at the closure of the mining site.

The International Finance Corporation (2012) provides guidelines for best practice in oil and gas and mines that are systematically implemented in all programs they fund and that have become a standard for many multilateral and bilateral institutions; thus many large-scale projects that require international funding de facto apply these rules. By applying these, or similar national standards, Congo Basin countries should be able to minimize and mitigate the environmental impacts of oil and industrial mining projects (▶ Chap. 14, "Timber Production and Ecosystem Functions and Services in the Congo Basin"), although Rainforest Foundation (2022) warn of the potentially catastrophic impacts of opening up new oil fields in the central Congo Basin that overlap protected areas, peat forests, and the traditional lands of forest peoples.

Shengo et al. (2026) estimates that around 30% of copper and cobalt production in DRC are from ASM (Fig. 2). Additionally, Mulenga et al. (2024) report that unregulated ASM gold mining in sub-Saharan Africa, including large parts of the Congo Basin, contributes up to 20% of global gold production and releases between 205–496 tons of mercury per year into the environment. Negative practices of this type are also common in the Amazon Basin in South America (Martins et al. 2022; Du et al. 2025). Megevand et al. (2013) state that ASM is often more difficult to monitor and control, partly because it is often undertaken illegally or informally. In this context, Rainer et al. (2014) and Junker et al. (2024) provide a review of the

impacts of both on the African forest ecosystem, including the Congo Basin and specifically on great apes (Abernethy et al. 2016). Shengo et al. (2026) propose that direct partnerships between LSM and ASM operators, which enable stronger application of mining and environment laws and implementation of best mining practices, are a mechanism for reducing ecosystem degradation and promoting the respect of environmental standards.

How to Optimize the Mining Economy?

As discussed in Chaps. 29, "Mining Influence on the Future of the Congo Basin," and ► 25, "What Might Influence Economic Forecasts for the Congo Basin?," when Africa's natural resources are exported without processing, the majority of the economy and jobs they generate are outside the continent and develop nations off the continent. This is particularly the case for non-oil minerals. For example, DRC accounts for 74% of global cobalt mining, sending 97% of its cobalt exports, primarily unprocessed, to China.

Indonesia, which is responsible for about 50% of global nickel ore production, signaled its intention to ban the export of unprocessed ore in 2014 and implemented the decision in 2020 (Guberman et al. 2024). The value of nickel exports rose as a consequence from about $3 billion in 2018 to over $30 billion in 2024 as a result of the transformation of ore in-country to higher value products, with the creation of an estimated 130,000 new direct jobs. However, Warburton (2024) argues that the jobs were mostly poorly paid manual work, that the increased revenues are unevenly distributed, and that there have been severe social and environmental consequences.

The international response to the ban of this critical transition mineral was not positive. The European Union (EU) stated that the ban of ore export and obligation to process nickel in-country "unduly and illegally restrict EU access to raw materials needed for stainless steel production and distort world market prices of ores." Having been unable to resolve the issue diplomatically, in January 2021 the EU requested the establishment of a panel to examine the matter as part of the World Trade Organisation (WTO) dispute settlement process. In November 2022 the WTO panel ruled that the ban was inconsistent with Indonesia's WTO obligations, a decision that was immediately appealed by Indonesia and remains pending.

Zimbabwe attempted to force local processing by introducing export bans of chromium ore between 2011 and 2015 and again in 2021 to the present, although its share in the global market was only about 3.5%. The government's stated intent was to spur job creation, increase foreign currency earnings, and increase steel manufacturing capacity in the country but the measure failed, perhaps at least in part because of Zimbabwe's small share in the international market (Perry et al. 2024). Similarly, DRC banned the export of copper and cobalt ore between 2017 and 2020 but failed to implement the policy. It tried again in 2019 but abandoned the decision after just a month owing to power constraints and insufficient processing capacity. Given DRC's large share in the global market for cobalt, the ban might have been expected to be more successful than that in Zimbabwe, but the lack of an

already developed industrial base and insufficient electricity availability meant that significant investment would have been needed to process in-country, which would have required several years. During those years DRC would have had to forgo revenues equivalent to 25% of GDP. However, restrictions in export of unprocessed cobalt combined with a quota system adopted in February 2025 show some promise.

Of these three examples, only Indonesia's ban of nickel ore exports has been successful, spectacularly so purely in terms of financial and employment statistics, and even there some analyses suggest there has been severe social, environmental, and diplomatic costs (Guberman et al. 2024; Warburton 2024). Governments in the Congo Basin will need to reinforce and support their Environment Departments and Agencies to ensure that environmental best practices are implemented in all oil and gas and mineral exploration and exploitation without exception, whether or not all private sector operators are fully engaged. For exports to some countries, there is legislation in place to oblige companies to justify that social and environmental norms have been respected and that all imports come from legal sources. For example, in 2022 the Ministry of Ecology and Environment and the Ministry of Commerce of the Peoples Republic of China issued an official policy entitled Ecological and Environmental Protection Guidelines for Overseas Investment and Cooperative Construction Projects, instructing all Chinese firms to respect local and international environmental standards whenever operating abroad. Similarly, the United States Government Dodd-Frank Wall Street Reform and Consumer Protection Act of 2010 (Bill H. R. 4173, Sections 1502–1504) requires that companies importing tin, tantalum, tungsten, and gold from DRC and adjoining states perform due diligence on sourcing to ensure they do not come from conflict-driven unregulated extraction and that social and environmental norms have been respected.

It certainly seems that if the Congo Basin nations are to harness the huge potential of their oil and gas and mineral reserves to strengthen their economies and create jobs for their young populations, there has to be a shift toward in-country processing. While an immediate ban may not be the optimal solution across the board, Indonesia's success with nickel and success with wood (Chap. 30, "Mining Influence on the Future of the Congo Basin") suggest that this sort of aggressive approach may sometimes be necessary in order to redress the balance of trade. It is certainly apparent that pressure will have to be brought if the region's industrial partners are to be convinced to share more equitably the benefits produced by the transformation of mineral wealth into manufactured goods. The business-as-usual scenario, whereby the Congo Basin remains the source of cheap raw materials that develop the rest of the world but do not create jobs and livelihoods for its people, is quite simply untenable. The Gabonese Republic recently announced it would be banning the export of unprocessed manganese in 2029. Its share in the global market in 2024 was about 23% (USGS 2025).

In Gabon, Deléchat et al. (2024) appraised the outcomes of the country's ambitious "Emerging Gabon Strategic Plan," launched in 2012 to boost economic diversification, promote foreign investment, and transform Gabon into an emerging and diversified economy by 2025. For Deléchat et al. (2024), despite its relatively limited progress, the Emerging Gabon Strategic Plan led to a notable diversification

of the country's economy, particularly in developing new sectors such as manganese and wood transformation, and palm oil and rubber production and refining. It led to a substantial increase in Foreign Direct Investments in the above new sectors. More importantly for Deléchat et al. (2024), the fact that the Emerging Gabon Strategic Plan established the vision and launched the horizontal, vertical, and social policies that were maintained over a period of more than a decade, it allowed the completion of the Nkok wood industrial zone, the construction of a mineral port, and the creation of skill-based professional courses.

Gabon's example clearly demonstrates the need for a clear vision of what nations want to do to diversify their economies; create horizontal, vertical, and social policies to promote social inclusion and social justice; and pursue these reforms unwaveringly over a period of several decades. Integrating revenues from oil, gas, and minerals into such a strategy and optimizing their use to grow the economy is critical. However, as documented by Myamayi et al. 2012), DRC previously had a thriving in-country textile industry that was undermined and destroyed through institutional instability, poor governance, which allowed the illegal import of cheap alternatives, and infrastructural challenges. Today DRC's cotton industry is in ruins. All of the factors that resulted in the failure of this industry will need to be addressed if local transformation of mineral resources is to be successful (Shengo et al. 2026). For industrialization to be truly successful, the Congo Basin countries' policymakers should identify ways to provide legal, financial, and material support to encourage the emergence of private entrepreneurship in the region while avoiding the pitfalls seen in Nigeria over the last decade where hugely profitable industrial development has not been converted into better salaries for the workforce, increased revenues for government, and general betterment of in-country social conditions (e.g., Itaman and Wolf 2021). The best way forwards may well be through striving for cooperation and synergies among the Congo Basin countries and a certain degree of regional protectionism.

Given the prevalence of ASM mining in the Congo Basin, a model for formally regulating this sector will be critical to the economic and environmental success of mining reforms in the region. The Alliance for Responsible Mining uses the Fairmined Standard certification system for ASM cooperatives, providing a model for transition to responsible practices that optimize environmental and social performance and include traceability.

The Rutongo tin mine, a public private partnership (PPP) between the Rwandan government and Switzerland-based Ruddington Services AG, is an example of a different model based on an ordered transition from ASM to LSM, in a public-private partnership (PPP) structure that ensures that the national economy benefits from improved productivity (Gathani and Stroelinga 2012; Rother et al. 2016; Gelata, pers. comm.). Over the past decade, Rutongo transformed from a largely artisanal operation into a model of organized, formalized mining. After decades of informal activity following the exit of colonial-era operators, Rutongo Mines Ltd (RML) was established in 2015, with a 25-year license to revitalize and professionalize the mine. Former artisanal miners were integrated into a structured workforce and performance-based bonuses were introduced to incentivize productivity. This

payment model, similar to the approach of Rwanda's leading mining cooperatives, ensured miners have stable incomes while still rewarding output.

The mine successfully transitioned from an artisanal, small-scale approach to modern mechanized mining. It now includes near-surface production areas operated by ex-artisanal miners from local communities and deeper underground levels and new mining areas employing mechanized techniques and industrial engineering. This blend of local miner engagement and technical advancement has pioneered a new model for organized artisanal mining: informal miners are transformed into trained employees, working in safer, managed conditions with proper equipment and supervision. As of 2024, the broader Trinity Metals group (which includes Rutongo) employs over 6000 people in Rwanda—99% Rwandan nationals and 98% from communities around the mines, with about 2400 staff at Rutongo alone. By professionalizing these miners, Rutongo has improved livelihoods and productivity without losing the local character of the workforce.

A cornerstone of Rutongo's success has been its mineral traceability and due diligence system, established in response to conflict-mineral regulations. Rwanda, though peaceful internally, is subject to Section 1502 of the US Dodd-Frank Act due to its 3T mineral (tin, tungsten, tantalum) production. This law and related initiatives (Organisation for Economic Co-operation and Development (OECD) guidance and the regional International Conference on the Great Lakes Region (ICGLR) certification) require mines to prove that their minerals are conflict-free and not linked to human rights abuses. Rutongo was the first mine in Rwanda to receive "conflict-free" certificates for its tin ore from the ICGLR, partnering with the ITSCI program (ITRI Tin Supply Chain Initiative) to implement a bag-and-tag traceability system at the mine site.

A Final Word of Warning

Considering Vedrine's (2021) warning that countries that possess strategic minerals vital for the triple ecological, economic, and energetic transition will become a battleground for the world's largest economies, effectively harnessing the power of mineral riches to transform the economies of the Congo Basin region will be much more complex and difficult than the timber model described in ▶ Chap. 12, "Agriculture, Ecosystem Functions, and Services in the Congo Basin." No country in the Congo Basin has the military and political might to stand against the pressure the richer and militarily superior nations will exert to have a share of these strategic minerals. If there is an area where "forest diplomacy" can play a greater role, it is bringing together countries of the Congo Basin so that they can stand together to insist on their rights to decide who their best partners are, in the interest of developing thriving and sustainable economies (Nago and Ongolo 2021). As Chasek and Rajamani (2003) suggested, the first step for becoming a voice that will count in global negotiations concerning global public goods is to be sufficiently (in numbers) and adequately (in terms of the variety of fora attended and the technical knowledge of negotiators) represented. The only means the Congo Basin nations have of achieving

this and leveraging their mineral wealth to improve the prosperity of current and future generations is to work together as a block, to identify and share win-win solutions (Nago and Ongolo 2021).

Competing Interest Declaration The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

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Cities, Infrastructure, Energy, and the Future of the Congo Basin

30

Lee J. T. White, Bila-Isia Inogwabini, and Suspense Averti Ifo

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Abstract

The Congo Basin is more highly urbanized than most of the African continent. Gabon, Cameroon, Equatorial Guinea, and Congo have been majority urban populations for decades, and DRC will pass beyond 50% by 2030. CAR will also reach that mark within 20 years. The rapid growth of urban populations in the Congo Basin nations is discussed and key challenges for city-dwellers are

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assessed. Unplanned, rapid urbanization and the development of extensive slums with few services and weak political voice is the norm in the larger cities, increasing social inequity and causing crippling damage to human well-being and environmental health in peri-urban haloes, sometimes extending hundreds of kilometers from the urban center. Solutions to this growing challenge are evaluated and recommendations are made which, if implemented, could help to improve health, resilience, quality of life, and security in urban settings, as well as improving biodiversity outcomes. In the light of the sparse literature on the subject, the authors call for an urgent increase in scientific research on this pressing topic within the Congo Basin, which is a clear priority for the region's majority urban population of the future.

Keywords

Rapid urbanization · Slums · Climate change · Disease · Food systems · Energy transition

Introduction

This chapter is as much a call to action as a vision for the sustainable development of cities, infrastructure, and energy in the Congo Basin. Although across the continent there has been increasing attention to the urban environment in the past 15 years (Awoyemi and Ibáñez-Álamo 2023), there is still a dearth of accessible academic research or publications on the subject from the Congo Basin. This is somewhat unexpected, given that the region is more highly urbanized than Africa as a whole. The United Nations Human Settlements Programme (UN Habitat) has published synthesis reports on "The State of African Cities" in 2010, 2014, and 2018, including short Central Africa sections, but no central African cities have yet been assessed on their flagship City Prosperity Index. The UK Foreign, Commonwealth and Development Office (FCDO) fund the African Cities Research Consortium (www.africancities.org), which is a leader in urban research on the continent, however, within the Congo Basin region, only Bukavu at its very eastern edge, has been a research focus (Nyenyezi Bisoka et al. 2021). An increasing range of data on African urban communities are available within the global Urban Prospects Database (https://data.unhabitat.org), but because this focuses on cities >750,000 people, only a handful of emerging cities in the Congo Basin yet qualify.

Without doubt, there are countless unpublished studies in planning, public works, and economic ministries across the region, and some countries have attempted to undertake integrated national blueprints and plans, but whether it is on cities, or the infrastructure/energy tandem, there have been very few scientific studies in the region. The Central Africa sections of the UN State of African Cities reports 2010 and 2014 (there is not a geographical structure in the 2018 report) do not cite any case study research directly from the Congo Basin (UN Habitat 2010, 2014). Primary research on urban ecology (the status, behavior, and interactions of non-human species living in urban environments) is especially lacking

(Awoyemi and Ibáñez-Álamo 2023). As a result, the guidance that science offers the region in other subjects is sorely missed. This surely is a priority for the future.

Abernethy et al. (2016) demonstrate that of the core Congo Basin countries, Cameroon, Congo, and Gabon have already experienced rapid urbanization, passing (as a group) the >50% urban dwellers mark in 1985, while CAR, DRC, and Equatorial Guinea have followed a more "rural" track. Equatorial Guinea hit the 50% urbanization mark in around 2002, after oil discoveries rapidly increased GDP. DRC is predicted to be 50% urban by 2027 and CAR by 2045 (United Nations 2025). Although pathways to urban society have been varied, the future for the majority of the people of the Congo Basin is urban.

Given the high rate of population increase across the region, increasing rural poverty and the concentration of energy access, communications, and other public services, including healthcare, education, employment, and social/cultural resources in urban areas, urbanization will probably accelerate in coming decades (Liddle and Lung 2014). Even in the less urbanized nations, the rapid, unplanned expansion of urban centers has been significant, with Kinshasa in DRC being the extreme example, growing from a population of less than 500,000 individuals in 1950 to an estimated 18 million residents in 2025 (Mufungizi and Akilimali 2024; ► Chap. 18, "Urbanization, Biodiversity, Ecosystem Functions and Services in the Congo Basin"). The African Cities Research Consortium (ACRC) transversal report on "Health, wellbeing and nutrition" (Tacoli et al. 2024) conclude that in most rapidly growing African cities, there are several common factors driving poor outcomes for human health and well-being, and there is little reason to think these would not also apply in the Congo Basin's cities. They highlight that access to safe drinking water is a priority for health in all growing cities. In addition, food systems are tipping toward widespread provision of cheap processed foods driving an ensuing obesity crisis with rising levels of diet-related diseases, such as high blood pressure, diabetes, and heart conditions. As dependency on imported foods raises prices, cheap domestic food processing becomes lucrative, yet is mostly unregulated. Owners of food businesses begin to act against street vendors of fresh, local foods using informal taxation to limit their market share. Over time, this drives deteriorating public health and raises profits for private healthcare providers.

Furthermore, the concentration of mouths to feed in a city creates a vast halo of environmental degradation and defaunation around urban centers, with city effects on the environment acting up to 1000 km way (Ahrends et al. 2010), as well as creating a huge demand for water. Even so, urban diets in rapidly expanding cities become impoverished, particularly in protein, as the aggregate demand simply cannot be filled from the wildmeat catchment, yet domestic food systems have not yet developed sufficient scale (Van Vliet et al. 2015). In studies on urban growth and deforestation in the Republic of Congo, Ifo et al. (2017) highlight the impact of uncontrolled urbanization, and Binsangou et al. (2025) document extensive deforestation for food production.

Table 1 illustrates a trend across all major Congo Basin cities of a progressive decrease in built-up area per capita between 2000 and 2020, which suggests that living standards have decreased over this period.

Table 1 Trends in built-up area per capita (2000–2020) in major cities of the core Congo Basin countries. (Data from UN Habitat Urban Indicators Database. https://data.unhabitat.org/search). *no data

		Built-up area per capita (m^2 per person)		
Country	City name	2000	2010	2020
Cameroon	Yaoundé	78	66	53
CAR	Bangui	98	94	98
Congo	Brazzaville	74	80	63
DRC	Kinshasa	47	45	37
DRC	Lubumbashi	170	123	113
DRC	Kisangani	71	67	65
Equatorial Guinea	Bata	*	*	*
Equatorial Guinea	Malabo	*	*	*
Gabon	Libreville	217	220	180

The ACRC sectoral report on "Safety and Security" (Adzande et al. 2024) also address the issue of space and overcrowding in cities, highlighting that security issues vary city by city, dependent on local factors, but are often greatly influenced by land value changes as city borders expand. Expansion of un-serviced slums often happens in areas further from formal road infrastructures, where land planners and law enforcement agents are less able to visit, leaving the poorest populations in the highest levels of insecurity. In Bukavu, social conflicts and gang violence were driven by illegal land sales and dispossession of families and politically motivated extortion of payments for security.

World Bank data show that the proportion of the population with access to safe, managed sanitation services in both CAR and DRC is decreasing, due to rapid slum urbanization. In 2022, only 13% in either country had access to decent sanitation (World Bank Open Data 2025). These areas lack physical and social infrastructure such as paved roads, public drainage, sewage networks, and health and education facilities. They also lack services like waste collection or public transportation. The result is the undermining of social norms, because the population lacks the normal societal framework, leading eventually to the development of an unregulated society, where antisocial yet unavoidable practices develop, such as the dumping of waste in open-air sewage pits. Populations of slums generally have poorer health than those living in rural, or well-structured city areas (Adzande et al. 2024), but all urban concentrations of people are extremely vulnerable to disease transmission. Despite the relative proximity of hospitals compared to rural areas, urbanites will likely suffer most from the increased frequency of emerging diseases that we are likely to see in the coming century. ▶ Chapter 18, "Urbanization, Biodiversity, Ecosystem Functions and Services in the Congo Basin" gives a detailed history of urban development across the Congo Basin and highlights that the speed of urbanization and the lack of timely urban planning have resulted in an estimated 75% of the urban population of DRC and around 40% in Cameroon, Congo, and Gabon living in slums.

Furthermore, climate change is resulting in multiple threats to urban populations, all of which are magnified in slums (Leck et al. 2025). Extreme heat linked to climate change, exacerbated by urban heat islands, is increasingly a significant cause of mortality, especially in cities (Tuholske et al. 2021; Vicedo-Cabrera et al. 2021).

Unplanned urbanization amplifies flood and drought risks, through a mix of direct impacts related to construction, runoff and waterway disruption, and halo effects of deforestation and degradation in wider water catchments flowing into cities (IPCC 2022). Douala, Libreville, Malabo, Bata, and Pointe Noire are at flood risk from sea level rise (which is often exacerbated by mangrove deforestation (Kulp and Strauss 2019), as well as resulting in salt-water infiltration of water supplies), while Brazzaville and Kinshasa risk floods from the Congo River.

Business-As-Usual Scenario

The unplanned, rapid, and sustained massive urbanization currently underway in the Congo Basin, alongside the depletion of natural resources around major cities, the impacts of climate change, and the likely rise in pandemics represents a perfect storm, which poses a severe threat to the societies of the Congo Basin (Prince's Foundation 2019). If unplanned urbanization continues, as has been the case, for example, in Kinshasa, (DRC), Brazzaville (RoC), and in the cities in the north of the Republic of Congo, more and more urban residents will be trapped in slums and subject to ever increasing health, social, and environmental issues (Ifo et al. 2017). Furthermore, lack of government controls on purchasing of urban land titles for large-scale real estate developments that result in economic segregation rather than favoring diversified neighborhoods will exacerbate the development of slums (Paula Sevilla and Jesse 2025).

Another recent phenomenon that has accelerated urban growth is the arrival of thousands of refugees fleeing the civil wars in Rwanda and the Central African Republic. The sudden influx of these refugees has caused a functional imbalance in the forest cities, with significant consequences in terms of health and food supply, in cities that were not prepared to accommodate such a large number of people. If nothing is done to ensure political and economic stability in the region, this trend may well be repeated in coming decades (Binsangou et al. 2025).

As urban populations continue to increase, this is ultimately a recipe for civil strife and insecurity. Currently, despite the existence of a multitude of donor-supported programs for urban planning, there is a growing trend toward urban sprawl and unplanned settlements (Prince's Foundation 2019).

Possible Solutions

Urban Planning and Zoning

Over 80% of global GDP is generated in cities (World Bank 2013). As such, urbanization can contribute to sustainable growth if managed well, by increasing productivity, allowing innovation and new ideas to emerge. Conversely, inadequate urban planning and infrastructure can significantly impede economic growth. There is an urgent need to develop solutions to improve quality of life in urban areas, including zoning and development of peri-urban lands at a pace that matches

increases in urban populations. Planned and sustained links within cities, and between them and the rural domain, are needed to promote socioeconomic and cultural exchanges, allow rural communities access to city markets, and promote sustainable food systems that do not rely on imports.

Developing full urban spatial plans is a complex and long-term endeavor and many fail because of a lack of public and government buy-in. Haas and Löffler (2025) review the financing mechanisms currently used in African cities, though none in the Congo Basin, which largely has a French administration-based financing system and may differ on some points. They find that African cities are all under-financed for the services required by the population, but that a lack of transparency and planning in the responsibility divide between civic and national governments weakens the political power of the population to demand better. In general cities have three sources of revenues: central government finance, self-revenues, and private finance through debt. Transfers from central governments are often unreliable and may not be clearly aligned to need, especially when cities' growth is beyond predicted levels. City authorities are weak at collecting self-revenues through taxes and are often unable to access debt finance—either through exclusion by their own national governments or through a lack of transparency in their accounting. This already hampers cities gaining direct access to climate funding, which is usually debt-based.

However, increasing international attention is focusing on creating pathways to sustainable cities across the world and in particular addressing the issues created by the rapidity of urbanization when population growth is high. The African Union's strategy for implementing the new urban agenda for Africa's transformation summarizes policy and implementation priorities for African urban planning (Economic Commission for Africa 2020; Fig. 1). This strategy underlines the critical importance that cities have to play in social advancement throughout Africa, including in

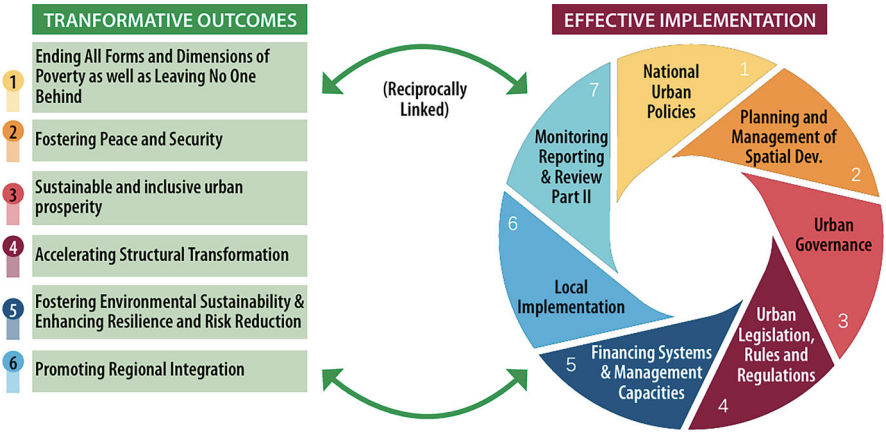

Fig. 1 Implementing the New Urban Agenda for Africa's transformation—Policy and implementation priorities. (Source: Economic Commission for Africa 2020)

fostering peace and security, accelerating structural transformation and promoting regional integration.

The Rapid Planning Toolkit for Urban Expansion, developed by the Prince's Foundation along with the Commonwealth Association of Planners and the Commonwealth Local Government Forum (Prince's Foundation 2019) recently adopted by the 56 member states of the Commonwealth, including Gabon, Cameroon, and Rwanda in the Congo Basin, as part of the 2022 Declaration on Sustainable Urbanisation, proposes practical solutions for in situ retrofitting of urban areas as well as a blueprint for urban expansion. The Rapid Urbanisation Toolkit and other models that have focused on African cities emphasize that it is critical for successful planning that extensive consultation with populations be undertaken and that local solutions to city life be prioritized over imposed "global governance" norms, which tend to miss how residents already make the city work through everyday infrastructures, vernacular finance, and hybrid governance. Success depends on plans being approved locally as well as at the level of the mayor's office and local government while conforming to national guidelines, plans, and legislation (Prince's Foundation 2014, 2019; Robinson 2022).

A place-based participatory approach engages with local authorities and communities and as a result is both politically attractive and effective. It is particularly effective when tackling the development of urban sites that are expanding out into peri-urban and more rural areas, which is a characteristic of most Congo Basin cities (Robinson 2022). Unplanned city extensions bring social tensions with rural dwellers who did not choose to urbanize and see their land, services, culture and food systems consumed by the advancing city. Land that is essential for local ecosystem services will lose its environmental value, reducing to the value of its geographical location in relation to the city. In addition, ecosystem services, such as drainage, agricultural potential, biodiversity value, and cultural significance, can all be lost as city infrastructure expands.

Planned city extensions will be one of the essential elements in the creation of sustainable urban development, in part because they can foster the development of new model cities that attract people out of slums, making retro-planning of these areas more practical. Formalization of land tenure and provision of basic services is a priority in these zones. Generally, the application of the principal of "upgrade in place, don't displace" (coined by various development agencies) is recommended as the most effective and sustainable solution in most cases (Robinson 2006, 2015).

The first step in the planning process is to map out key constraints, including principal transport routes, areas currently or predicted to become subject to flooding, particularly low-lying zones close to water courses, sensitive ecological formations and steep slopes, and existing habitations. Working to ensure the principal transport routes in cities are fast flowing makes a huge difference to the efficiency of the city and should be prioritized. (Robinson 2022; Robinson et al. 2025) recommends formalizing paratransit feeders and roll out of bus transit systems adapted to the make-up of Congo Basin cities such as Kinshasa or Douala, including creation of dedicated bus lanes, formalized minibus routes, simple shelters/platforms at regular intervals, off-board cashless payments, corridor traffic management by traffic police,

and regulating traffic on the 2–3 highest-demand corridors per city, before considering costly solutions like rail.

Having completed this initial analysis, a participative, stepwise rapid urbanization process can be undertaken, identifying growth area options and designing walkable neighborhoods (Prince's Foundation 2019). The urbanization process should be planned for the long term. It should provide the spine or frame—the streets on which planners build, which in turn lead to the main transport axes; the matrix, the blocks formed by the streets; and the pattern of how the city will expand, including the local spaces/buildings/uses/green spaces. Over time, economic activities and the various social needs will shape urban land uses, but not the pattern. This essential element must be defended and protected by the local authority, the repository of political legitimacy, and the rule of law. By replicating the walkable urban village design, building up using walkable neighborhoods that are equivalent to traditional villages, with residential areas, services, schools, and medical facilities all withing walking distance, this process builds on and re-enforces traditional community values rather than imposing an artificial matrix on top of them. The process can also involve the development of model buildings, integrating fundamental concepts of tropical low-energy architectural design in line with any local innovations and cultural expectations, such as a preference for external kitchens and use of local materials.

Planning should integrate a range of population densities, with higher concentrations in the inner zones while respecting the principal of walkable urban villages as much as possible. Robinson et al. (2025) underline the fact that in African cities funding is rarely dependable and governance can be irregular, so master planning of cities should adopt incremental upgrades, developing investment pipelines that braid sovereign funds (national programs), developmental money (MDBs/donors), and private capital around clearly scoped, modular projects, rather than symbolic mega-projects that tend to become white elephants. They also recommend creation of lean urban observatories that incorporate planning departments and universities in each major city that promote iterative learning, to track issues such as serviced-plot delivery, flood losses, commute times, and affordability and publish quarterly dashboards to steer donor/sovereign/private pipelines.

To avoid uncontrolled expansion of existing cities, strong policies, produced through participative and democratic processes, should aim at delineating city limits, with strong negative incentives for unplanned constructions in and in areas adjacent to current cities.

Nature-Based Solutions

Nature-based solutions are an integral component of urban planning generally and could be particularly beneficial in the Congo Basin specifically. They should be considered an integral part of core infrastructure in cities. Resilient cities rely on a diverse range of ecosystem services. These include provisioning services such as access to food, water, raw materials, and medicine; regulating and maintenance

services such as climate moderation, stormwater management, bioremediation, pollination, and noise control; and cultural services that offer recreational opportunities, aesthetic enjoyment, health benefits, and cultural enrichment. A review of studies assessing regulating and cultural ecosystem services from urban green and blue infrastructure found a strong concentration of research in the Northern Hemisphere and no evidence related to the Congo Basin region (Veerkamp et al. 2021).

There is extensive evidence that trees and green spaces in cities improve health, particularly psychological and stress-related illnesses and allergies (e.g., Vujcica et al. 2017; Li et al. 2025), reduce pollution related mortalities (e.g., Sicard et al. 2025), reduce temperatures and heat-dependent mortality (e.g., Ettinger et al. 2024; Xi et al. 2023; Yan et al. 2023), mitigate the effects of flooding and drought (e.g., Gaines 2016; Konijnendijk 2023), and generally contribute to climate change adaptation (e.g., Dodman et al. 2022). Yan et al. (2023) demonstrated that planting trees along city roads can reduce temperatures by up to 10–15 °C when tree density and shade are optimized.

Konijnendijk (2023) describes the global 3-30-300 norm that is gaining traction internationally, whereby there should be "3 well-established trees in view from every home, school, and place of work, no less than a 30% tree canopy in every neighbourhood; and no more than 300 m to the nearest public green space from every residence" in order to optimize nature-based solutions within cities. In addition to this generic rule, specific actions such as protecting and restoring mangroves close to coastal cities; protecting and restoring forests in the water catchments flowing into cities; developing artificial lakes, managed wetlands and drainage corridors in and around cities, are all important measures for flood mitigation, which are appropriate for many major Congo Basin cities, although designing permeable streets and maintenance of drains are also critical (e.g., see Dobkowitz et al. 2025; Robinson 2022). The Gikondo and Nyabugogo wetland rehabilitation program in Kigali is a good example of how this can be retro-implemented (Yankurije et al. 2025).

Table 2 shows that the major cities in the core Congo Basin nations fall far short of 3-30-300 norm. Hu and Xi (2023) suggest that in the ecological context of urban management, nature-based solutions should be based on the concept of the "ecological city," which takes into account a defined set of indicators. This is a complex approach but is appropriate for urban ecosystems, as it considers both living and nonliving components in the development and implementation of urban management policies. The concept of the ecological city is holistic and promotes the consideration of all living beings: humans, as well as other fauna and flora. However, a recent study conducted in Brazzaville and Pointe-Noire revealed that they do not qualify as being ecological cities (Ifo, unpublished data) and it seems likely most or all Congo Basin cities will fail this test.

In the Congo Basin context, where cities are expanding into and even being created in forest ecosystems and are exerting a halo effect on natural resources, there is possibly greater potential for nature-based solutions than the highly developed cities in developed nations (McPhearson et al. 2025). Furthermore, this argues for the development of landscape-scale ecosystem-based approaches rather than relying on single actions such as planting trees and creating green spaces. For example,

Table 2 % surface area comprised by areas of open-access and % of the population with access to public spaces in the major cities of the key Congo Basin countries. (Data from UN Habitat Urban Indicators Database. https://data.unhabitat.org/search). *no data

	City name	Average share of the built-up area of cities that are open space for public use for all (% 2020)	Average share of urban population with convenient access to open public spaces (% 2020)
Cameroon	Yaoundé	*	*
CAR	Bangui	10.9	24.7
Congo	Brazzaville	10.9	17.2
DRC	Kinshasa	18.0	17.3
DRC	Lubumbashi	17.7	6.8
DRC	Kisangani	*	3.0
Equatorial Guinea	Bata	*	9.5
Equatorial Guinea	Malabo	13.6	36.9
Gabon	Libreville	10.7	8.8

managing deforestation or ecosystem restoration in watersheds flowing into cities will provide significant flood mitigation for downstream urban areas. These solutions also will play a critical role in strengthening connections between people, who are more and more disconnected from the natural world and nature. On the bright side, urban social-ecological systems are dynamic and rapidly evolving and the Congo Basin has the opportunity to develop a nature-based approach to urban planning, for new developments that are unconstrained by old infrastructure.

Keeler et al. (2019) highlight that the majority of studies on the application of nature-based solutions in cities have been undertaken in Europe, China, and the United States and that conclusions drawn from high-income countries may be of limited value for nations in the Global South, which are projected to have highest population growth in urban centers in the coming decades. Here, in cities characterized by high levels of informality and decentralization, nature-based solutions may look very different. It is a priority that research on urban ecosystem services and the social, ecological, and technological factors impacting urban nature-based solutions in the Congo Basin address these disparities, in order to provide appropriate guidance to both leaders and communities.

Energy Transitions

Cities and their peripheries act as magnets for development and are the sources of approximately 70% of all greenhouse gases (e.g., Dodman et al. 2022). As such, green energy transitions in urban areas are critical, both for the global environment as well as for quality of life of their inhabitants. Furthermore, the switch from fossil fuel energy sources, particularly for transport, results in significant increases in air

quality, with significant health benefits for urban populations (e.g., Lyu et al. 2024; Pennington et al. 2024). Joshi et al. (2021) demonstrated that solar panels fitted on rooftops in urban agglomerations currently account for 40% of solar capacity and that if all suitably oriented usable space in cities was exploited it would generate enough electricity to provide just over 90% of current global energy demands. While Africa was found to have much less potential than Asia, North America, and Europe, this is an indication of the potential of solar energy to power cities with clean, renewable energy and should be fully investigated in urban planning exercises in the Congo Basin region. Another very important area identified among measures to mitigate climate change is the recycling of household urban waste and its use in incinerators equipped with electric generators. This option was included in the Republic of Congo's Nationally Determined Contribution (NDC) (Republic of Congo 2021).

Multiple Projects Are Underway

Several major Congo Basin cities are actively implementing substantial urban-planning/urban-resilience programs:

- Kinshasa (DRC)—The World Bank's $500 m Kin Elenda multisector urban development and resilience program is underway to strengthen urban management and expand access to services.
- Douala (Cameroon)—Part of the nationwide Inclusive & Resilient Cities Development Project (PDVIR) to improve urban management and infrastructure in selected cities (incl. Douala).
- Yaoundé (Cameroon)—Has a current Urban Master Plan (PDU 2023–2035) and an adopted Sustainable Urban Mobility Plan (SUMP) now moving into implementation.
- Libreville (Gabon)—The Akanda Masterplan & SmartCode guides growth at Libreville's northern edge; in parallel, new urban development and flood-risk reduction projects are being financed for Gabonese cities.
- Brazzaville and Pointe-Noire (Republic of the Congo)—The Ongoing Urban Development and Poor Neighborhood Upgrading Project (PDUE) includes resilience mainstreaming.
- Bangui (Central African Republic)—A World Bank–supported program (PROVIR) is scaling nature-based and gray infrastructure for urban flood resilience in Bangui.

If these projects embrace the principals identified above, there is reason to hope that quality of life, health, and climate resilience in the Congo Basin's major cities can be significantly improved in coming decades. However, the lack of scientific literature relating to the outcomes of urban planning and the state of the urban environment generally suggests that these programs could be further supported by better integration of the region's university departments and scientists in

implementation plans. Given the numbers of people currently living in cities, and the current rates of population growth and urbanization in Congo Basin countries, we recommend that the Science Panel for the Congo Basin pay particular attention to this subject in the future.

Making Rural Areas More Attractive

Finally, we suggest that in national planning exercises, governments also focus on policies that will make rural areas, including small- and medium-sized towns, more attractive, in order to slow migration to urban areas and to attract people out of the slums to places where they can achieve better quality of life. These will necessarily include improved access to communications, energy, water, healthcare, and education, as well as carefully planned infrastructure developments making travel between rural and urban areas more efficient. The advances in internet technology, such as satellite internet systems, should facilitate this objective, making it possible to run businesses efficiently in areas that were previously disadvantaged.

While the Congo Basin contains many large and growing cities where access to space is challenging, it continues to be a region with extensive undeveloped land. It would perhaps be interesting to investigate the model used by the government of Korea in the early 1950s to reform land tenure and allocate land (an asset) to all citizens, which is accredited with greatly stimulating the economic development of the country (Jeon and Kim 2000). Considering that in the Congo Basin countries most land belongs to the state, a variation on this policy, alongside strategic investments in infrastructure, might have potential to slow the flight of rural populations to the big cities and develop a more balanced mix of small and medium cities and larger villages as well as the urban agglomerations that are currently dominating population re-distribution.

Looking to the Future

Considering the lack of scientific research on the urban environment and planning in the Congo Basin, the authors are hesitant to propose a theory of change for urban development and renewal. However, given rapid development of cities such as Kinshasa, Douala, and Yaoundé, and the high proportion of urban dwellers living in slums across the Congo Basin region, it is clear that this is a priority for future research and planning, as well as for development cooperation.

We highlight the existence of city assessment tools, such as the UN Habitat Global Urban Monitoring Framework (UN Habitat 2022) and planning guidelines such as the New Urban Agenda for Africa's Transformation (Economic Commission for Africa 2020) and the Commonwealth Rapid Planning Toolkit for Urban Expansion (Prince's Foundation 2019). We also underline the potential of nature-based solutions to make the Congo Basin's cities more livable and resilient. It is clear that this should be a priority for the Congo Basin countries, where over half the

population either is already or will be living in an urban setting by 2030. Business as usual will inevitably result in more slums, deteriorating health, and environmental degradation, and perhaps also increased criminality and possibly even civil instability. It will also result in further increases in land and spatial occupation of areas adjacent to current cities.

Competing Interest Declaration The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

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31 Future Risks of Disease Emergence in Humans, Wildlife, and Livestock in the Congo Basin: Predicting Outcomes Under Current Trends and Policy-Driven Solutions

Eeva Kuisma, Nicole L. Gottdenker, and Sarah H. Olson

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Abstract

The Congo Basin, one of the world's most biodiverse ecosystems, is experiencing some of the globe's fastest and most extensive demographic changes and faces accelerating anthropogenic pressures that threaten both ecological and health stability. Rapid deforestation, land conversion, mining, agricultural expansion, and climate change are fundamentally altering ecological systems and increasing the risk of disease emergence.

Evidence links land-use change and habitat fragmentation to elevated spillover risk by creating high-contact interfaces among humans, wildlife, and livestock, while forest degradation erodes "landscape immunity." Climate change further amplifies disease threats by altering host and vector distributions, increasing pathogen shedding, and compounding stress in wildlife.

Under current trajectories, biodiversity loss, habitat degradation, and weak health systems across much of the region heighten vulnerability to disease outbreaks and ecological collapse. Species declines among great apes, elephants, and amphibians illustrate how environmental stress and disease interact to drive extinction risk and destabilize ecosystem services. Mining-related mercury contamination, agricultural intensification, and bushmeat hunting continue to degrade ecological integrity and elevate risk of disease emergence.

Policy-driven, One Health-based interventions offer pathways to resilience. Primary prevention, integrating wildlife health into Environmental and Social Impact Assessments (ESIAs), National Biodiversity Strategies and Action Plans (NBSAPs), applying the mitigation hierarchy, and embedding health safeguards into mining, agriculture, and infrastructure planning can reduce ecosystem disruption and promote disease resilience. Strengthening surveillance, supporting sustainable livelihoods, and prioritizing high-risk taxa in health monitoring programs can improve early detection. Protecting intact forests, maintaining wildlife corridors, and adopting climate-smart land-use planning are vital to sustain ecological and community health.

The Congo Basin's future depends on aligning conservation, development, and health agendas under a coordinated One Health framework. Proactive investment in prevention, rather than reactive response, will deliver the most effective, equitable, and cost-efficient outcomes for biodiversity conservation, climate mitigation, and pandemic prevention.

Keywords

Land-use change · Climate change · Spillover · Emerging disease · Zoonosis · One Health · Congo Basin

Introduction

Anthropogenic Changes Increasing Disease Emergence in the Congo Basin

Emerging infectious diseases (EIDs) are increasing in frequency and severity. Spillover events and deaths are rising annually by 5%, and approximately 70% of these infections originate in animals, roughly half from wildlife (Meadows et al. 2023). While global human health metrics are improving overall, endemic zoonoses and vector-borne diseases still cause billions of illnesses and millions of deaths annually (Baker et al. 2022; WHO 2025). In the face of unprecedented human-driven environmental change, a key question emerges: what role does anthropogenic land-use change play in pathogen transmission between wildlife, humans, and domestic animals, and in disease emergence (Carlson et al. 2022)? Recent intergovernmental reports have drawn focus to this nexus and to the Congo Basin, where recent decades have seen an increase in disease emergence in wildlife, livestock, and people.

Land-Use Change and the Disease Emergence Landscape

Globally, growing evidence shows that land-use change drives disease emergence and deforestation and forest fragmentation create ecological conditions that facilitate disease spillover, including zoonosis. Areas that contain large amounts of forest edge are associated with increased yellow fever virus transmission, while low-connectivity regions act as barriers (Wilk-da-Silva et al. 2023). Deforestation is shown to increase abundance of a key malaria vector, *Anopheles darlingi* (Vittor et al. 2006), and agricultural expansion has been linked to hantavirus outbreaks (Baker et al.; 2022). In Uganda, forest disturbance increased bacterial transmission across species (Goldberg et al. 2008), and Ebolavirus spillover in West and Equatorial Africa correlates with forest fragmentation and crop-driven resettlement (Telford et al. 2025).

Anthropogenic land-use change heightens disease spillover risk from wildlife to humans and domestic animals by creating conditions that fundamentally alter ecosystems (Plowright et al. 2021). These mechanisms are complex and include altered nidality, the concept of confinement of diseases to specific ecological settings, promoting cross-species transmission (Pavlovsky 1966); shifts in host and vector diversity that favor short-lived, highly competent pathogen carriers, increasing transmission (Gibb et al. 2020; Mahon et al. 2024); behavioral and movement changes, enhancing contact among vectors and hosts; altered population dynamics of reservoirs and vectors; disrupted food webs, such as predator loss increasing rodent reservoirs; and greater pathogen virulence or success of generalist pathogens capable of host switching (Fig. 1) (Gottdenker et al. 2014).

Data specific to the Congo Basin, while increasing, is still scarce so addressing these knowledge gaps is essential. The region has seen an increasing number of

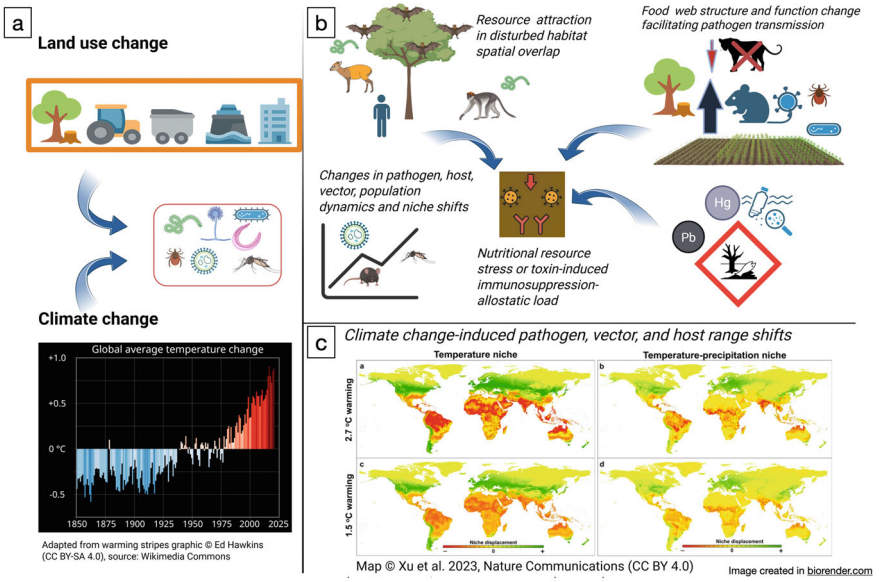

Fig. 1 Key mechanisms of land-use and climate-change induced infectious pathogen transmission and disease emergence. Anthropogenic climate and land-use change, marked by substantial modification of the global land surface and over 1°C of average warming since the pre-industrial revolution, are linked to heightened disease emergence and spillover risk (**a**) through complex mechanisms that fundamentally alter ecosystems and pathogen-host dynamics, including alterations in food webs, host-habitat overlaps and increase in allostatic load and immunosuppression through nutritional resource stress and toxin exposure (**b**), and pathogen, vector, and host range shifts (**c**)

novel and repeated zoonotic spillover events in the past two decades, including Ebola virus, Marburg virus, and monkeypox virus, the virus that causes mpox (WHO 2025). Forest fragmentation and human encroachment have been associated with Ebola spillovers in Gabon and the Republic of Congo (ROC), with outbreaks often emerging near recently disturbed forest edges (Ryan & Walsh 2011; Olivero et al. 2017; Telford et al. 2025). Rodent populations increase at forest-farm interfaces in disturbed habitats, possibly facilitating virus transmission and roads created for logging and mining concessions have facilitated bushmeat hunting and increased wildlife-human contact (Gibb et al. 2020; Poulsen et al. 2009). Given what we know to date about land-use-associated pathogen emergence, a better understanding how and why these associations occur is critical for their prevention in the Basin.

In the DRC, shifting cultivation drives rapid turnover in small mammal communities, creating novel interactions at agriculture-forest edges (Tyukavina et al. 2018; Molinario et al. 2020). Reservoir hosts exposed to land conversion or fragmentation may also suffer nutritional stress, and displaced human populations may face food insecurity; both can elevate allostatic load and weaken immunity, increasing infection and pathogen shedding (Plowright et al. 2024; Eby et al. 2023). These

stress-mediated dynamics (Fig. 1) are particularly relevant in the Congo Basin where agricultural expansion, infrastructure projects, war, and unrest are displacing both people, livestock, and wildlife (Olivero et al. 2017).

At the landscape scale, disease models predict that pathogen transmission is often highest at forest edges or at intermediate levels of habitat loss. In the Congo Basin, edge-dominated mosaics are projected to expand under high-development scenarios, driven foremost by smallholder clearing and selective logging, and suggesting elevated risk zones for zoonotic spillover (Olivero et al. 2017).

In sum, ecological disruptions reduce "landscape immunity" and weaken natural barriers to disease emergence across wildlife, humans, and domestic animals. Land-use change drives not only ecological disturbance but also host-pathogen contact, disturbances to immunity, and disease emergence across species (Gottdenker et al. 2014; Bloomfield 2020; Johnson et al. 2020).

Climate Change and Disease Emergence

Climate change is closely linked to infectious disease emergence. It drives species declines by altering habitats, and with the IPCC (2023) reporting rising global temperatures, shifting and more variable precipitation, and increased summer drying, these changes will continue to significantly affect wildlife, livestock, and human health. Altered weather patterns are changing species distributions and behavior, while heat and shifting food resources directly stress wild and domestic animal and influence life history traits such as growth, body weight, and sex ratios (IPCC 2023; OHHLEP et al. 2023).

Shifts in mean temperature and climate variability heighten disease emergence risk (Mahon et al. 2024; Eby et al. 2023 Mora et al. 2022; Baker et al. 2022) while expanding vector ranges and modifying the prevalence of vector-borne infections (IPCC 2023). Greenhouse gas-driven climatic events further exacerbate these impacts—78% of 286 human pathogens were worsened by at least one climatic hazard, including droughts, floods, heatwaves, and wildfires (Mora et al. 2022). These effects are often complex; for instance, droughts can reduce mosquito breeding sites yet increase virus-carrying mosquito density in remaining pools.

Ectothermic hosts and pathogens with environmental lifecycle stages, such as fungi, are particularly sensitive to temperature and precipitation changes. Range shift vulnerabilities are highlighted by the chytrid fungus *Batrachochytrium dendrobatidis* (Bd), a leading driver of amphibian declines. As amphibians shift to cooler, higher habitats, Bd is projected to track these hosts, potentially worsening population declines (Box 2). In Cameroon's Campo Ma'an, Mbam and Djerem, and Lobéké National Parks, which are amphibian diversity hotspots, increased rainfall is projected to further favor Bd spread (Seimon et al. 2015; Re:wild et al. 2023).

Simulations of mammalian host-virus interactions predict climate and land-use change driven viral sharing between species to further increase by 2070 (Carlson et al. 2022).

Especially High-Risk Disease Emergence Interfaces in the Congo Basin

Certain human activities and environmental changes create locations and situations with markedly higher pathogen transmission risks. These especially high-risk interfaces often occur where human-wildlife or livestock-wildlife interactions overlap intensely.

Hunting, handling, and transporting wild animals form one such particularly relevant interface for zoonotic emergence, as they bring people into direct contact with potentially infected wildlife (Magouras et al. 2020), and have facilitated the establishment of wildlife-origin diseases in humans, including human immunodeficiency virus from its ancestor, simian immunodeficiency virus (Box 1). Risk levels vary with the phylogenetic proximity of hunted species to humans and the diversity of pathogens they harbor and increase further when hunters collect sick or dead animals (Geraerts et al. 2024).

Live wildlife trade amplifies spillover risks by imposing stressful, unsanitary, and highly unnatural conditions on animals. Moving live animals along the trade chain weakens their immune function, increasing pathogen prevalence, co-infection, and shedding of viruses like coronavirus (Huong et al. 2020). Human contact occurs throughout this chain, creating multiple spillover opportunities. Some taxonomic groups such as ungulates, primates, and bats harbor a disproportionately high number of zoonotic pathogens. Approximately one quarter of traded mammal species host roughly 75% of recognized zoonotic viruses (Ingram et al. 2021).

Bats, an important protein source in the region (Fig. 2), are a particularly relevant example of a high-risk taxa for zoonotic viruses. Environmental and anthropogenic stressors can alter bat ecology and viral dynamics, often pushing bats to forage in human-dominated landscapes. This shift brings people into indirect contact with bat excreta on fruits and other surfaces, increasing pathogen transmission risk, while ecological stress simultaneously elevates viral shedding (Plowright et al. 2021, 2024; Eby et al. 2023). Caves shared by bats and humans are further spillover hotspots; contact with Egyptian fruit bats (*Rousettus aegyptiacus*) has been implicated in multiple Marburg virus outbreaks, including recent events in Equatorial Guinea and Rwanda (Branda et al. 2025; see Box 3).

Wild meat is an important food source in the region, and rather than focusing solely on restrictions, recent studies highlight the importance of developing safe alternatives and risk-reduction pathways.

Shared food and water sources accessible to wildlife and livestock or people can facilitate cross-species transmission. Natural resources such as water points and grazing lands act as hubs for indirect pathogen exchange, amplifying disease risk (Kock & Caceres-Escobar 2022).

In the Congo Basin, traditional pastoral transhumance increases livestock–wildlife interfaces by moving cattle, sheep, and goats seasonally between pastures. While essential to pastoralist livelihoods and cultural identity, these extensive systems

Fig. 2 Live straw-colored fruit bats (*Eidolon helvum*) for sale at a market in Brazzaville. The close interaction between bats and people can create opportunities for a pathogen spillover. (Source: Brent Stirton/Getty Images)

bring domestic animals, wildlife, and humans into prolonged contact, facilitating both spillover and spillback of pathogens. Notable transhumance areas include the Mbam and Djerem NP in Cameroon, which supports about 25,000 cattle. Livestock often graze alongside wildlife, while insecurity and climate change are pushing pastoralists into new areas of the Congo Basin (▶ Chap. 12, "Agriculture, Ecosystem Functions, and Services in the Congo Basin").

Water and pasture contaminated with excrement facilitate the spread of resilient pathogens such as anthrax spores and foot-and-mouth disease virus. Grazing livestock are routinely exposed to insect vectors (e.g., ticks, tsetse flies, and mosquitoes) that transmit parasites such as *Trypanosoma* spp. and *Anaplasma* spp. to both livestock and wildlife (WOAH 2024). Rinderpest once decimated wild ungulates before its eradication, and in the case of the similarly destructive small ruminant plague (Peste des Petits Ruminants), exposure to wildlife complicates control and confirmed sustained wildlife reservoirs remain under study (FAO 2017).

Many pathogens are species- or taxa-specific, and genetic relatedness between species, for example, between domestic cattle and wild buffalo, can increase the likelihood of pathogens crossing species barriers. Spillovers to immune-naïve populations can cause severe disease. Pathogen examples relevant to regional wildlife are discussed in ▶ Chap. 21, "Effects of Diseases on Wildlife Species in the Congo Basin."

Box 1. Simian Immunodeficiency Virus (SIV) and Human Immunodeficiency Virus (HIV)

An example of viral disease emergence from wildlife, followed by adaptation and permanent establishment in the human population, is the human immunodeficiency virus (HIV) pandemic, originating from simian immunodeficiency virus (SIV).

Simian immunodeficiency viruses (SIVs) are a diverse group of lentiviruses naturally infecting more than 40 African primate species and typically causing subclinical infections in their host species. Genomic data suggest that SIV has been circulating among African primates for thousands or tens of thousands of years (Steve et al. 2017).

*HIV types 1 and 2 originated through at least four independent cross-species transmissions of SIVs over an extended period of time (*ca. *1915–1941), connected to hunting of primates. While the majority of these isolated spillover events produced viral lineages that either failed to adapt sustainably into human physiology, or spread only locally within the human populations, a single transmission from a chimpanzee-derived virus in southeastern Cameroon, SIVcpz, seeded the HIV-1 group M, the lineage that is responsible for driving the global AIDS pandemic. HIV-1 groups N and O remain largely restricted to Central Africa, and groups O and P arose more recently from SIVgor in western lowland gorillas* (Sharp and Hahn 2011).

Humans have hunted primates for millennia, but the transformation of the incidental SIV spillovers into a human disease pandemic was multifactorial. It required a variant capable of serial human-to-human transmission and social factors to sustain transmission. The latter was likely facilitated by human movement, urbanization, and social upheaval. Human practices such as use of unsterile medical injections, and sexual transmission, have then further facilitated the spread in human populations.

HIV and the genomic and evolutionary findings outline a complex history in which ancient, co-evolved primate viruses crossed into humans on multiple occasions, but only under the socio-historical and ecological conditions of the twentieth century did certain lineages adapt sufficiently to become HIV-1 and HIV-2, igniting one of the most consequential human pandemics in history. Understanding of SIV genetic diversity and geographic distribution is still expanding, and humans continue to be exposed to relatively high proportions of infected primate wild meat in the Congo Basin region (Steve et al. 2017).

Scenario One: Continuation of Current Trends in Conservation, Land Use, and Natural Resource Management

By 2050, the Congo rainforest will have shrunk by more than a quarter based on current trends with projected intact forest landscapes varying by region (Tyukavina et al. 2018). One study projects 3.7–4.0% (174,860–204,161 km^2) forest loss from 2020 to 2050, while another estimates that 25–30% of the forest area in the DRC may be cleared under business-as-usual conditions (Shapiro et al. 2021). ► Chapter 27, "How Could Logging Policies and Practices Influence the Future of the Congo Basin Biodiversity and Ecosystems?," review the consequences of future forest and biodiversity losses.

A major challenge due to the ongoing degradation and loss of habitat is increased emergence of diseases that threaten wildlife, livestock, and the human population living in its countries. Understanding and mitigating disease emergence threats from anthropogenic activities to wildlife, livestock, and human well-being are essential.

In this scenario we consider the continued growth of human activities in the Congo Basin. While serving important economic aims, human activities have significant impacts on biodiversity and ecological stability and disease emergence. Understanding the implications of the current trends is therefore important for planning and prioritisation.

Land Use and Climate Change Continue to Drive Biodiversity Loss and Disease Emergence

Landscape alteration is creating physical barriers to wildlife movement, causing habitat fragmentation and population isolation. This particularly affects the region's large land mammals. Over time, isolation increases inbreeding and reduces genetic diversity, weakening immune systems and raising disease susceptibility. It also leads to inbreeding depression, marked by lower reproductive and survival rates, and higher genetic disorders (Hohenlohe et al. 2021; Xue et al. 2015, Plumptre et al. 2016). In wild mammals and birds, inbreeding significantly increases juvenile mortality and, subsequently, extinction risk (Xue et al. 2015; Plumptre et al. 2016).

Habitat degradation is integrally connected to food availability and quality for both wildlife and local communities. In Lopé National Park, Gabon, fruit yields declined 80% over 30 years (Bush et al. 2020). This climate change-driven reduction caused an 11% drop in African forest elephant body condition, leading to nutritional stress and increased disease susceptibility, highlighting the link between environmental change, wildlife health, and ecosystem vulnerability. Malnutrition, as a result of anthropogenic habitat degradation, is discussed in ► Chap. 21, "Effects of Diseases on Wildlife Species in the Congo Basin."

As discussed earlier, habitat alteration can reshape disease ecology, heightening risks of emerging infections. Past Ebola outbreaks with mortality exceeding 90% have decimated gorilla and chimpanzee populations within protected areas. Recovery from such declines is especially difficult for large mammal populations due to low reproductive rates and added poaching pressure (Ryan & Walsh 2011). Similarly, African forest elephants' recovery from poaching may take decades; a study on populations along the CAR, ROC, and Cameroon borders found extremely slow growth, with a population doubling time of nearly 60 years—three times that of savanna elephants. The study pointed out that controlling the illegal killing would shorten this time to 41 years (Turkalo et al. 2017).

As hunting pressure intensifies and large-bodied mammals become increasingly depleted, wildlife value chains shift toward smaller, more abundant generalist taxa such as rodents and bats (Ripple et al. 2016; Benítez-López et al. 2017). This shift is also a public health concern, as these smaller taxa are recognised reservoirs for a wide diversity of zoonotic pathogens (Olival et al. 2017).

At the same time, the growing demand for wild meat in rapidly expanding urban centers is unsustainable, with extraction rates far exceeding ecological regeneration and local availability (Ingram et al. 2021; Willis et al. 2022, ▶ Chap. 16, "Hunting, Fishing, and Ecosystem Functions and Services in the Congo Basin"). The commercialisation of wild meat through increasingly organised value chains also facilitates the movement of pathogens from remote ecosystems into densely populated cities, where conditions for amplification and spread are much greater. Together, these dynamics highlight how unsustainable exploitation not only threatens biodiversity but also elevates risks of zoonotic disease emergence along the rural-to-urban continuum (Ingram et al. 2021; Huong et al. 2020; WOAH 2024), which is expected to intensify (Fanelli et al. 2025). Studies from comparable ecosystems, such as the Amazon Basin demonstrate that deforestation rates above 30% correlate with a surge in spillover events (Mahon et al. 2024). High-risk interfaces, such as wildlife markets and artisanal mining camps, will proliferate, increasing the chances of disease emergence. Without interventions, the likelihood of new zoonotic diseases emerging from species such as fruit bats, primates, and rodents will continue to rise.

The region represents the most important habitat for great apes globally. All great ape species now face a very high or extremely high risk of extinction in the wild and are listed as Endangered or Critically Endangered on the IUCN Red List. The two eastern gorilla subspecies have undergone a prolonged population decline over the past 100,000 years, resulting in low genetic diversity. Current estimates place the total population of mountain gorillas (*Gorilla beringei beringei*) at around 1000, over half of which inhabit the Virunga volcanic range spanning Rwanda, Uganda, and the DRC (Plumptre et al. 2016). Grauer's gorilla (*Gorilla beringei graueri*), found only in the DRC, declined from roughly 16,900 to fewer than 4000 individuals in the 20 years to 2015 (Plumptre et al. 2016). Further recent declines in mountain gorillas have led to extensive inbreeding, with individuals homozygous at 34% of their sequence (Xue et al. 2015).

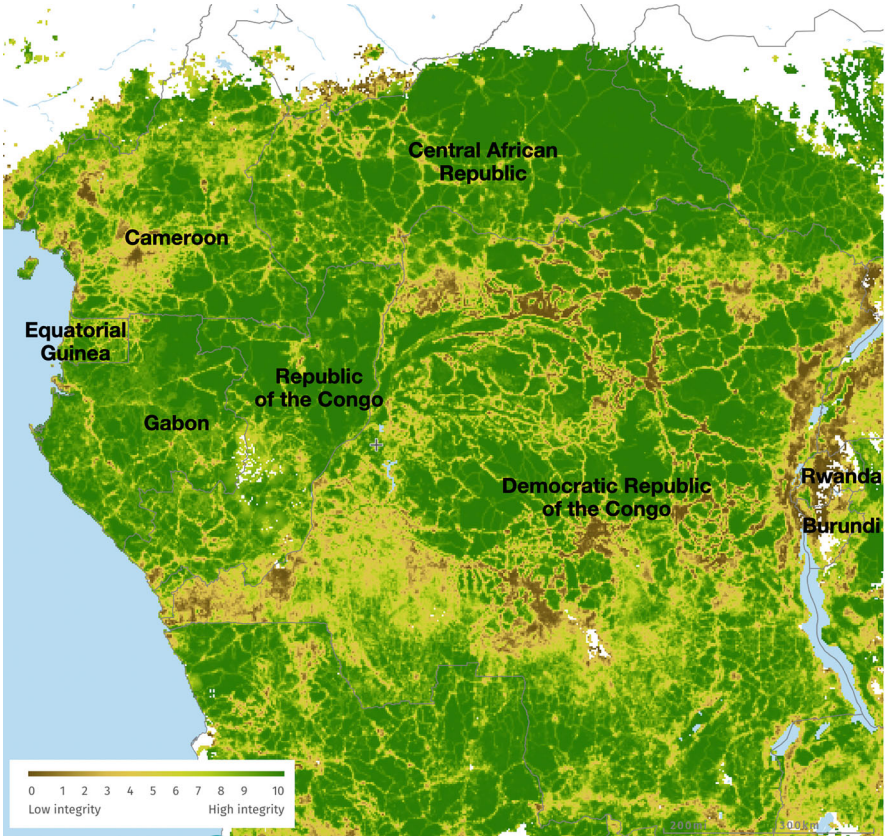

Fig. 3 Forest landscape integrity index. Forest condition as a continuous index determined by degree of anthropogenic modification. Data from 2019 indicated only 40% of remaining forests with high ecological integrity. "Forest Landscape Integrity Index". WCS. Accessed from Global Forest Watch on 18/10/2025. www.globalforestwatch.org

Maintaining viable wildlife populations requires connected habitats that enable movement and preserve genetic diversity for long-term survival (Hohenlohe et al. 2021). Western chimpanzee numbers have fallen by 80% in 24 years, and the species has disappeared from 3 of the 11 countries where it once occurred. Reflecting this crisis, the IUCN reclassified the western chimpanzee as Critically Endangered in 2016 (IUCN 2025 (Humle et al. 2016)) (Figs. 3 and 4).

Impact of Mining

Mining is one of the rapidly expanding economic activities across the Congo Basin, with profound and growing impacts on ecosystems, human, and vertebrate health.

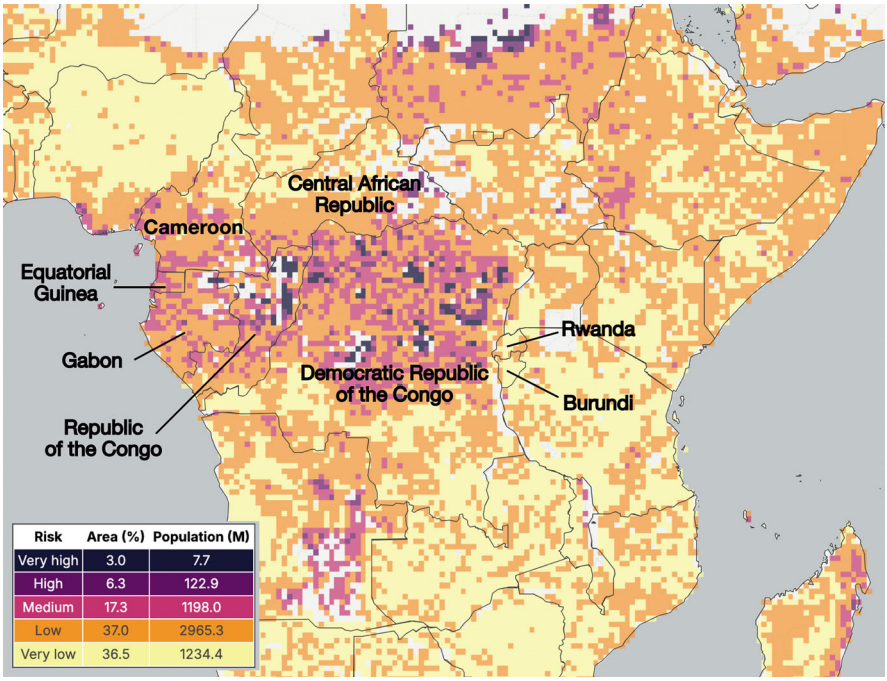

Fig. 4 Disease emergence and spillover risk in the Congo Basin. Relative risk of emergence of WHO priority diseases across the Congo Basin (COVID-19; Crimean-Congo hemorrhagic fever [CCHF]; Ebola virus disease [EVD] and Marburg virus disease [MVD]; Lassa fever; Middle East respiratory syndrome [MERS] and Severe Acute Respiratory Syndrome [SARS]; Nipah virus disease [NiV]; Rift Valley Fever [RVF]; Zika; and a placeholder for an unknown "Disease X"). The risk surface shows the percentage of land area and average population (in millions) falling within each risk category (very low to very high). The data integrates land-use change, biodiversity, livestock density, and human-animal contact, to identify areas with elevated potential for pathogen spillover and outbreak emergence. Fanelli et al. (2025) and European Commission Joint Research Centre (JRC)

Both large-scale industrial operations and artisanal and small-scale mining (ASM) and gold mining (ASGM) suffer from improper management practices that contribute to this footprint. ASM, now responsible for 20–25% of global gold production, has surged alongside a 720% rise in global gold prices over the past two decades, driving extensive deforestation (Fig. 3), biodiversity loss, and climate impacts (Yin et al. 2024). These pressures are degrading habitats, reducing wildlife populations, and exposing miners and nearby communities to health and safety risks.

A major concern linked to ASM is mercury (Hg) pollution. Mercury is widely used to amalgamate gold from ore, but once released into soils and waterways, it is converted by microbes into methylmercury, a highly toxic compound that bioaccumulates through aquatic food webs. In ROC alone, gold mining releases an estimated 15.9 kg of mercury annually, and studies have revealed widespread contamination across the region, including fish, crocodile, and other aquatic species'

muscle tissues exceeding safe consumption limits (Lemaire et al. 2024; Mikala Okouyi et al. 2024) (also see Chaps. 20 and 28). These impacts extend beyond ecotoxicology to food security, as contaminated fish and wildlife pose direct human health risks if consumed by local populations. Artisanal miners consume wild meat, often due to lack of available alternatives, contributing to species' decline and zoonotic risk (Spira et al. 2019).

Without substantial investment in protective measures and governance, both industrial and artisanal mining will continue to drive habitat loss, pollution, and toxicological and zoonotic risks extending far beyond mining sites into regional food systems and urban centers.

Agriculture Expansion, Habitat Conversion, and Disease

Smallholder farming accounts for most agricultural activity in the Congo Basin, producing the majority of the region's food. Increasing smallholder productivity is expected to be the main growth driver for the sector, both through intensification of production and expansion of medium-sized farms (Fraval et al. 2019).

Agricultural intensification, including crop and livestock production, can create conditions that heighten disease vulnerability to people, livestock, and wildlife. Meanwhile, despite the region's dependence on livestock and its high zoonotic disease risk, supporting services such as veterinary capacity, remain limited and unevenly distributed (Criscuolo et al. 2025).

Agricultural systems vary widely, with production modes that can either promote or reduce disease emergence, just as they can destroy or protect biodiversity. Ecological and socioecological characteristics ultimately shape their risk profiles. For example, both the abundance and number of zoonotic host species tend to rise along a gradient from natural to heavily altered environments generated by agricultural activities; people living in modified, agricultural landscapes face roughly twice the infection risk compared to those in less disturbed areas (Gibb et al. 2020) (Fig. 5).

Limited Spillover Detection and Response Capacity

The capacity to detect and respond to spillover events often lags behind ecological risk, particularly in regions with under-resourced health systems. Areas with higher human populations often benefit from stronger infrastructure, healthcare access, and disease control measures; however this is not the case across much of the Congo Basin. The region includes countries with some of the weakest health systems globally (WHO 2023), meaning that even as ecological pressures from land-use change increase, the public health capacity to detect and contain emerging infections remains limited.

The legacies of colonial exploitation, conflict, and chronic underinvestment in health systems have left many countries with inadequate resources for prevention, surveillance, and outbreak response. In such contexts, the likelihood that spillover

events escalate into epidemics, and epidemics into pandemics, is substantially higher. Strengthening community- and national-level health systems is therefore critical, making the Congo Basin a high-priority region for investment in disease surveillance, preparedness, and prevention.

Even with a shift in emphasis from mitigation to prevention, spillover events cannot be fully avoided in landscapes undergoing rapid environmental change. Where robust health systems exist, early detection and rapid response can greatly reduce the health and economic consequences of spillovers (see Box 3).

WHO AFRO has officially adopted the 7-1-7 indicators as a key target for timeliness in its 2022–2030 Regional Strategy for Health Security and Emergencies (Table 1).

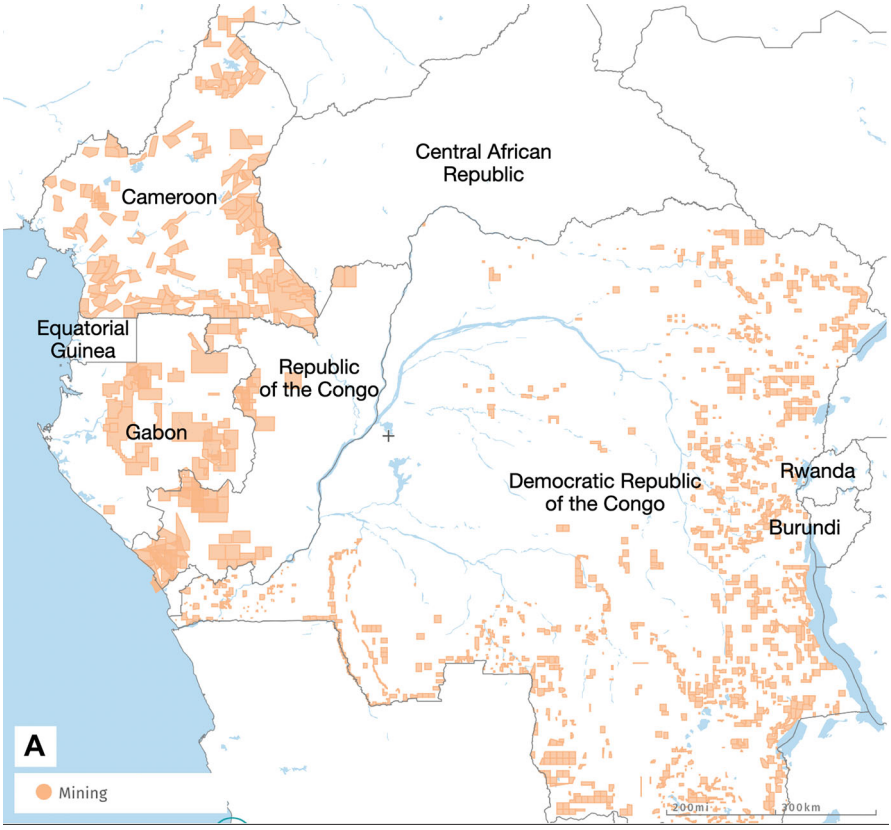

Fig. 5 Mining, logging, and tree cover loss. Boundaries of forest areas allocated by governments to companies for extraction of minerals (**a**); harvesting timber and other wood products (**b**, page 15); and tree cover loss with >30% canopy density in 2024 (**c**, page 16). Accessed from Global Forest Watch on 18/10/2025. www.globalforestwatch.org

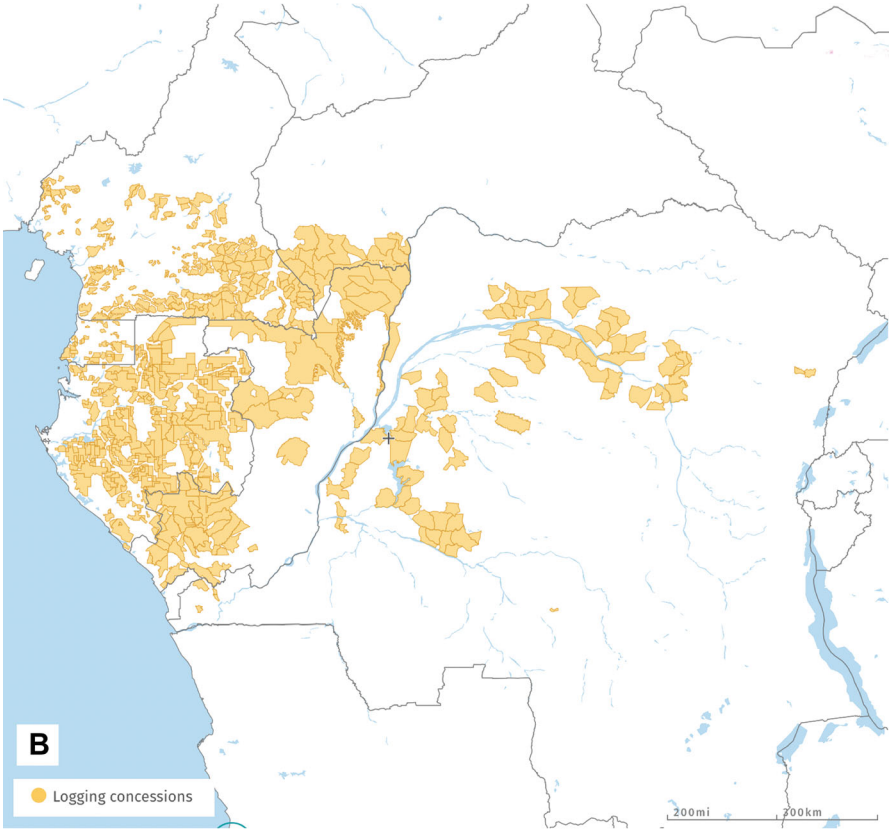

Fig. 5 (continued)

War and Displacement

The Congo Basin has a long history of war and unrest that continues to affect parts of the region.

War and unrest are significant but understudied contributors to disease. It is estimated that conflict doubles the number of reported outbreak cases (compared to those in peaceful countries). Armed conflict often leads to overcrowding and poor sanitation, heightening disease transmission risk, while simultaneously disrupting or preventing monitoring and intervention efforts (Sundaram et al. 2023).

In CAR, following political instability in the 2000s, African elephant (*Loxodonta africana*), water antelope (*Reduncinae*), and topi (*Damaliscus lunatus*) populations each declined by over 90%. Other species declined by 70–80% during the same period, leading to a 94% reduction in large mammals over 30 years due to poaching,

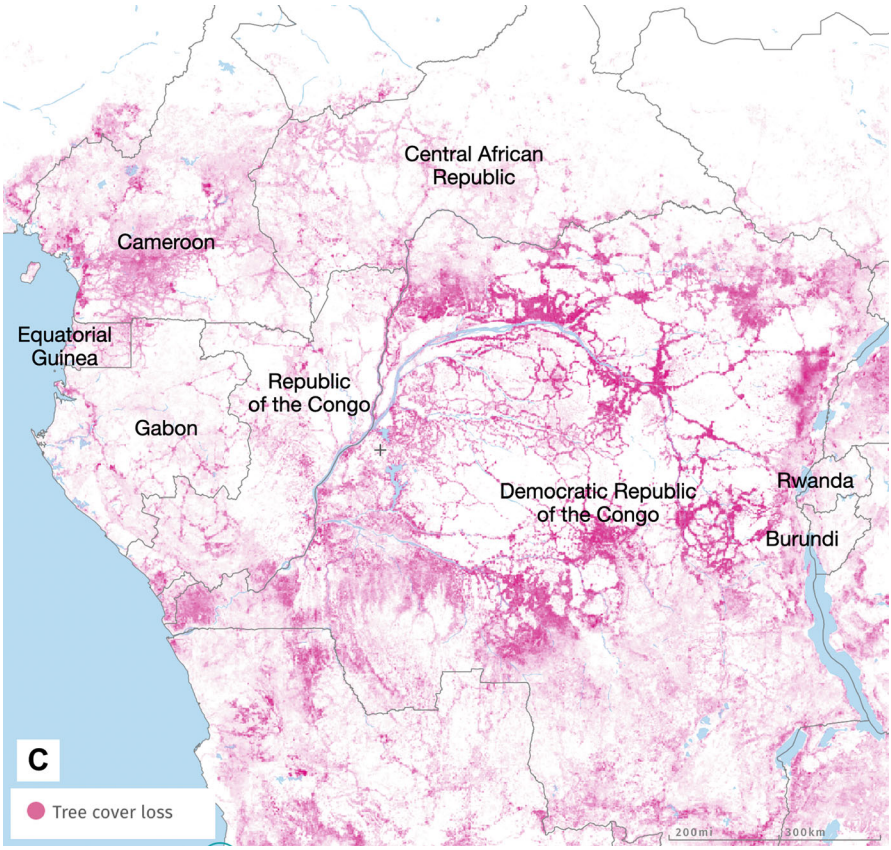

Fig. 5 (continued)

habitat loss, and diseases introduced through illegal cattle movements (Bouché et al. 2012), highlighting the critical resources needed to protect wildlife during conflict.

Box 2. The Disease and Conservation Frontline: The Congo Basin's Amphibians

The Congo Basin is a key region for amphibian conservation. Although the Afrotropical realm has received limited research attention, it likely harbors many undiscovered species, particularly within two hotspots, the forests of West and Central Africa and Madagascar. Amphibians worldwide are threatened by land-use change, climate change, and disease. The Congo Basin, the

(continued)

Box 2. The Disease and Conservation Frontline: The Congo Basin's Amphibians (continued)

Cameroonian Highlands, and the DRC's Albertine Rift are major Threatened Amphibian Landscapes, described as "treasure troves" of species. Disease poses a significant threat to 26% of the 310 species (10% endemic) in the Highlands and 10% of the 54 species (11% endemic) in the Rift (Re:wild et al. 2023).

Since 1980, the extinction risk of 63 species has been reduced, thanks to conservation interventions. The Second Global Amphibian Assessment identifies landscapes with high concentrations of threatened species, the most imperilled genera, and globally important conservation sites, while emphasizing the urgent need to address disease and climate change (Re:wild et al. 2023).

Infectious diseases, particularly chrytridiomycosis, a skin disease caused by the fungus Batrachochytrium dendrobatidis (Bd) poses a major threat to amphibian populations, and continue to cause severe declines even in protected habitats, with no effective treatment for wild populations (▶ Chap. 21, "Effects of Diseases on Wildlife Species in the Congo Basin"). *Despite progress, urgent, coordinated action among governments, donors, academia, and NGOs, guided by the Amphibian Conservation Action Plan and the Global Amphibian Assessment, is needed to secure amphibian recovery worldwide* (Fig. 6).

Table 1 Sustainability indicators and WHO targets for 2030 and/or 2050

Ecological sustainability indicators	Targets for the Congo Basin countries for 2030/2050
Forest cover %	Commitment by the Congo Basin countries to the target of zero deforestation by 2030
Outbreak detection	**Commitment to 7-1-7 Global Framework that sets three time-bound performance targets for human outbreaks** 1. ≤7 days from pathogen's *emergence* to *detection* of a suspected outbreak 2. ≤1 day from *detection* to formal *notification* and initiation of investigation 3. ≤7 days from notification to completion of essential early-response actions (e.g., case confirmation, contact tracing, risk communication, infection-control measures) (WHO 2023; OHHLEP et al. 2022, 2023)
PA coverage (%) and habitat connectivity index	Global commitment, including all Congo Basin countries, to increase protected areas to 30% by 2030 (Kunming-Montreal Global Biodiversity Framework, GBF, Target 3)

Fig. 6 A frog from the *Leptopelis* genus photographed in Bwindi Impenetrable National Park, Uganda. (Photo: Tracie Seimon/WCS)

Scenario Two: Coordinated Implementation of One Heath and Primary Prevention to Protect Biodiversity and Reduce Disease Emergence

Developing effective policy requires an understanding of the links between ecosystem degradation, and disease, and ensuring long-term resilience requires evidence-guided policy interventions that promote sustainable stewardship.

In this scenario, we envisage a future where One Health guides decisions and actions across the Congo Basin. One Health is defined as:

> An integrated, unifying approach that aims to sustainably balance and optimise the health of people, animals, and ecosystems. (OHHLEP et al. 2022).

This whole-of-society approach to health and well-being lends itself to sustainable development, reduced disease emergence, and improved conservation and health outcomes for all.

Primary prevention aims to reduce the chances of a pathogen spillover at the source (Fig. 7; OHHLEP et al. 2022). For example, this includes promotion of landscape immunity through actions that protect and restore wildlife habitat or mitigate wildlife-human interactions to reduce the risk of pathogen spillover (Plowright et al. 2024). The costs of addressing these root causes of pathogen spillover are significantly lower than the costs of responding to emerging viral

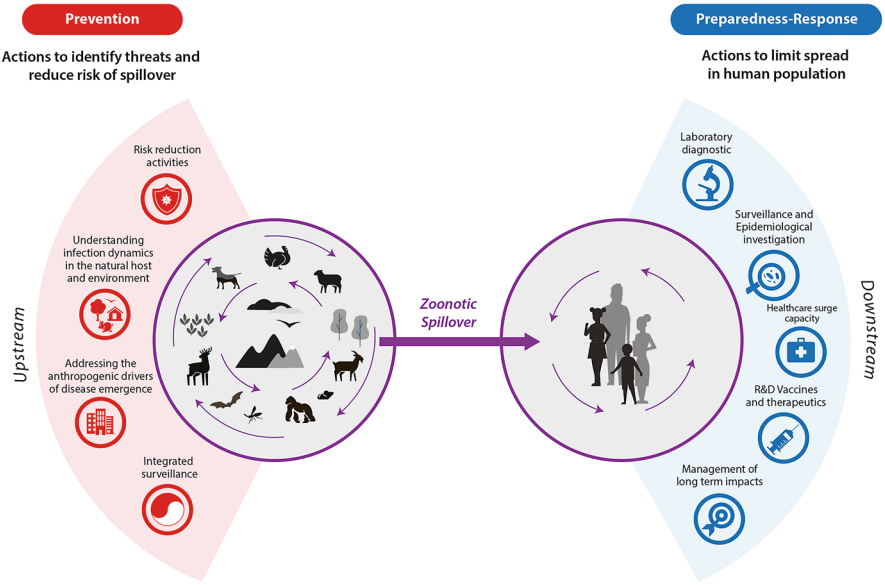

Fig. 7 Prevention of zoonotic spillover to humans: shifting the infectious disease control paradigm from reactive to proactive. (Source: One Health High-Level Expert Panel (OHHLEP). Prevention of Zoonotic Spillover. WHO, 2023. CC BY-NC-SA 3.0 IGO)

zoonoses, and there are substantial co-benefits to climate (Bernstein et al. 2022). Given the inevitable delays in outbreak detection and the unequal access to medical interventions, prevention at the source is an effective, fair, and economically sound approach to global health security and should be prioritised alongside preparedness and response (Bernstein et al. 2022; OHHLEP et al. 2023). Thematically building on the work of Olson et al. (2025), this section outlines a landscape scale approach to reducing disease emergence and proposes policy frameworks for their implementation (see also Table 2). Plowright et al. (2024) identify further actionable ecological interventions and countermeasures that can disrupt spillover mechanisms.

Coordinated Spatial and Infrastructure Planning

Retaining existing ecological integrity to the greatest extent possible should be at the forefront of primary prevention planning in the region (Fig. 3). Given the region's global significance as a carbon sink, these measures are both globally and locally effective. Locally, actions that support climate adaptation also address disease emergence and are both feasible and vital. Key measures include maintaining networks of large, connected forest areas, securing wildlife corridors, and reducing barriers to movement as well as tracking and monitoring for any unintended effects on disease (Thurman et al. 2024). Expert reviews emphasise land-use planning for

Table 2 Broad health and conservation guidance for Congo Basin areas varying from intact to partially disturbed areas

In large, intact, mostly natural areas	In shared and already partially disturbed areas
Retain ecosystem integrity to the greatest extent possible, avoiding expansion of intensive extractive uses (e.g., industrial logging, harvest of animal and plant products); not fragmenting areas with infrastructure, pastures, and farmland; not disrupting natural fire and flood regimes; and removing and restoring anomalies resulting from historical damage. Establish large, effectively managed protected areas, titled Indigenous and community lands, and Indigenous and community-conserved areas. Secure Indigenous knowledge and livelihoods. Ensure multi-stakeholder spatial planning and policies to reduce threats arising from specific economic sectors. Address the commercial and harmful wildlife trade where it begins to emerge.	Avoid further degradation and fragmentation of natural ecosystems. Establish "ecologically representative and well-connected systems of protected areas" with a focus on key biodiversity areas (KBAs); restore and maintain ecological processes and viable populations of native species (between 25% and 75% of the total area of each ecoregion should be under effective protection). Where communal management systems remain, secure Indigenous and community tenure. Integrate sustainable natural resource extraction and activities such as tourism, grazing, and use of wildlife with Indigenous knowledge and protected area networks. Ensure multi-stakeholder spatial planning and policies to reduce threats arising from specific economic sectors. Integrate ecological and human health impact assessments for development projects. Address the wildlife trade that is harmful and not sustainable.
Additional One Health considerations	
Strengthen healthcare infrastructure to meet the needs of Indigenous Peoples and Local Communities, enhance emerging infectious disease surveillance in collaboration with them, and better understand the patterns of exposure and immunity that they experience at wildlife interfaces. Implement or grow wildlife health monitoring or surveillance in and around natural areas with information designed to flow to human health and domestic animal health sectors and stakeholders. Support access to healthcare and treatment, as well as outreach and education on local human health issues and veterinary care for livestock and domestic animals.	Plan land uses, zoning (and restoration) in ways that reduce the degree of existing contact and the extent of high-risk interfaces (e.g., minimize edges, restrict usage, and create buffer zones) where possible. Mitigate the risks of contact where they remain, and be aware of factors (e.g., changing farm practices, further fragmentation of habitats) that may increase levels of risk. Support and grow OH governance from national to local scales. Recognize and embed the conservation sector as core OH actor, acknowledging its critical role in maintaining ecological integrity, regulating human-livestock-wildlife interfaces, and reducing EID risk. Engage communities in human health and education programs that are linked to conservation outcomes.

promoting One Health where avoiding ecosystem conversion and degradation remains a priority (Table 2) (Olson et al. 2025).

A global consensus supports protecting at least 30% of land as natural ecosystems by 2030 ("30 × 30"), and this would make a major contribution to reducing many of

the drivers of spillover and disease emergence (Reaser et al. 2021). However, PAs alone cannot sustain viable wildlife populations and healthy ecosystems. Much suitable habitat lies in non-protected landscapes such as community lands, production forests, and agricultural landscapes, which provide critical corridors and seasonal ranges. As climate change shifts species' distributions, these areas are increasingly vital for connectivity.

Conservation and health planning must therefore extend beyond existing PAs to include other effective area-based conservation measures (OECMs) such as community-managed lands, corridors, and integrated land-use policies (Carvalho et al. 2021). PAs should include zones where biodiversity conservation is the primary goal, alongside management systems led by Indigenous Peoples and local communities. Landscape strategies to reduce spillover risk should integrate a diverse mix of designation types, tailored to local social contexts and the perspectives of rights holders.

Spatial planning, such as zoning, ideally led by local or national governments to ensure legal authority and long-term impact, strengthens conservation by reinforcing existing protected areas and establishing broader designations like conservation mosaics. It helps identify new zones for protection or recognition of traditional land tenure while safeguarding important undesignated landscapes. Steering infrastructure and other high-impact activities away from sensitive areas reduces habitat fragmentation, limits high spillover-risk edges, and separates intensive livestock operations from vulnerable ecosystems. Spatial planning also enhances landscape connectivity (Reaser et al. 2021) and balances ecological benefits, economic costs, and land-use trade-offs. An example is the Kivu-Kinshasa Green Corridor initiative, launched in 2025 in the DRC. Building on the success of commercial activities led by Virunga National Park, the initiative seeks to catalyse sustainable commodity supply chains within a newly created special economic zone that links the east to the west of the country, with explicit environmental protections and outcomes (Virunga Foundation, 2025).

Effectively Managed Protected Areas

Biodiversity conservation through protected areas (PAs) in Central Africa is a relatively old practice, and PAs now cover close to 10% of total land area. The history and future of land protection in the Congo Basin are discussed in ► Chap. 19, "History, Development, and Politics of Protected Areas in the Congo Basin Countries."

Socioeconomic-environmental analyses have found consistent statistical evidence that PAs positively enhance human well-being. Protected areas with positive socioeconomic outcomes are more likely to achieve positive conservation outcomes, particularly when arranged in co-management that empowers local people (Naidoo et al. 2019). Consequently, protection of natural ecosystems through PAs is also central to minimising disease emergence and spillover risk.

The effective enforcement of the rule of law, and in particular of environmental and wildlife law, is relevant to many disease emergence drivers, including land-use

conversion and damage, pollution, and illegal harvesting of wildlife products. However, many existing environmental laws are poorly enforced in the region. Enhanced enforcement could result in reduced ecological damage in landscapes at high risk of spillover. Structures needed for this include building high level political will, capacity-building for law enforcement staff, and increased transparency that enables watchdog organisation to raise awareness about ongoing breaches of the law and encourage state action.

Promoting sustainable livelihoods for communities living in and around PAs is a core function of these areas. When local livelihoods are aligned with conservation and health objectives, this can have a protective effect on ecosystems helping to reduce the pressures that drive disease emergence. Conversely, sustainable ecosystem use reduces environmental degradation and reinforces landscape management by improving economic outcomes for local communities. By easing pressure on wildlife and habitats, such measures lower spillover risks at high-risk interfaces.

Employ Rights-Based Conservation Approaches

Health interventions and measures that strengthen local legitimacy, accountability, and trust are shown to improve long-term success of integrated health-environment interventions (Naidoo et al. 2019; Laird et al. 2020). These could include:

- Community guardianship or stewardship contracts that legally recognise local custodianship of forests and wildlife and allocate defined responsibilities and benefits for surveillance, conservation, and reporting;
- Revenue-sharing mechanisms (e.g., allocating a percentage of sustainable resource-use revenues directly to community-managed funds to strengthen local incentives for biodiversity protection and compliance);
- Transparent data- and benefit-sharing agreements, ensuring that pathogen, biodiversity, or genetic data collected from local landscapes are co-owned and accessible to national institutions and community representatives, following the principles of the Nagoya Protocol;
- Participatory grievance and monitoring systems, where communities can report rights violations or project harms, and where gender-inclusive co-management key performance indicators are tracked.

Limiting the Impact of Extractive Industries and Agriculture

Sector-specific interventions can complement site-based protection and spatial planning by reducing environmental damage. Such actions may be led by development-focused bodies adopting sustainability goals, i.e., environmental agencies, civil society, and local communities advocating for damage prevention, for example, company commitments to zero deforestation or communities opposing harmful mines.

In agricultural expansion and development, the promotion of diverse agroecological matrices that are populated by small- and medium-scale farmers can support biodiversity and also promote robust local food systems, enhance food sovereignty and security, mitigate climate change impacts, and importantly, decrease the probability of disease emergence (Perfecto et al. 2023).

Mining companies have employed a mitigation hierarchy in land-use planning to protect sensitive habitats by rerouting infrastructure and implementing advanced restoration techniques post-mining. The sequential approach of avoidance (steering clear of sensitive areas), minimisation (reducing unavoidable impacts), restoration (rehabilitating ecosystems after disturbance), and, as a last resort, compensating for residual effects through offsets is applied across the life of a mine and helps guide responsible decision-making and contribution to biodiversity goals. Especially focusing on early, preventative stages of the mitigation hierarchy is most effective framework for managing ecosystem impacts (Fernandez Aguilar et al. 2020).

Frameworks such as the Taskforce on Nature-related Financial Disclosures (TNFD) can further help align corporate reporting and investment decisions with biodiversity and health objectives, encouraging companies to integrate ecosystem and spillover risk mitigation into their operational planning and disclosure practices.

In order to effectively manage disease risks, the extractive industries must also integrate health considerations into their Environmental and Social Impact Assessments (ESIAs). Human activity in remote ecosystems can introduce pathogens, pollutants, and stressors that endanger wildlife. Mitigation measures should include healthcare access for workers, strict hygiene, and waste protocols, prohibiting hunting and wildlife consumption by personnel and requiring pre-deployment health screenings, vaccinations, and tuberculosis testing, especially to protect great apes. These safeguards align with IUCN Best Practice Guidelines that emphasise minimising human-wildlife disease transmission.

Improving Local to National Surveillance and Outreach

Mainstreaming wildlife health surveillance and outreach as part of coordinated One Health surveillance is essential (WHO 2023). Across the Congo Basin, the WHO's Joint External Evaluation (JEE) reports and the Pandemic Agreement signed in May 2025 recommend creating systems for routine information sharing and a platform integrating human, animal, and environmental surveillance data (WHO 2023, 2025). It is also called out under Article 5 of the Pandemic Agreement (WHO 2025) and included in the Convention on Biological Diversity (CBD) Global Action Plan on Biodiversity and Health (CBD, 2024). Such early warning systems for disease emergence and other health threats need to involve local to national wildlife health monitoring efforts, including protected area and community-based surveillance with associated outreach and education programs benefiting community well-being (Montecino-Latorre et al. 2025). Rwanda's Gorilla Health Monitoring Program and Uganda's Conservation through Public Health are successful examples of

integrating health and conservation, improving outcomes for both wildlife and humans (Conservation Through Public Health 2025).

Box 3. Lessons from Rwanda's Rapid Marburg Containment: A Model for Global Epidemic Preparedness

In September 2024, Rwanda's Ministry of Health declared an outbreak of Marburg virus disease following the confirmation of a case in Kigali. The index patient, a man in his twenties with a history of bat exposure in a cave, triggered rapid investigations and contact tracing that identified a concentrated cluster of infections among healthcare workers and local residents. By the end of October, 66 confirmed cases had been reported, including 15 deaths. Through swift containment, effective communication, and coordinated national and international response, transmission was halted within weeks. After 42 days with no new cases, Rwanda officially declared the outbreak over on 20 December 2024, marking a successful example of rapid epidemic control.

Despite limited economic resources, the country demonstrated that foresight, coordination, and community trust can overcome material constraints and prevent widespread transmission.

Rwanda's ability to identify cases at the earliest stages was central to its success. Strong surveillance systems, advanced diagnostics, and swift activation of emergency protocols enabled the rapid isolation of suspected cases, preventing wider spread. This prevention-first approach exemplifies the shift from reactive crisis management to proactive preparedness.

The government leveraged trusted local health workers and community leaders to spread accurate information and counter rumors, maintaining public confidence. Clear, consistent communication helped prevent panic, encouraged cooperation, and ensured that control measures were widely followed.

Partnerships with the WHO, the US Center for Disease Control and Prevention (CDC), and the Africa CDC provided real-time data exchange, rapid access to diagnostic tools, and alignment with global best practices. Such collaborations underscore the value of a connected international health network.

Preparedness depends more on foresight and coordination than on wealth alone. Rwanda's preparedness reflects long-term investment in public health infrastructure, laboratory capacity, and workforce training. Political commitment ensured that resources and coordination mechanisms were in place before the crisis.

Finally, Rwanda's example also highlights the importance of equitable global support and the ethical responsibility to strengthen systems in lower-resource settings.

(continued)

Box 3. Lessons from Rwanda's Rapid Marburg Containment: A Model for Global Epidemic Preparedness (continued)

The experience shows that every outbreak can be a catalyst for innovation and stronger health systems. The Marburg response serves as a model for how collective responsibility, transparency, and preparedness can safeguard global health in an interconnected world (Nsanzimana et al. 2025; Branda et al. 2025).

Reducing Spillovers at High-Risk Interfaces

Although some research and interventions target high-risk interfaces in the region, limited publication of results has created a major knowledge gap that limits learning and progress.

Wildlife hunting is one such high-risk interface. It remains vital for many subsistence communities, yet when exploitation exceeds species' reproductive rates, wildlife populations decline, undermining both livelihoods and biodiversity (Abernethy et al. 2016; Coad et al. 2019; Ingram et al. 2021; Willis et al. 2022, ► Chap. 16, "Hunting, Fishing, and Ecosystem Functions and Services in the Congo Basin").

World Organisation for Animal Health (WOAH) provides guidance and tools for risk assessment and reduction measures at critical control points and interfaces along wildlife trade supply chains (WOAH 2024). These systematically address options from risk avoidance, substitutions, implementing engineering solutions, and supporting administrative controls in a hierarchy of controls framework (Fig. 8).

Prioritising collaboration with government forestry, wildlife, livestock, and fisheries agencies is critical to strengthen awareness of protected species and reduce wild meat hunting at high-risk interfaces. Government-led One Health platforms, supported by veterinary and laboratory services, play a key role in addressing the human health risks linked to bushmeat (IPBES, 2020).

Curbing the sales of wildlife products and developing principles that support the sustainable and safer trade of wildlife could be cost-effective investments, given the potential risk and consequences of zoonotic outbreaks. Trade bans however, even selective ones, can have unintended consequences, driving wildlife trade underground and fostering criminal activity due to their socioeconomic and food security impacts. The 2014–2016 bushmeat ban following the Ebola outbreak in West Africa, for instance, led to an expansion of informal trade networks (Bloomfield 2020). Conversely, during COVID-19, no bans were introduced, but media attention on wild meat and disease risks was increased. During this time, nearly half of Cameroonian and one-third of DRC respondents reported reducing their consumption of wild meat. Over half of respondents to these surveys opposed outright bans, underscoring the need for credible communication, local buy-in, and affordable protein substitutes (Li et al. 2025).

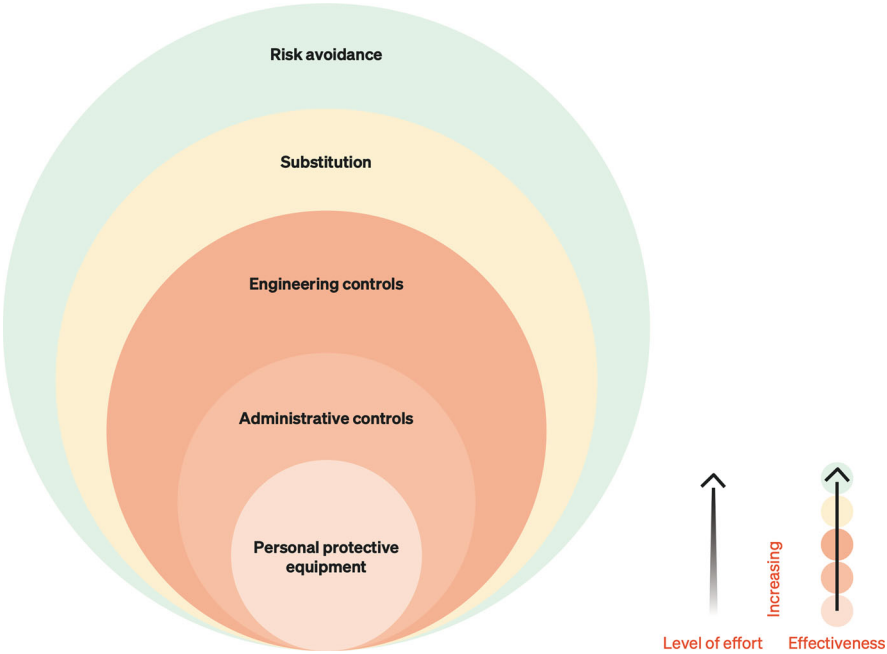

Fig. 8 The hierarchy of controls. At high-risk disease emergence and spillover interfaces, the hierarchy of controls prioritises measures that remove or reduce hazards at their source— beginning with risk avoidance and substitution, followed by engineering and administrative controls, and finally personal protective equipment. Controls higher in the hierarchy are generally more effective but require greater effort and systemic change to implement. (Source: WOAH 2024)

The most effective approaches focus mitigation measures and restrictions on high-risk taxa and species with the highest risk of carrying zoonotic viruses such as bats, rodents, and primates (Ingram et al. 2021; Huong et al. 2020; Osofsky et al. 2023). Affected communities must be involved in decision-making, and alternative livelihoods and food security must be promoted. Likewise, pathogen surveillance should prioritise any high-risk species to maximise cost-effectiveness.

Comparative Analysis of the Future Scenarios

See Table 3.

Potential Tipping Points and Critical Thresholds

Critical thresholds may be reached when ecosystem degradation and species loss undermine ecological resilience beyond recovery. In the status quo scenario, tipping points such as the collapse of keystone species populations could trigger irreversible

Table 3 Comparative policy pathways: continuation of business-as-usual practices versus coordinated, regional, and integrated One Health-aligned environmental management

	Scenario 1: "Business as usual" Lack of integrated One Health and primary prevention management strategies	**Scenario 2: Effective regional and landscape-level One Health and primary prevention management strategies**
Surveillance and early warning	• Lack of collaborative One Health surveillance and reporting. • Delayed detection and response to spillovers, possible regional zoonotic or agricultural pathogen outbreaks. • Poor communication and collaboration between government forestry, wildlife and livestock and fisheries, and public health agencies.	• Public health, animal, and plant diagnostic laboratory networks with effective collaborative One Health surveillance and regional, landscape, and community-level communications. • Focuses on primary prevention of disease emergence with measures that support landscape immunity. • Identifies high-risk interfaces for surveillance—wild meat and priority species. • Early 7–1–7 detection, reporting, and response to zoonotic and epizootic disease transmission. • Integrates wildlife health monitoring with land-use planning. • Minimizes community economic and subsistence losses to pathogens. • Prioritizes communication and collaboration between government forestry, wildlife and livestock and fisheries, and public health agencies.
Protected areas and biodiversity	• Erosion of protected area networks and continued forest loss, uncontrolled mining, and other land use. • Loss of biodiversity leading to erosion of ecosystem and community functions provided by lost species. • Loss of endangered species and changing of ecological interactions, creating new opportunities for spillover. • Increased opportunities for cross-species pathogen transmission, due to increased stress-related pathogen shedding, resources in matrix habitats attracting species displaced from habitat/forest loss or fragmentation. • Food web disruptions (e.g., mesopredator release), possibly increasing disturbance-tolerant species who are highly competent zoonotic disease reservoirs.	• Regional, landscape, and community-level protected area networks and wildlife and ecological management areas. • Increased habitat connectivity. • Areas allowing for integrative management of wildlife and plant communities for holistic ecological community structure and function. • Management strategies enabling endangered species long-term survival. • Utilizes spatial planning (e.g., zoning) led by local and national governments to balance ecological, economic, and land-use trade-offs.

(continued)

Table 3 (continued)

Climate change adaptation	• Limited coordination of land-use planning at scale that could promote climate resilience. • Continuing destruction and fragmentation of intact ecosystems.	• Acknowledges the global importance of the still large areas of intact ecosystem in the region. • Incorporates into activities actions that support key elements for climate adaptation. • Climate-smart development land-use planning. • Strengthening and maintaining the network of intact forest.
Mining and extractive industry practices	• Exploitation of artisanal miners and large-scale mine workers, exposure to contaminants. • Continued contamination of water and land and bioaccumulation in animal tissues with heavy metals (e.g., iron, aluminum, and methylmercury) endangering human, domestic and wild animal, and plant health.	Minimizing negative environmental impacts of mining: • Uses mitigation hierarchy (MH) and commits to its actions to reduce damage. • Economic benefits of mining returning to workers, miners, and local communities. • Incorporates wildlife health considerations with ESIAs to mitigate human impacts.
Agricultural development	Extensive agro-industrial development: • Continuing drive of deforestation and fragmentation. • Displacement of smallholders. • Environmentally costly agricultural production processes. Tend to erode "landscape immunity," increasing zoonotic risk.	Promote diverse agroecological landscapes managed by small- and medium-scale farmers. • Maximize benefits of biodiverse agroecosystems for wildlife, human, and domestic animal health. • Mainstream sustainable practices such as protecting good farmland, practicing productive regenerative agriculture, and keeping nitrogen out of freshwater. • Maintain pollinators and support strategic ecological restoration. • Disturbance-resilient agricultural production. • Strengthen landscape immunity, can simultaneously reduce zoonosis emergence while supporting food security, climate resilience, poverty reduction, and biodiversity conservation.
Social and policy context	• Continuing exploitation of resources with limited benefit to local communities. • Limited health care infrastructure, especially in high-disease-risk interfaces.	Within-country policies prioritizing human and worker rights, environmental justice, and cultural sensitivity: • Protect communities and refugees from displacement to marginal environments. • Prioritize sustainable wildlife use strategies in healthy forests.

(continued)

Table 3 (continued)

		• Infrastructure development for access to clean water, housing, and health care access. • One Health governance structures, processes, and mechanisms implemented to support better decision-making and accountability surrounding management of multisectoral health threats.
Law enforcement	Many existing environmental laws are poorly enforced. Gaps in law enforcement are seen within and outside protected areas. • Driving ecological and disease emergence risk. • Continuing ecosystem conversion and damage, pollution events, and illegal harvesting or transportation of wildlife products.	Enhance enforcement to promote reduced ecological damage in landscapes at high risk of spillover. • Improves capacity-building for enforcement staff. • Increases transparency that enables watchdog organizations to raise awareness.

ecosystem changes that have negative impacts for the well-being of both social and ecological systems. Research suggests that, beyond a certain threshold of wildlife decline, wildlife community collapse and ecological decay are likely (Tagg et al. 2020), and inseparably, these have profound impacts on human populations, livelihoods, and well-being. Policy-driven approaches aim to prevent these thresholds from being crossed by maintaining biodiversity and ecosystem functions and supporting local communities.

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The Climate and Land-Use Change Feedback in the Congo Basin

32

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Abstract

The Congo Basin, home to the world's second-largest tropical rainforest, plays a pivotal role in regulating global climate through carbon sequestration, rainfall recycling, and temperature regulation. However, the acceleration of the land-use changes—driven by agriculture, logging, mining, and urbanization—is eroding these vital ecosystem services. This chapter examines potential feedbacks between land-use change and climate, focusing on how deforestation and degradation disrupt biogeophysical processes and amplify the regional and global climate risks. Using observational evidence and modeling approaches, we show that continued forest loss could transform the Congo Basin from a net carbon sink to a carbon source, exacerbate extreme events such as droughts and floods, and destabilize regional rainfall systems. Future scenarios indicate that deforestation could reduce rainfall by up to 10% and raise surface temperatures by about 0.7 °C by mid-century (~2050). Unfortunately, these impacts extend beyond central Africa and influence tropical circulation and global climate stability. To safeguard the Congo Basin's ecological integrity and climate functions, urgent action is required—through integrated land-use planning, forest conservation, climate-smart agriculture, and robust governance. The chapter underscores that the Congo Basin is both a frontline victim of global change and a critical lever for achieving climate resilience worldwide.

Keywords

Deforestation · Albedo · Evapotranspiration · Sustainability · Earth system · Ecosystem services

Introduction

Climate change and land-use alterations are two of the most critical environmental challenges of the twenty-first century. Human-driven activities, such as deforestation, agriculture expansion, and urbanization, significantly alter natural landscapes, further exacerbating the climate disaster. These processes are deeply interconnected, with land-use changes contributing to climate change, and climate change, in turn, reshaping the earth's ecosystems. Understanding these feedback mechanisms is crucial for formulating effective climate policies and ensuring the resilience of both ecosystems and human societies.

This chapter focuses on the role of the Congo Basin forests in the climate system and how changes in land use and climate interact. In the Congo Basin, the world's second-largest tropical rainforest, these activities threaten not only regional ecosystems but also global climate stability. The basin's forests play a critical role in sequestering carbon, regulating rainfall, and modulating temperatures, which makes their preservation essential for mitigating climate change. However, ongoing deforestation and land-use alterations undermine these ecological functions, leading to more extreme weather events and a destabilization of both local and global climate systems. By examining the biogeophysical processes that govern these interactions, the chapter provides a comprehensive understanding of the dynamics at play and informs strategies for mitigating climate impacts through sustainable land use.

The Importance of the Congo Basin Forest Ecosystems in Global Climate Regulation

The Congo Basin covers an area of around 3.710^6 km^2. This vast forested region plays an essential role in global climate regulation due to its ability to absorb and store carbon dioxide (CO_2) from the atmosphere. The region's forests act as a major carbon sink, sequestering about 1.1 billion tons of CO_2 each year (Eba'a Atyi 2022), making them indispensable for mitigating global climate change. In addition to the carbon sequestration, the Congo Basin forests influence the earth's water and energy cycles and regional and global rainfall patterns through evapotranspiration (te Wierik et al. 2022; Worden et al. 2021), contributing to precipitation through the moisture recycling processes not only across Africa but also impacting weather systems globally (Semazzi and Song 2001). Their ability to moderate temperatures (Nogherotto et al. 2013) and maintain atmospheric moisture is critical in mitigating extreme weather events such as droughts, floods, and tropical storms (Akkermans et al. 2014). However, the Congo Basin is increasingly threatened by deforestation and land-use changes driven by agriculture, logging, and infrastructure development (Eba'a Atyi 2022). The loss of this critical ecosystem would result in a significant reduction in carbon sequestration capacity and destabilize both regional and global climates. Protecting the Congo Basin is not only a regional issue but also a global imperative for maintaining climate stability.

Global Feedback Loops Between Land Cover, Land Use, and Climate and Biogeophysical Interactions

Land cover and land-use changes can significantly affect climate systems through complex biogeophysical feedbacks. Deforestation and land conversion alter surface albedo, evapotranspiration rates, and carbon sequestration capacity, resulting in changes to local temperatures, precipitation patterns, and atmospheric moisture levels. These effects can cascade, creating feedback loops where climate change drives further ecosystem degradation, which in turn accelerates climate impacts.

Globally, the shift from natural landscapes to agricultural and urban areas has led to increased greenhouse gas emissions, reduced biodiversity, and disrupted water cycles, all contributing to the intensification of climate change.

Forests and climate are linked through complex biogeophysical processes that include energy exchanges, moisture dynamics, and greenhouse gas fluxes. Forests absorb more solar energy than more reflective landscapes, shaping local and regional climate. However, evapotranspiration, the process by which trees and plants release water vapor into the atmosphere, helps cool the surface and contributes to cloud formation and precipitation. In tropical rainforests like the Congo Basin, evapotranspiration significantly influences rainfall patterns (te Wierik et al. 2022; Worden et al. 2021), which are essential for maintaining the forest's ecological balance. Furthermore, forests store large quantities of carbon in both vegetation and soil. When forests are cleared or degraded, this stored carbon is released into the atmosphere as CO_2, a potent greenhouse gas, thus contributing to global warming. Additionally, forests affect atmospheric circulation (Nogherotto et al. 2013). The dense vegetation of tropical rainforests reduces surface friction, helping to regulate the movement of air masses, which in turn affects weather patterns around the globe. The biogeophysical interactions between forests and climate are a delicate balance. Human-driven changes in forest cover, especially through deforestation, can disrupt these processes, leading to local, regional, and global climatic shifts. Understanding these interactions is key to addressing the feedback loops that exacerbate climate change.

Biogeophysical and Climate Feedback in the Congo Basin

Carbon Sequestration and Storage

The Congo Basin forests, encompassing the second-largest tropical rainforest in the world, play a critical role in the global carbon cycle (Jiang et al. 2023; White et al. 2021). Acting as a significant carbon sink, these forests absorb approximately 600 million metric tons carbon dioxide per year more than they emit, making them a critical net carbon sink in the global fight against climate change (Harris and Gibbs 2021). This massive carbon sequestration helps offset a portion of global CO_2 emissions, thus mitigating the impacts of global climate change (Ussiri and Lal 2017). Carbon is stored in the vast biomass of trees (Hubau et al. 2020), vegetation (Wang et al. 2021), and soil (Ontl and Schulte 2012), preventing it from being released into the atmosphere and contributing to global warming. The dense vegetation of the Congo Basin forests ensures a continuous cycle of carbon absorption and storage, making these ecosystems essential for maintaining global climate balance (Wang et al. 2021; Molua 2019).

However, the Congo Basin's carbon sequestration capacity is under threat due to deforestation, logging, and other land-use changes (Dargie et al. 2019; Molua 2019). The clearing of forests leads to a reduction in the region's carbon storage potential. When forests are logged or cleared, stored carbon is released into the atmosphere as

CO_2, exacerbating climate change. This shift from carbon sink to carbon source accelerates global warming, as the forest's ability to absorb CO_2 diminishes (Alsdorf et al. 2016; Hubau et al. 2020). Additionally, the degradation of forest ecosystems reduces biodiversity, undermines the resilience of these ecosystems, and increases the likelihood of further emissions through soil degradation and the destruction of remaining vegetation. Protecting and restoring forested areas in the Congo Basin is essential for preserving their role as a global carbon sink (Jiang et al. 2023; White et al. 2021; Molua 2019).

Albedo and Surface Temperature Regulation

The Congo Basin forests significantly influence local and regional climate through the albedo effect, which measures the surface's reflectivity of solar radiation (Moparthy et al. 2019). Forests, with their dark, dense canopies, tend to absorb more solar energy than non-forested areas like grasslands or deserts (Jackson et al. 2008). This absorbed energy heats the surface, affecting local and regional climate systems (Sanderson et al. 2012). When forests are removed, the landscape's albedo increases, as exposed soil or agricultural fields reflect more sunlight (Defries et al. 2002). This alteration in the energy balance can lead to changes in local temperature dynamics, influencing weather patterns and potentially contributing to regional climate shifts.

The changes in albedo caused by deforestation can trigger a series of climate feedbacks (Jiao et al. 2017), particularly regarding surface temperature regulation (Chapin et al. 2008). In tropical rainforest regions like the Congo Basin, forest cover plays a crucial role in moderating temperatures by providing shade and releasing water vapor through evapotranspiration, which cools the surface (De Wasseige et al. 2015). Deforestation reduces these cooling effects, leading to increased surface temperatures. This warming can intensify local and regional climate effects, such as more frequent and severe heat waves, droughts, and changes in precipitation patterns (Mariappan et al. 2023). These changes, in turn, contribute to further forest degradation, creating a dangerous feedback loop where rising temperatures exacerbate the conditions that lead to more deforestation and land degradation (Findell et al. 2017). Effective management of the Congo Basin forests is vital to prevent these feedbacks and maintain stable climate systems.

Present Trends in Land-Use Practices

Agriculture

Shifting cultivation remains a primary driver of land-use change, in the Congo Basin, leading to substantial deforestation and the expansion of the rural complex (see ► Chap. 25, "What Might Influence Economic Forecasts for the Congo Basin?"). This traditional agricultural practice, which involves rotating forested

and fallow land in a slash-and-burn cycle, creates a mosaic of secondary forests, active fields, and fallows (Molinario et al. 2017, 2020). Between 2000 and 2015, subsistence agriculture accounted for the majority of forest clearing, both for the expansion of settled areas and the creation of new clearings in isolated forest regions (Molinario et al. 2020).

Farmers increasingly convert forested areas to cropland to boost production, often employing shifting cultivation techniques (Enongene and Fobissie 2016; Molua et al. 2023). This process is accelerated by population growth, economic development, and the pursuit of food security. The conversion of forests to agricultural land not only causes biodiversity loss and soil degradation but also increases carbon dioxide emissions, contributing to climate change (Ngoma and Yang 2024; Raihan et al. 2022).

The Congo Basin is undergoing rapid land-use changes due to agricultural expansion. Studies warn that planned infrastructure development could potentially triple deforestation rates (Mosnier et al. 2012). Population growth, settlement expansion, and local policies further exacerbate the situation, intensifying the pressure on forest resources (Berakhi et al. 2014). As a result, deforestation in the region is contributing significantly to increased CO_2 emissions. One study estimates that a 1% decrease in forested area could lead to a 5.41% rise in CO_2 emissions over time (Raihan et al. 2022).

Efforts to mitigate these effects include policy initiatives aimed at balancing agricultural development with forest conservation. Various countries in the Congo Basin have proposed REDD+ activities that promote sustainable farming, forest certification, and improved land-use planning (Enongene and Fobissie 2016). However, there is an inherent trade-off between agricultural growth and forest preservation (Mosnier et al. 2012). Policymakers are thus encouraged to prioritize forest protection when planning infrastructure development (Li et al. 2014) and adopt land management strategies that address both food security and environmental sustainability (Molua et al. 2023). Promoting renewable energy and agroforestry can also help balance economic growth with environmental conservation. While commercial activities like mining, plantations, and logging directly account for less than 1% of forest clearing (Molinario et al. 2020), they contribute indirectly to forest loss by attracting worker populations reliant on shifting cultivation for their livelihoods. Additionally, infrastructure developments, such as road construction, are projected to further accelerate deforestation, leading to both the reduction of forest resources and an expansion of agricultural land (Li et al. 2014).

The expansion of agriculture into forested areas in the DRC follows two main patterns: rural complex expansion (RCE) and isolated forest perforations (IFP). Between 2000 and 2010, the rural complex expanded by 10.2%, while perforated forests increased by 74.4% (Molinario et al. 2017). These trends indicate greater intrusion into core forest areas, which further highlights the urgency for sustainable land-use planning and conservation efforts. Strategies such as agricultural intensification, combined with forest protection measures, could help balance agricultural expansion with conservation priorities (Li et al. 2014; Nackoney and Williams 2013). Shifting cultivation, driven largely by subsistence agriculture, is a major

cause of these changes. This practice has created a rural mosaic that includes secondary forests and fallows but also leads to the degradation of large swaths of forested land (Molinario et al. 2020). Between 1990 and 2018, the DRC experienced an estimated net annual deforestation rate of 2.12% ± 0.07%, with an additional annual forest degradation rate of 0.12% (Achille et al. 2021). Such land-use changes are having profound effects, disrupting normal ecosystem functions and resulting in the loss of biodiversity at both genetic and species levels.

Less than 1% of clearing is directly attributable to commercial operations like mining, plantations, and logging (Molinario et al. 2020). However, the indirect effects of these activities are notable. The influx of worker populations dependent on forest products and subsistence farming further exacerbates forest degradation in surrounding areas. Addressing these challenges requires the adoption of sustainable farming practices, improved land-use planning, and climate-smart agricultural techniques (Mangaza et al. 2021; Molua et al. 2023). Such efforts could help balance the pressing need for agricultural productivity with vital conservation efforts, ensuring a more sustainable future for both people and the environment.

Logging and Timber Extraction

Recent scientific findings have revealed the exceptional capacity of the Congo Basin's forests to capture and store atmospheric carbon dioxide at a rate approximately six times higher than the Amazon forests (Harris et al. 2021). It underscores the vital role of the forests in regulating the Earth's climate. Forest degradation and deforestation disrupt carbon storage and influence the hydrological cycle through altering local water recycling patterns (Haensler et al. 2013; Li et al. 2022). Within the context of degradation-driven emissions, timber harvests are the primary contributor in tropical Africa, accounting for approximately 32% (Umunay et al. 2019). Therefore, the importance of sustainable forest management in logging concessions in the Congo Basin cannot be overstated. This approach encompasses selective harvesting along with sustainable production of wood products in areas that have previously undergone logging, with a specific emphasis on the preservation of forest structure, the conservation of biodiversity, and the cultivation of economically valuable species (Doetinchem et al. 2013).

As of 2020, nine tropical countries—Cameroon, Central African Republic, Democratic Republic of the Congo (DRC), Equatorial Guinea, Gabon, Liberia, Republic of the Congo and outside Africa, Indonesia, and Malaysia—allocated an average of 21% of their land to timber concessions, reaching up to 50% in Gabon and 44% in the DRC, making selective logging one of the Congo Basin's most extensive land uses (Burivalova. et al. 2022). While forest management plans (FMPs) are designed to promote sustainable timber production, their effectiveness in reducing deforestation varies. Between 2000 and 2010, deforestation was 74% lower in logging concessions with an FMP compared to those without (Tritsch et al. 2020), indicating that FMPs can help mitigate deforestation through better timber extraction regulation and controlled access to concessions. However, more recent evaluations, such as

those from the Democratic Republic of Congo (DRC), reveal no significant difference in deforestation rates between concessions with FMPs and control areas, raising concerns about inconsistent implementation and monitoring (Chervier et al. 2023). In addition to logging, the Congo Basin is affected by a broader spectrum of land-use activities, including subsistence agriculture, agro-industrial plantations, and wood extraction (Tegegne et al. 2015). Although industrial activities like mining have less widespread impacts, they are often more permanent and contribute significantly to carbon emissions and biodiversity loss. Forest degradation and disturbances have become substantial sources of carbon emissions, with an annual deforestation rate of 0.17% and degradation at 0.09% between 2000 and 2005 (Ernst et al. 2013). Deforestation and other land-use changes, in DRC for instance, released an estimated 530 million tons of CO_2 in 2018—nearly three-quarters of the country's total greenhouse gas emissions—underscoring the Congo Basin's dual role as both a vital carbon sink and an emerging source of emissions (Climate Analytics 2022; Carbon Brief 2023). The environmental impacts of deforestation and forest degradation in the Congo Basin are extensive, affecting biodiversity, climate regulation, soil health, and local ecosystems. Forest degradation not only reduces carbon stocks but also alters precipitation patterns, with some areas experiencing a 5–10% reduction in rainfall due to deforestation (Akkermans et al. 2014). The reduced evaporation and increased albedo contribute to regional warming, with projected further temperature increases of 0.7 °C by the mid-twenty-first century (Akkermans et al. 2014). These changes also affect water quality, as deforestation leads to increased sedimentation and pollutant levels in water bodies (Ngwane 2024). Furthermore, the disruption of the water cycle is impacting both forests and human populations. The slow modification of the water cycle, exacerbated by climate change, poses risks to livelihoods and watershed management (Sonwa et al. 2020). These environmental changes underscore the interconnectedness of land-use decisions and ecosystem services, highlighting the urgent need for integrated environmental management.

In response to these challenges, policy trends in the Congo Basin are increasingly focused on promoting sustainable land use and reducing emissions from deforestation and forest degradation (REDD+). The implementation of REDD+ strategies, along with climate-smart practices like agroforestry, is being promoted to conserve forests, maintain food production, and mitigate climate change. However, despite these efforts, significant challenges remain in addressing institutional and policy factors, which are often the root causes of deforestation and degradation (Tegegne et al. 2015). Forest management plans and REDD+ initiatives are essential steps toward sustainable land use, but their success depends on effective implementation and enforcement. Issues such as illegal logging, land grabbing, and the phenomenon of protected area downgrading, downsizing, and degazettement (PADDD) continue to threaten forests and carbon stocks (Forrest et al. 2014). Additionally, there is growing recognition of the need to incorporate gender considerations into REDD+ strategies, as men and women interact with forests differently and are affected in diverse ways by land-use policies (Brown 2011).

The basin is at a critical juncture, where balancing economic development with environmental conservation is essential for the region's future. While initiatives like

REDD+ and FMPs offer potential pathways to sustainable land management, their effectiveness is often hindered by weak governance and inconsistent implementation. To ensure the long-term protection of the basin's forests and their vital ecological functions, there is an urgent need for improved policy frameworks, stronger enforcement mechanisms, and inclusive approaches that consider the diverse needs of local populations and ecosystems.

Mining and Urbanization

Mining in the Congo Basin is expanding rapidly, with more than a quarter of 4151 recorded mineral occurrences concentrated in areas of high biological endemism, such as the Cameroon-Gabon Lowlands, Eastern DRC Lowlands, and Albertine Rift Mountains (Edwards et al. 2013). These areas, known for their unique ecosystems, face growing pressure from habitat alteration, infrastructure expansion, and increased human migration associated with mining operations (see ▶ Chap. 16, "Hunting, Fishing, and Ecosystem Functions and Services in the Congo Basin"). While small-scale mining, particularly of diamonds and gold, directly supports the livelihoods of around 5% of the population in some areas, the environmental impacts of mining—though currently temporary and localized—are likely to intensify with population growth and insufficient environmental awareness (Ingram et al. 2011). The region's mining sector, especially in biodiversity hotspots, contributes to bushmeat hunting and further forest degradation, putting pressure on both wildlife and local ecosystems (Edwards et al. 2013).

In addition to mining, urbanization is another key driver of land-use change in the Congo Basin. This trend is having profound impacts on local climate patterns. The region is already experiencing the effects of climate change, with increasing temperatures, greater precipitation variability, and shifting seasonal patterns (Molua 2015). Climate models predict that by 2050, the Congo Basin could experience a 7.3% increase in rainfall and temperature rises of 1–3 °C (Molua 2015). These shifts are expected to be further amplified by the continued deforestation and urbanization, both of which disrupt the local climate. For example, the complete removal of the Congo Basin rainforest could cause a 42% decrease in rainfall in the western Congo and a 10% increase in the eastern part, illustrating the complex relationship between land-use change and climate dynamics (Bell et al. 2015).

Recent data from the Yangambi biosphere reserve, located in the heart of the Congo Basin, confirms long-term warming trends and increasing temperature extremes since the 1960s, with notable intensification since the 1990s (Kasongo Yakusu et al. 2023). Moreover, the data points to a drying trend in the dry season and an intensification of the wet season since the early 2000s, likely driven by global climate change and local urbanization. These shifts are already impacting agricultural productivity, further emphasizing the need for climate-smart agriculture and agroforestry systems to mitigate the effects on crop yields. Despite the significant impacts of mining and urbanization, the environmental consequences of these

activities vary across the Congo Basin. For example, artisanal mining in some regions, such as the Sangha Tri-National (TNS) landscape, has so far had limited and temporary environmental effects (Ingram et al. 2011). However, as mining intensifies and populations grow, these impacts are expected to become more severe. Forest ecosystems are particularly at risk, as mining directly leads to deforestation and forest fragmentation, further threatening biodiversity and water resources (Ngamba et al. 2018). The long-term sustainability of forest ecosystems in the Congo Basin is uncertain, given the cumulative effects of mining, urbanization, and climate change.

In addition, the most significant direct environmental impacts of large-scale mining are associated with the discharge of polluted solid and liquid effluents from mining and milling operations that decrease water quality and cause the loss of aquatic habitats and species (Banze wa Mutombo et al. 2022). The loss of terrestrial habitat and biodiversity can be acute, mainly due to anthropogenic activities such as logging and hunting. Generally, mining within forested ecosystems necessitates the removal of trees to facilitate tunneling and pit mining operations and access to mineral deposits beneath the forest canopy (Galli et al. 2022). Timber consumption for constructing wood shaft support, making cooking fires, generating heat to crack rocks in underground workings, and constructing dams to store effluent leads to deforestation (Mwitwa et al. 2012). Most artisanal and small-scale miners lack the knowledge to preserve topsoil and vegetation. The continuous disturbance of soil through repeated turnover, coupled with the thorough extraction of root systems associated with mining activities, significantly hinders ecological regeneration and promotes the proliferation of invasive species. The environmental impact of such practices can be severe and long-lasting. However, mining has a relatively minor impact on large-scale deforestation and forest degradation compared to other land-use-intensive practices, notably agriculture and logging (Mwitwa et al. 2012). The accelerating rate of urbanization in the Congo Basin has been accompanied by growing transportation demands, heightened energy consumption, and intensified industrial activities, which all result in increased greenhouse gas emissions in urban areas (Sun and Weng 2024). Deforestation associated with urban development alters the interaction between atmosphere and land and affects the roughness of the surface, thermal inertia, hydraulic properties, and radiative balance, which leads to changes in meteorological conditions of the surface and the occurrence of urban heat and cool island phenomena (Zeleke et al. 2023).

Addressing these challenges requires a balanced approach that considers both economic development and environmental conservation. The current paradigm of profit maximization in the mining sector is unsustainable and calls for a shift toward sustainable livelihoods and forest conservation programs (Check 2011). The integration of REDD+ initiatives, land-use planning, and zoning of mined areas could support the transition to a green economy and low-carbon development (Enongene and Fobissie 2016). Strengthening governance, improving environmental impact assessments, and promoting sustainable practices are crucial steps in mitigating the negative effects of mining and urbanization on the Congo Basin's forests (Ngoma and Yang 2024; Edwards et al. 2013).

Land Cover and Land-Use Change and Its Impact on Global Climate

Changes in land use and land cover in the Congo Basin could have far-reaching implications for the Earth's climate system. The reduction of the forested area would weaken the basin's role as a carbon sink, leading to higher atmospheric CO_2 levels. This loss of forest cover could also disrupt the basin's influence on global weather patterns, including shifts in tropical rainfall and temperature regulation. Furthermore, as deforestation progresses, the region may transition from being a net carbon sink to a carbon source, potentially accelerating global warming and influencing climate outcomes worldwide.

Understanding how vegetation influences the distribution of energy in the environment is challenging, especially when trying to apply findings across large regions due to limited data from both observational studies and modeling efforts (Kang and Sridhar 2020). Despite these difficulties, several studies offer insight into how energy is divided among different components using hydrological models and remote sensing datasets—specifically, net radiation being distributed into latent heat (associated with evaporation and transpiration), sensible heat (related to temperature changes in the air), and ground heat flux (energy transferred into the soil) (Sridhar et al. 2013). Generally, the proportion of energy allocated to these components varies significantly based on soil moisture conditions, with dry, moderately wet, and wet soils showing distinct patterns of sensible, latent, and ground heat fluxes (Sridhar 2013; Sridhar and Valayamkunnath 2018).

In Africa, significant changes in land cover and land use have occurred over the past few decades, including deforestation, expansion of agriculture, and urbanization. These changes have considerably impacted the way vegetation mediates exchanges between the land and atmosphere, influencing energy fluxes and water cycles. Vegetation plays a critical role in regulating the energy budget through processes like transpiration, which drives latent heat flux, and shading, which affects sensible heat flux. As land use and land cover evolve, so do these dynamics, leading to alterations in regional climate patterns and hydrological cycles.

Research has consistently shown that vegetation plays a substantial role in modulating the interactions between the land surface and the atmosphere. Changes in vegetation cover can shift the balance between latent and sensible heat, impacting local temperatures, humidity levels, and even precipitation patterns. The transformation of landscapes through deforestation or reforestation or agriculture, for instance, can either amplify or dampen these exchanges, highlighting the significant influence of vegetation on climate regulation (Sridhar and Anderson 2017). Thus, understanding these processes is crucial for predicting future climate scenarios, especially in regions undergoing rapid land-use changes. A comparison of land use and land cover in the Congo River Basin between 1992 and 2015, using the annual land cover maps from the European Space Agency Climate Change Initiative (ESA-CCI) at a 300-meter resolution, reveals notable shifts in some land cover types (Sridhar and Rangarajan 2022). The basin displays considerable variability in land use and land cover, with 37 distinct classes identified based on the United Nations Land Cover Classification System. For analysis of major changes, these classes were

consolidated into 10 categories following the International Geosphere–Biosphere Programme (IGBP) framework.

Evergreen broadleaf forests dominated more than 40% of the basin, particularly in the subbasins of Middle Congo, Ruki, Yangambi, Sangha, Kinshasa, and Matadi. Cropland areas were also found within these regions, while deciduous forests were primarily located in the Kasai, Upper Congo, Tanganyika, and Oubangui subbasins. Overall, forests covered more than 80% of the Congo Basin. Additionally, Lake Tanganyika in the southeast accounted for over 1.5% of the basin's total area.

Some regions, particularly in the western and eastern border areas, exhibited human activity, including cropland (9.9%), bare soil (2.2%), and shrubland (2.8%). Cropland was also sparsely scattered across Middle Congo. Anthropogenic impacts became more pronounced over time, with forest areas decreasing by 746 km^2, natural vegetation shrinking by 30,000 km^2, urban areas expanding by 883 km^2, and cropland increasing by 3866 km^2 between the periods of 1992–2003 and 2004–2015. Significant deforestation occurred across the rainforests in the Middle Congo and Oubangui regions from 1990 to 2010. Specifically, in Middle Congo, tree cover fell by 2.2%, grassland diminished by 47.9%, while cropland and urban areas grew by 13.3% and 94.4%, respectively, between 1992 and 2012. In the Oubangui region, cropland expanded by 17.6%, urban areas by 42.5%, and shrubland declined by 68.5%. The impacts of these land cover changes on hydrology were assessed using simulations based on land cover data from 1992 to 2012.

Climate Modeling and Vulnerabilities in the Congo Basin

The ecosystem degradation, primarily driven by anthropogenic activities such as deforestation, urbanization, and agricultural expansion, significantly alters climate systems at both regional and global scales. Changes in land cover directly affect energy fluxes, evapotranspiration, hydrologic processes, and carbon sequestration, leading to alterations in local climate and contributing to broader climate change (Houghton 2005). These land-use changes can drastically disrupt the water cycle, intensify land degradation, and reduce ecosystem resilience, particularly in tropical regions where deforestation and land conversion are dominant (Foley et al. 2005). The Congo River Basin, one of the largest tropical rainforests, is especially vulnerable to such changes. The basin serves as a critical carbon sink and is home to one of the most significant hydroclimatic systems in the world (Alsdorf et al. 2016). In particular, the Congo Basin faces threats from deforestation and land-use changes, which contribute to biodiversity loss and weaken the resilience of ecosystems to climate change. Recently, many parts of the Congo River Basin were selected as "Recent human impacts on the terrestrial biodiversity hotspots" (Costello et al. 2022), as discussed in the IPCC's Sixth Assessment Report (AR6), highlighting the significant effects human activities have had on biodiversity-rich regions globally.

Deforestation and land conversion in the Congo Basin result in more frequent and intense droughts and floods, particularly in areas already vulnerable to climatic

fluctuations (Lima et al. 2014). In tropical regions, the removal of forest cover increases soil erosion, decreases infiltration rates, and disrupts the hydrological balance (Borrelli et al. 2017). These changes to local ecosystems have profound implications for regional and global water cycles (Lawrence and Vandecar 2015). The acceleration of deforestation in the Congo Basin negatively impacts hydrological processes, threatening biodiversity and diminishing the water flow, exacerbating droughts and floods. In addition, increased temperatures, driven by global climate forcing, are expected to exacerbate heatwave intensity and duration, further increasing evapotranspiration rates and water stress (IPCC 2021).

Climate change is particularly concerning for the Congo River Basin, where projected temperature increases could significantly alter rainfall patterns and reduce water availability (Malhi and Wright 2004). Precipitation is highly sensitive to shifts in climate, leading to increased drought conditions in the entire Congo River Basin (Karam et al. 2022). The Congo River Basin faces many environmental challenges due to land-use changes. In conjunction with population growth, forest clearing for agriculture and logging has significantly transformed the landscape (Tshimanga et al. 2022). Such transformations can lead to reduced evapotranspiration, greater surface runoff, and increased sediment transport into rivers, which can alter aquatic habitats and water quality (Laraque et al. 2001). Moreover, as the basin continues to experience rapid urbanization, the impervious surfaces created by urban areas exacerbate flooding risks and reduce groundwater recharge, placing additional strain on water resources (Bilgiç and Baba 2023).

In this section, we utilize the Soil and Water Assessment Tool (SWAT; Arnold et al. 1998) model with climate projections to examine the impacts of land use and climate changes on ecosystem degradation, specifically focusing on shifts in precipitation and temperature patterns. The SWAT model has proven effective in capturing the hydrological impacts of land-use changes, such as deforestation and agricultural expansion, particularly on runoff (Ghaffari et al. 2010; Wang et al. 2014), soil erosion (Zhang et al. 2017; Halecki et al. 2018), and drought (Zhu et al. 2022). Additionally, the SWAT model has been applied to assess climate change impacts on large river basins, including the Congo River Basin (Sridhar et al. 2021). It provides a robust framework for examining how projected land use and climate scenarios will affect water availability, erosion, and ecosystem health in the region. By applying the SWAT model to regions undergoing rapid land-use changes, we can assess the influence of land degradation and climate change on hydrological cycles and highlight the compounding effects on water resources, offering critical insights for the Congo River Basin.

Climate change is projected to intensify extreme weather in the Congo River Basin, with future shifts in rainfall patterns and river discharge suggesting more frequent and severe flood and drought events (Karam et al. 2022). The SWAT model quantifies these changes and helps identify the most vulnerable areas from ecosystem degradation and hydrologic stress (Datok et al. 2021; Karam et al. 2022) as shown in Fig. 1. This information is essential for developing effective adaptation and mitigation strategies to preserve the basin's ecological integrity and sustain its vital ecosystem services. Integrating land use and climate models offers a comprehensive

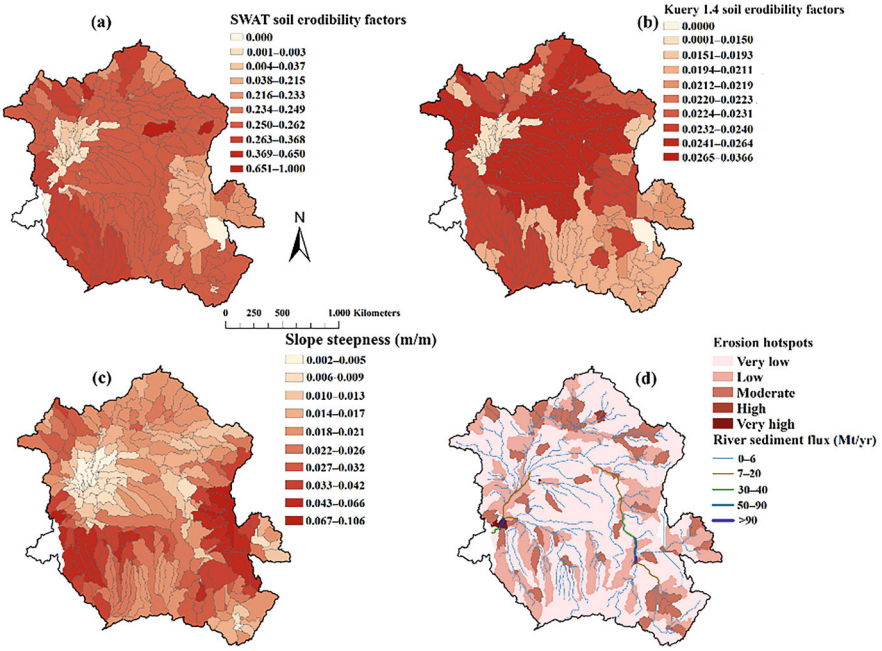

Fig. 1 Four-panel map showing soil erodibility and erosion characteristics of the study area for the simulation period 2000–2012. Panel (**a**) presents SWAT soil erodibility factors, and panel (**b**) presents Kuery 1.4 soil erodibility factors, with darker shades indicating higher erodibility. Panel (**c**) presents slope steepness, with darker colors representing steeper terrain. Panel (**d**) presents erosion hotspots and river sediment flux, with erosion intensity and sediment flux distinguished by color. A scale bar and north arrow are included (Source: Datok et al. 2021)

approach to understanding the future of the Congo River Basin and informing policy decisions that promote sustainable management of natural resources.

Future Scenarios and Best Practices

Recently, an observational study (Tyukavina et al. 2018) revealed that between 2000 and 2014, Congo basin forests lost 0.92% of their total area. This deforestation is due to the predominance of small-scale subsistence farming, which is largely driven by the poverty stemmed from political instability and conflict in the region (Tyukavina et al. 2018; Norris et al. 2010). But further demand for agricultural land is expected to increase due to the growth of the population over the coming decades and that will likely yield important deforestation by the end of this century. Subsequently, this will impact the climate patterns at local, regional, and global scales through the modification of biogeophysical interactions between land and atmosphere (i.e., fluxes of energy, moisture, and momentum) and so affecting directly the land surface properties by changing the albedo. To realistically quantify the deforestation impact on the

future climate in the Congo Basin, many studies have been performed (Polcher and Laval 1994; Varejao-Silva et al. 1998; Semazzi and Song 2001; Osborne et al. 2004; Nogherotto et al. 2013; Akkermans et al. 2014). The idealized scenario used in early numerical modeling studies consisted in removing all forest to replace it by a single land cover type such as bare soil or grass. In response, these studies found a surface warming and decrease in regional precipitation, with larger amplitude when the deforestation occurs in regions close to the ocean (van der Molen et al. 2006). In addition, there is a substantial increase of moisture convergence, which is attributed to enhanced convective activity associated with the intertropical convergence zone (Polcher and Laval 1994). To improve the understanding of the atmospheric response to a total forest removal, Nogherotto et al. (2013) performed an experiment on a regional climate model (RCM), with higher horizontal resolution. They revealed that over deforested areas of Central Africa, a thermal low can form locally and be associated with a reduction of both evaporation and precipitation. But the changes in atmospheric circulation induced by the deforestation play a crucial remote role to influence the regional monsoon dynamics (Nogherotto et al. 2013).

Unfortunately, abovementioned studies are based on the unrealistic assumption of total forest removal with furthermore a completely homogeneous conversion to pasture. For realistic projections in which five improvements have been performed (Akkermans et al. 2014): (i) the first step is to improve the deforestation scenario—instead of simply removing all the forest or using chessboard-type deforestation patterns, spatially explicit scenarios should be used, which are often based on algorithms using socioeconomic input data and assumptions for the future. (ii) A necessary condition for such spatially explicit scenarios is an improvement of the horizontal model grid resolution. (iii) Apart from the spatial patterns of future deforestation, the absolute amount of future forest removal should be within the range of plausible estimates instead of earlier-used rough assumptions such as a complete basin-wide conversion of forest to, for example, pasture or crops. (iv) Given the crucial importance of the interplay between vegetation and the overlying atmosphere and acknowledging the great progress that the scientific community has made in recent years to develop comprehensive land surface models, the use of a state-of-the-art soil–vegetation–atmosphere transfer (SVAT) scheme within the climate model is mandatory for deforestation impact studies. (v) An increase in complexity is only beneficial when detailed information about replacement vegetation is available, that is, what vegetation type(s) will substitute the removed forest. They found that by 2050, the surface temperature will increase by 0.7 K due to the reduction of the cooling effect as the evaporation decreases. This mitigates the albedo and increases the sensible heat loss to the atmosphere. As for the rainfall, it will decrease by 5–10% because the thermal low is likely to form over the deforested areas, which reinforces the low-level convergence and so distributes the moisture at near surface and stabilizes the atmospheric column, suggestive of convection suppression and its associated reduced rainfall over the underlying region.

Furthermore, the choice of realistic experiments of deforestation over Congo Basin is crucial to underscore the importance of the biodiversity conservation in the Congo Basin, from genes to ecosystems, but also highlight substantial uncertainties surrounding the future persistence of Congo Basin biodiversity in the face of current and future global changes (see ▶ Chap. 23, "Opportunities and Potential for Sustainable Development in the Congo Basin from an Environmental Sustainability Perspective"). However, many potential impacts on Congo Basin ecological processes are undocumented (Beekmann et al. 2024). Deforestation in the Congo Basin is projected to lead to substantial economic losses due to climate damage. The release of stored carbon from deforestation contributes to global climate change, which is associated with increased costs related to extreme weather events, health impacts, agricultural productivity declines, and infrastructure damage. Estimates suggest that the economic value of climate damage from deforestation in the Congo Basin could be billions of dollars annually, reflecting the high cost of lost ecosystem services and increased climate-related risks.

Achieving sustainable levels of natural resource use and transitioning to net-zero or carbon-positive economies in the Congo Basin would significantly improve the future for biodiversity and ecosystems. Sustainable management practices, such as agroforestry, conservation agriculture, and forest restoration, could help maintain habitat connectivity, reduce deforestation, and enhance ecosystem resilience. If countries in the region achieved net-zero emissions, the basin's ecosystems would likely experience a revival in biodiversity, stabilization of local climates, and a restoration of critical ecosystem services, thus contributing positively to both regional and global environmental goals.

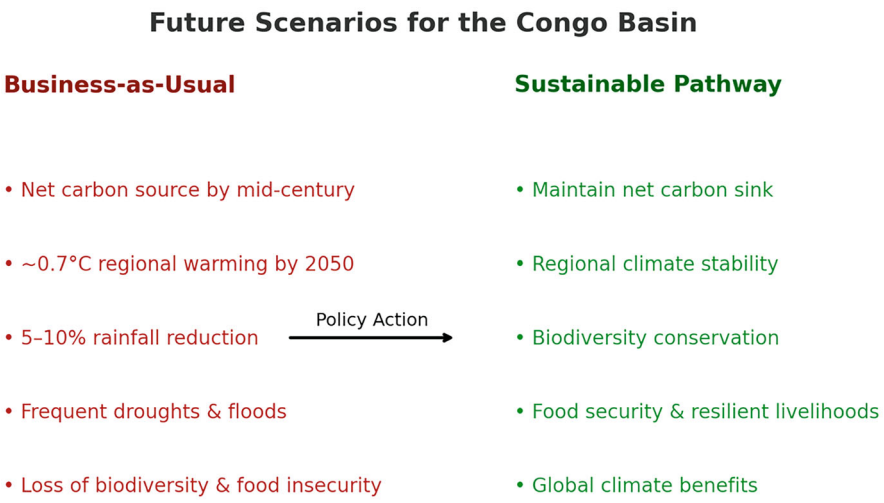

Fig. 2 Diagram comparing business-as-usual and sustainable future pathways for the Congo Basin, showing contrasting climate, environmental, and socio-economic outcomes, with policy action enabling a transition to sustainability

Summary

The future of the Congo Basin and its critical role in the Earth's climate system hinge on the adoption of integrated land-use planning, conservation efforts, and sustainable resource management. The main messages can be summarized in Fig. 2.

The Congo Basin is a global climate regulator, but ongoing deforestation risks shifting it from a carbon sink to a carbon source, accelerating warming.

- Future scenarios project up to 0.7 °C regional warming and 5–10% rainfall reduction by 2050 if deforestation trends persist, with cascading impacts on agriculture, water resources, and biodiversity.
- Feedback loops between land-use change and climate amplify vulnerabilities: forest loss increases heat and reduces evapotranspiration, reinforcing droughts, floods, and ecosystem degradation.
- Socioeconomic drivers—population growth, food insecurity, logging, and mining—will intensify pressure on land unless addressed through sustainable policies.
- Best practices include agroforestry, conservation agriculture, REDD+ initiatives, and strengthening governance over land tenure and logging concessions.
- Achieving net-zero or carbon-positive economies in the basin could restore biodiversity, stabilize regional climates, and provide global climate benefits.
- The Congo Basin's future is a tipping point for climate stability: protecting it is not only a regional necessity but also a global imperative.

Competing Interest Declaration The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

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Section IV

How Can Scientific Data Inform Climate-Resilient Sustainable Land-Use, Help Address Poverty, and Achieve Sustainable Development Goals Across the Region?

Spatial Dimensions of Existing Conservation Areas and Other Land Uses in the Congo Basin

33

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Abstract

Remote sensing (RS) techniques and Geographic Information Systems (GIS) for earth observation have significantly improved the ability to map and measure forest composition, estimate height and biomass, detect degradation and deforestation, implement land use planning, track land use changes as well as monitoring the implementation and respect of land development policies at a finer scale. Machine learning approaches further enhance these capabilities by integrating multiple data sources to produce improved maps of forest attributes and track changes over time. Recent advances in remote sensing techniques and artificial intelligence (AI) now enable detailed mapping and modelling of conservation areas especially the demarcation of High Valued Conservation Forest. National governments follow an administrative procedure for national map design, validation, and standardization. National governments together with the national mapping institutions select particular government officials, the private sector, civil society organizations, and foreign partners to produce national maps. On the other hand, scientists use a rigorous methodology that combines cutting-edge

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tools and peer review approaches. Even if some of the maps mentioned have not undergone the validation process by the various governments of the sub-region, they are widely used or referred to in international negotiations and discussions. Adopting innovative policies on mapping (Indonesia's one map policy, Rwanda National land registry) and spatial data management (Geoportal for the Region, The INSPIRE Directive) will be very helpful in planning and conserving the Congo Basin. Non the less, Gabon, the DRC and Cameroon have made exceptions by producing and using renowned National Geoportal.

Keywords

Congo Basin · Remote sensing · GIS · Mapping · Biodiversity conservation · Spatial demarcation · Land uses · Overlapping land uses

Introduction

Tropical forests have been at the center of global issues for several years now, either being at the forefront of international conventions or due to biodiversity (Seymour and Busch 2016). They are reservoirs of carbon and biodiversity, offering means of subsistence for millions of people. The forests in the Congo Basin represent 22% of the world's forest cover. However, forest cover in west African countries declined by 20% between 2000 and 2010 (FAO 2022; FDA 2022). From 2002 to 2024, Cameroon and DRC lost 1.07 Mha and 7.45 Mha of primary rainforest respectively, which represents 49% and 36% of its total loss of tree cover over the same of its total tree cover loss over the same period.

In the Congo Basin, different types of land cover have contrasting floristic and faunistic composition and functions (Réjou-Méchain et al. 2021) and thus play different roles in biogeophysical and chemical fluxes (e.g., C storage in Congo Basin peatlands, soil carbon, sediment load in watercourses). The growing demand for food, water, and shelter change the way people use land. Small-scale forest clearing for agriculture is particularly prevalent in the Congo Basin Forest where it accounts for more than 80% of the total forest cover loss in the region between 2001 and 2015 (Curtis et al. 2018; Tyukavina et al. 2018).

Another characteristic of the Congo Basin is that forest exploitation is mainly performed through selective logging which represents the second most significant disturbance driver in the region (Tyukavina et al. 2018). On the contrary, large-scale deforestation was the main driver of forest loss in the Amazon and Southeast Asia, accounting for more than 60% (Curtis et al. 2018), National pledges have set a shared intention to halt and reverse deforestation and ecosystem degradation by 2030. But in 2023, tropical forests remained under massive pressure putting the forest and biodiversity goals under threat.

Gaining better knowledge of these changes is a pre-requisite for implementing and tracking policies for the conservation of natural resources and land use planning. Recent developments in remote sensing and GIS technologies have shown there are

significant overlaps between mining concessions and pre-existing forms of land tenure (Mitchell 2016; Walker et al. 2023). In sub-Saharan Africa where these technologies are underused by sectorial ministry, there is still effort to be done. Conflicts from these overlapping situations do not erupt in isolation; they are the result of multiple interacting causes.

Mapping land use in regions of the Global South had been aiding decision-making. The successful Indonesia's one map policy, Rwanda National land registry are some examples that provided a consistent record of land tenure with a view to resolving land-use conflicts in the forestry sector. There is still a lack of appropriation and use of spatialized land use data and monitoring of changes in the Congo Basin.

The Congo Basin countries has been highlighted as a region with insufficient monitoring capacities for REDD+ purposes (Romijn et al. 2012; Romijn et al. 2015). Consequently, these tropical countries have been in a recurrent need of technical knowledge and financial means to perform the process, particularly in the areas of the forest monitoring, biomass and carbon stock evaluation, forest mapping, and reporting systems required to claim a payment (Sufo et al. 2020). The last decade has seen an increase in the technical knowledge especially in the field of GIS and remote sensing though the central African states are not taking advantage of this to develop land use systems. Gabon and Rwanda have the most advanced systems in terms of land allocation. Gabon undertook itself a successful REDD+ process and is one of only two countries in Africa with REDD+ results verified on the Lima Hub (Fig. 1).

All these findings raise several fundamental questions relating to the categorization of land uses, their dynamics, and the management problems they may give rise to. How can remote sensing (RS)/GIS technologies help to improve conservation in the region? How can spatially explicit demarcations help untangle conflicting land uses due to overlapping interest? How are maps constructed, validated, and used by the various stakeholders in Central Africa, in particular governments, the private sector and civil society? Who are the various stakeholders and capacities involved in producing and disseminating spatially explicit data? Can a Regional Spatial Data Infrastructure be established? Can maps contribute to sustainable development in the region?

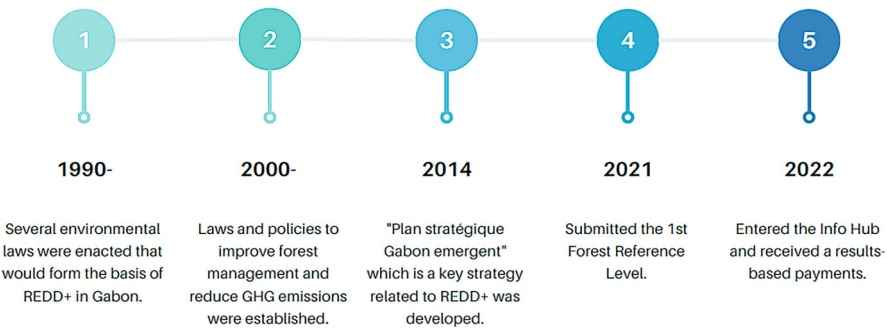

Fig. 1 REDD+ history in Gabon

This chapter aims to demonstrate the importance of maps and spatial databases in conservation, land allocation, and land use planning. It also shows the low level of interest shown by the sectoral ministries and central government in the production and usage of maps and spatial databases. Despite the efforts of national, sub-regional, and international institutions to produce maps, these tools are still under-used by States to resolve conflicts and structure land use. Finally, the chapter proposes the creation of a Regional Spatial Data Instructure by the central governments in order for them to be fully implicated and benefit from recent remote sensing and GIS technologies including artificial intelligence.

The Evolution of RS/GIS, Digital and Technological Tools in the Region

The management of forests in the Congo Basin is increasingly relying on various tools for assessment and management. Digital tools have become a significant milestone in the region, marking a transition from traditional non-digital methods to a new digital era. The use of remote sensing for mapping has evolved, offering new perspectives for sustainable management. To support this evolution, the AGEOS structure in Libreville, result of the Gabon-France-Brazil cooperation, has been established. However, its potential has not yet been fully realized by governments and stakeholders. The OFAC (Observatoire des Forêts du Bassin du Congo) has utilized digital tools for data storage and dissemination among Congo Basin states. The Global Forest Watch (GFW) promoted by WRI, and its partners has also contributed by providing geospatial tools for broader public access and monitoring of forests. Additionally, the OSFAC (satellite observatory of Central African Forests) has been created to deliver digital earth information to scientific communities and decision-makers, while also building capacity in the Congo Basin.

Effective conservation of tropical forests would be greatly facilitated by accurate, near real-time monitoring of forest disturbance, carbon stocks, and biodiversity. In Central African Republic, the GIS tool has demonstrated its utility to be used as strategic and operational decision support tool (Mokpidie et al. 2014). Remote sensing techniques, including multi-spectral data, lidar-based canopy height and vertical structure detection, and radar interferometry, have significantly improved our ability to map forest composition, estimate height and biomass, and detect degradation and deforestation features at a finer scale (Bossy et al. 2025).

There is progress at several levels in central Africa, in that while Gabon, Cameroon, and Rwanda are making lightning progress, the other countries are lagging.

Until the mid-1990s, maps were mostly paper and difficult to obtain. Mining and logging permit map in Gabon were a tightly kept secret. If we refer on the publication of Barnes et al. (1991) and Tutin and Fernandez (1993), it shows that there is a huge work on monitoring resources by using maps in Gabon. In fact, during the late 1970s and early 1980s, Tutin and Fernandez (1993) did the national ape survey in Gabon (1979–1983), compiling for the first time a national database on a component of the country's biodiversity. Then Barnes et al. (1991) did a national elephant

survey in Gabon between 1985 and 1988 using early GIS programs to analyze the data. This effort was extended to all Congo Basin forest elephant surveys.

ECOFAC, which was launched in 1992, then undertook radar mapping of all its sites in the Congo Basin and began to compile biodiversity GIS databases. WCS launched the Nouabalé Ndoki project in ROC in 1990, using maps to work with the Congolese government to create the Nouabale Ndoki National Park in 1993 amid various logging permits. Around 1999 WWF launched its ecoregion mapping project, holding a workshop in Libreville in 2000 to validate maps with 160 national and international experts.

Maps played a key role in the fight over forestry in protected areas and FSC certification in Lopé, Gabon in 1996—an early example of overlapping land use where forestry permits were overlaid onto a protected area, where, by law, logging was not permitted. Global Forest Watch was launched in 1997 by WRI and, for the first time, worked with forestry departments in the Congo Basin to produce GIS maps of forest permits. In Gabon this resulted in maps that were produced by WRI in 2000 (Collomb 2000).

From 1999 to 2002 Gabon's protected areas evaluation, supported by WCS and WWF, compiled forestry, mining, oil concession, and biodiversity in an ArcView database. The Ministry of water and forest / WRI logging permit map was an important tool for this evaluation. This resulted in the creation of 13 National Parks and the cancellation of 2 million ha of logging concessions on the basis that logging permits had been put everywhere without consideration of other priorities. It was around 2000 when MapInfo and ArcView became standard tools in conservation planning.

In 2002 CBFP was launched, UASID announced $53 million for Congo Basin protected areas, in several GIS defined priority landscapes. The University of Maryland launched the CARPE GIS map database including people, infrastructure, protected areas, forestry, and mining concessions. The first basin-wide vegetation map using Japanese JERS radar data was used to develop a Gabon's first carbon map (Saatchi et al. 2011). The creation of the National Satellite and GIS Data Center (AGEOS) in 2010 and, later, the National Land Use Planning Commission has helped support the publication of the first national land use plan in 2015, national agricultural land allocation in 2017 (Burton et al. 2017), and oil palm strategy in 2021.

Advanced Forest Monitoring and Analysis Using GIS

High spatiotemporal resolution: The launch of Sentinel-1 and Sentinel-2 satellites provided openly available, high-resolution imagery (10–20 m). Recent synergistic advances in remote sensing products and artificial intelligence open new perspectives in distinguishing and mapping different forest types. The increasing availability of satellite data with high spectral, spatial and temporal resolutions, such as Sentinel 2 data, offer a great potential, provided that careful image processing is made to minimize known biases, such as variability in sun-sensor acquisition conditions (bidirectional reflectance distribution function [BRDF]) or atmospheric pollution

(Phiri et al. 2020). Indeed, many vegetation types can be distinguished from their specific textural and spectral signals (Viennois et al. 2013). In the recent years, deep learning approaches also have permitted significant progress in forest properties mapping from space-borne data with the development of performant convolutional networks and, more recently, of vision transformer models.

Near real-time monitoring: This allowed for improved near real-time monitoring of forest changes, including road development and other disturbances.

Cloud computing platforms: Cloud-based platforms like Google Earth Engine (GEE) and FAO's SEPAL have enabled large-scale data processing and analysis, facilitating multi-source data fusion and biomass estimation.

Focus on forest degradation: Remote sensing approaches are now used to assess forest degradation using direct and indirect methods.

Integration with GIS: GIS is used to integrate remote sensing data with other datasets to create more comprehensive and informative products to support sustainable development objectives.

Multi-sensor fusion: Researchers are increasingly exploring multi-sensor fusion techniques to combine data from different sensors and improve the accuracy of forest monitoring.

Machine learning and AI: Artificial intelligence and machine learning are being applied to analyze satellite imagery for tasks like road detection and forest change analysis.

Designing, Validation, and Standardization of National Land Use Maps

Geospatial information has been used in many initiatives around the world and is increasingly used in decision-making processes. In a region such as the Congo Basin, shared geospatial data standards, cross-border collaborations become easier and more efficient, particularly in trade, transport, or environmental management.

As described by Usongo and Nagahuedi (2007), the Yaoundé Declaration of 1999, signed by the Central Africa States, provides an institutional framework for collaboration on cross-border forest issues, creation of protected areas, and the development and the implementation of sustainable forest management. In May 2000, the signatory States established the Central African Forests Commission (Commission des forêts d'Afrique Centrale, COMIFAC) to coordinate, harmonize, and monitor forest and environment policies and initiatives in the subregion. In 2005, COMIFAC was transformed into a legal entity empowered with full responsibility to coordinate all conservation initiatives in the Congo Basin. This paved the way, for example, for Governments of Cameroon, the Central African Republic, and the Republic of Congo, to sign an agreement establishing the Sangha Tri-national transboundary area (4.5 million hectares) and arranging for its collaborative management an important step towards managing poaching and illegal logging in the subregion. Other cross border conservation initiatives have followed.

Institutional Validation and Ownership

Cameroon

An example of validation and collaborative appropriation is that of World Resource Institute (WRI) and the sectoral ministries concerned in Central Africa. This collaboration has made it possible to set up dynamic platforms and downloadable GIS databases, used today by public administrations, the private sector, and civil society.

For the case of Cameroon, the forest atlas database is implemented by a joint Ministry of Forest and Fauna (MINFOF-Cameroon) and WRI team. MINFOF members, made up of staff from the cartographic service, manage the database daily. They are in charge to update spatial data from different services involved, by integrating new forest titles, archiving obsolete data, and modifying the attributes of existing titles based on the gazettement, classification, and management status. The exchange of up-to-date data between team members is done through a local server equipped with a synchronization system based on ESRI technology. Up-to-date data are shared with other services both at central and decentralized levels based on their needs. WRI provides software, support troubleshooting of the information system to ensure the local database functions properly and ensures synchronization of data updating on the interactive forest atlas platform online. The online data is accessible and downloadable by various stakeholders as suggested by the structure depicted by Figs. 2 and 3.

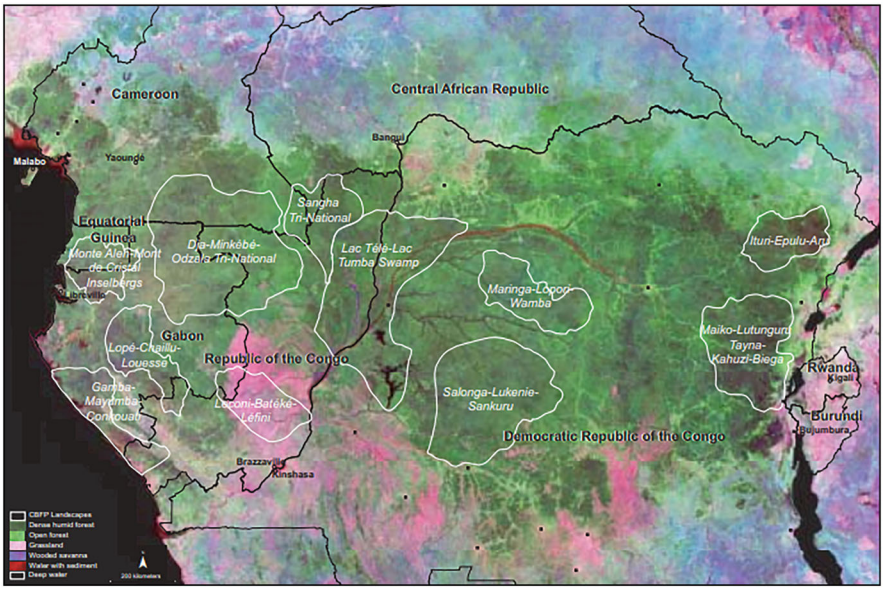

Fig. 2 MODIS satellite images collected between 1999 and 2002 to obtain a cloud-free view. It shows dense forest in dark green and degraded forest or agricultural areas in light green. Grassland appears in pink and wooded savanna in violet (http://carpe.umd.edu/). The Forests of the Congo Basin: A Preliminary Assessment

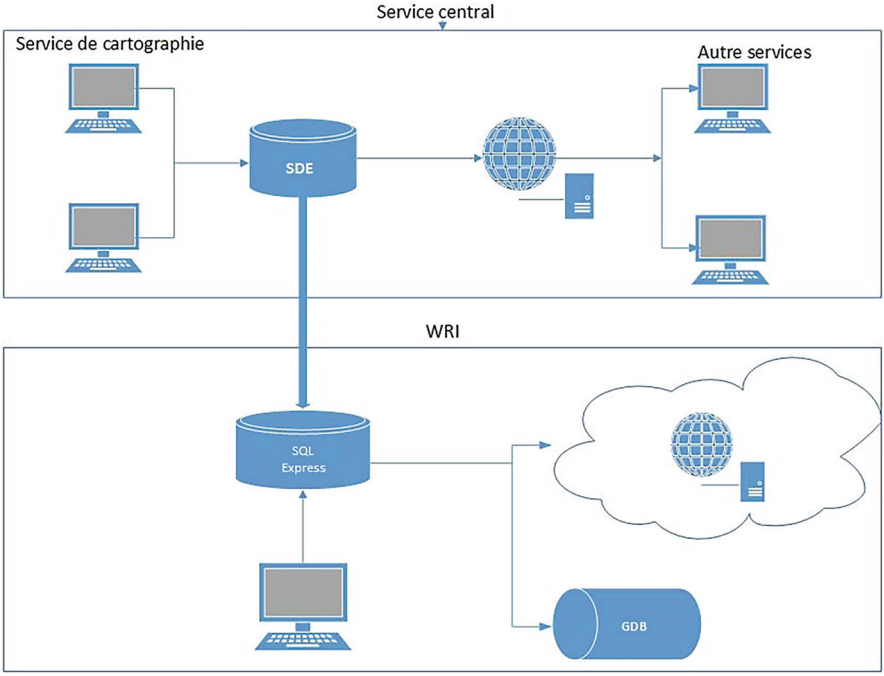

Fig. 3 Structure for collaboration/validation of maps and data by MINFOF and WRI

Democratic Republic of the Congo

The DRC created an Inter-Ministerial Commission to improve the governance of the forest sector in 1999, which recommended the cancellation of all forest agreements without an inventory report or that were not being exploited at that time. This effort resulted in the canceling of 25 out of 41 million ha of active agreements in 2002. It also imposed a national moratorium on the allocation of new forest area agreements, although 3 million ha were eventually allocated, thus bringing the total of forest area allocated to 19 million ha. All of the agreements were to be reviewed in 2005, in line with the conversion of forest concessions (Debroux et al. 2007).

The study by Kanyinda et al. (2024) presents the role played by the map in conflict resolution, particularly in the Faradje and Aru territories, as well as in the Haut-Uele and Ituri provinces. The socio-political crises that have shaken the eastern part of the DRC for decades are linked to land tenure, requiring spatialization and recognition by state actors at the provincial and territorial level. The Geographical Institute of DRC is the leading supplier of maps used for economic and social planning and development, influencing land-use policies and decisions on the siting of infrastructure. It has produced more than 1400 national maps on multiple themes at a scale of 1:2,000,000, 26 provincial maps at a scale of 1:500,000 and 1:750,000, and 145 territorial maps at a scale of 1:200,000.

Gabonese Agency for Space Studies and Observations (AGEOS)

Faced with the current challenges of climate change, Gabon has put in place a strategy aimed at preserving biodiversity. One of the first important measures was the creation of national parks in 2002. Indeed, as part of its national policy on climate change and in accordance with Ordinance n°019/2021 of September 13, 2021 on climate change, Gabon is putting in place all measures, activities, and initiatives in various sectors that could have an impact on climate change.

The creation of AGEOS in 2010 is a considerable advantage for Gabon's climate policy. The implementation of several projects and initiatives (GSE-FM, GeoforAfri, OSFACO, CAFI, etc.…) has enabled its operationalization and the strengthening of its forest cover monitoring capacities. In Gabon, the creation of the Natural Resources and Forest Observation System (SNORNF) ensures effective monitoring of land use, land use change and forestry (LULUCF) through the production of land cover data, among others. Moreover, the work initiated by AGEOS and other national institution has led to creation of National Land use commission and plan, the national agricultural land allocation, and the Oil Palm strategy.

Scientific Maps Widely Used and Sometimes Vilified

This section will be a demonstration of remote sensing and GIS as tools to monitor Biodiversity for Conservation purposes.

Vulnerability Map of the Congo Basin

This map can be used to identifying areas most at risk, to develop policies and to sustainably protect and manage forests.

Human activities and climate change are impacting the sequestration capacities of natural carbon sinks and other ecological regulation processes in the Congo Basin. Protecting the High Value Conservation Areas can increase the resilience of carbon sinks to human pressures and global warming. Figure 4 is taken from a study conducted in 2021, which projects the vulnerability gradient of Central Africa's forests to climate change and increased human pressure by 2085. Areas with a greater capacity to adapt to climate change are assumed to be those with the least human-induced pressures. In addition to reducing deforestation in areas with high rates of forest loss, limiting the degradation of intact forests can help reduce their vulnerability to human pressures and global warming.

The color gradient indicates the vulnerability rates to climate change and anthropogenic pressure: magenta indicates areas most vulnerable to both phenomena and green corresponds to areas least vulnerable to both phenomena. Blue indicates areas that are very vulnerable to climate change and less vulnerable to anthropogenic pressure, and vice versa for the areas indicated by orange.

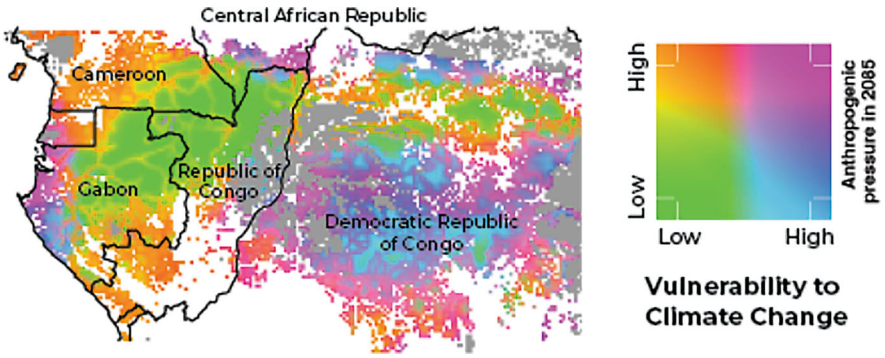

Fig. 4 Vulnerability map of climate change in the Congo Basin. (Adapted from Réjou-Méchain et al. 2021)

Lidar Contribution to Upscaling Data Acquisition

Indeed, Congo Basin exhibit complex spatial dynamics driven by factors such as biodiversity, human activity, and climate change. Monitoring these dynamics involves tracking structural attributes, including canopy height, vegetation cover, basal area, and aboveground biomass (Camarretta et al. 2020). These features are critical for understanding carbon storage and forest health (Fig. 5).

The integration of terrestrial and airborne lidar technologies allows for high-resolution analysis of forest structure. This approach can bridge the gap between field-based and satellite-derived observations. Actually, a few case studies at local (e.g., Sagang et al. 2020, 2024) and at national scales (e.g., in Gabon Sagang et al. 2024; Fig. 6) are setting up such systems, to provide several products for monitoring a wide range of modifications or changes in forest cover (Fig. 7).

Mapping Tree Height and Forest Biomass Using MODIS

The first continuous global maps of forest characteristics like height and AGB relied on remote sensing forest height measurements from the ICESat/GLAS mission (from 2003 to 2009) (Lefsky 2010). Combining Terra-Aqua/MODIS reflectance data with ICESat/GLAS enabled the generation of global 1 km resolution height maps (Lefsky 2010) as well as 500 m resolution AGB maps by combining these maps with field inventories (Baccini et al. 2012). Saatchi et al. (2011) built upon these sensors and incorporated field data from forest inventory plots to derive site-specific allometric equations, ultimately proposing a carbon stock map for tropical forests across three continents. ICESat/GLAS became a cornerstone for forest characteristics mapping when it was, used in conjunction with other radar sensors like ALOS-PALSAR (Mitchard et al. 2012; Santoro et al. 2018) and Landsat (Wang et al. 2018; Zhang-

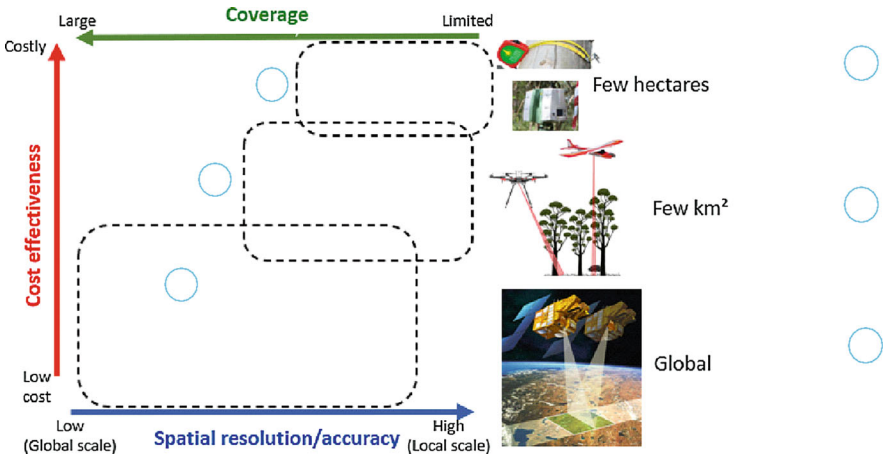

Fig. 5 Upscaling data acquisition from ground to satellites. (Modified from Ganivet and Bloomberg 2019)

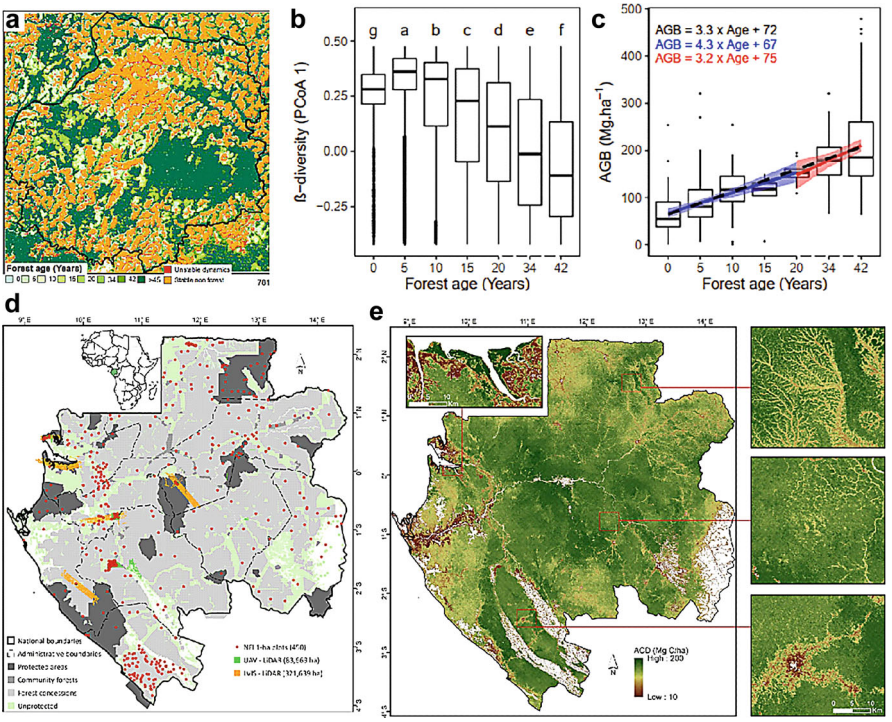

Fig. 6 Different types of products derived from upscaling approaches. (Modified from Sagang 2022; Sagang et al. 2024). (**a**) vegetation transition map, (**b**) relationships between forest age, spectral diversity, (**c**) Forest age, structure, (**d**) Field and airborne sampling data over the different land cover in Gabon, (**e**) Spatial distribution of the aboveground carbon density (Mg C ha-1) of Gabon's forests at 1 ha resolution for the year circa 2019

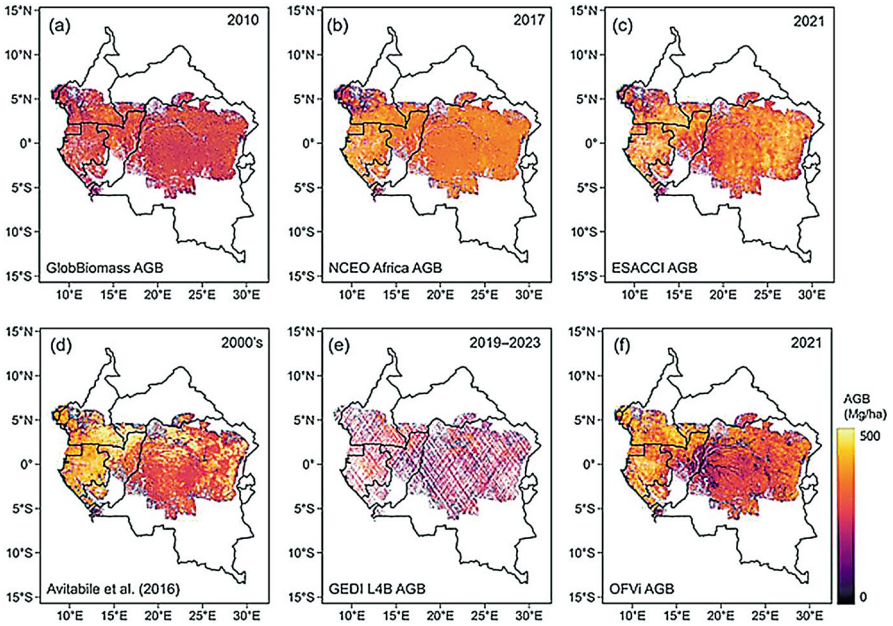

Fig. 7 Comparison of spatial distribution above-ground biomass (Mg/ha) in the Congo Basin forests (Avitabile et al. 2016; Santoro et al. 2018; Rodriguez-Veiga and Balzter 2021; Dubayah et al. 2023)

Zheng et al. 2024) to achieve wall-to-wall mapping. More recently, thanks to GEDI L4 data it is possible to produce biomass density mapping at 1 km resolution based on the GEDI waveform and statistical hybrid inference method (Dubayah et al. 2023). For example, 30 m spatial resolution from Landsat optical reflectance data was combined with sparse height measurements from GEDI to generate global, 30 m resolution canopy height maps (Fig. 8).

Mapping Forest Degradation Using Sentinel-2 Satellite

Sentinel-2 satellite was used in detecting forest degradation by Vo Quang et al. (2022). The results highlight the significant contribution of Sentinel-2, thanks to its broad range of spectral reflectance, including the mid-infrared region, which considerably improves the separability between dense and degraded forests. This allowed to train a Convolutional Neural Network (CNNs) able to detect degraded forests in similar biogeographic contexts as for the training dataset, as the method is transferable and applicable across different years and similar forest types. However, the generalization of this CNN model to other forest and climatic contexts needs to be studied. Also, forest degradation was detected using C-band COSMO-SkyMed InSAR data with an accuracy above 75% in two sites in Central Africa, X-band TanDEM-X InSAR data over hilly areas in Gabon, or selective logging sing

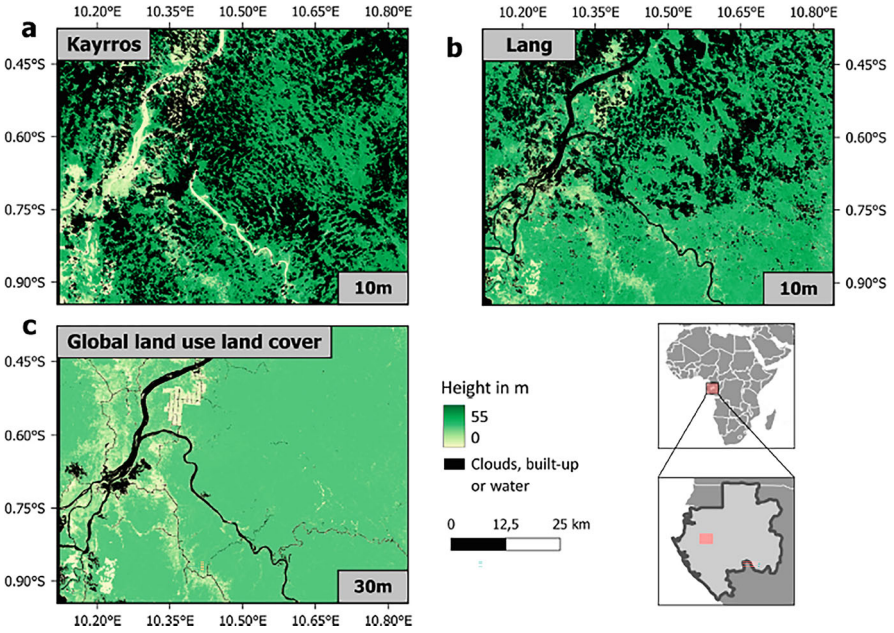

Fig. 8 Canopy heights in a small area of 6057 km^2 in Gabon (Bossy et al. 2025)

C-bandRADARSAT-2 InSAR data with an accuracy above 75% in RDC. There are various forms of degradation and degraded forests, and it is unclear whether the methods can be well suited to monitor them.

Monitoring Deforestation Using High Resolution Images

Deforestation, unlike degradation, has long been monitored because it is easier to detect using remote sensing (Tyukavina et al. 2018). Recently, the processing of very high resolution (about 3 m) images from the Planet NICFI mosaics (archives since 2015) has significantly improved the mapping of deforestation for Mato Grosso and the entire Brazilian Amazon. The latter approach uses deep learning classification algorithms, complemented by other high-resolution data such as SPOT, MAXAR, and Terrasar-X. It is based on a manual labelling of a large set of anthropogenic disturbances such as roads, logging, and fires, and other factors such as wildfires and mortality events from droughts.

Using Satellite Image Classification to Produce Forest Maps

The satellite image classification method used to produce forest cover maps for 1990, 2000, 2010, and 2020. The maps were constructed by combining a semi-automatic classification procedure with manual refinements to ensure the highest

possible accuracy (Sannier et al. 2013). This method is known as wall-to-wall-to-wall. Land cover data can also be obtained from methods using estimators, such as the direct expansion method described by Sannier et al. (2013). Wall-to-wall maps provide useful complementary data for forest management but require a large volume of work and data. The second, by sampling, provides a better understanding of changes over a longer period and is suitable for a more regional scale. The latter is now more widely recommended for estimating annual land-use changes in order to produce LULC-related activity data. These two methods (Wall to wall) are used by AGEOS to produce land cover change data. Other data sources are also available (OFAC, GFW, JRC, etc.). There is also the use of stratified sampling as described by (Olofsson et al. 2014). For both methods, reference data are used. These are created by independent expertise to ensure significant objectivity in sample interpretations.

Mapping Forest Composition and Function

Participatory Mapping Technics

The past 20 years have witnessed an explosion of participatory mapping initiatives throughout the world, in both developing and developed countries. Participatory mapping is, in its broadest sense, the creation of maps by local communities often with the involvement of supporting organizations including governments (at various levels), non-governmental organizations (NGOs), universities, and other actors engaged in development and land related planning. The International Fund for Agricultural Development (IFAD) supports many projects that use participatory mapping processes and tools to assist in resource decision making. Participatory maps provide a valuable visual representation of what a community perceives as its place and the significant features within it. These include depictions of natural physical features and resources and socio-cultural features known by the community.

Refiring to (IFAD 2009), one of the biggest challenges for natural resource management across the Congo Basin is the reestablishment of resource use systems in which local people have tenure over the land, based on the ethic of self-regulation. This is to maintain the resource base they need and where un-regulated commercial off-take by outsiders is prevented. In the Sangha Tri-National Landscape, resource managers are working with local people, both indigenous and immigrant, to establish viable tenure systems based on traditional patterns of land use—in which hunting, fishing, and agriculture serve subsistence purposes—and to establish small-scale income diversification. Traditional hunting zones are mapped, hunting and fishing committees set and enforce quotas, and results are monitored in terms of catch per unit effort and remaining wildlife stocks. Government, conservation NGOs, and the private sector all have a strong role to play in guiding and supporting such initiatives on community lands, which meet local needs and maintain forest ecosystems (CARPE 2005) (Figs. 9, 10, and 11).

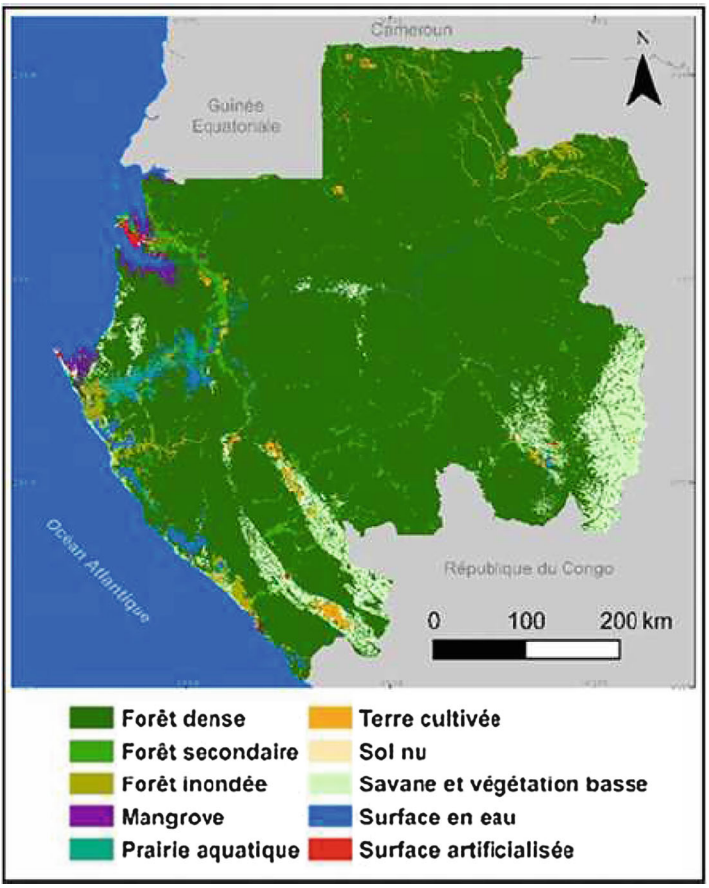

Fig. 9 Satellite Image Classification for Land use in Gabon in 2015

A credible participatory map goes through several stages and phases. In the digital age, the tendency is to digitize the paper data collected during fieldwork, geo-reference it and validate it later (Sufo and Tiani 2014).

An Overview of Institution with Online Geoportal for the Congo Basin

How these mapping exercises can be a tool for optimizing development across the basin into the future Moving towards regulative harmonization and minimum standards within the region for the sustainable optimization of all resource and land use in order to support conservation, biodiversity, and sustainable management

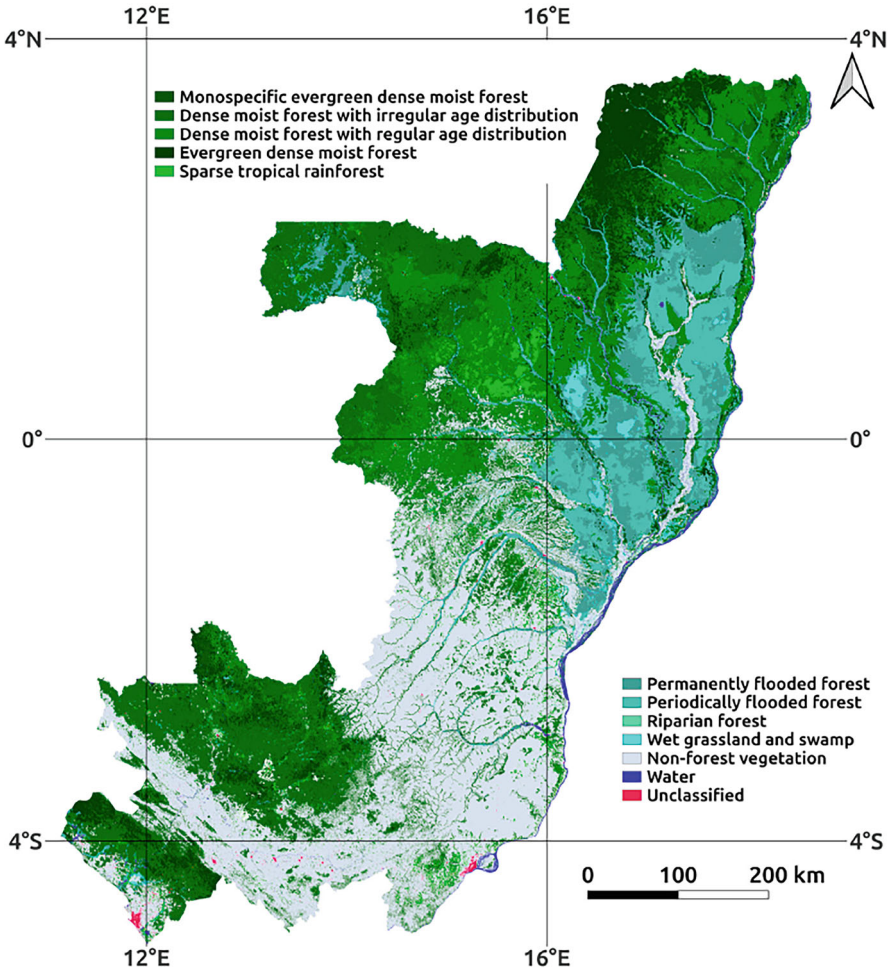

Fig. 10 Forest type in republic of Congo

and above all, the economic development of the populations of Central Africa. Creating a single Geoportal of the Congo Basin which will be an online platform where stakeholders can access various geographic data related to the Congo River Basin. This includes maps, satellite imagery, environmental information, Shapefile, and other datasets, allowing users to explore and analyze the region's geographic features. This includes various topic like forest, agriculture, water, and soil. To better understand the dynamics and to identify the need and priority of Central African forests there are recent initiatives such as co-creation and networking with among local researchers. For example, the Congo Basin Science Initiative (CBSI) will focus on capacity building for observation and data collection in the central African tropical forest (Table 1).

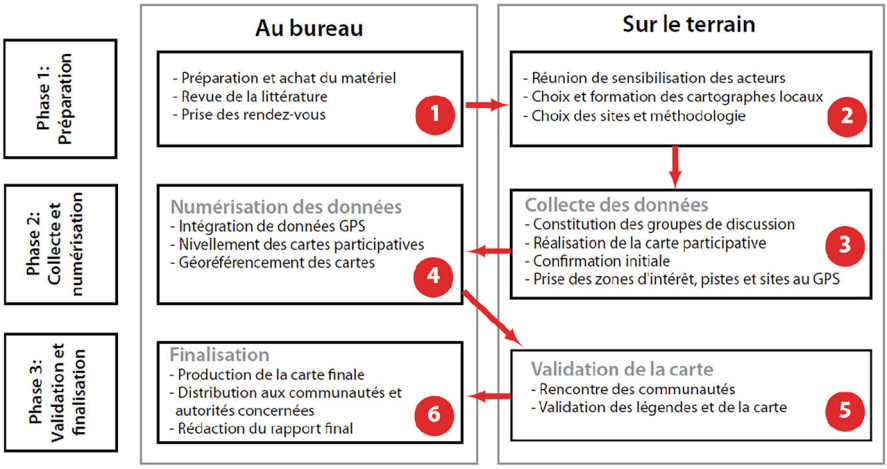

Fig. 11 The main phases and stages of georeferenced participatory mapping (Sufo and Tiani 2014)

Table 1 Some online geoportals for the Congo Basin

Institution	Website
World Resource Institution (WRI)	https://portals.landfolio.com/cameroon/fr/ https://drclicences.cami.cd/EN/
Global Forest Watch (GFW)	https://www.globalforestwatch.org/
UN Biodiversity Lab Portal	https://unbiodiversitylab.org/en/
Central African Regional Program for the Environment (CARPE)	http://maps.geog.umd.edu/carpemapper
OFAC	https://www.observatoire-comifac.net/analytical_platform
OSFAC	https://osfac.net/fr/donnees/images-satellite
AGEOS	https://gofcgoldvh1.umd.edu/sites/default/files/2021-08/D1-07_AGEOS_Conan%20Vassily%20OBAME.pdf
CARPE	https://carpe.umd.edu/carpemaps/ https://carpe-worldresources.opendata.arcgis.com/
NASA Earthdata	https://www.earthdata.nasa.gov

The One Forest Vision initiative (OFVi) aims to provide scientific support for the development of IT platforms for continuous monitoring of carbon and biodiversity reservoirs in the Congo forest basins. Although not fully confirmed, NASA's PANGEA project has a broader scope as it aims to better understand the combined effects of climate and land-use change in tropical forests within and between continents by combining in situ field data with remotely sensed airborne and spaceborne data. Overall, what should be aimed is a synergy among researchers and stakeholders with interest in the forest sector that will likely contribute in improving the design of a single Geoportal for the Region.

Recent studies have shown spatial data economic value in stimulating innovation, encouraging economic growth and helping to improve the delivery of public services (CARTO 2018). Though there is a lack of consensus around the best research methods to use when attempting to quantify the economic and social value of data, these studies consistently illustrate the value of geospatial data, at both a macroeconomic and microeconomic level.

Illustration of the Value of Geospatial Data

A 2017 study by AlphaBeta, for instance, concluded that each year geospatial data and services generate $400bn in global revenue, save people $550bn worth of time and fuel when traveling, and drive $1.2bn of indirect sales worldwide. In the European Union (EU), the benefits of the INSPIRE Directive—which aims to create a European-wide geospatial data infrastructure—are estimated to be between €770 m and €1.15bn per year (against costs of €93 m to €138 m).

More recently, a 2018 study by the UK Cabinet Office, predicted that making parts of the Ordnance Survey's OS MasterMap more openly available would boost the UK economy by at least £130 m each year.

Successful Mapping Strategies

An example of a very successful regional Geoportal is the INSPIRE Database and Geoportal. There is also successful national mapping strategy like the Indonesia: ONE MAP POLICY, One Map is about how the government can make policies that are based on data, especially policy on spatial planning. The Rwanda Spatial Data Infrastructure initiatives.

A European Union comprehensive spatial data infrastructure for EU environmental policies and policies or activities that may impact the environment. The basic idea of INSPIRE is a network of national Spatial Data Infrastructures created by the Member States. The directive's text specifies in total 34 data themes, arranged in three annexes. For every data set, detailed technical documents, called data specifications, have been retained, that specify the structure and data model of the datasets. Other texts, called "implementing rules" describe how the infrastructure has to be realized.

The overall aim is to ensure that the national nodes are fully compatible and usable by the EU bodies, also in regional and trans-border contexts. They concert the essential parts of the infrastructure, like the metadata (descriptive information on data and services), technical specifications of data and services, or the monitoring and reporting procedure. In the process of adopting the rules, the EU Commission is assisted by an official committee (comitology process).

The obligations produced by this text are numerous and have a strong impact on the national ministries and administrations, who create, detain and update spatial

data that has a link with environment themes. https://www.geoportail.lu/en/questions/what-inspire/

The INSPIRE directive fixes a strict agenda accordingly to which the member States have to:

- Annually inform the European Commission about the existence of geodata that might enter the scope of the directive
- To create, update and provide the metadata sets about the geodata sets and services
- To set up and maintain a national infrastructure capable of delivering this information to national and European actors
- To create, prepare, update, and modify the geodata sets, series, and services according to the themes in the annexes

The Interactive Forest Atlas is a dynamic forest monitoring system that provides credible and up-to-date information on the forestry sector. Built on a Geographic Information System platform, the Atlas aims to strengthen forest management and land use planning by bringing together information on the main land use categories on a single standardized Plateform. These systems have been developed for Cameroon (cmr.forest-atlas.org), RoC (cog.forest-atlas.org), DRC (cod.forest-atlas.org), Gabon (gab.forest-atlas.org), Central African Republic (car.forest-atlas.org), and Equatorial Guinea (gnq.forest-atlas.org).

The Forest Atlases address challenges to make key data available by combining forest registries with satellite borne data from the near-real-time monitoring system Global Forest Watch (globalforestwatch.org). Users can perform complex analyses such as forest cover dynamics, forest carbon fluxes across a variety of land uses through these platforms. The Forest Watcher mobile app available in play store makes Global Forest Watch's dynamic online forest monitoring and alert systems available offline and easy use for field investigations. All these spatial data geoportals played a key role in data sharing, helping to monitor and manage forest resources effectively.

Overlapping Land Uses in the Congo Basin

Mining in Forest Management Units (FMUs)

Overlaps between mining permits and FMUs in TRIDOM-Cameroon concern approximately 61% of the landscape's FMUs This situation implicitly leads to non-respect of the management plan of the forest concessions. CAMIRON, the Cameroonian subsidiary of Australian company Sundance Resources is the owner of the Mbalam iron ore mine. The LOREMA-SOCIB forest concession comprises five FMUs that are exploited by SFID at Djoum. The overlay affects one FMU (09-003) and covers around 1/6 of it, i.e., five AACs of a 5-year block. This will have a significant impact on the profitability of the activities of this forestry company.

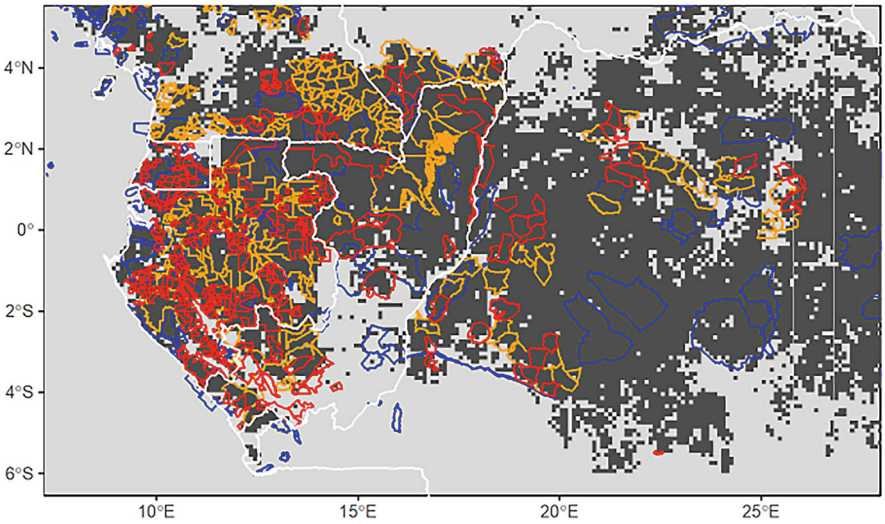

Fig. 12 Conflict in Land allocation. Areas in blue represent protected areas. Areas in orange represent logging concessions known to have a formally validated sustainable forest management plan or one under development. Areas in red illustrate forest areas currently dedicated to logging but which have no formal management plan or whose status is uncertain. (Adapted from Réjou-Méchain et al. 2021)

Mining in Communal Forests

Conflicts over overlapping titles extend beyond private investors in different sectors and even affect forests allocated to decentralized local authorities such as communes (Fig. 12). The TRIDOM-CAM landscape includes around 10 communal forests, of which more than 50% are classified and 60% are overlapped by mining permits (Fig. 13). The map below gives an overview of the mining permit allocations that overlap with them.

The Djoum 3 prospecting permit awarded to CAMINEX in 2006 and renewed for the second time in the second renewal of which took effect in July 2013, is in the same locality and overlaps with the northern part of the Communal Forest (Fig. 11). More than half of the forest (communal) forest is affected by this overlap. These observations concern the opening of roads, the construction of bridges, logging, and poaching (Fig. 14).

Mining in and Around Protected Areas, Conservation Corridors, and ZICs (ZICGC)

The manifestation of land-use conflicts in the TRIDOM is effective in the context of mining permit allocations in and around protected areas, some of which are protected areas, some of which are subject to international conventions. All PAs in the TRIDOM-CAM are affected by mining. As illustrated in Table 2 below, each protected area in the landscape overlaps with at least two mining permits. According to Schwartz et al. (2012) for example, about 44,689.80 ha of forest overlap between

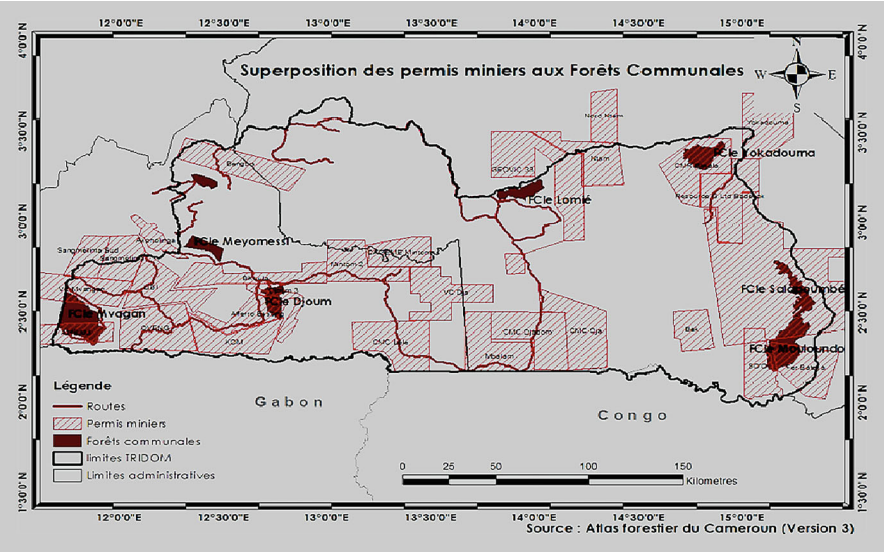

Fig. 13 Overlay of mining permits on communal forests in TRIDOM-Cameroon

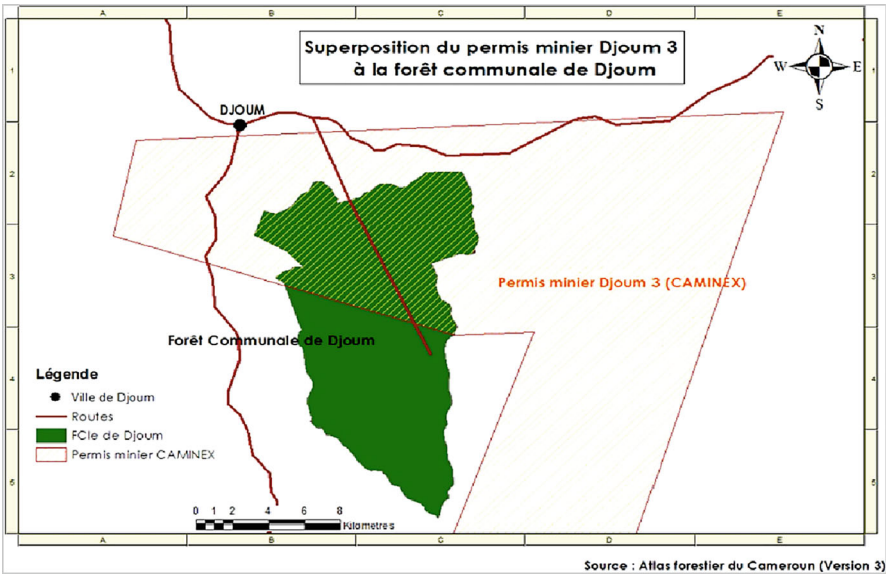

Fig. 14 Djoum 3 mining permit superimposed on the Djoum loop

the mining permits and protected area of the tri-national Dja-Odzala-Minkébé, approximately 8.70% of the tri-national (Fig. 15).

Table 2 Overlapping mining permits in the TRIDOM-CAM PA (Schwartz, 2012)

Permis minier	Société	Substance	Aire protégée	Surface en superposition (ha)
	HDS Cameroon sarl	Substances minérales	Boubabek	188,006,1
Badekok	Camerican mining	Or.uranium	Boubabek	2728,3
Mintom Nord	Limestone	Calcaire	RBD	3389,4
Mintom 2	EGBTP	Calcaire	RBD	10,176,2
Bengbis	Venturecapital PLC	Or, fer, uranium	RBD	61,727,4
Oveng	Luzmining service LTD	Tous minerais	Kom	32,806,6
Kom	BEIG3 Sarl	fer	Kom	42,563,8
Essong	Ridgeway Energy LTD	Uranium, or, fer, diamant	Kom	4143,2
Ambam	GIE minerais du Cameroun	Or	Mengamé	15,387,4
Oveng	Luzmining service LTD	Tous minerais	Mengamé	6898,2
Bek	Coast investments international sarl	Uranium	Nki	43,378,8
Dja		Or, fer, uranium	Nki	34,984,4
TOTAL				**446,189,8**

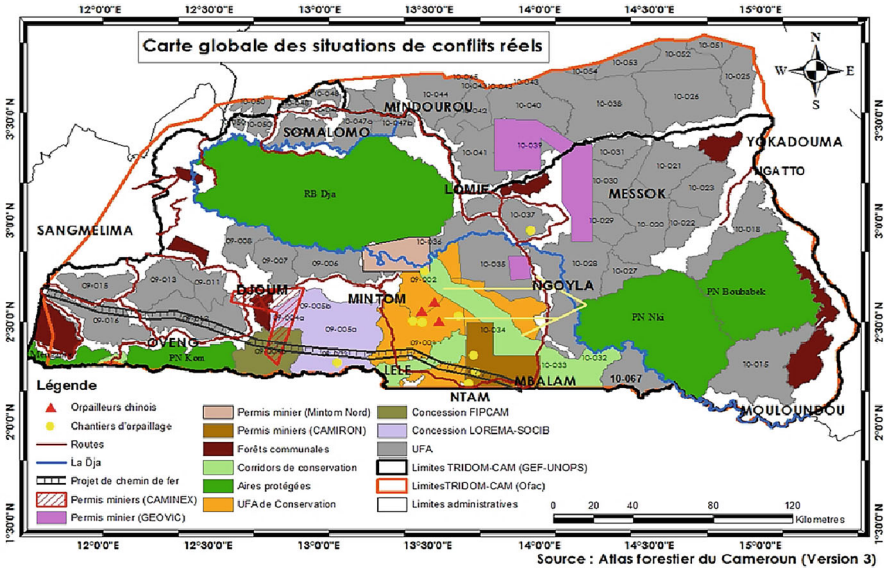

Fig. 15 Map of Conflict situations in TRIDOM-Cameroon

Overall Map of Real Land-Use Conflict Situations in TRIDOM-CAM

Land allocation and use in TRIDOM-CAM reveal a series of situations that have been described as current real conflicts. These include boundaries of this landscape, which have yet to be definitively defined. The map below illustrates two different situations: On the one hand, the boundaries that are currently used by a considerable number of players in the TRIDOM-CAM sector, and on the other, the boundaries proposed by De Wasseige (2009). Cases of overlapping mining permits to FMUs and Communal Forests are summarized by the superimposition of the CAMINEX permit to the FMUs exploited by SFID and FIPCAM, and to the Djoum Communal Forest. But also, by the superimposition of the Géovic permit on the UFA 10-033 managed by Pallisco in Lomié. These three FMUs are also home to gold panning, which is a threat to conservation in view of its impact on the environment. China's growing involvement in artisanal mining reflects the level of the level of threat to which these conservation areas are exposed, we note their progression in the Nki-Boubabek complex.

Forest Zoning in the Congo Basin

The following analysis is based on a literature review of LUP experiences in the Congo Basin published from 2010 onwards. Note that the experience of the preceding two decades of Forest Zoning in the Congo Basin (1990s–2010) was primarily a single sector forest "Zoning" exercise. The goal was to orient forest development and conservation endeavors to support local, national, and international objectives. Forest Zoning Plans were largely driven by international conservation NGOs and donors whose primary objective was to establish a Permanent Forest Estate rather than any broader sustainable development planning objectives typical of historical national and sub-national LUP efforts conducted in at least some of these counties at that time (Table 3).

Table 3 The current status of the permanent forest estate in the Congo Basin

	Protected areas			Forest concessions	
Country	Number	Terrestrial area (km^2)	Protected land area (%)	Number	Area (million ha)
Cameroon	35	52,726	11.3	105	6.28
Central African Republic	32	111,400	18.0	14	3.69
Chad	20	248,851	19.7	–	0
Congo (Brazzaville)	31	129,308	38.0	50	13.91
DRC	48	322,947	13.9	57	10.76
Equatorial Guinea	16	5199	19.3	48	0.74
Gabon	61	61,450	23.2	97	14.19
TOTAL	243	931,881	**17.5**	371	49.59

Source: Protected areas; Forest Concessions

For example, Cameroon had systematically prepared Regional and Local Development Plans up till the late 2000s. These focused on planning investments and were not spatial in nature. By 2010, 46% of the 1.6 million km^2 of the dense humid African forest had already been allocated for timber concessions or designated as protected areas. By 2016, in Central Africa, the network of protected areas included more than 160 sites, covering more than 4.4 million square kilometers, representing more than 10% of the sub-region's area despite the lack of any national LUPs in most of the countries. At that time, it was estimated that given the current pace of zoning it was likely that most forests in the Congo Basin would be zoned within 20 years. De Wasseige et al. (2012) summarized efforts made by Central African countries and partners to zone forests as a part of national and sub-national LUP during the preceding two decades (1990–2010). We note that during this period most countries were not engaged in any multi-sectoral national or sub-national LUP and had no legal frameworks or guidelines to orientate such planning,

The Governments of CB countries have already designated substantial areas of land to their respective PFEs. According to the Observatoire des Forêts d'Afrique Centrale, Central Africa now has more than 200 protected areas covering a total area of 800,000 km^2, or about twice the total land area of Cameroon. In the 10 countries of the region, protected areas have doubled in number and size over the past 20 years. Central Africa almost meets international objectives in terms of protected area. Gabon has committed 66% of its national territory to Forest Management Units and Protected Areas compared to DRC with 16.5% (Fig. 16).

These figures compare with 1.4% of land allocated to commercial agriculture concessions in Cameroon and 0.1% and 0.2% in Gabon and Republic of Congo respectively. This low level of commercial agriculture may be compared with 12% of Indonesia's national land allocated to oil palm concessions. The process of identifying future protected areas and forest management units (for industrial forest exploitation) has been heavily supported by the international community over the past decades (Figs. 17 and 18).

However, the benefits promised to local communities at the time of gazettement of these PFEs have been largely elusive with many rural communities living in the vicinity of these protected areas and logging concessions remaining very poor and in a constant cycle of conflict with the respective management authorities, as summarized by Angu et al. (2013).

The forest legislation provides adequate basis for land-use planning, forests are divided into permanent and non-permanent domains. In the permanent domain are the State forests (*forêts domaniales*), including national parks, wildlife reserves, hunting zones, game ranches, zoological gardens, wildlife sanctuaries, buffer zones, strict nature reserves, production forests, and protection forests. The non-permanent forests (or in Gabon rural forest, *domaine forestier rural*) are those that are not legally required to remain forest in the long term. In Cameroon the non-permanent forests include all community forests and forests belonging to private persons.

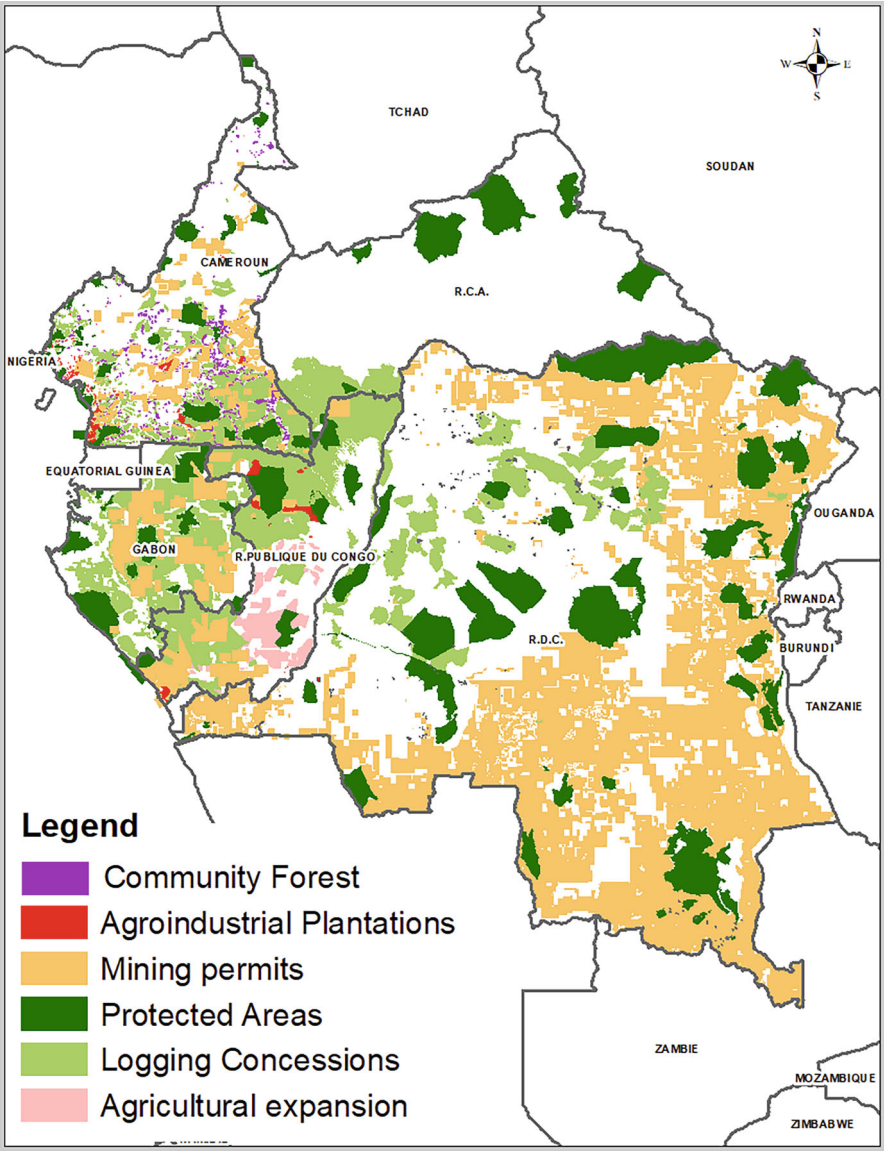

Fig. 16 Map showing land use in 5 countries of the Congo Basin (WRI Cameroon)

Synthesis

The aim of this chapter was to take stock of the evolution of cartography and geospatial tools, to analyze the role of maps in conflict resolution and, finally, to look at the contribution of maps to the sustainable management of natural resources.

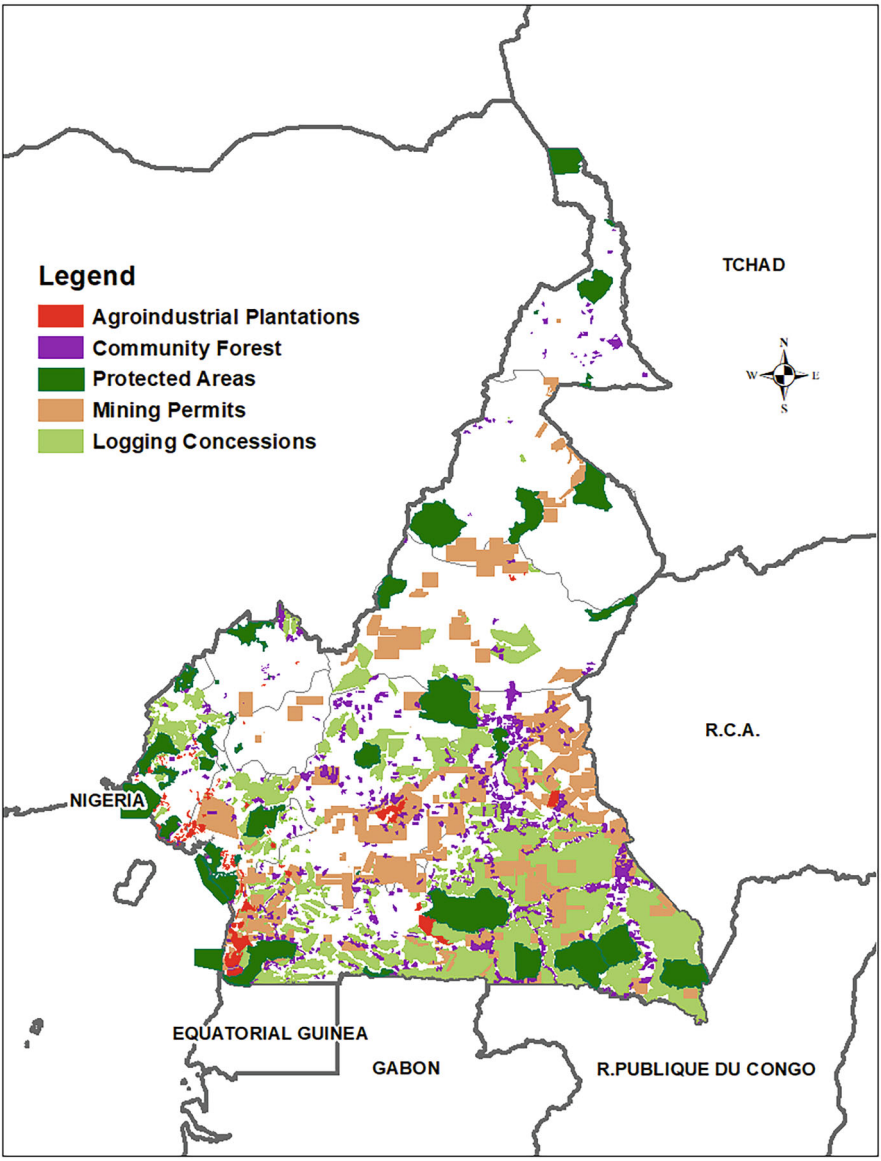

Fig. 17 Land use in Cameroon (WRI Cameroon)

Recent assessments show that a significant portion of these protected areas overlap with existing or planned logging, mining activities, and oil and gas exploration or extraction. Nearly one-third of Central Africa's logging concessions overlap with protected areas. It is important to note that networks of protected areas often overlap with lands owned by local and Indigenous communities.

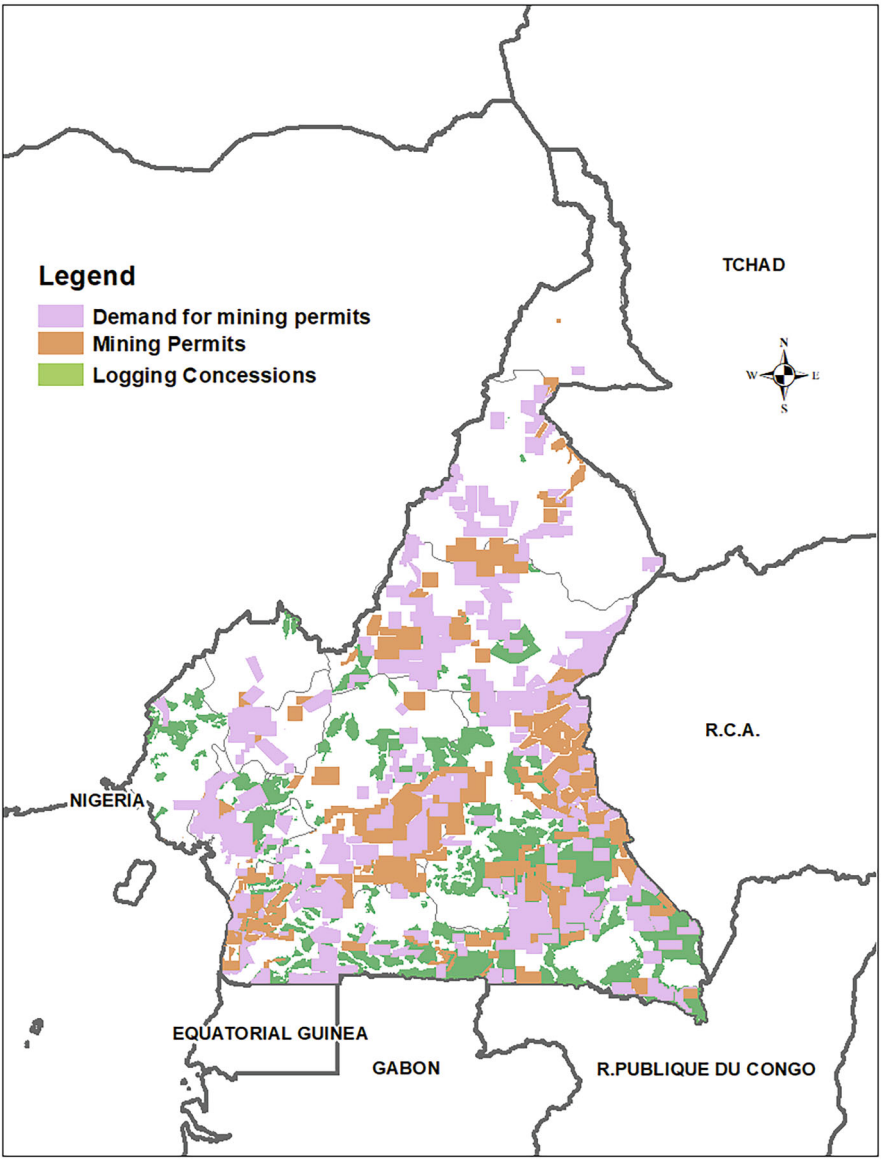

Fig. 18 Commercial Land use in Cameroon (WRI Cameroon)

The need for higher resolution land use maps that focus on agricultural fields and their expansion patterns. Most agriculture fields in these regions are very small in size and have irregular shape, often partly obscured by neighboring forest canopy. Researchers and scientists at large can use Remote Sensing, GIS techniques, field

surveys, and local knowledge, in solving this problem. There is still limited ownership of state institution for spatially explicit data. Despite numerous regional institutions like OFAC, OSFAC, WRI, and AGEOS providing consistent spatial data, there are still gaps.

Efforts and resources that have been invested by NGOs and private mapping companies will potentially go to waste if there is a poor handover strategy. Some of the NGOs and private mapping agencies find it very difficult getting political attention from the central government and regional authorities. Adapted local land use planning processes can serve as a foundation for securing tenure, reducing social conflicts between external and local actors, or even within forest adjacent communities meeting the SDGs, implementing REDD+ and operationalizing the many commitments to zero deforestation commodity production (CBFP 2021).

The Yaoundé Declaration of 1999, signed by Cameroon, Central African Republic, Chad, RoC, Equatorial Guinea, and Gabon, provides an institutional framework for collaboration on cross-border forest issues, creation of protected areas and the development and implementation of sustainable forest management. This same agreement can be done to create a Regional Spatial Data Infrastructure (RSDI) for the Congo Basin owing the fact that these countries already have a common trade zone (CEMAC) (Makanga and Smit 2008).

The countries of the Congo Basin have underdeveloped national map development institutions. Problems relating to human resources, technical platforms, and financial resources are recurrent. A notable absence of maps produced and validated by these institutions has been noted. International institutions are producing digital maps available on websites and sometimes on paper. Apart from these technical gaps, there is a scarcity of spatial data and maps in the various strategic areas that could be used to aid decision-making. Rwanda is the only country in Central Africa to have a land registry, which is a key decision-making tool. The presence of national mapping institutes demonstrates the good will of the States, but this does not lead to the production of maps for better resource management. In addition, there is a significant vacuum in terms of these resources which sometimes gives rise to open or latent conflicts. Hopes are pinned on the Regional Spatial Data Infrastructure.

The progress made over the past half-century in the Congo Basin shows a certain enthusiasm, but different levels of progress. The creation of AGEOS has enabled Gabon to become the locomotive in terms of geospatial data production, resource management strategies, and conflict resolution. However, the steps involved in validating these maps are still unclear, but more at state level than at scientific level. In addition, there is an overlap of land use types that can lead to open or latent conflicts. The maps are used to monitor the territory and illegal activities, as well as to optimize sustainable development.

Competing Interest Declaration The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

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Tapping into Indigenous and Local Knowledge in the Congo Basin to Increase Understanding of Its Ecology

34

Bila-Isia Inogwabini, Robert E. Moïse, Takanori Oishi, Virginia Zaunbrecher, and Soh Wenda Boris Dinictri

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Abstract

This chapter explores "indigenous" and "local" knowledge of "Pygmy" and "Bantu" peoples, respectively, and its relation to scientific understandings of Congo Basin ecology from historical and contemporary perspectives. Both peoples are heirs to extensive traditions of ecological knowledge. In the precolonial era, Indigenous knowledge was highly valued in regional societies, providing Pygmies with key roles to play in wider social systems. However, colonial policies had significant negative impacts on traditional knowledge, especially among Bantu communities. In the postcolonial era, more substantial challenges have occurred, undermining both traditional knowledge and the access of forest-dependent communities to their lands. Traditional knowledge has contributed to modern understandings of Congo Basin ecology since the colonial era, yet often without formal acknowledgment. Whereas scientists have tended to take an "extractive" approach to traditional knowledge, the chapter argues for the development of a more equal and "co-creative" approach to the sharing of knowledge. Acknowledging the complementarity between scientific and traditional knowledge, the chapter recommends that scientists communicate across disciplinary lines to develop methodologies to collect, assemble, and store Indigenous and local knowledge as a matter of urgency, before key forms of oral knowledge are lost. Bringing Indigenous and local peoples into the mainstream scientific research agenda should become a priority, for both regional policies and specific initiatives. By examining various cases of traditional knowledge, the chapter illustrates how important these forms of knowledge are, not only for furthering understanding of Congo Basin ecology but also for solving some vexing questions faced by local peoples across countries.

Keywords

Traditional ecological knowledge · Knowledge production · Knowledge transmission · Oral tradition · Land tenure · Ecology · Conservation · Colonial history

Introduction

Some of the contents of this chapter overlap with the discussions in ▶ Chap. 9, "Critical Interconnections Between Cultural and Biological Diversity in the Congo Basin." However, the two chapters are clearly distinguishable in their respective objectives and focuses. Indeed, as its authors note, ▶ Chap. 9, "Critical Interconnections Between Cultural and Biological Diversity in the Congo Basin," focuses on important interconnections between biological and cultural diversity in the Congo Basin. On the other hand, this chapter focuses on the knowledge systems,

worldviews, human-nature relationships, and livelihood strategies of farmers, fishermen, and hunter-gatherers in the Congo Basin, as documented in ethnographic, ethnobiological, human ecology, and participatory ecosystem service studies.

The aim of this chapter is not simply to describe the practices of Indigenous and local communities across the Congo Basin, but rather to explore the contours of what is understood by Indigenous and local knowledge, their sources, and how they can be utilized to increase understanding of Congo Basin ecology. Beyond this, the chapter presents examples of Indigenous and local knowledge to illustrate how important these forms of knowledge are, not only for furthering understanding of Congo Basin ecology but also for solving some vexing questions that communities across countries grapple with. Furthermore, the chapter discusses methodologies to collect, assemble, format, and store Indigenous and local knowledge, while outlining strategies for maintaining Indigenous and local knowledge as a "living archive" for future generations.

Terminology Employed

Before beginning the discussion, a brief explanation of the terminology used in this chapter is necessary for the sake of clarity. The term "indigenous" is employed for the populations commonly referred to as "Pygmies" (*Pygmées*, in French),[1] while the term "local" is used for those populations commonly referred to as "Bantu (*Bantou*, in french)." In the Congo Basin, the term "Bantou" is commonly employed for all non-Pygmy populations, regardless of whether they speak Bantu, Oubangian, or Sudanic languages.

Given that the term "indigenous" can be highly politicized, some additional clarification is also needed. Based on archaeological evidence, Bantu populations are considered to have migrated into the region during the last 3000–5000 years (Ehret 2001; Montano et al. 2011; Lupo 2014; Bostoen 2020), although there is also evidence for an earlier presence along the Atlantic coast (Clist 1999; Klieman 2003). Employing a definition of indigeneity used in European settler colonies—i.e., presence prior to the arrival of European colonists in the modern era—Bantu would certainly be classified as "indigenous." However, various forms of evidence—archaeological evidence of human settlement in the region for over 40,000 years (Clark 1970; Cornelissen 2002), ancient DNA evidence from 8000-year-old human remains linking them to the genomes of contemporary Baka Pygmies (Gibbons 2020), and widespread Bantu oral traditions of Pygmies as the original inhabitants of the forest (Bahuchet and Guillaume 1982; Deschamps 1962; Seitz 1993; Vansina 1990)—indicate that Pygmy populations were present in the

[1] Since the term "Pygmy" has been employed pejoratively in certain circumstances, some scientists and human rights organizations have argued it should no longer be used. It is used here simply to clarify which communities are being considered in this chapter. Wherever "Indigenous peoples" are mentioned, this will refer to people formerly called "Pygmies," unless otherwise stated. The term Pygmy is also kept as such in all references.

region prior to Bantu arrival and at least some of them are descended from the ancient populations documented by archaeology. As such, it is historically accurate to refer to Pygmy populations as "indigenous," while it is also common usage among both Bantu and Pygmy groups in the region.

This terminology is also consistent with that used in the field of forest management, in which the term "indigenous peoples and local communities" is employed to refer to Pygmy and Bantu communities, respectively. In addition, the term "traditional knowledge" is used for the sake of brevity when the knowledge of both Indigenous and Bantu groups is being referred to.

Indigenous and Local Knowledge Over the *Longue Durée*

In order to provide important context for the question of how Indigenous and local knowledge can be used to increase understanding of Congo Basin ecology, we begin by describing the key role it has played in regional societies over the millennia. In an influential study on the precolonial societies of the Congo Basin, Guyer and Belinga (1995) emphasize the "centrality of knowledge" and consider individuals to have been "singularized repositories of a differentiated and expanding repertoire of knowledge." In addition, they argue that "social mobilization was in part based on the mobilization of different bodies of knowledge, and leadership was the capacity to bring them together effectively,"—i.e., to assemble communities that included individuals possessing all the essential forms of knowledge (Ibid.).

That knowledge was, and is, a critical resource in daily life is reflected in various social roles based on specialist knowledge that continue to operate in Congo Basin societies, such as that of *tuma* (master hunter) and *nganga* (healer, diviner, and ritual specialist). In addition, it is reflected in the fact that: (1) The exchange of such specialist knowledge has always been the basis of social networks spread across the forest landscape, through which mobile specialists circulate, linking communities, regions, and ecological zones (Kisliuk 1998; Lloyd 1907); (2) in spite of the existence of these specialist positions, every individual is encouraged from an early age to develop their knowledge of medicinal plants used for healing; and (3) women, especially elders, possess specialist knowledge of medicinal plants used for childbirth and conditions associated with female reproduction (Kisliuk 1998; Motte 1980). In terms of the sociopolitical realm which is the focus of Guyer and Eno Belinga's study, the centrality of knowledge is also reflected in the character of the relationship that developed between Indigenous hunter-gatherers and incoming Bantu during the millennia of their interaction in the precolonial era.

In Bantu oral traditions throughout the Congo Basin, Indigenous groups were represented as the original inhabitants of the region who guided immigrants to their present locations, but also as holders of specialist knowledge (Deschamps 1962; Bahuchet and Guillaume 1982; Seitz 1993). As a Gabonese man stated in the 1890s:

> The (indigenous) Ba-Kweya… have a knowledge of the dance, the virtues of plants and many other things… *It is they who were at the beginning* and who have maintained a

> knowledge of secret things. *They are at the root of the world.* (quoted in Avelot 1905; emphasis in original)

Due to their "knowledge of secret things," Bantu conferred on Indigenous groups a unique ontology, which was critical for various ritual contexts, with them playing the roles of guardians of the spiritual powers of precolonial kingdoms, intercessors to the spirits of the land, and essential participants in royal rituals (Vansina 1978; Vansina 1990; Seitz 1993; Klieman 2003; Moïse 2014). In addition, their various forms of specialist knowledge led them to occupy the role of "masters of the forest," acting as purveyors of forest products to local Bantu, regional trade networks, and precolonial states (Schweinfurth 1874; Stanley 1885; Harms 1981; Klieman 2003; Moïse 2014). In all these ways, Indigenous knowledge was of crucial importance for the precolonial societies of the Congo Basin and provided Indigenous groups with key roles to play in regional societies: as masters of the forest, purveyors of forest products, and conduits to the mystical powers on which the reproduction of the social order was based.

Beginning in the late nineteenth century, European colonization introduced various challenges to the reproduction of traditional knowledge, especially for Bantu, as successive generations were pulled away from their forest-based subsistence activities by the regimes of forced labor imposed by colonial administrations (Bahuchet and Guillaume 1982). On the other hand, Indigenous groups managed to retain much of their traditional knowledge, due to their strategy of trying to escape these same regimes by taking refuge in the forest (Ibid.). Nevertheless, despite the challenges presented by colonization, many Bantu groups still retain significant forest knowledge, as will be detailed in later sections. Furthermore, in spite of the brutalities of colonial rule, it had a relatively minor impact on forest ecologies, which remained largely intact.

In the postcolonial era, much more substantial challenges to forest ecologies and traditional knowledge have been introduced. Once global postwar expansion ground to a halt at the end of the 1970s, various forms of economic turbulence emerged, and prices for the region's cash crops, on which many Congo Basin economies depended, collapsed (Makki 2004). Lacking a steady flow of foreign exchange, regional governments soon fell into arrears and were obliged to take out loans from international financial institutions—i.e., the World Bank and the International Monetary Fund—to survive. Yet because the export economy remained depressed, a regime of debt dependency came to be the "new normal" for the countries of the region, while international financial institutions began shaping both economic and forest management policy.

As these institutions looked to the extraction of natural resources as a solution to the economic crisis, a regime of large-scale extractive projects—e.g., industrial logging, mining, and agribusiness—took hold, exerting profound pressures on forest ecologies as well as the subsistence economies of local peoples. In addition, the economic crisis introduced mass unemployment, subsequent impoverishment, and a turn to the (often illicit) extraction of natural resources. In this way, tremendous pressure on natural resources and traditional lands has been driven by economic factors, coming from both above and below. Indeed, such extractive pressure is one

of the major historical dynamics of recent decades. This regime, in turn, has posed serious threats to the land base of local communities, on which the reproduction of traditional knowledge depends.

Indigenous People in the Congo Basin

In a famous work, Turnbull (1962) described the Mbuti of the Ituri forest in the Democratic Republic of Congo (DRC) as being heavily dependent on forest resources and having acquired a large storehouse of knowledge of the environments in which they have lived for centuries. Other important works that followed (e.g., Hewlett 2014) took it that the definition Turnbull used constitutes what Indigenous communities share in common: heavy dependence on forest natural resources and specialized knowledge and skills to sustainably use the environment and its resources.

In various countries in the Congo Basin, many Indigenous groups have become semisedentary during the twentieth century (Heymer 1985; Pagezy 1992). Based on field research in the Lake Tumba area of DRC, Pagezy (1992) argues that many Indigenous groups now have diversified livelihood activities, combining hunting, fishing, gathering, agriculture, and paid labor, with some having formal employment, while generally still living in close contact with slash-and-burn farmers, hunters, and fishermen. Exploitation of forest timber resources, urbanization, and the conversion of forests to agricultural land, associated with the expansion of maize, cassava, and other plantations, has led to an increase in the number of Indigenous communities whose lives are divided between foraging camps in the forest, settlements near swidden fields, and urban areas. However, the degree to which Indigenous people have become more agrarian than they previously were varies significantly, depending on group and region. For example, Baka in Cameroon have adopted crops that can be produced without necessarily being constantly settled, such as plantain banana, a crop derived from Southeast Asian rainforests (Kitanishi 2003). Some Baka also engage in cacao cultivation to generate a cash income (Oishi 2012), while the more sedentary Bakoya in Gabon, and Bagyeli in Cameroon, cultivate cassava in slash-and-burn fields managed by women (Soengas 2009; Bitouga 2016).

Getting an accurate estimate of how many Indigenous People live in the Congo Basin is difficult because of a lack of adequate statistics in most countries in the region. Indeed, to address this lack of statistics, Olivero et al. (2016) estimated Indigenous communities' populations based on modeling from actual demographic data from dozens of researchers. Their model estimated approximately 920,000 Indigenous People, living in forest areas of good condition in the Congo Basin, with over 60% of them residing in the DRC (Olivero et al. 2016). On the other hand, Berger et al. (2024) estimated their population in the above six countries to be about 2,300,000 people, with an estimated two million in DRC alone (for a detailed account, see Table 1 below). However, it should be noted that Berger et al. (2024), from whose data the demographic synthesis below is constructed, recommend caution with respect to the figure for the DRC, which varies significantly depending

Table 1 Indigenous people in the Congo Basin and their estimated populations

Country of the Congo Basin	# People	Ethnic composition
Cameroon	80,000	Baka, Bagyeli (Bakola), Bedzan, and Mbororo Fulani[a]
Central African Republic	39,299	Aka, Litho, and Mbororo Fulani
Democratic Republic of Congo	2,000,000	Baka, Balumbe, Batwa, and Mbuti
Gabon	20,000	Baka, Babongo, Bakoya, Baghame, Barimba, Akoula, Akowa, Bavarama, and Bakouyi
Equatorial Guinee	40,000	Bubi
Republic of Congo	50,000	Baka, Babi, Babongo, Bagombe, Bakola, Batwa, Mbendjele, and Mikaya
Total	2,229,299	

[a]It should be noted that the Mbororo Fulani listed in this table are pastoralists living in northern Cameroon and Central African Republic, whom the UN classifies as "indigenous people" based on cultural criteria. However, all other groups listed are peoples conventionally referred to as "Pygmies," living in forested environments

on whether one uses the state's official figure (750,000 people) or the 2,300,000 figure quoted above, which comes from Civil Society organizations. Even with this precaution in mind, it is clear that Indigenous people in the Congo Basin occupy a minority status, both in terms of their numbers and their relative power vis-à-vis their respective national societies.

As Table 1 shows, the ethnic composition of Indigenous people across the different countries of the Congo Basin is varied, with the exception of Equatorial Guinea, where there is only one group. Hulstaert (1961) and, particularly, Thomas et al. (2019) have shown that, through various processes of exchange and interaction, the languages of Bantu and Indigenous People have merged to the point where most of the Indigenous people of the Congo Basin speak the same language as their immediate Bantu neighbors (Bahuchet 1993). Ichikawa (1987) also noted how the food systems of the two groups have evolved to become similar.

Traditional Knowledge of Indigenous Peoples: Framing and Issues

Traditional knowledge is understood and defined in various ways by different authors. According to Warren (1991), "local knowledge" refers to knowledge within a given culture or society that can be derived from intellectual activity in a traditional context, as well as know-how, practices, skills, and innovations. "Traditional" knowledge remains distinct from "scientific" knowledge, in that the latter favors analytical and reductionist methods, whereas the former favors an intuitive and holistic vision. At the same time, traditional knowledge assets are gradually finding their way into different currents of scientific thought. Integrating them with modern

scientific perspectives is still a challenge, though, as both differ in their characteristics and points of view.

Employing current scientific principles to frame the domain of traditional knowledge could help it appear more valid and thereby gain wider acceptance as a legitimate form of science or knowledge. This is important for establishing a solid foundation for future research and innovation. Although we have made significant strides in bringing traditional and scientific cultures closer together, attitudes are still evolving and much work still needs to be done.

Indigenous Versus Scientific Knowledge

Traditional Knowledge Systems are gaining ground in modern (i.e., Western-centered) scientific discourse and communities. Although they are generally not considered scientific, over the years various currents of thought have given this knowledge a place in their research. Residing locally, and using the land on a daily basis, Indigenous and local populations are well placed to observe and understand local ecosystems. As a result, Indigenous and local knowledge systems constitute one of the largest bodies of human knowledge on biodiversity and ecosystems. Unfortunately, however, they have yet to be generally recognized as essential resources for understanding and managing biodiversity.

Over the centuries and millennia, traditional knowledge has developed a model of the environment that emphasizes the symbiotic nature of man and nature. In addition, it usually includes spiritual dimensions and, in fact, makes no distinction between the empirical and the sacred (Roué and Nakashima 2002), in direct contrast to modern science, which is both materialist and positivist. The revival of pharmacological repertoires whose properties are now fading from memory is important today. Such initiatives could assess traditional repertoires with modern testing methods, and thereby prove a useful, relevant, and inexpensive source of potentially therapeutic compounds to promote human health and well-being.

In the past few years, scholarly discussions have characterized Indigenous knowledge as a significant resource for development. However, the material presented in this chapter suggests that, to productively engage Indigenous knowledge in development, we must go beyond simple dichotomies of Indigenous versus scientific.

Contributions of Indigenous Knowledge to Modern Ecology

Perhaps the most obvious form of knowledge possessed by Indigenous people of the Congo Basin is ethnobotany. Its study by scientific researchers began in the 1960s (e.g., Letouzy 1976; Raponda-Walker and Sillans 1962), and various studies on Indigenous knowledge of medicinal plants have been published over the last few decades (e.g., Bourobou-Bourobou et al. 1996; Magilu et al. 1996; Motte 1980; Betti 2004; Bachiri et al. 2009; Shalukoma et al. 2015; Bigombe et al. 2018;

Tchicaillat-Landou et al. 2018). Although a comparison of the findings of these studies across the Congo Basin is beyond the scope of this chapter, some common themes emerge. These studies suggest the potential of Indigenous and local knowledge to treat sicknesses such as hypertension, diabetes, anemia, asthma, ulcers, cough, and viral hepatitis, but they are also used to fight other pathologies such as infertility, blood oxidation, etc. (Tchicaillat-Landou et al. 2018). Plants are also used as analgesics, antiseptics, and aphrodisiacs, while the hallucinogenic plant, *iboga*, has shown promise for curing addictions and possibly for treating Parkinson's and Alzheimer's diseases. More broadly, Indigenous ethnobotanical knowledge has helped modern botany in the identification of species. For example, French botanist Rene Letouzey relied on Indigenous people, particularly the Baka, to create his monumental works on phytogeography in Cameroon (Letouzey 1968). In the process, he helped establish both ethnobotany and modern botany traditions in Cameroon.

It is also noteworthy that those who have collected pharmacological data in the Congo Basin (e.g., Shalukoma et al. 2015) have not been able to distinguish clearly between knowledge of Indigenous communities and that of Bantu communities, with whom Indigenous peoples share their forest territories. This is a clear indication of the regular exchange of knowledge between these communities, to the point that it would be preferable to speak more generally of "traditional knowledge" of plants and to include forms of knowledge possessed by Bantu communities in future research. Indeed, in the markets of large cities such as Brazzaville, Libreville, Kinshasa, or Yaoundé, what traditional healers sell is often from a large spectrum of communities (e.g., Betti 2002).

Indigenous communities across Central Africa also enjoy a mastery of ecological knowledge of a diverse range of fauna, including large mammals, such as elephants, gorillas, and chimpanzees. This knowledge has been put to use in ape habituation programs and for tracking elephants through the forest, but it is also critical in crafting biodiversity monitoring programs, where knowledge of species' movements is critical. To illustrate how knowledge from Indigenous people has contributed to ecological sciences, Blake et al. (2008) acknowledged the contribution of their Indigenous colleagues, particularly Gregoire Mambeleme and Eric Mossimbo, without whose impressive ecological knowledge and forest skills their scientific study on forest elephant ranging ecology in Congo and Gabon would not have been possible (also see Moïse 2020).

More globally, Indigenous knowledge has contributed to systematic studies of both plants and wildlife species (Jessen et al. 2022) across the world's forests, including in the Congo Basin. For example, Lindsey et al. (2010), who chronicled the process leading to the discovery by Western scientists of the Okapi (*Okapia johnstoni*), indicated how important the knowledge of the Mbuti was to the definitive scientific identification of the zebralike animal, which remained unknown to the global scientific community until the early years of the twentieth century. In fact, the Mbuti not only provided specimens of skins that were used for final identification but

also contributed their name, Okapi, which local Mbuti pronounce *O'api* (Kümpel et al. 2015). Indigenous knowledge is also essential for determining the geographic distribution of rare or hard-to-find species in recent days. Hongo et al. (2025) used camera trapping and interviews with Baka to confirm the presence of Mandrills in Nki National Park in eastern Cameroon. Another example of how Indigenous knowledge has contributed to scientific knowledge and the conservation of a charismatic species and its habitat is that of gorillas in the Kahuzi-Biega National Park of eastern DRC, where wild gorillas were first habituated to human presence (Shalukoma 2007). To reach that goal, researchers, park guards, and park wardens relied heavily on the knowledge of Batwa hunter gatherers to track gorillas daily (Casimir 1975; Mutimanwa 1996; Shalukoma 2007; Yamagiwa et al. 2012). Furthermore, as already noted, ecological studies of forest elephants have drawn heavily on knowledge from Baka in Dzanga-Sangha (Central African Republic), and Nouabale-Ndoki (Republic of Congo) National Parks. Indeed, pioneering ecological studies on forest elephants such as those produced by Carroll (1988), Fay and Agnagna (1999), and Turkalo et al. (2013, 2018), to name but a few, relied heavily on the critical ecological knowledge that Baka shared freely with these experts.

Crucially, Indigenous communities that live by gathering plant food in the forest have a wider knowledge of what is edible and what is not (Hladik et al. 1993; Sartoretto et al. 2017). In the context of climate change and food crises, their knowledge could prove to be essential for identifying new staple species, and collecting their seeds, in order to fight hunger by augmenting the number of species available to support human life (Kehlenbeck et al. 2013; F.A.O. 2025). This is what, for example, Fungo et al. (2015) did when they demonstrated that plants such as *Baillonella toxisperma*, *Trichoscypha acuminata,* and *Pentaclethra macrophylla*, which Indigenous communities in Cameroon have been using for generations, had great potential to provide necessary life-sustaining nutrients. In addition, Dupriez and De Leener (1986) suggested that the wild yam, which ceased to be used by many African communities in the course of modernization, was one of the most productive staple plant species. Although they are rare, one single plant of wild yam can produce up to 50 kg when it grows under fertile ecological conditions. Shalukoma (2007) reported that the Batwa of the areas adjacent to Kahuzi-Biega National Park preferred this plant and possessed important knowledge about how to keep it growing abundantly to sustain their livelihoods. As presented in ▶ Chap. 8, "Human Occupation of the Congo Basin," yams have also been identified as a staple wild species, of which the Baka of Southeastern Cameroon possess thorough ecological knowledge, which could be used to support its cultivation, in order to provide cheap staples to local communities with a lower ecological impact.

As the above examples demonstrate, the traditional knowledge of the Indigenous peoples of the Congo Basin, especially their ethnobotanical knowledge, has made important contributions to modern scientific knowledge of the region. Although scientists have tended to take an "extractive" approach to the traditional knowledge of Indigenous peoples in the past, what is now required is a more equal and cocreative approach—a true "sharing of knowledge" between collaborators, drawing on different, but equally valid, bodies of knowledge.

Contributions of Local Knowledge of Bantu Peoples to Modern Ecology

Bantu-speaking agricultural communities have tended to be represented as ecological "baddies," in contrast to Pygmy hunter-gatherers (Köhler 2005), particularly because of their practice of shifting cultivation. This kind of binary epistemology, contrasting Indigenous groups with Bantu, has been constructed by both internal and external actors, including scientists, from the colonial period to the present. A few examples can serve to illustrate the shortcomings of this approach as well as the extensive ecological knowledge found among certain Bantu communities.

Bakwele Fishermen

Knowledge of fish ecology and species diversity in the Congo Basin is still underdeveloped, especially compared to other tropical waterways, such as those of the Amazon Basin. While the rainforest regions of Western and Central Africa support 85% of the nearly 3300 species on the African continent (Chapman 2001), it is estimated that there are numerous species which remain to be identified.

One of the few studies to examine local knowledge of fish ecology is that of Ankei (1989), who describes detailed ichthyological knowledge of the Songola fishermen of the upper Lualaba river, who exchange fish for agricultural foods in local markets by barter. Songola fishermen have developed a complex fish classification system which includes 108 vernacular names and 12 folk categories, involving 6 levels of categorization.

Congo Basin rivers have numerous rapids and waterfalls that cause seasonal fluctuations, creating extremely diverse temporary aquatic microhabitats. Oishi (2016) documents local knowledge of fish among Bakwele of the Dja river basin in Cameroon, showing that they have developed a variety of fishing techniques drawing on their extensive knowledge of fish ecology, diet, and behavior, as they interact with diverse aquatic microhabitats. The Bakwele have 69 vernacular names for 97 scientific species, as well as a disease category referred to as the "sickness of fish" (Oishi 2016). In addition, cultural values are attributed to particular species of fish, which takes the form of food taboos.

Sustainable Cultivation by Ntumu Farmers

Shifting cultivation—aka "slash and burn" agriculture—has often been represented as a driver of deforestation of tropical forests, but this is not necessarily the case. Studies have demonstrated that the traditional farming systems of some local communities in the Congo Basin embed conservation practices within their small-scale agricultural regimes. For example, Ntumu farmers in the central region of Cameroon do not cut all trees for shifting cultivation. Those that are not cut down, and are left in the field (referred to as "orphans of the forest" by Ntumu), produce

quantities of seeds, which form seed banks that contribute to the early regeneration of arboreal species (Carrière 2003). Similar practices of shifting cultivation leaving trees intact are found in cocoa agroforestry in the eastern region of Cameroon: Bangando farmers leave larger number of trees in their cacao fields than in their fields dedicated to food crops. This strategy provides for a quick regeneration of forest vegetation when cacao fields are abandoned (Shikata 2007).

Bongando Conservationists

The Bongando of Équateur province (DRC), who live in areas adjacent to wild bonobo populations, maintain a food taboo against consuming them. The reasons behind this taboo have been explored by Lingomo and Kimura (2009), who note that, in Bongando ethnobiology, Bonobos are not classified as animals, but as humans. As a result, they do not eat them (Ibid). Even in areas where great apes are hunted and consumed as bushmeat, local people do not see them simply as food. Oishi (2013) documents how local Bantu (Bakwele) and Pygmies (Baka) in eastern Cameroon hold ambivalent emotions and attitudes toward western Gorillas: They are not just an animal species, but social entities often representing ethnic "others." These case studies demonstrate how ethno-anthropologies, drawing on metaphors of human diversity, can intersect with wildlife conservation contexts. In addition, they show that it is not sufficient to look at bodies of traditional knowledge simply in terms of their conservation utility for Western science. Rather, it is critical to understand how local people perceive, and confer value on, living organisms within their environments.

Maintenance and Intergenerational Transmission of Traditional Knowledge

There is substantial evidence of the value of traditional knowledge for the sustainable development agenda. It has proven effective for sustainable land and resource management, climate change adaptation, biodiversity conservation, and disaster risk reduction (Magni 2017). However, as previously noted, for several decades effective practices and technologies originating from Traditional Knowledge Systems have been extracted, rebranded, and promoted as novel technologies, without paying due recognition to their original sources (Bello et al. 2024; Makondo and Thomas 2018; Zvobgo et al. 2022). This has contributed to the perception that practitioners of Traditional Knowledge Systems contribute nothing to the progress of science, technology, arts, and the humanities (Battiste 2002).

At the same time, there has been a recent surge of interest in restoring and mainstreaming the value of Traditional Knowledge Systems, with initiatives aimed at promoting them having increased over the years. For some, traditional knowledge constitutes a potential alternative for sustainable development (Briggs 2005). Yet attempts to encourage the transmission of traditional knowledge across generations

have been impeded by several bottlenecks, including knowledge maintenance and transmission mechanisms, contemporary educational institutions and agendas, and societal issues such as gender discrimination and intergenerational frictions between young and old.

In terms of knowledge maintenance and transmission mechanisms, traditional knowledge is passed on from generation to generation through an experiential learning process consisting of constant interaction with the adult members of society and the natural environment (Batibo 2013). It generally involves practical demonstrations, oral approaches, storytelling, mythical narratives, metaphors, and songs (Battiste 2002). However, this process has often been interrupted by the penetration of Western lifestyles into African communities. Contacts between youth and the natural environment (flora and fauna) have tended to decrease, while negative attitudes toward traditional ways of life have also developed over time (Batibo 2013).

Additionally, although Western knowledge systems have tapped into the wealth of Traditional Knowledge Systems, the latter have been systematically excluded from contemporary educational institutions, with a conscious effort to erase them (Battiste 2002). Indeed, a great deal of traditional knowledge has been eroded because of the penetration of the contemporary educational system, whose teaching curricula discourages plurality, and whose assessment methods and teaching methodologies lack contextual relevance and even discredit Indigenous knowledge (Barnhardt and Kawagley 2005; Batibo 2013; Stavenhagen 2015). Yet rather than being a stumbling block to the promotion of traditional knowledge, contemporary educational institutions and facilities *could* be harnessed to transmit it (Batibo 2013). Several attempts to restore and scale up Traditional Knowledge Systems and practices through formal education channels are underway, and many successful efforts are being recorded in diverse regions of the world (Magni 2017).

As Hattori (2020) documents, there are both similarities and differences in terms of plant knowledge between Baka individuals: People seem to share knowledge extensively on food and material culture, but not on medicinal plants. Hattori (2020) argues that this reflects the medical history of particular individuals. In general, women and elders play a special role in upholding traditional knowledge. They are custodians of traditional knowledge, culture, and biological diversity, making them valuable sources of transmission. However, recent ethnobiological studies (e.g., Gallois et al. 2017a, b) also indicate the importance of childhood for the creation and maintenance of traditional knowledge among forest hunter-gatherers. Women take up most tasks in crop cultivation and play a key role in soil and water management and household gardening, all of which equip them with a deep knowledge of seeds, crops, and plant varieties. They later transfer this knowledge to younger generations, highlighting the important role of women in preserving biodiversity. However, women's knowledge is often undervalued and they can find themselves in a vulnerable position within their societies (Rocheleau 1991; Schmink and Gómez-Garcia 2016). Generally, as the generation gap grows wider between youth and elders, conflicts can constrain the interactions and social cohesion between different age groups, as was found to be the case in Kenya

(Rocheleau 1991). These factors may jeopardize the effective maintenance and transmission of traditional knowledge. In the context of the Congo Basin, however, Gallois et al.'s (2017a, b) research on Traditional Ecological Knowledge among Baka children found that children also generate their own knowledge about their surrounding environment.

Despite the value of traditional knowledge for sustainable development, the numerous barriers to its transmission underline the need for concerted efforts from formal education stakeholders and Indigenous communities to develop reforms that create more intercultural and inclusive education systems, empower Indigenous peoples, and scale up traditional knowledge. In addition, initiatives at local, national, and international scales that promote gender equality and aim to close the generation gap could be enhanced to limit traditional knowledge loss. Indeed, much of the traditional ecological knowledge that Indigenous people possess is related to foraging activities in the forest, such as hunting, gathering, and fishing (e.g., Fongnzossie et al. 2023). Restrictions on, or the criminalization of, Indigenous peoples' forest activities have become major contributors to the loss of their traditional knowledge.

Methodologies to Collect, Assemble, Format, and Store Indigenous and Local Knowledge

Since traditional knowledge is a key part of what Congo Basin Indigenous peoples and local communities have to offer a wider world faced with environmental crises, it should be seen as part of the capacity-building efforts of the Framework for the Development of Indigenous People, which is based on the need to create a tailored development program adapted to the culture and living conditions of Indigenous peoples. Thirty years ago, Poole described several projects in which Indigenous people were involved in mapping exercises to delineate their own lands across the world, but he did not find any such exercises in the Congo Basin. In recent years, however, such efforts have been carried out by various international NGOs (see www.mappingforrights.org). However, only two articles (i.e., Mutimanwa 1996; Bikopo 2013) were published by people from Congo Basin Indigenous communities in the literature used in this assessment. Although there are certainly others that were missed, this provides an illustration of how little Indigenous knowledge has been gathered, treated, and disseminated in the last several decades. The very limited number of authors reviewed in this chapter who are from Indigenous communities also suggests that capacity-building efforts have failed to adequately address the inclusion of Indigenous peoples in these initiatives.

As discussed above, Indigenous Knowledge is built on the epistemic grounds of oral tradition (Jessen et al. 2022), in which knowledge is generated by a group's material and immaterial experiences, while that knowledge is acquired collectively, possessed, and shared with the group, without being written down for future generations (Langley 1976) or for a wider world. Knowledge maintained orally survives only with strong transmission frameworks and the persistence of the

communities that have generated it. Studies (e.g., Turnbull 1983; Stephenson and Newby 1997) have shown that long-term interactions between Indigenous communities and their Bantu neighbors have evolved over the millennia (Moïse 2014). For De Meester (1980), these changes include the fact that the repertoires of many oral traditions are threatened by modern historical change, whereby not only languages (e.g., Mangulu 1994) but also practical knowledge (e.g., Bahuchet 1985) specific to some particular communities is slowly, but inexorably, being eroded.

Asserting that there are changes that affect the transmission of oral traditions, languages (e.g., Mangulu 1994), and practical knowledge (e.g., Bahuchet 1985) of Indigenous communities implies the need to gather, format, and store Indigenous and local knowledge, as well as to find ways to link these forms of knowledge to that of Western science. As Zinsser (1994) suggested three decades ago, doing so will not only pave the way for bringing Indigenous knowledge to the forefront of ecological research but also expand the collective knowledge that future generations will possess to address global, ecologically vexing questions, including the loss of biodiversity, climate change, and sustainable development.

One of the pioneer works in constructing Indigenous and local knowledge platform for collecting and sharing is AFlora developed by Center for African Area Studies of Kyoto University. The AFlora database project has been launched since 1987 that aims to compile and retrieve information on traditional knowledge of plants in tropical Africa cross-culturally (Kimura 2013). It contains a lot of firsthand data obtained from Indigenous and local communities of Congo basin over decades, enabling comparative study of ethnobotany of Indigenous plant knowledge (e.g., Ichikawa and Terashima 1996; Terashima and Ichikawa 2003). Data collected in AFlora contain a variety of information aspects of human-plant interactions that are not only limited to economic, material, and pharmaceutical utilities but also religious and spiritual uses. AFlora is a database of cultural heritage and its "principal users should be the African people themselves" for the preservation of their knowledge (Ichikawa et al. 2001). For this purpose, AFlora database had once been made available to the public as a web-based database from 1997, so that anyone interested can access it. However, with the increasing reports of "biopiracy" cases on Indigenous knowledges, AFlora became closed again for general public (Kimura 2013). Whereas sharing and exchanging knowledge between scientists and Indigenous and local communities are indispensable for collaboration, the question of intellectual property rights should also be addressed. Unfortunately, this chapter appears to indicate that the gap between the hopes raised since the 1992 Biological Diversity Convention and achievements thus far realized is still very large in terms of capacity building for Indigenous communities, acknowledgment of their intellectual property rights, and facilitating their contributions to modern scientific disciplines.

It is, therefore, a major conclusion of this chapter to call on the scientific community working in the Congo Basin to communicate across disciplinary lines to come to an agreement on methodologies to collect, assemble, format, and store Indigenous knowledge, as a matter of urgency, before the most important forms of

oral knowledge that Indigenous communities hold are lost. To achieve this, bringing Indigenous people into the mainstream scientific research agenda is crucial. In addition to formal academic training for Indigenous people, developing some creative-yet-effective methods will also be critical for preserving the historical knowledge these communities possess. One example, currently being implemented in the Congo Basin, comes from Cameroon and represents one of the more promising efforts to facilitate a dialogue between Indigenous and scientific knowledge (see below).

School for Indigenous and Local Knowledge for Baka (Cameroon)

The Congo Basin Institute's School for Indigenous and Local Knowledge (SILK) keeps the Traditional Ecological Knowledge (TEK) of Indigenous Baka communities of Cameroon alive. In addition to facilitating Baka-taught courses and Baka-led documentation of TEK, the project engages Baka in science through partnerships with researchers: Baka act as research guides and are integrated into research teams. Researchers provide scientific training and work with Baka to weave TEK into scientific knowledge frameworks. In addition, Baka earn livelihoods through participation in data collection. In this way, SILK valorizes Baka TEK while also providing formal training on new technologies and techniques. This valorization also promotes intergenerational TEK transmission, keeping these largely oral traditions alive within their communities of origin.

It also creates opportunities for TEK and scientific data to be woven together to enhance our understanding of, and appreciation for, the natural world. As a result, researchers have collected data they would not have been able to collect without TEK, and the Baka researchers have been listed as coauthors on peer-reviewed articles and have presented their TEK to protected area managers.

Together with Baka experts from around the Dja Reserve, SILK's research is focused on plant-animal interactions: SILK has been collecting long-term monthly data on tree phenology and the frugivores that disperse their seeds at Boaumir Research Station, a 30 km walk into the Reserve. Based on this, a network analysis of these mutualistic interactions was performed to capture and predict the vulnerability of the Dja forests to faunal loss, as well as the seasonal availability of food in forest pipelines. This is also a way of highlighting the key role animals play as seed dispersers for youth involved in bush meat hunting.

Furthermore, SILK is working with Baka communities south of the Reserve, where they attempt to facilitate the transmission of Baka TEK between older and younger generations by conducting studies in the interzone between the Dja and Ngoyla, with teams composed of Baka men, women, and youth from ten villages. The project conducts participatory mapping, creates line transects to estimate great ape populations/presence based on nest counts, and encourages the transmission of various aspects of TEK related to flora and fauna.

The Territorial Anchor for Sustaining Indigenous Knowledge

For tens of thousands of years, traditional knowledge in the Congo Basin has been embedded in local systems of customary land management, which have sustained the rich biodiversity of forest ecosystems over the millennia. Proof of their effectiveness is provided by early accounts of European explorers in the late nineteenth century, all of whom recorded a landscape filled with abundant flora and fauna (Stanley 1885; Parke 1891). In the customary system, the landscape is divided into local forest territories, each of which is held by a particular community, or group of communities, and is passed on to their descendants to sustain their livelihoods. In this way, each forest territory is treated as a local commons and the community with rights to it acts as a trustee for a collective patrimony that is passed down through the generations (Moïse 2017).

The local customary territory is the primary context in which knowledge of subsistence activities (e.g., animal behavior and hunting techniques) and forest lore (e.g., knowledge of medicinal plants and oral traditions about the forest) are passed on from elders to youth (Ibid.). Such knowledge is transmitted vertically from a father to his sons and from a mother to her daughters; it is also transmitted horizontally, by other children in multiage play groups and by other adults on daily hunting and gathering expeditions (Hewlett 1991). In this way, the local customary territory functions as a "classroom" for the school of Indigenous knowledge, as it is here that the entire corpus of knowledge is transmitted from one generation to the next.

Given the key role that customary territories play in the transmission and reproduction of Indigenous knowledge, outsiders seeking to make use of such knowledge should make an effort to ensure that each generation of its bearers has access to the "classroom" in which its rich corpus is learned and transmitted. For, without access to functioning customary territories, there can be little transmission of Indigenous knowledge. In addition, if transmission is interrupted and Indigenous knowledge is lost, there can be no collaboration with science. Thus, outsiders seeking to preserve Indigenous knowledge should not only collaborate with its bearers but should also support them in their efforts to secure and retain rights to their customary lands. In this way, Indigenous knowledge will cease being a commodity extracted by outsiders for their own benefit and instead become what it had always been prior to the arrival of Europeans in the nineteenth century: a living archive, enduring in perpetuity.

Synthesis

This chapter reviewed published materials on the extent to which existing ecological knowledge includes Indigenous knowledge and the gaps between modern science and Indigenous folk science. Assessing how much Indigenous knowledge is represented in published materials is difficult because, although Indigenous peoples contributed to research conducted by contemporary scientists, they generally do not

appear as authors in publications; at most, they are acknowledged as having helped in conducting the research, but not listed as authors. A thorough examination of how much knowledge Indigenous communities possess, but still remains outside mainstream science, shows that there are large gaps to be filled. Areas where this could be done include the following: identification of new molecules for public health applications; identification and documentation of new species; and identification of species with potential to fight food insecurity. Acknowledging that complementarity between science and traditional knowledge is essential, the chapter has argued that the scientific community working in the Congo Basin should communicate across disciplinary lines to develop methodologies to collect, assemble, format, and store Indigenous Knowledge, as a matter of urgency, before the most important forms of oral knowledge held by Indigenous communities are lost. Bringing Indigenous people into the mainstream scientific research agenda should become a priority, for both regional policies and specific initiatives. Schemes such as the School for Indigenous and Local Knowledge for Baka (located in Cameroon) should be pursued by all the countries of the Congo Basin. Finally, as a first step, gaining an understanding of how many Indigenous people actually live in the Congo Basin is essential; this could be done via specific censuses conducted by demographers and other social science experts.

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Nature-Based Solutions in the Congo Basin 35

Lydie-Stella Koutika, Denis Jean Sonwa, and Venkataramana Sridhar

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Abstract

Nature-based approaches have the potential to address challenges such as climate change, biodiversity loss, pollution, flood and drought mitigation, land and soil restoration, and to sustain agricultural productivity, including maintaining pollinators, and regulation of pests and diseases. Case studies from the Congo Basin with the potential to scale up across countries to support efforts being invested in other parts are presented. This chapter highlights the role of local, indigenous, and endogenous knowledge in addressing some of the most intractable current ecological, economic, and social challenges. Although engaging local communities directly is sometimes difficult, their knowledge remains highly valuable. Building trust between the scientific and indigenous communities is crucial to scaling up the contributions of traditional knowledge in evaluating the impact of various nature-based solutions (NbS) across different biomes in the Congo Basin. To support its argument about how science can contribute to sound decision-making processes, we demonstrate in this chapter how NbS can generate non-climate benefits, including biodiversity conservation, which contribute to climate benefits (global cooling, rainfall pattern), food security, water quality improvement, better water penetration into soil, food for livestock, and fuel wood energy supply. We also show how NbS help countries contribute to international commitments, such as the Paris Agreement, 4 per 1000 Initiative "soils for food security and climate," the Convention on Biological Diversity (CBD), and the Agenda 2030 Sustainable Development Goals (SDGs).

Keywords

Nature-based approaches · Climate change resilience · Biodiversity conservation · Soil restoration · Non-climate benefits · Sustainable development

Introduction

Nature-based solutions (NbS) aim to conserve, restore, and manage natural or altered ecosystems in a sustainable way to tackle societal challenges, providing both human well-being and biodiversity benefits (Cohen-Shacham et al. 2016). Addressed societal challenges include climate change mitigation and adaptation, biodiversity loss, pollution, food insecurity, and land degradation (Seddon et al. 2020; Dunlop et al. 2024). Studies have shown that the impact of climate change on river basins, including floods and droughts, and unsustainable land-use and water management may be mitigating by NbS around the world (Fig. 1, Setti et al. 2020; Kang and Sridhar 2022; Sridhar and Anderson 2017). The effectiveness of NbS implementation must be supported by legal, policy, and planning frameworks (Seddon et al. 2020). However, in the Congo Basin, because of weak implementation and planning frameworks, barriers to adopt NbS must be overcome, e.g., by enhancing economic support to smallholder farmers, promoting responsible markets, efficient private sector support, and extension services, in order to encourage investments (Koutika et al. 2025). This support may be

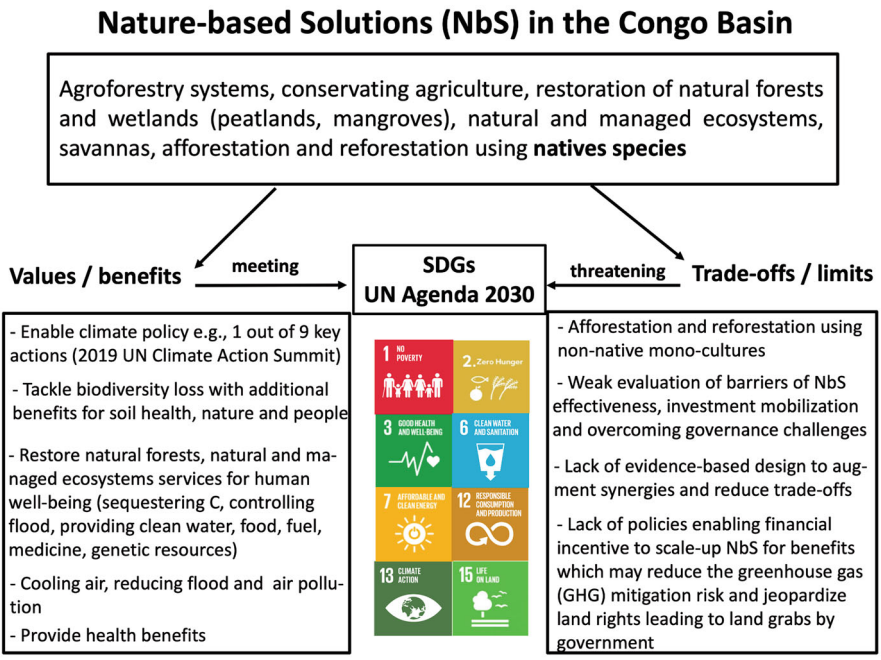

Fig. 1 Values and trade-offs of NbS which may be applicable to the Congo Basin

provided in part through the framework of the Comprehensive Africa Agriculture Development Programme (CAADP) (Koutika et al. 2025).

A global and regional systematic review highlighted three main pathways: (i) lessening the exposure to effects of climate change and social sensitivity to climate change; (ii) enhancing biodiversity of sources of food and income; and (iii) building resilience ability, projecting, applying, and governing NbS interventions (https://www.naturebasedsolutionsinitiative.org/work-theme/nbs-for-adaptation).

Within the frame of the International Union for Conservation of Nature (IUCN) and building on the foundations of NbS research and overlooked societal challenges, Dunlop et al. (2024) identified six additional research pathways to advance the evidence of NbSs: maintain, expand, pilot, innovate, re-assign, and connect (Fig. 2).

Despite the increasing deforestation rate over the past decade (Tyukavina et al. 2018; Shapiro et al. 2023), the Congo basin still longer-term stability of live biomass carbon stocks compared to the Amazon, where a declining trend has been reported (Hubau et al. 2020). NbS have long been used in Africa as part of traditional and cultural livelihoods, although documentation is limited. In fact, for centuries African populations have practiced NbS, particularly agroforestry systems, without any science-based evidence (Mbow et al. 2014). NbS such as forest and savanna management, reforestation, afforestation, and agroforestry improve soil and ecosystem health, contributing to the objectives of the "4 per 1000" initiative for the

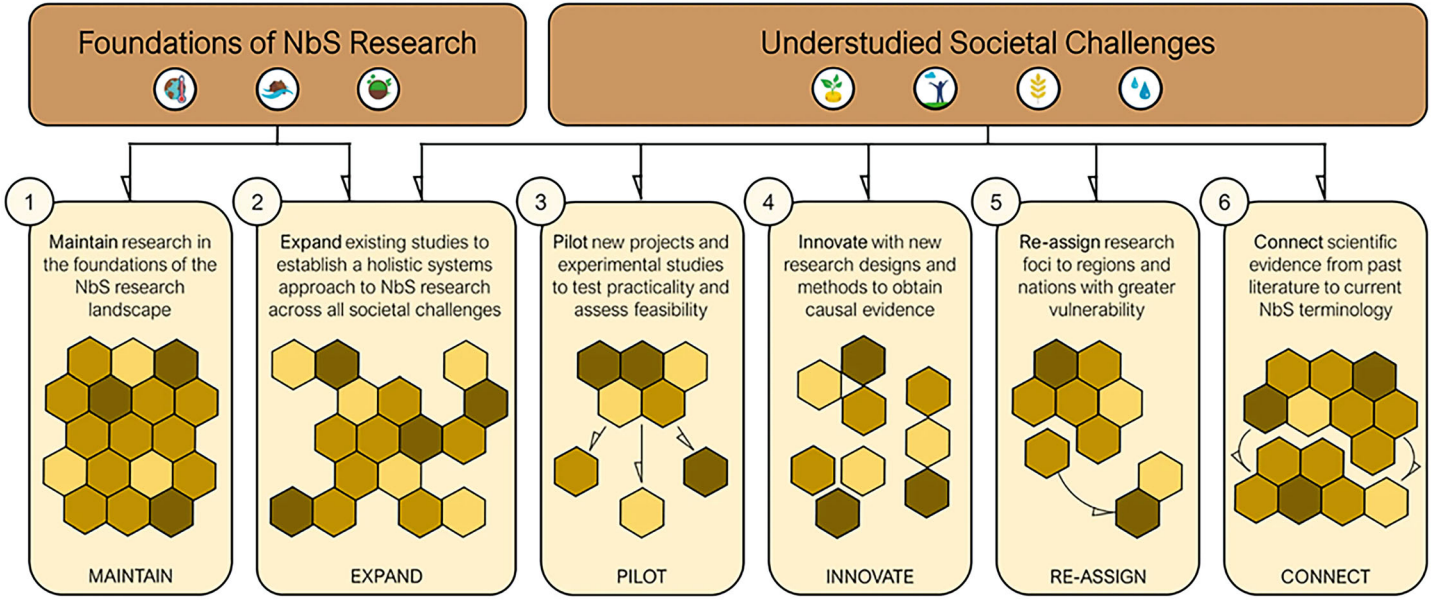

Fig. 2 Six research pathways proposed by Dunlop et al. (2024) to advance the scientific basis for NbS to address the societal challenges that are currently understudied within the NbS research landscape. Societal challenges are represented through IUCN icons: climate change, disaster risk, economic and social development, human health, food security, and water security

sustainable development goals (SDGs 2, 3, 7, 12, 13, and 15 of the UN Agenda 2030) (Kasongo et al. 2009; Dubiez et al. 2019; Koutika 2022; Koutika et al. 2022b; Olago et al. 2024).

Afforestation plays a crucial role in enhancing carbon storage and improving soil health, to mitigate climate change and land degradation, preserve ecosystem services (Lescuyer et al. 2009; Asaah et al. 2011), and provide fuel wood energy (Shure et al. 2012). The region has high wood consumption; in countries such as Cameroon, DRC, and RoC, over 90% of households use fuel wood energy (Shure et al. 2012). The forest plantations in the Congo Basin are composed of exotic and local species, e.g., Okoumé, Teak, Eucalyptus, Acacias, Pines, Ayous, Limba, rubber trees, etc. (Eba'a Atyi et al. 2022).

NbS offer significant benefits for climate policy, such as being one of the nine key action tracks at the 2019 UN Climate Action Summit, and addressing biodiversity loss, providing additional benefits for both nature and people. They help to restore natural forests (increasing carbon storage and enhancing and protecting biodiversity), and enhance ecosystem services for human well-being, sequestering carbon, controlling floods and providing clean water, food, fuel, medicine, and genetic resources. NbS also contributes to local and global cooling, reducing floods and air pollution and providing health benefits.

However, benefits from planting tree can be undermined by afforestation/refforestation with non-native monocultures, weak evaluation of barriers to NbS effectiveness, challenges in mobilizing investment, governance issues, and a lack of evidence-based design to maximize synergies and reduce trade-offs (Fig. 1). Also, the absence of policies that enable financial incentives to scale up NbS may reduce greenhouse gas (GHG) mitigation efforts and jeopardize land rights, leading to land grabs by governments (Seddon et al. 2020; Koutika et al. 2025). While plantations of exotics can be an effective means of increasing soil organic carbon (SOC) storage and provide fuel wood energy and other ecosystem services, it does not align with ecological principles and the use of mixtures plantations of native species is strongly encouraged (UNCBD 2022).

Therefore, more emphasize should be put on other NbS, such as the preservation and/or sustainable management of the largest peatland in the Cuvette Centrale depression, which stores 30.6 Gt of C, i.e., 29% of the world's tropical peat carbon (Dargie et al. 2017) and, implementing NbS in the world's largest terrestrial biome, the savannas, to mitigate climate change, restore land and biodiversity, secure food, supply bioenergy, and foster human health and well-being (Nyika and Dinka 2022; Djiofack et al. 2024; Olago et al. 2024; Chausson et al. 2020; Enu et al. 2023; Beekmann et al. 2024). The use of savannas is strategic since it is located at the northern and southern ends of the Congo Basin. They are, as degraded forest areas, often used for new plantations, to reduce the pressure on natural forests (WWF 2020).

Case studies are helping to test various nature-based approaches to address challenges including climate change adaptation, soil fertility, agricultural productivity, and pest control. This chapter explores the potential to scale up case studies across the Congo Basin. It highlights how local, indigenous, and endogenous

knowledge can help solve some of the most complex ecological, economic, and social challenges. Full credit will be given to traditional and indigenous knowledge, fostering trust between the scientific community and knowledge holders. This collaboration could pave the way for scaling up the contributions of all communities in evaluating the impact of different NbS across various biomes of the Congo Basin in a cost-effective manner in the future.

This chapter aims to demonstrate how science can contribute to sound decision-making processes, while demonstrating how NbS can provide both climate and non-climate benefits, such as enhancing biodiversity, water quality, soil health, disaster resilience, food security, air quality, human health, economies, cultural values and urban livability, and global cooling, while supporting sustainable development (Fig. 1). Additionally, it offers insights into how NbS can enhance the contributions of Congo Basin countries to international commitments, including the Paris Agreement, Kyoto Protocol, Koronivia Joint Work on Agriculture and the United Nations Agenda 2030.

Background and Status on Various Nature-Based Solutions

Mitigation of and Adaptation to Climate Change

The Congo Basin is undergoing significant climate and land-use changes, which are particularly sensitive in sectors such as food, water, health, and energy (Sonwa et al. 2012; Sridhar et al. 2022). Urban areas are especially vulnerable, where extreme climate conditions like heat and flooding affect infrastructure and result in loss of life (Kiribou et al. 2024). NbS also mitigate floods through watershed management, enable cooling cities, towns, and villages induced by trees (Jones et al. 2022). IPCC reports and other studies predict future scenarios that will impact the SDGs, but NbS present opportunities for countries in the region. Various ecosystem services can be harnessed for both climate change mitigation and adaptation.

In Central Africa, only Cameroon and RoC have included NbS in their Nationally Determined Contributions (NDCs),[1] with RoC clearly outlining NbS implementation projects.[2] Unfortunately, the Congo Basin has seen the least investment in NbS compared to other parts of Africa, where NbS is viewed as a tool for achieving the African Union's Agenda 2063 (Kiribou et al. 2024). In 2023, an assessment of NbS for mitigating hydrometeorological risks found only three case studies in Cameroon and the Democratic Republic of Congo (DRC) (Enu et al. 2023). The application of NbS to address these risks is more advanced in Europe, as well as in Southern and Eastern Africa (Enu et al. 2023).

[1] See, for details, page 46 of the Cameroon NDC (https://unfccc.int/sites/default/files/NDC/2022-06/CDN%20r%C3%A9vis%C3%A9e%20CMR%20finale%20sept%202021.pdf).

[2] See, for details, page 41 of the RoC NDC (https://unfccc.int/sites/default/files/NDC/2022-06/CDN_Congo.pdf).

The German Federal Ministry for Economic Cooperation and Development (BMZ) is supporting NbS initiatives in the Congo Basin. BMZ is directly funding initiatives that enhance nature-based solutions (NbS) to reduce vulnerability to climate change and biodiversity loss, while safeguarding ecosystem services and supporting the livelihoods of vulnerable populations. BMZ also supports multilateral initiatives such as AFR 100 (African Forest Landscape Restoration Initiative). Additionally, USAID is specifically funding NbS in Cameroon, the Republic of Congo, and the Democratic Republic of Congo as part of its Natural Climate Solutions program, which focuses on the conservation, management, and restoration of forests, mangroves, wetlands, peatlands, and agricultural lands (Pettinotti and Quevedo 2023). As climate and carbon finance become increasingly complex, countries in the region must strengthen their capacity to secure resources from various donors and funding opportunities, investing more of their national budgets (Pettinotti and Quevedo 2023). This includes funding from the Global Environment Facility's Eighth Replenishment Period (GEF-8), which is allocated to support NbS and ten other integrated programs in this GEF cycle. Infrastructure development, primarily driven by multilateral banks, is a key sector where NbS could be formally adopted (Pettinotti and Quevedo 2023). Several financial institutions are exploring ways to integrate Nature-Based Green Infrastructure (NB-GI) into their investment strategies (Dupar et al. 2023).

Despite the significant potential of NbS, countries in the region have not yet fully capitalized on available opportunities. Integrated watershed management in a dynamic framework that can provide tools for decision making in real time can be important to protect from floods and other natural disasters (Buri et al. 2024; Venkata Rao et al. 2024; Hoekema and Sridhar 2011; Sridhar et al. 2021). Embracing these solutions will enable more effective responses to climate change, especially for adaptation, through technologies aligned with nature conservation, which is crucial for the Congo Basin. Additionally, the evidence base must be strengthened, and the benefits of nature must be protected and harnessed to build global climate resilience (Chausson et al. 2020). This is particularly important in the Global South, including the Congo Basin, where communities are more vulnerable to climate impacts (Chausson et al. 2020).

Soil Health, Soil Fertility, Agricultural Productivity, Agricultural Pests, and Ecosystem Services

While investigating the impact of climate change on biodiversity in the Congo Basin, Beekmann et al. (2024) identified data gaps, highlighting the under-researched status of the region's rainforests, including key soil parameters. Leguminous planted fallows, nitrogen-fixing species (NFS) intercropped with non-NFS, are one approach to improve soil health. Healthy soils are essential for sustainability, due to the various ecosystem services they provide (Mrunalini et al. 2022). NbS can tackle multiple challenges such as microclimate, soil, and water management

including urban soils (Bouzouidja et al. 2021). They help restore soil health, i.e., lost soil productivity and sustain agricultural production (Nesshöver et al. 2017).

Improved soil health, e.g., N status, N being one of the most limiting nutrients in many African soils, has been reported in leguminous planted fallows (Pueraria and Mucuna) in southern Cameroon (Koutika et al. 2001; Kiboi et al. 2019). Improvements in soil fertility, such as increased carbon and nitrogen stocks, have been observed in mixed-species plantations of Eucalyptus clones and *Acacia mangium* in RoC (Koutika et al. 2014, 2021; Tchichelle et al. 2017). Increased carbon stocks were greater in mixed-species and Acacia monoculture stands (0.8 t/ha and 1.9 t/ha, respectively) compared to Eucalyptus stands (Koutika et al. 2021). Nitrogen stocks were 1.25 ± 0.02 t/ha in *A. mangium* and 1.19 ± 0.02 t/ha in Eucalyptus stands, with the highest value (1.28 ± 0.03 t/ha) found in the top 25 cm of mixed-species stands (Koutika et al. 2014).

Although plantations involving non-native species do not align with ecological principles and cannot be defined as NbSs (UNCBD 2022), they do have improved soil health via increased phosphorus availability in the surface litter (Koutika et al. 2020a) as compared to native savannas (Koutika and Mareschal 2017). This may be due to Acacia's ability to utilize organic forms of P by secreting phosphatase enzymes, and to access P from deep soil layers (Sitters et al. 2013). Soil health was also enhanced by the prevalence of *Actinobacteria*, beneficial for decomposing a broad range of hydrocarbons, pesticides and feather waste in bacterial communities (Koutika et al. 2020b). Changes in fungal community structure and diversity favour soil mycobiota, which boost the potential of mixed-species forest plantations to withstand environmental stress (Koutika et al. 2024). Research priorities for sandy soils on the Batéké plateaux, spanning from DRC to Gabon through RoC, emphasize agroforestry using nitrogen-fixing species, forest plantations, manure application and organic residue management as practices that improve soil health (Kasongo et al. 2009; Dubiez et al. 2019; Koutika et al. 2021, 2022a). NbS also maintain local communities' reliance on forest products (e.g., non-timber products) and other ecosystem services, including improved livelihoods, increased crop yields and incomes, and greater fuel energy availability (Lescuyer et al. 2009; Asaah et al. 2011; Shure et al. 2012; Koutika et al. 2022b).

Delaying the implementation of NbS in agricultural landscapes will increase the costs of achieving societal beneficial goals, such as agricultural production, climate mitigation, and conservation, while reducing the ability of natural systems to deliver these and other ecosystem services (Miralles-Wilhelm 2023). The scalability of perennial seeds as NbS enhances resilience and reduces risks in addressing global change, while alleviating social and soil-related drivers of low and variable production for smallholder farmers on marginal lands (Peter et al. 2017). In Latin America and the Caribbean, the development of NbS in the agricultural sector, alongside their potential for upscaling, is demonstrated through case studies that highlight the "triple-win" formula—environmental, social, and economic benefits—that sustain long-term positive impacts (Meza and Rodríguez 2022).

Frameworks that integrate NbS integrated pest management, and One Health, acknowledging the close connections between people, animals, and environmental health, are key to designing climate-resilient plant health systems that reduce the

need for pesticide use and mitigate emerging risks from pests, including insects, nematodes, weeds, and diseases, as a result of climate change. These frameworks focus on five nature-based solutions: host plant resistance and tolerance, habitat manipulation, biological control, semi-chemical control, and the use of biopesticides (Egan et al. 2021). Neuenschwander et al. (2023) identified five key strategies to reduce annual harvest losses—often by up to 50%—due to pests: (i) sanitation at national borders, (ii) good soil management, (iii) biological control, (iv) the use of resistant crop varieties, and (v) bio-pesticides based on viruses, bacteria, and fungi, to combat insects.

Forest and Land Restoration, Management, and Biodiversity Conservation

Central Africa's forests play a critical role in the global carbon cycle, storing some of the highest carbon densities and proving to be more resilient in the face of climate change compared to other tropical forests (Koch and Kaplan 2022). The Congo Basin is globally classified third in terms of species richness, spanning across broad rainforests of diverse forest types, e.g., Atlantic coastal evergreen to the semi deciduous (Mittermeier et al. 2003; Réjou-Méchain et al. 2021 in cited in Beekmann et al. 2024), enabling livelihoods for about 100 million people (Eba'a Atyi et al. 2022). Yet, they are under severe threat due to human-induced disturbances such as land-use changes, wildfires, and shifting agriculture, which exacerbate climate change and biodiversity loss. It is recognized that restoration of these ecosystems can serve as an effective NbS to counter these impacts. Although global studies have highlighted the potential of forest restoration, much of central Africa remains understudied relative to other rainforest ecosystems (White et al. 2021). Several articles identified in this chapter focus on the DRC, where artificial savannas—created largely through human activities like regular burning—offer an opportunity to restore forests and increase carbon sequestration if fire is excluded from the landscape (Djiofack et al. 2024).

Well-managed forests can provide sustainable NbS to address challenges related to water, food security and quality, energy, and poverty eradication, while contributing to several Sustainable Development Goals (SDGs). Although the Congo Basin Forest Commission (COMIFAC) aims to sustain and coordinate the management of its forests and biodiversity, the region's 180 million hectares constituting the world's second-largest tropical forest face increased degradation and biodiversity loss (Shapiro et al. 2023; Beekmann et al. 2024). Bele et al. (2015) emphasized the crucial role of Congo Basin forests in terms of vulnerability and adaptation to climate impacts, recommending sustainable management not only for the benefit of forest resources and biodiversity but also for broader sustainable development goals, such as poverty reduction, increased income, and job creation. Multiple-use forest management offers an effective alternative, integrating timber and non-timber resources, which are essential to the economies of rural communities (Nasi et al. 2012). However, the authors argue that expanding the boundaries of formal management

units and accommodating the interests of local communities, conservationists, and extractive industries within the same management area will be necessary.

Land Tenure: A Foundational Challenge and Opportunity for NbS

Secure and equitable land tenure is a critical enabling condition for the successful implementation of nature-based solutions (NbS). However, in the Congo Basin, land tenure is often complex, presenting both significant barriers and transformative opportunities. The coexistence of colonial-era legal frameworks with customary systems has created tensions, but also points to the need for inclusive, community-based reforms that recognize local rights and promote stewardship. NbS are best promoted in countries where land tenure and other tenures have a long history and are still evolving. In the Congo Basin countries, we encounter a complex situation characterized by layers of colonial and post-colonial legislation that coexist with various customary perceptions and practices regarding land and forest resources (Long 2011). Land tenure policies in the Congo Basin are diverse and complex, varying across countries like the DRC, RoC, Cameroon, and Gabon. These policies regulate land and forest ownership, access, and use but face significant challenges due to historical factors, conflicting legal frameworks, and the coexistence of customary and statutory systems.

As poverty has increased during the last decades, inequalities have become apparent in the forestry sector, illustrating significant injustices in forest resource management, despite efforts at devolution, such as community forestry initiatives in some countries (Donn et al. 2016; Nielsen et al. 2012). The overlap of various laws has created conflicts and inconsistencies within the tenure system. Such conflicts and inconsistencies can negatively impact nature-based solutions, which generally rely on the sustainable use of forest resources to address various challenges.

In most Congo Basin countries, when we consider legal versus customary tenure systems, formal legal systems coexist with customary tenure practices, rooted in local traditions. Statutory laws, often inherited from colonial systems, frequently clash with customary rights, leaving indigenous and local communities with limited recognition of their land claims (Samndong and Vatn 2018). This duality leads to conflicts, especially when land is allocated for commercial uses like logging or agriculture, without regard for customary rights.

In several Congo Basin countries—such as the Democratic Republic of Congo (DRC) and the Republic of Congo (RoC)—land is generally considered state-owned unless formally registered as private property. This arrangement complicates long-term tenure security for local communities, who often struggle to formalize rights to land they have traditionally used.

In addition, large-scale land concessions for agriculture, logging, and mining often overlap with areas traditionally used by local communities, leading to conflicts over access to land and resources. Some countries, such as Cameroon, Gabon, and the DRC, have introduced community forestry schemes to allow local communities to manage forests (Tsanga et al. 2022). However, the process for securing these rights is often complex and difficult to navigate.

There is also a need for recognition of indigenous land rights. In particular, indigenous forest peoples like the Baka, Aka, and Mbuti face major challenges in securing formal land rights, as national laws rarely fully recognize their customary claims. These communities, traditionally reliant on forests for their livelihoods, often encounter land dispossession due to conservation efforts, logging, mining, and other land-use changes. Though international frameworks like the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) aim to protect indigenous rights, implementation at the national level remains limited.

Some Congo Basin countries have attempted land reforms, promoting decentralization and community rights. For instance, Cameroon's reforms include recognizing customary land rights and encouraging community forestry. However, these reforms have been inconsistently applied, and local governments often lack the capacity to manage land resources effectively (Tsanga et al. 2022).

In the forestry sector, land tenure is already recognized as a critical issue when it comes to understanding the drivers of deforestation and identifying effective strategies for reversing it. In the DRC, it has been observed that the success of REDD+ initiatives, which aim to promote good practices for reducing deforestation and forest degradation, largely depends on considerations related to land tenure (Samndong and Vatn 2018).

To ensure that restoration, one of the main NbSs, serves as a driver of inclusive transformation and does not lead to the disappearance of customary law in favor of a more Western approach, Larson et al. (2024) make several recommendations. These include policies that would allow for the recognition of customary lands and tenure, along with multiple legal options. Key elements of these recommendations involve strong cross-ministerial collaboration and coordination, significant engagement from civil society and an awareness of existing inequalities. Additionally, they emphasize the importance of a gender-responsive and gender-transformative approach that takes into account customary perceptions and practices.

To fully harness the potential of NbS, it is essential to establish an institutional environment that addresses and removes barriers related to land tenure and tree/forest tenure. This requires inclusive and transformative policies that seek to reconcile ecological considerations with customary perception and practices. Therefore, the engineering of land tenure policies is a critical factor in promoting NbS in the Congo Basin.

Successful Case Studies from the Congo Basin

Extend the Efforts Invested in Other Parts of the Region Across the Entire Congo Basin

This section illustrates successful efforts to sustain NbS across the Congo Basin, including fire exclusion, agroforestry, afforestation, restoration and management of peatlands, and community forestry:

Fire Exclusion in a Human-Modified, Mesic Savanna for Carbon Storage

Easy and cost-efficient measures for fire exclusion in artificial savannas may serve as an effective NbS to address climate change and biodiversity loss. Djiofack et al. (2024) evaluated the success of forest restoration after fire exclusion in a human-modified, mesic savanna patch and examined the implications of similar NbS for climate mitigation efforts across central Africa. Forest restoration through fire exclusion on an 88-ha area in the Kongo Central province of the DRC has resulted in an average carbon storage of 11.40 ± 0.85 Mg C ha^{-1} in above ground biomass after 17 years (Table 1, Djiofack et al. 2024). The authors argue that approximately 112 ± 3 years are needed to recover up to 90% of aboveground carbon stocks in old primary forests. This approach may be applicable to similar savannas across the DRC, RoC, and Angola (Djiofack et al. 2024).

Afforestation of Native Savannas for Sustainable Development

In the neighboring Congolese coastal plains of the RoC, planting trees on nutrient-poor soils using improved germplasm, fosters high stand biomass, healthier soils, and enhanced wood and fuel wood energy supply, contributing to climate change mitigation and adaptation, food security, and the restoration of land and ecosystem biodiversity (Table 1, Koutika et al. 2021, 2022a, b). Overall findings over nearly three decades contribute to 10 of the 17 SDGs of Agenda 2030 and could be extended to neighboring countries from the DRC to Gabon and Angola (Koutika et al. 2022b).

Conservation of Peatlands to Enhance C Storage

The Cuvette Centrale depression in the central Congo Basin, located in DRC and RoC, contains extensive peat deposits that have been accumulating for about 10,600 years beneath swamp forests (Table 1, Dargie et al. 2017; Sonwa et al. 2022; UNEP 2022). These peatlands store around 30.6 petagrams of carbon below ground, with a 95% confidence interval of 6.3–46.8 petagrams of carbon. This amount is comparable to the above-ground carbon stocks of the tropical forests across the entire Congo Basin (Dargie et al. 2017). The Cuvette Centrale in the central Congo Basin—shared by the Democratic Republic of Congo (DRC) and Republic of Congo (RoC)—holds one of the most extensive tropical peatland complexes in the world. These peatlands have accumulated below swamp forests for over 10,000 years and store approximately *30.6 Pg of carbon*, a volume comparable to the total above-ground carbon stock of Congo Basin forests (Dargie et al. 2017; Sonwa et al. 2022; UNEP 2022).

While much of the discourse on Nature-based Solutions (NbS) emphasizes active restoration and climate mitigation through additional carbon uptake, the *conservation of intact peatlands represents a critical form of NbS through avoided emissions*. By safeguarding these ecosystems from degradation due to land-use change or hydrological disruption, we prevent the catastrophic release of carbon. This "protection-as-solution" model should be recognized alongside more proactive NbS

Table 1 Societal challenges, Sustainable Development Goals (SDGs), and deficiencies of some Nature-based Solutions (NbS) in countries of the Congo Basin

Nature-based solutions	Potential societal challenges to tackle	SDGs agenda 2030	Deficiencies	Involved Congo Basin countries	References
Agroforestry	Climate change mitigation and adaptation, land (soil) restoration, food security, fuel wood energy	SDGs 1, 2, 12, 13, and 15	Biodiversity conservation	Cameroon	Asaah et al. (2011)
Sustainable forest management	Climate change mitigation and adaptation, conservation of biodiversity, poverty alleviation (income generation and job opportunities)	SDGs 2, 3, 13, and 15	Fuel wood energy	Cameroon, CAR, DRC, Equatorial Guinea, Gabon, and RoC	Bele et al. (2015)
Natural forest management	Biodiversity loss, climate change mitigation, drought	SDGs 3, 13, and 15	Lack of research resources	Cameroon, CAR, DRC, Equatorial Guinea, Gabon, and RoC	Beekmann et al. 2024)
Sustainable peatlands management	Climate change mitigation, biodiversity loss, autochthone population wellbeing	SDGs 3, 12, 13, 15, and 17	Food security	DRC and RoC	Dargie et al. (2017)
Restoration of degraded forest and savannas using fire exclusion	Climate change (C storage in soil and biomass) biodiversity loss	SDGs 13 and 15	Food security, fuel wood energy supply	DRC, Angola, and RoC	Djiofack et al. (2024)
Rotational agroforestry systems	Climate change mitigation and adaptation, food security, land (soil) restoration	SDGs 1, 2, 3, 12; 13, and 15	Biodiversity loss, fuel wood energy supply	DRC	Dubiez et al. (2019)
Agroforestry systems	Climate change adaptation and resilience, land (soil) restoration, food security	SDGs 1,2, 3, 12, 13, and 15	Biodiversity loss, fuel wood energy supply	DRC	Kasongo et al. 2009)

(continued)

Table 1 (continued)

Nature-based solutions	Potential societal challenges to tackle	SDGs agenda 2030	Deficiencies	Involved Congo Basin countries	References
Agroforestry and forest plantations	Climate change adaptation, land (and soil) restoration	SDGs 2, 3, 7, 12, 13, 15, and 17		DRC and RoC	Koutika et al. (2021)
Sustainable soil management in agricultural, agroforestry, forest systems	Food security, climate change mitigation and adaptation, conservation of biodiversity loss	SDG 2, 12, 13 and 15	Fuel wood energy, biodiversity loss	DRC, Gabon, and RoC	Koutika et al. (2022a)
Sustainable forest plantation management	Global climate change, food insecurity, land degradation, and desertification	SDGs, 1, 2, 3, 4, 6, 7, 12, 13, 15, and 17	Biodiversity loss	RoC	Koutika et al. (2022b)
Natural forest management	Biodiversity loss, land and ecosystem restoration	SDGs 3 and 15	Climate change, food security	Cameroon, CAR, DRC, Equatorial Guinea, Gabon, and RoC	Nasi et al. (2012)
Sustainable management of savanna ecosystems	Climate change mitigation and adaptation, biodiversity loss, food security, land (soil) restoration	SDGs 1,2, 3, 7, 12, 13, and 15	Southern part of the savanna belt	Cameroon, CAR, and DRC	Olago et al. (2024)
Natural forest management	Climate change mitigation, energy, water, health, food security	SDGs 2, 3, 6, 7, and 13	Biodiversity loss	Cameroon, CAR, and DRC	Sonwa et al. (2012)

measures, such as reforestation or restoration. In fact, **keeping both peatlands and intact forests standing is not merely about preventing loss, but about sustaining globally significant carbon sinks, climate regulation systems, and biodiversity reservoirs.** The Congo Basin's peatlands exemplify how strategic protection is not a passive act, but a powerful form of climate and ecosystem stewardship.

Community Forestry to Mitigate Climate Change and for Productive and Economic Purpose

Awazi et al. (2024), in their review of nature-based solutions (NbS) in Cameroon, highlight various instances where community forestry, introduced in Cameroon since 1994, has significantly contributed to the advancement of NbS across different ecosystems in the country. This contribution has been realized through climate change mitigation efforts under REDD+ and by enhancing the climate resilience of local communities. Forest restoration by farmers was mainly made in degraded areas in Cameroon and the DRC with the focus on productive and economic purposes (wood fuel production and diversification of farmers' incomes) (Peroches et al. 2025).

NbS for Recovering Biodiversity, Economic Viability

A recent systematic review of literature in the savanna belt of Africa, showed that diverse NbS are used in this region (Olago et al. 2024). However, few strategies described as NbS actually met the IUCN criteria. The criteria that were least encountered included biodiversity recovery, economic viability, governance, trade-offs, and adaptive management. Most research was driven by the global north and focused on small-scale agriculture in a few countries. To date there is limited intra-African and interdisciplinary collaboration in these research efforts (Mbow et al. 2014; Peroches et al. 2025). In the future, NbS should prioritize having integrated approaches that are inclusive, involve a range of stakeholders, are relevant to the local context and show clear biodiversity and climate change mitigation potential along with being easily applicable and mainstream-able.

Science Supporting Decision-Making Processes

The most active institutions, authors, and countries involved in NbS in Africa, are from four leading countries: South Africa (47 studies), Kenya (9), Ethiopia (5), and Côte d'Ivoire (2), with the majority of research output in environmental sciences and ecology (Nyika and Dinka 2022). To amplify research conducted in other parts of Africa, the authors recommend studies for further reference on raising awareness for the sustainable built environment and mitigating hydrometeorological risks (Aghimien et al. 2024; Enu et al. 2023).

Although there has been a steady rise in research publications on NbS, particularly in the last decade, collaboration among African countries remains limited, as most institutions conducting NbS research are based in developed countries, with the exception of South Africa (Nyika and Dinka 2022). This situation is attributed to limited research capacity and unresponsive policies and institutions that hinder the promotion of NbS on the continent.

The authors recommend reanalysing NbS and their associated benefits to design adaptive frameworks tailored to the specific challenges faced in Africa. They also

advocate for inclusive participation of all stakeholders in decision-making, evidence-based research, integration of grey infrastructure, adaptive institutional and policy modifications, and regulation of financial support from both government and the private sector through a trans- and multidisciplinary approach (Nyika and Dinka 2022).

NbS and Non-Climate Benefits

Biodiversity Conservation, Food Security, and Water Quality Improvement

Nature and society are interlinked and crucial for ensuring food and water resources, income, and human health, all of which are increasingly affected by environmental changes (Dunlop et al. 2024). Based on primary themes from the NbS research landscape (1990–2021), the authors reported four underrepresented societal challenges: economic and social development, human health, food security, and water security. Biodiversity conservation, food security, and water quality improvement are among the seven societal challenges that NbS can address according to the IUCN (Dunlop et al. 2024).

However, Beekmann et al. (2024) reported significant uncertainties regarding the sustainability of biodiversity in the Congo Basin, in light of current and future global changes. Additional research resources are strongly recommended to fill identified gaps, such as the sensitivity of Congo Basin organisms and ecosystems—particularly peatlands—to rising temperatures, changes in flowering and fruiting phenology among trees and their implications across taxonomic groups, and compositional shifts and tipping points within Congo Basin ecosystems (Nasi et al. 2012; Dargie et al. 2017; Beekmann et al. 2024).

Agroforestry systems enhance food production, including wood production which is particularly important in the Congo Basin, which faces high wood consumption and food insecurity (Bisieux et al. 2009; Kasongo et al. 2009; Shure et al. 2012; Nsombo 2016; Dubiez et al. 2019). In the DRC, 8000 ha of forest (industrial plantations) and agroforestry have been established using *Acacia auriculiformis*, a NFS (1987–1993) in the Batéké Plateau (Mampu) (Bisiaux et al. 2009). In agroforestry systems, yields of cassava and maize increased by 6 t ha^{-1} (9–15 t ha^{-1}) and 1 t ha^{-1} (0.5–1.5 t ha^{-1}), respectively, (Nsombo 2016), highlighting the improved availability of staple crops in NbS agroforestry systems that integrate NFS in the Batéké Plateau in DRC (Nsombo 2016), even when using non-native species (UNCBD 2022).

NbSs promote emerging best practices enabling equitable and appropriate water use and efficiency (Bremer et al. 2021). Africa dedicates a greater proportion of NbS research to governance and planning, with food security prioritized over the lowest percentage of NbS research focused on water security and human health (Dunlop et al. 2024). In the forest plantations established in the Congolese coastal plains, extremely

low nutrient concentrations were reported in solutions collected at all measured depths using tension lysimeters (Laclau et al. 2003), likely due to the high nutrient requirements of low-input forest plantations and the low nutrient availability of weathered soils.

Non-Timber Products

Non-Timber Forest Products (NTFPs) are integral to various NbS that aim to tackle environmental challenges. In the context of climate change, the sustainable use and management of vegetation are recognized as essential for both adaptation and mitigation efforts. While NTFP plants can be utilized to support climate change responses within technical nature-based solutions, the diverse products they yield—such as roots, leaves, and bark—can also provide co-benefits.

Given their close ties to the livelihoods of communities across different landscapes, the utilization of NTFPs adds significant value, enhancing the effectiveness of nature-based technologies. NTFPs play a crucial role not only in climate change mitigation—by sequestering and storing carbon—but also in reducing the vulnerability of ecosystems and the communities (Nkem et al. 2010; Tieminie et al. 2021) that rely on them. Furthermore, they can create additional livelihood opportunities for these communities (Bele et al. 2013).

While plant-based NTFPs are integral to the structural framework of NbS, other NTFPs, such as those derived from bees and animals, can also thrive as a result of the enabling environment created by these solutions.

Nature-based Solutions (NbS) provide benefits that extend well beyond climate mitigation and adaptation. Among these are a range of socio-economic and ecological advantages linked to the plant species used within NbS interventions. In particular, species that yield Non-Timber Forest Products (NTFPs)—such as fruits, nuts, resins, fibers, and medicinal resources—offer direct livelihood benefits to local and rural communities. Therefore, the selection and integration of NTFP-producing species should be a central consideration in the design of NbS, ensuring that ecological restoration efforts also contribute to food security, income generation, and cultural resilience.

Fighting Pollution, Supplying Fuel Wood Energy, and Providing Other Ecosystem Services

Among the non-climate benefits provided by NbS, fuelwood energy, along with other ecosystem services, ranks among the most significant in regions characterized by high wood consumption (Lescuyer et al. 2009; Shure et al. 2012; Bele et al. 2015). With a population exceeding 100 million, about 60% of whom live in rural areas, the DRC has the highest production and consumption of fuelwood and charcoal energy in the Congo Basin (Shure et al. 2012). Fifteen years ago, fuelwood represented a significant portion of the total biomass harvested in country (including

logging), accounting for 94% in DRC, 79% in Cameroon, 35% in RoC, and 24% in Gabon, according to Shure et al. (2012).

NbS and Contribution to International Initiatives and Country Engagements

Paris Agreement, Nationally Determined Contributions (NDCs), 4p1000 Initiative, etc.

The most comprehensive viewpoint on the use of NbS in addressing environmental, economic, and human health challenges is provided by the IUCN (Anderson and Gough 2022). NbS engender several benefits, including climate mitigation, land and biodiversity conservation and restoration and improvements in human health and well-being, all of which significantly contribute to sustainable development (Bremer et al. 2021; see next section).

Research and innovation on NbS have received considerable funding since 2015, coinciding with the declaration of the UN SDGs and the negotiation of the Paris Agreement. Currently, several countries have listed NbS in their updated climate pledges and Nationally Determined Contributions (NDCs) (Seddon et al. 2019; Bakhtary et al. 2021; Dunlop et al. 2024). NbS also strongly support advanced science, with high priority given to the Convention on Biological Diversity and the United Nations Framework Convention on Climate Change (UNFCCC) (Boran and Pettorelli 2024). A clear policy window for both conventions, introducing a formal governance structure to foster ideas, people, organizations, and processes necessary to stabilize the climate and recover nature, have been presented at the UNFCCC Conference of the Parties (COP) 29 and the Convention on Biological Diversity COP16 (Boran and Pettorelli 2024).

Established during COP21 held in Paris in 2015, the International "4 per 1000" Initiative encourages stakeholders to embrace sustainable soil management, which generates jobs and income, leading to sustainable development (Rumpel et al. 2019). The initiative aims to promote concrete solutions to tackle climate change and food insecurity through agricultural practices adapted to local conditions, benefiting farmers, herders, and the global population. Although no country in the Congo Basin is a member, national farmers' and foresters' organizations, civil society associations and NGOs—mainly in the DRC and Cameroon, but also in Gabon, the CAR, and the RoC—are participants in this initiative (www.4p1000.org).

A systematic literature review reported that introducing nitrogen-fixing trees (NFTs) enhances crop yields, carbon sequestration and other ecosystem services in forest (RoC) and agroforestry systems (DRC), contributing to the objectives of the 4 per 1000 Initiative (Koutika et al. 2021). Other ecosystem services include the supply of pulp and fuelwood energy, poles for electricity networks, food availability and land restoration, as well as improved soil health and food security, mainly through non-timber products (Fig. 3).

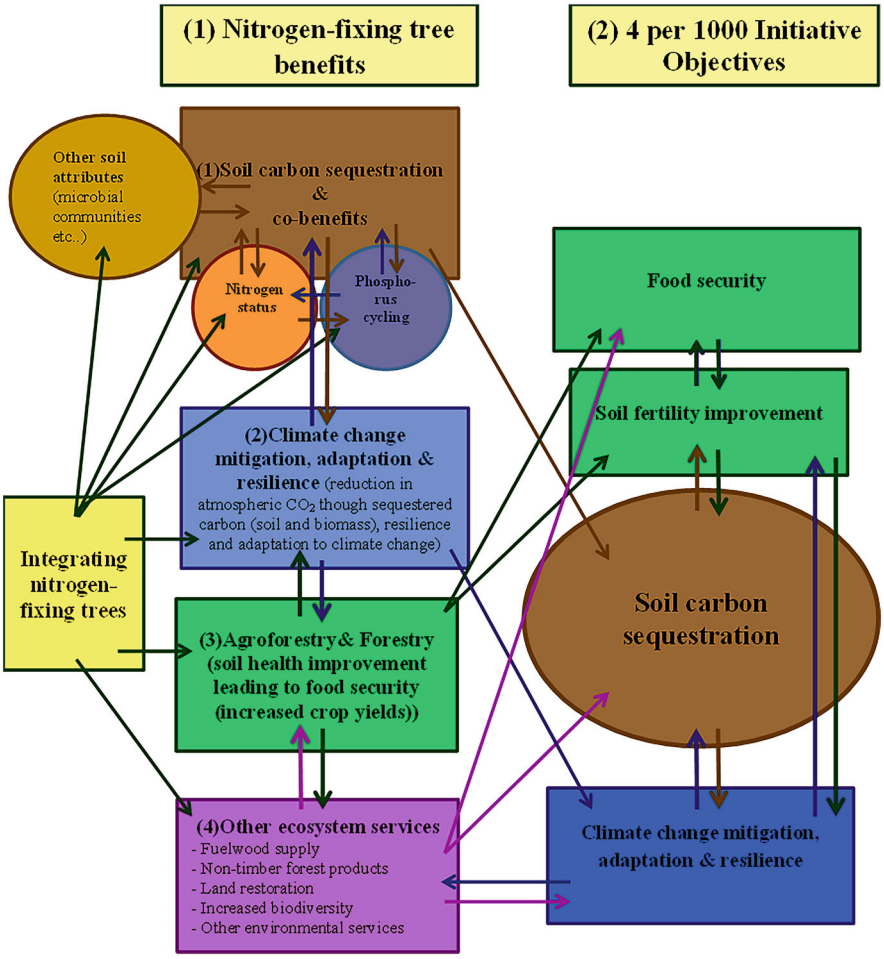

Fig. 3 Conceptual scheme of benefits from (1) introducing nitrogen-fixing trees; and (2) linked to 4 per 1000 Initiative objectives in agroforestry and forestry, leading to carbon sequestration and co-benefits and other ecosystem services and promoting the 4 per 1000 Initiative in the Congo basin (DRC and RoC). (Soil carbon sequestration and co-benefits (brown); climate change (blue); soil improvement and food security (green); other ecosystem services (violet); shapes used do not have any significance). (According to Koutika et al. 2021)

Sustainable Development Goals (SDGs) of the UN Agenda 2030

Research conducted on NbS, i.e., genetics, breeding and diversity, plant and environment interactions, socio-environmental management, sustain forest productivity, and improve the livelihoods of rural populations in the Congolese coastal plains (Koutika et al. 2022b). These investigations, conducted over nearly three decades, contribute directly and/or indirectly to 10 out of the 17 United Nations SDG

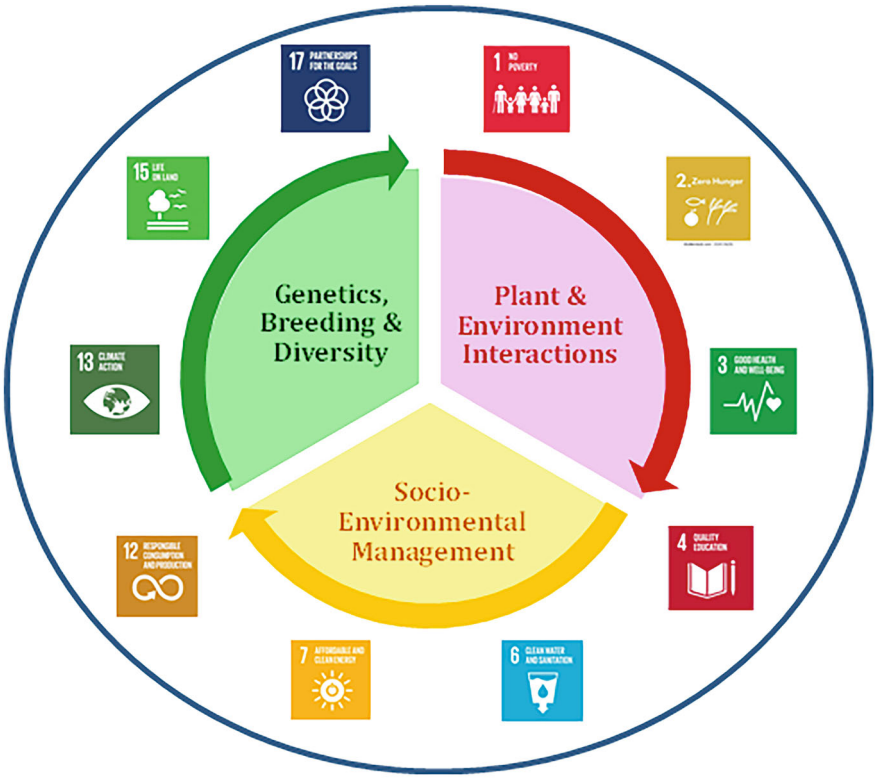

Fig. 4 Sustaining forest plantations contribute to sustainable development by tackling 10 out of the 17 SDGs of United Nations Agenda 2030. (According to Koutika et al. 2022)

(Fig. 4). The relevant SDGs include: eradicating poverty (SDG 1) and hunger (SDG 2), improving health (SDG 3), fostering higher education through MSc and PhD programs (SDG 4), and ensuring sanitation and access to clean water (SDG 6). Other related SDGs are energy supply (SDG 7), sustainable production and consumption (SDG 12), action on climate change (SDG 13), life on land (SDG 15), and partnerships for the goals (SDG 17). This NbS contributes to addressing important societal challenges, tackling more than half of the UN's SDGs (Koutika et al. 2022b).

Synthesis

Many societal challenges, such as mitigation and adaptation to climate change, biodiversity loss, pollution, land and soil degradation, food security, and human health and well-being, may be entirely or partly resolved through nature-based approaches. Although few and scattered, some evidence-based findings conducted in the countries of the Congo Basin confirm the beneficial effects of NbS solutions

on climate change mitigation and adaptation (Enu et al. 2023; Kiribou et al. 2024), biodiversity recovery (Nasi et al. 2012; Beekmann et al. 2024), food availability (Bisiaux et al. 2009; Kasongo et al. 2009; Nsombo 2016; Dubiez et al. 2019), water quality improvement (Laclau et al. 2003), fuelwood energy supply (Lescuyer et al. 2009), land and ecosystem restoration (Koutika et al. 2014; Dubiez et al. 2019; Peroches et al. 2025), and human health.

Land conflicts are common, especially when local communities are excluded from decisions about large-scale land projects. Tenure insecurity can undermine sustainable development using NbS approaches and conservation efforts. Initiatives like REDD+ emphasize the need to secure land rights for indigenous communities, to ensure their participation in climate change mitigation. However, corruption and bureaucratic inefficiencies often hinder progress in securing formal land rights.

This chapter identifies several gaps in nature-based approaches in the Congo Basin, particularly concerning their effective implementation through inclusive collaboration at the local level, as well as at regional levels. NbS responses, both currently and in the future, to ecological, economic, and social challenges across the different biomes of the Congo Basin may be more effective if they consider inclusive collaboration that integrates scientific, local, indigenous, and endogenous knowledge.

Despite the evidence-based benefits and co-benefits of NbS across various biomes in the Congo Basin the lack of policies and limited effective implementation of NbS have been reported. Investigations highlight low research capacity, limited collaboration between countries in the Global South and unresponsive policies and institutions that hinder the promotion of NbS in Africa, especially in the Congo Basin. Notably, none of the Congo Basin countries were listed among the four most active and leading countries (South Africa, Kenya, Ethiopia, and Côte d'Ivoire) involved in NbS in Africa (Nyika and Dinka 2022).

The effectiveness of implementing NbSs, both currently and in the future, supported by scientific solutions to tackle major societal challenges (climate change, biodiversity loss, pollution, land degradation, food insecurity), relies on reinforcing NbS and its associated benefits by designing adaptive frameworks tailored to the specific challenges of the Congo Basin, enabling application of workable solutions across its various biomes. However, the following gaps need to be overcome:

- Unreliability of Nbs in terms of climate change mitigation and biodiversity efficiency
- Scarcity of technical, economic, political, and cultural knowledge related to the design and implementation of NbS
- Limited documentation of genetic variation within and among native tree species, with broad use of exotic species in forestry and agroforestry threatening the alignment with ecological principles
- Low investment in Nbs that promote healthy ecosystems and human well-being

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Solutions of Global, International, Regional, and National Economic Initiatives

36

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Abstract

Due to its mitigation potential, the Congo Basin attracts attention from regional and international stakeholders. Its sustainable management and conservation is essential for climate regulation, biodiversity preservation, and the livelihoods of billions. Yet, the Congo Basin has not attracted much attention from the scientific community and remains relatively understudied. With respect to public investments, the Basin receives less international financial flows that promote ecological, social, and

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economic sustainability. This chapter assesses the role of data generated knowledge and reliable information in guiding policy. It surmises that research and sustainable development projects are not adequately financed in the region to produce knowledge that inform policymaking. Over the previous decades, some efforts have been made at the different scales under the Congo Basin Forest Partnership, the World Bank's Congo Basin Carbon Partnership Facility and the Central African Forest Initiative, the Congo Basin Blue Fund, and the Congo Critical Forest Biome Integrated Program, among others. Nonetheless, the Congo Basin remains enormously underfunded comparatively. There is need for an expanded Congo Basin Climate Science Initiative, which comprises of both infrastructure and human capacity building programs. Such an initiative should seek to transform the understanding of the Basin and provide crucial inputs for policymaking. A properly conceived blended finance model shall be required to attract public and private investments needed to strengthen knowledge systems for data generation and information to guide attainment of global sustainable development objectives.

Keywords

Science for policy-making · Climate finance · Blended finance · Sustainable development

Introduction

The potential of the Congo Basin's extraordinarily diverse ecosystem is well established (Dezfuli 2022), as it provides a sufficient proportion of Africa's fresh water, vital irrigation to around 75 million people, and 70% of the forest cover on the continent (Atyi 2022). Spanning over 6 million km^2, the global, international, and regional potential is marked by over 10,000 species of tropical plants, hundreds of different mammals, 1000 species of bird, and more than 700 species of fish including 150 different ethnic groups and holding 25% of the total carbon stored in tropical forests worldwide (Atyi 2022; Peya 2018; Harrison et al. 2016). The economic potential of these endowments is huge. The Basin's diverse ecosystem is essential not only for biodiversity but also for the livelihoods of local communities. The use of its natural resources for eco-tourism, forestry, natural resource beneficiation, and value chain supports local livelihoods, and national development objectives, alongside conservation efforts (Streck et al. 2023; Abernethy et al. 2016). Being a major carbon sink of global significance, its net annual absorption of carbon dioxide is suggested to be more than that of the Amazon rainforest (World Bank 2024; Seo 2021). Estimates of the value of carbon sequestration services provided by the Basin forest indicate at least $55 billion per year, representing 36% of the region's GDP (World Bank 2024). Protecting this critical frontier remains a top priority for policymakers in the region and beyond. However, this must be balanced against the needs of the households and communities that directly depend on its natural wealth (Molua 2019; Brown et al. 2011).

Continent-wide, the Basin presents considerable opportunities for development through the exploration and utilization of its abundant natural resources, demographic advantages, and strategic geographic location, thereby facilitating economic growth, energy development, food security, and environmental sustainability (Kabulo et al. 2023; Abernethy et al. 2016). The Basin thus attracts keen attention from diverse regional and international organizations. Some agencies acknowledge the importance of the Basin while cognizant of the challenges to sustainable development in the region (IPBES 2024). In light of these, a plethora of initiatives have emerged. The solutions of global, international, regional, and national economic initiatives in the Congo Basin have been addressed by both public and private agencies operating within and beyond the Basin. The crucial drive among these efforts is the recognition that scientific data can inform policy-decisions to drive sustainable forest land-use to curtail poverty and achieve other sustainable development goals across the region (Palazzo et al. 2024).

Projections still ascribe future important roles to the Basin with growing interest to protect and maintain biodiversity, natural resources, landscapes, and related cultural values (World Bank 2024; Abernethy et al. 2016). However, at the moment less than 15% of its total surface area enjoy protected area status. Yet, the Congo Basin has not attracted as much attention among the scientific community as the Amazon and southeast Asia and remains relatively understudied with much less academic and public attention (White et al. 2021; Trigg and Tshimanga 2020; Abernethy et al. 2016). With respect to public investments and scientific assessments, the region is neglected even by comparison with the rest of Africa (Dezfuli 2022), receiving less than 10% of international financial flows for forest protection and sustainable management in tropical areas, compared with more than 50% for Southeast Asia and over 30% for the Amazon region (Atyi et al. 2019). Forest-related support for the Congo Basin countries are estimated at $2 billion from bilateral (52.5%) and multilateral (47.5%) sources, with Germany accounting for 25% of funding, followed by the European Union and the Global Environment Fund (GEF) (Atyi et al. 2019; Boone et al. 2019; Favada et al. 2019), as well as the disparity in allocations among countries within the basin, with most funds allocated to the Democratic Republic of Congo (40%), Chad (17%), and Cameroon (14%) (ibid.).

Despite the relative low levels of international financial support to encourage processes related to data generation and management, the issue of data and reliable information remains relevant in guiding policy in the Basin. Responsive and adaptive policymaking in the Basin could be better served by real-time continuous-monitoring systems. Given the multidimensional crises plaguing the Basin, including security threats, climatic events, and geopolitical tensions which policymakers face driven by complex social, economic, environmental, and technological dynamics, real-time data and continuous-monitoring systems would enhance the effectiveness of conservation efforts in the Basin through systematic monitoring and evaluation of ecological and socioeconomic data. However, this would require investing in institutional development with robust technology-enabled monitoring infrastructures. This is more critical as research is not adequately financed in the

region to produce knowledge that inform policymaking for sustainable development. Despite the challenges, some scientists continue to engage with stakeholders and policymakers to understand the needs and constraints of decision-making within the Basin (Chukwudum 2024). The rationale for this collaboration is that working at the intersection of science and policy, where knowledge and action converge, paves the way for a sustainable and thriving future, especially in the Basin (Kankeu et al. 2020). This has also implied cross-border cooperation so that countries in the region can become more resilient not only to ecosystem degradation but also to economic shocks, health crises, or climate threats. Such resilience curbs migration and contributes to building stronger local economies and communities, and these improvements are global public goods that benefit all nations, including the Congo Basin (Somorin et al. 2012).

This assessment on the transformative potential of data and the economics in policy decision in the Basin surmises that promoting and achieving a sustainable green economy in the Basin demands a multidimensional policy approach that links environmental conservation with economic transformation and social equity. Accomplishing these, the countries in the Congo Basin would require policy measures to facilitate data technologies that enable comprehensive monitoring, analysis, and decision-making; as well as concerted efforts to improve governance, invest in sustainable infrastructure, protect the environment, and empower local communities. This may depend on a deliberate blend of finance opportunities to drive ecological stewardship, inclusive economic growth, and robust governance. By capitalizing on carbon finance, renewable energy, sustainable resource management, and eco-tourism, the Basin can transition into a resilient low-carbon economy. However, this would require the generation and strategic deployment of data sources. Adequate finance would be needed to facilitate data generation which may guide policymaking to attain the SDGs in the Basin. Though insufficient, nonetheless, the Basin is beginning to experience diverse stakeholder engagement, bridging top-down and bottom-up approaches, which is pivotal in fostering the use of data to promote sustainability and resilience. By strengthening governance, securing finance, promoting knowledge and skills, ensuring inclusivity, and fostering regional cooperation, the Basin can safeguard its ecological wealth while driving prosperity.

Accessing Scientific Data for Policymaking

The Basin's complex environmental and socioeconomic landscape demands informed and adaptive decision-making. Despite its resource base, the Basin countries significantly rely on overseas development assistance, with such support required to address research and development (R&D). Through their participation in many foras, these countries recognize that data generation is the foundation of policy-relevant research and policy-recommendations for choices that prioritize a sustainable green economy, strategic management of extractive industries, adding value through industrialization, leveraging agricultural potential, expanding renewable energy development, investing in human capital, promoting technology and

innovation for resource utilization, and facilitating intraregional trade. However, policymaking in the Basin is continuously bedeviled by missing data, corrupt information, and institutional inadequacies.

In future, these challenges could be reinforced since the sustainable management of the Basin shall continue to depend on policies that are based on accurate, timely, and complete data. This data must include among others information on the rates of deforestation and biodiversity loss, as well as estimates of the natural asset value of forests, water, biodiversity, and carbon stocks. This necessitates in-depth investigation, oversight, and assessment of both the natural asset worth of the Basin and the factors that jeopardize it. Through the generation and strategic use of diverse data sources such as satellite imagery or basic community mapping, stakeholders of the Basin would be better equipped to address deforestation, promote conservation, and support sustainable livelihoods. Currently, there are some efforts though limited such as the Satellite Observatory of the Central African Forests (OSFAC) under the Global Terrestrial Observing System (GTOS) that supports the management of natural resources and promotes sustainable development by producing land cover information, distributing satellite data, building capacity, and providing technical assistance to implementing partners (OSFAC 2016). The data generated by OSFAC and other agencies is used by governments, NGOs, researchers, and local communities striving to balance conservation efforts with human development, in the face of increasing pressures from deforestation, land degradation, and socioeconomic instability. In some countries including Cameroon, Gabon, and the DRC, the generation and strategic use of these data have become vital tools for informed decision-making (Mitchard et al. 2012). For instance, in the DRC, OSFAC datasets are integrated into the National Forest Monitoring System, which informs policymakers and forest managers about deforestation trends and hot spots. In addition, the implementation of the National Forest Monitoring System, supported by the Food Agriculture Organization (FAO) and some REDD+ initiatives, provides an institutional framework for collecting and analyzing spatial data on forest cover, carbon stocks, and land-use in the DRC.

Some international NGOs continue to support the Basin's needs for data. For instance, platforms like the Global Forest Watch (GFW) and the Forest Atlas allow decision-makers to overlay real-time alerts from satellite systems with data on logging concessions, protected areas, and community lands. The GFW initiative hosted by the Congo Basin Forest Partnership (CBFP) member the World Resources Institute (WRI) offers Forest Atlases as a collection of interactive map-based applications that facilitate visualization and management of forest information in the Basin. In partnership with the Ministries of Forests in the six Basin countries, GFW employs a combination of Geographic Information Systems (GIS), remote-sensing, and field-based technologies to access high-quality forest information on protected areas, logging permits, mining permits, community forests, and other land-use allocations. This provides the understanding of forest loss, particularly distinguishing between legal harvesting, agricultural expansion, and illegal logging. These spatial technologies contribute to enhance transparency, accountability, conservation planning, and enforcement in forest governance. Moreover, national forest

inventories feed into REDD+ frameworks, enabling countries to track carbon emissions reductions and access climate finance for the Basin (Mitchard et al. 2012).

At the national and community levels, countries in the Basin make cooperative efforts to translate data into evidence-based decision-making and improvements in resource management and livelihood. For example, the Integrated REDD+ project (PIREDD) in Mai-Ndombe province, supported by the World Bank in the DRC, encompasses measures such as payments for logging companies and annual results-based payments (RBPs) for smallholder farming communities (Pietarinen et al. 2023; Pirker and Carodenuto 2021). This initiative integrates remote sensing, household surveys, and geospatial data to guide interventions such as agroforestry development, land-use planning, and Payments for Environmental Services (PES). Recent estimates indicate that over 480 local land-use plans have been developed using community-generated data, more than 4000 ha of agroforestry has been established, setting aside nearly 10,000 ha for fire protection and natural regeneration, and US$1.7 million has been provided in PES (ibid.), all grounded in community-driven data and planning thus demonstrating that data-driven approaches can simultaneously advance conservation and improve livelihoods.

In addition to satellite data, grassroots data generation is being deployed to bridge gaps between national policy and local reality, promoting accountability and strengthening community stewardship. However, using grass roots ultimately requires capacity building. Recently, the Congo Peatlands Initiative led by the United Nations Environment Programme (UNEP) with the support of the FAO launched the peatlands data campaign and research capacity building of Congo Basin researchers to improve the conservation, restoration, and sustainable management of peatlands, while strengthening on-the-ground cooperation for peatlands in the region. Such cooperation for community-generated data primarily adds essential local context and legitimacy. For example, the Mapping for Rights project[1] by the Rainforest Foundation of the UK (RFUK) empowers Indigenous and Local Peoples (IPLCs) to map their traditional lands using simple GPS and mobile tools. These participatory maps could be crucial for asserting land rights, avoiding conflict, and guiding inclusive development. Another innovative tool for Community-Based Monitoring and Empowerment is the ForestLink,[2] a real-time forest-monitoring system that enables communities to report illegal logging and encroachment using handheld devices, even in remote areas in the Basin without Internet access. This information is transmitted via SMS to centralized databases, enabling swift responses from government agencies or NGOs.

Such lessons, for effective management via conservation-driven technological innovations for data collection, have been learned overseas in the Amazon and

[1] MappingForRights is a set of tools and approaches aimed at putting rainforest communities on the map and promoting sustainable, transparent, and equitable governance of the Congo Basin https://www.mappingforrights.org/

[2] Innovative, practical, and low-cost, the ForestLink technology connects communities and law enforcement to monitor tropical forests in real time: reducing deforestation, protecting human rights, and putting power back in the hands of those who call the forest home https://forestlink.org/

Borneo-Mekong areas, where innovations in artificial intelligence, remote sensing, blockchain technology, and bioengineering are helping scientists, policymakers, and conservation entrepreneurs track endangered species and restore ecosystems (Lahoti 2025; Bhambri and Kautish 2024). For the Congo Basin, though not fully deployed, applying advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), blockchain, and remote sensing technologies holds immense promise to check biodiversity decline, climate change, and livelihoods (Distor et al. 2023). By providing real-time data and enabling early detection, these technologies may contribute to addressing illegal logging, deforestation, proliferation of plant diseases, and forest fires (Albar et al. 2018). For instance, the recent development and recognition of blockchain-based applications may potentially revolutionize forestry by providing a secure and transparent method of tracking and verifying the origin and movement of forest products. The application of blockchain technology targets forest management, traceability of forest-based products, and forest fire detection. This could help combat illegal logging and fraudulent labeling of timber. In the DRC, blockchain is being used to track the cobalt value chain from artisanal mines to products used in smartphones and electric cars (Mugurusi and Ahishakiye 2022; Mpufane and Kohler 2018).

The deployment of data management technology, nonetheless, remains inadequate in the Basin, nonetheless, as countries continue to face challenges to establish robust data-monitoring systems, driven by budgetary as well as capacity constraints. Building a robust Data-Driven Policy Framework for the Congo Basin requires institutional capacity to collect, manage, and analyze diverse datasets. This includes integrating environmental data with socioeconomic indicators to address the interconnectedness of ecological health and human well-being. Regional cooperation among Congo Basin countries remains insufficient though critical, given the transboundary nature of the ecosystem. Furthermore, investment in open data platforms are required to enhance transparency, enabling researchers, civil society, and the public to participate in conservation decision-making. However, while obstacles remain, such as limited infrastructure, conflict, and governance issues, the continued investment in data systems and local capacity-building is essential.

Cognizant of these challenges, calls are increasing for policymakers and scientists in the Basin to engage with each other so that scientific evidence could be employed to properly influence laws and legislation (IPBES 2024; White et al. 2021; Mulatu et al. 2017). For instance, White et al. (2021) have called for a Congo Basin Climate Science Initiative (CBCSI), which should comprise a $100-million decade-long program of research, tied to a separate $50-million fund to train Congo Basin nationals to become PhD-level scientists. Such funding should seek to transform the understanding of the Basin by generating data, and providing crucial input for policymakers to help them enact policies to avoid the region's looming environmental crises. Building of capacity is important, since beyond identifying environmental problems, science helps design policy solutions that alleviate poverty and promote sustainable development thus ensuring that environmental protection goes hand in hand with improved livelihoods and inclusive growth in the Congo Basin.

The deployment of data management and the rationale of a CBCSI for good policy management hinges on the premise that effective science has to be leveraged to detect and provide early warning to enable timely and preventive action from environmental threats. Modern technologies are indispensable in strengthening early warning systems (EWS) and enabling timely, evidence-based policy interventions in the Basin. These technologies which range from Remote Sensing and Earth Observation and GIS may be used to document communities most at risk from flooding along the Congo River or are employed to map wildlife corridors under threat from infrastructure development (Bossy et al. 2025; Mulatu et al. 2017; Hansen et al. 2008). Beyond identifying environmental problems, generating information on environmental issues may also help design local solutions, for instance, the response of actors in the Virunga National Park in launching economic initiatives like the cocoa production and artisanal chocolate exports which offer alternative livelihoods while reducing pressure on forests (Muyisa 2025; SABC 2025). These ventures are supported by data on land suitability, market analysis, and community needs assessments, thus showing how economic resilience and conservation can be jointly pursued (Kamath et al. 2024; Corbino 2021).

An important process yet underexploited in the Basin is the collaboration between science and politics in decision-making. The collaboration may address the need to finance effective science to cater for conservation and protection and efficient resource-use. According to White et al. (2021), the CBCSI should focus on three important overarching questions: How does the Congo Basin currently operate as an integrated system? How will changes in land-use and climate affect its function? And how sustainable are different options for development? Recent global and regional assessments indicate the growing role of scientific evidence that could be used to support governance of the Basin's natural wealth for future generations (IPBES 2024). However, regional assessments and research require investment (public and private, national and international) to produce relevant knowledge. So far, there is inadequacy between official speech and commitments to finance research and the reality is the lack of means faced by universities, research centers, and researchers in the region. They depend almost up to 90% on international cooperation for research funds. Private agencies and States in the region would be required to make substantial efforts to address the needs for research.

To close the data deficiency gap, some international bodies continue to invest resources to generate information to guide effective policymaking in the Basin, such as the Intergovernmental Science Platform for Ecosystem and Biodiversity (IPBES), Intergovernmental Panel on Climate Change (IPCC), the United Nations Convention to Combat Desertification (UNCCD) Science-Policy Interface, the United Nations Development Programme (UNDP) (e.g., Human Development Report), the United Nations Environment Programme (e.g., Global Environmental Outlook), Global Sustainable Development Report (GSDR), the Convention on Biological Diversity (e.g., Global Biodiversity Outlook), the United Nations Convention to Combat Desertification (e.g., Global Land Outlook), and the Ramsar Convention on Wetlands (e.g., Global Wetland Outlook). However, these efforts are not yet sufficient to

cover needs in regard to the importance of Congo Basin and in comparison to other Basins like the Amazon.

Clearly, the Congo Basin countries can progress sustainably and equitably by investing in science and data infrastructure, capacity building, and inclusive engagement. These particularly requires funding initiatives to supplement current efforts. Countries in the Basin, in collaboration with partners and their funders, will need to develop an overarching science program which scales up many efforts that are already under way, but which are currently insufficient in scope or unreliably funded.

Enhancing Sustainable Practices Through Data Initiatives

Global

It is obvious that the Congo Basin countries cannot realistically achieve their national development plans without international cooperation. Generating data requires enormous human, material, and financial resources. However, despite increasing attention to biodiversity financing and increasing funding flows across several sectors, for instance, most particularly for climate mitigation, these flows significantly fall short of what is needed (Berghöfer et al. 2017; Miller 2015). Africa receives just 3–4% of global climate finance, although it is home to countries that are most vulnerable to climate change, and the climate finance gap is approximately $213.4 billion annually through 2030 (Gemayel et al. 2025; Tamasiga et al. 2023). Notwithstanding, the growing international cooperation to leverage resources remains an important conduit to address resource constraints. Increased international funding, coupled with robust regional cooperation, can ensure this vital ecosystem thrives for generations to come (White et al. 2021). While international, regional cooperation remains essential, there is an inherent potential for countries in the Basin to mobilize resources through effective domestic resource mobilization (DRM), natural resource beneficiation, and value chain developments, as well as improved valuation of natural capital in their GDP to unlock financing, and more strategic public finance management (Chukwudum 2024; Streck et al. 2023; Aquilas and Atemnkeng 2022). This shift would align with the evolving global aid landscape, where countries are increasingly expected to complement external support with strengthened internal financing mechanisms to ensure long-term sustainability and ownership.

While discussions on financial resource mobilization to support biodiversity conservation, ecosystem restoration, and sustainable resource use is gaining steam globally, however after more than five decades of multilateral cooperation, shortfalls remain in generating sufficient volumes. The Kunming-Montreal Global Biodiversity Framework of the UN Convention on Biological Diversity (CBD) makes clear that a biodiversity finance gap of $700 billion per year must be closed to achieve the 2050 Vision for Biodiversity (Stephens 2023; UNCBD 2022). Despite this assertion, finance flows to the Congo Basin are minuscule. Developed-country parties to the United Nations Framework on Climate Change (UNFCCC) have previously failed to

deliver upon pledges to finance adaptation and mitigation schemes that deal with the Congo Basin. There is, nonetheless, considerable potential for climate change mitigation-related disbursements to support the simultaneous achievement of biodiversity and other interlinked sectors in the Basin (Streck et al. 2023).

Over the previous decades, some initiatives have been sponsored and lessons learned, such as the Congo Basin Forest Partnership (CBFP). Anchored on its goal to source for information about the ecologically important landscapes, it has been financed to promote economic development, alleviate poverty, and improve governance and natural resource conservation through support for a network of protected areas and well-managed forestry concessions—and through assistance to communities that depend on the conservation of the outstanding forest and wildlife resources in the region.

The CBFP followed previous efforts, when the US Agency for International Development (USAID) launched the Central Africa Regional Program for the Environment (CARPE)[3] in response to the growing international recognition of the Congo Basin forest and the need for a more coordinated approach to manage the resources sustainably. CARPE became USAID's main climate change mitigation program in Africa and supported local, national, regional, and international efforts to develop sustainable, low-emissions economies in the Congo Basin. With their insightful outcomes, the CBFP and CARPE models could be propagated in the Basin as well as in other regions in the continent.

Recently, some ambitious pledges have been made which may contribute to improved environmental management in the Basin. At the COP-29 in Baku, the UK government announced £9.1 million ($11.7 million) in funding to scientists to provide the data and knowledge needed for policies to protect the Congo Basin (UK GOV 2024). The grant seeks to investigate the value and vulnerability of the Congo Basin rainforest and translate this new knowledge into policy action to protect forests, improve livelihoods, and support sustainable development. This built from the Congo Basin Pledge[4] a Promise of collective financing for the Congo Basin, at COP-26 in Glasgow whereby donors committed to a collective Congo Basin Pledge of at least US$1.5 billion of financing between 2021 and 2025 (CBFP 2022). Prior to these pledges, the Congo Basin witnessed some stakeholder engagement, bridging top-down and bottom-up approaches, which is pivotal in fostering the use of earth data to promote sustainability. For instance, the most prominent conservation trust fund active in the region has been the Central African Forest Initiative (CAFI). Capitalized with US$718 million from a coalition of donor countries, CAFI provides funding for sustainable land management policies and

[3] US Agency for International Development Central Africa Regional Program for the Environment (CARPE)—https://2017-2020.usaid.gov/central-africa-republic/fact-sheets/central-africa-regional-program-environment

[4] Congo Basin Pledge: Promise of collective financing for the Congo Basin https://pfbc-cbfp.org/en/thematics/congo-basin-pledge

practices based on beneficiary countries achieving agreed policy milestones (CAFI 2025).

However, some other programs that support conservation are not ambitious enough in promoting overall sustainable development in the Basin. The African Forest Landscape Restoration Initiative (AFR100), for instance, a pan-African effort financed with US$1.40 billion, is however limited to restoration activities, while the Legacy Landscapes Fund, financed with US$0.10 billion, is limited to protected areas. In addition, some efforts to establish jurisdictional REDD+ programs in the region (Maniatis et al. 2013) require upscaling. Nonetheless, there is expectation that funders appreciate the urgency for significant financial commitments. For instance, programs that support REDD+ of the Forest Carbon Partnership Facility (FCPF) and the Forest Investment Program (FIP), both administered by the World Bank, have each leveraged more than US$1 billion globally. However, jurisdictional REDD+ projects continue to face significant implementation challenges in the Congo Basin.

The case of the World Bank's Congo Basin Carbon Partnership Facility and the Central African Forest Initiative: The Forest Carbon Partnership Facility (FCPF) is focused on reducing emissions from deforestation and forest degradation, forest carbon stock conservation, the sustainable management of forests, and the enhancement of forest carbon stocks via REDD+ (Sacherer et al. 2022; Favada et al. 2019; Lotsch 2013). Operating in developing countries across Africa, Asia, and Latin America and the Caribbean, along with some donors that have made contributions and commitments totaling about $1.3 billion, the FCPF supports REDD+ efforts through its Readiness and Carbon Funds (Reinsberg et al. 2020; Favada et al. 2019). The support for REDD+ efforts is through two separate but complementary funds, viz, the FCPF Readiness Fund and the FCPF Carbon Fund (Andoh et al. 2022; Lotsch 2013). The Carbon Fund pilots results-based payments to countries that have advanced through REDD+ readiness and implementation, and have achieved verifiable emission reductions in their forest and broader land-use sectors. FCPF participant countries that have made significant progress in their REDD+ readiness endeavors are selected to participate in the Carbon Fund (Yanai et al. 2020).

The Congo Basin Forest Initiative which is funded by the Central African Forest Initiative (CAFI) essentially seeks to mitigate climate change by preserving vital forest resources, reduce poverty and boost sustainable development via national-scale REDD+ frameworks, and coordinate investments and policy dialogue across partner countries (Maniatis et al. 2013; Brown et al. 2011). To support these initiatives, CAFI teamed up with UNEP and the United Nations Capital Development Fund (UNCDF) to launch the $15 million blended-finance initiative aimed at empowering local green businesses and mobilizing up to $30 million in sustainable investment across Cameroon, DRC, Gabon, and Republic of Congo (Milson et al. 2025). In addition, CAFI funded FAO-led efforts totaling about $10 million to operationalize DRC's National Forest Monitoring System (SNSF), including satellite land monitoring, national forest inventories, greenhouse gas inventories, and a web portal for deforestation alerts (CAFI 2025). In Gabon, capacity-building efforts supported 1.67 million hectares of community forests, empowering local

communities with sustainable management planning. At the 2024 Congo Basin Forest Partnership meeting in Kinshasa, CAFI announced new investments—including $6.5 million for a Scientific Platform to better inform policymakers and strengthen the science-policy interface (ibid.). Despite CAFI's ambitious financing and programming, challenges remain including the underdelivery of funds. For instance, of the $500 million pledged at COP-26 for DRC forest protection, only $150 million has been delivered to date, thus raising concerns about funding gaps weakening conservation efforts and increasing pressure for oil and gas expansion (Milson et al. 2025; Atyi 2022).

Continental

At the continental level, the African Union (AU) is taking important initiatives and actions to mobilize resources for the promotion of data generation and policy evaluation on the management of Congo Basin natural assets. At the 38th summit of AU under the theme "Justice for Africans and people of African descent through reparations," it not only addressed issues relating to historical injustices, financial autonomy, and ongoing security challenges, but it also addressed the abuse of African natural resources (including oil, minerals, and forests) especially in the Congo Basin forests. The AU summit acknowledged the recognition and inclusion of the rights of IPLCs (guardians of the Congo Basin and its resources and whose ancestral knowledge and in-depth knowledge of the ecosystem allow coexistence of man and nature as well as sustainable forest resources management), and the direct funding for real forest protectors, particularly IPLCs. The AU also approved the creation of the African Financial Stability Mechanism with capacity to mobilize resources for environmental management.

Similarly, scientists and activists too are making efforts. For instance, the CBSI,[5] an independent scientist-led platform that promotes long-term investment in science in the Congo Basin, has sought to transform the understanding of the Basin, build scientific capacity in the region, and use this knowledge to support sustainable development (Trigg and Tshimanga 2020). In addition, the World Wide Fund (WWF) for nature has entrenched its presence in the Basin via the Congo Basin Monitoring and Evaluation Database[6] designed to enhance conservation efforts through structured data management and sharing. The WWF-supported programs integrate ecological, socioeconomic, and policy-related data from various sources and serve as repository to facilitate information sharing, communication, and management decisions in the region.

[5] The CBSI brings together regional scientists, science stakeholders, and other partners to jointly promote and coordinate opportunities for investments in science on the Congo Basin. See more at the Congo Basin Science Initiative: https://congobasinscience.net/about/about-us/

[6] See Congo Basin Monitoring and Evaluation Database: https://wwf-congobasin-monitoring.org/

The case of the Congo Basin Forest Partnership (CBFP): As a multistakeholder partnership, the CBFP promotes the conservation and responsible management of the Congo Basin's tropical forests (Pokem 2024; Trefon 2017; Angu et al. 2011; Du Preez 2010). Being a nonbinding partnership based on voluntary agreements between governments, the private sector, civil society, and developmental organizations, it enhances natural resource management to improve the standard of living in the Congo Basin (Trefon 2017). The CBFP, built on the same framework as the Yaoundé Declaration, with the stated aim "to protect forests through the harmonization of forest policies, protected areas, regulations against poaching, and the adoption of practices for sustainable forest use," recognizes COMIFAC as the central policy and decision-making body for conservation and management of Central African forests (Trefon 2017; Angu et al. 2011). The rationale of the CBFP and the COMIFAC is to harmonize forest policy and taxation, resource knowledge and inventory, ecosystem management, biodiversity conservation, sustainable use of forest resources, alternative income generation, capacity development and training, research, innovative financing mechanisms, and regional cooperation and partnerships (Pokem 2024; Berghöfer et al. 2017).

Regional

The governments of countries in the Basin together with partners such as the World Bank, the African Development Bank, the FAO, and some other UN Agencies are implementing diverse regional initiatives, such as the Blue Fund for the Congo Basin, to build on other activities under the Central African Forest Initiative, Forest Carbon Partnership Facility, Forest Investment Program, Global Environment Facility projects, and REDD+ initiatives (Assani et al. 2022; Kankeu et al. 2020; Peya 2018; Karsenty 2017).

The Case of the Congo Basin Blue Fund: The Congo Basin Blue Fund (CBBF)[7] is a special purpose vehicle to help the countries of the Congo Basin finance a shift in their economies from reliance on forest-based resources to much greater use of renewable river- and water-based resources (Peya 2018; Fondation Brazzaville 2017). The CBBF shifts efforts in the Basin to a new form of sustainable development based on making much greater use of the renewable resources represented by the waters of the Congo and its tributaries. Regional transformation is to be promoted by targeting blue economic assets (Kabulo et al. 2023), such as the improvement of navigation and transport through the construction of small ports, infrastructure, and maintenance works; small hydroelectric infrastructure and dam; strengthening irrigation in view of modernization and increased productivity;

[7] The Blue Fund is in line with blue economy and as defined by UN Economic Commission for Africa: "Blue economy concerns all water bodies, including lakes, watercourses and groundwater, not forgetting seas and coasts. The main economic activity domains of Africa based on marine and aquatic resources include fishing, fish farming, tourism, transport, the port sector, mining and energy."

sustainable fisheries, pisciculture, and aquaculture development; water treatment and reuse; and the development of ecotourism (Peya 2018; Fondation Brazzaville 2017). However, the greatest challenge of this fund is the insufficient mobilization of financial resources despite the existence of the necessary legal and institutional frameworks established through collaboration with the World Bank and the UNDP.

National

As established in section "Accessing Scientific Data for Policymaking," while collaboration between politics and science is key for sustainable solutions, yet it faces major issues in the Congo Basin. However, at the national level, the situation is better than at the regional or continental levels (through differences between countries). Considering the case of the DRC, for instance, with some project-driven initiatives, the RFUK and the Turing Foundation finance the online database on community forestry. In addition, the WRI, UKAID, ESRI, etc. support the forest-interactive atlas of the DRC. The Ministry of environment collaborates with the Biodiversity Monitoring Centre based at the University of Kisangani in partnership with CEBios to design the National Biodiversity Strategy and Action Plan. There are also project-driven initiatives, for instance, the Yangambi Scientific Pole at the service of man and forests (YPS)[8] project. CIFOR also implements projects for training and research in Tshopo which strengthens the sustainable participatory management of the Yangambi Biosphere Reserve and implements the first-ever accurate and continuous monitoring of atmosphere-ecosystem GHG exchange in the Congo Basin forest. The CongoFlux research site also provides qualitative and continuous meteorological data and collects ancillary data such as site characterization, species composition, mortality, trait, and soil data of several plots within the footprint of the flux tower (Sibret et al. 2022). These efforts alleviate the weaknesses associated with incomplete data and missing information.

Generally, national efforts in the other countries in the Basin to preserve biodiversity and deliver positive cobenefits in the Basin remain significantly underfunded. Other global supplementary efforts to mobilize private investment into conservation have included blended finance and carbon market mechanisms. Innovative financial mechanisms such as public-private partnerships, green bonds, and targeted tax incentives could play a pivotal role in mobilizing resources and engaging a wide array of actors. Governments, international organizations, and private investors could contribute funds, while governments may use tax incentives to stimulate investments in conservation-aligned projects. The private sector, nonetheless, remains key in unlocking new financing sources and attracting additional investors through certification networks (Berghöfer et al. 2017). However, there are reported estimates that public finance surpasses private finance efforts in the Basin (Bos and

[8] CONGOFLUX: Yangambi Scientific Pole at the service of man and forests https://www.congo-biogeochem.com/congoflux

Thwaites 2021). The vast majority of global finance for biodiversity and related sustainability objectives like the SDGs has been provided by public entities via domestic budgets, and to a lesser degree through bilateral and multilateral cooperation or via other environmental policy instruments. These resources are allocated for meeting the interrelated objectives of the CBD, UNFCCC, and UN Convention on Combatting Desertification (UNCCD). However, it is unlikely that public finance alone can be relied upon to close existing biodiversity and sustainable development financing gaps without contributions from other sources (Berghöfer et al. 2017). Moreover, the private sector is more responsible for exploitative use and damage to the environment. The Kunming-Montreal Global Biodiversity Framework emphasizes that closing the biodiversity financing gap will necessitate increases in biodiversity financing from all sources, including domestic and international, public and private sources (UNCBD 2022). Encouraging the involvement of the private sector in biodiversity financing is expected through leveraging private finance, blended finance, impact funds, or other means. The use of innovative financial instruments such as PES schemes, green bonds, biodiversity offsets and credits, and other benefit-sharing mechanisms could be encouraged, but with environmental and social safeguards.

The Case of the Congo Critical Forest Biome Integrated Program: To invest in the conservation and effective governance of critical forest biomes, the GEF allocated finance to advance the Congo Critical Forest Biome Integrated Program (CFBIP). The CFBIP seeks to improve the conservation and effective governance of critical landscapes in the Congo Basin Forest Biome, via effective forest governance within multiuse landscapes (Endamana et al. 2010). It is expected to bring conservation effectiveness to scale across landscapes through policy coherence, regional collaboration, and enhanced access to benefits by forest dwellers committed to protecting the forest. The Program also promotes transformational change by establishing new and creative methods like ecosystem value, NBS, and inclusive agreements to improve landscape conservation. The Program collaborates with local, national, and international partners to meet the Rio Convention's worldwide obligations through supportive national and regional frameworks using a gender-transformative strategy.

In addition to the experiences from projects being implemented in the Basin, the Congo Basin can draw lessons from the developments in the other forest regions. For instance, in both the Amazon in South America and Borneo-Mekong in Southeast Asia as pressures mount, the development and use of advanced data systems are used for balancing conservation goals with socioeconomic needs. To enable monitoring, planning, enforcement, evaluation, and community engagement in the Amazon, Platforms like Brazil's DETER (Real-Time Deforestation Detection) and PRODES (Annual Deforestation Monitoring) provide frequent updates on forest cover change (de Almeida et al. 2021; Shimabukuro et al. 2012). In the Borneo forests, Indonesia's SiPongi and Malaysia's Forest Monitoring System track forest loss and fire hot spots using MODIS, Landsat, and Sentinel imagery (Albar et al. 2018; Hansen et al. 2008). These systems use high-resolution satellite data to identify deforestation events and feed information to law enforcement agencies. However, the high-resolution monitoring and data management require significant financial investment,

with funds mobilized from diverse sources. In both the Amazon and the Borneo-Mekong forests, integrated or blended financing of different funding sources, financial instruments, and policy incentives have offered a promising pathway to sustain and scale conservation while enabling local socioeconomic development (de Mariz et al. 2025; Rode et al. 2019). These finance opportunities are coordinated by effective governance mechanisms. The Amazon and Borneo's governance mechanisms to support SFM combine institutional arrangements, legal frameworks, multi-stakeholder platforms, and cross-border initiatives. For instance, with respect to National Laws and Policies, Brazil's Forest Code (Law 12.651/2012) requires private landowners in the Amazon to maintain 80% of native vegetation and mandates Legal Reserves and Permanent Preservation Areas (Carneiro et al. 2024; Humphries et al. 2014). There is also a National Policy on Climate Change which includes targets for reducing deforestation through SFM and low-carbon agriculture. At the Indonesia Kalimantan region, National Laws and Policies (e.g., Forestry Law No. 41/1999) establishes principles for forest use, zoning, and conservation (Nurhidayah and Alam 2020).

Overall, despite its ecological significance, the Congo Basin remains hugely underfunded compared to the other tropical Basins (Atyi et al. 2022; Brandt et al. 2014). Congo Basin countries received around US$40 million for forests and environmental protection between 2017 and 2021 estimated at just 4% of the amount that went to either the Amazon Basin or Southeast Asia in the same period (Streck et al. 2023). Carbon markets have drawn some investment to the region, but they do not meet the substantial cost-effective mitigation potential of nature-based solutions (NBS) in the Congo Basin countries (Miller 2015). Diverse proposals to improve finance flow to the Basin have suggested blended finance approaches by possibly creating a Congo Basin Guarantee Facility (CBGF) which could attract private investments in sustainable forest management, deforestation-free supply chains, or other activities that commit to a zero-deforestation policy (Chukwudum 2024; Streck et al. 2023; Favada et al. 2019; Brandt et al. 2014). Streck et al. (2023) propose the establishment of a sustainable forest trust fund, assigning monetary value to natural assets, issuance of forest bonds for payments for ecosystem services, creation of a CBGF, establishing an environmental markets investment promotion agency, and the creation of investment and technical assistance facility for environmental markets. While the CBGF could thus be part of a portfolio of innovative financial approaches needed to address the region's challenges, however, these approaches must be integrated with green economic practices that ensure sustainable and just livelihoods in the long term (Moral-Pajares et al. 2024; Aquilas and Atemnkeng 2022; Favada et al. 2019).

Economic Transformation for Improved Policymaking in the Basin

Business-as-usual would perpetuate the in inequitable and fragmented actions and unsustainable and unjust development outcomes for the Congo Basin. Fundamental changes to underlying values, structures, and power relationships shall be required

across sectors, systems, and scales in order to promote effective and sustainable use of resources. Transformative efforts that could alter the governance, political economies, development logic, and knowledge in the Basin will have to contend with a future green economy in the Basin. In fact, the future of the Congo Basin shall be determined by a new green sustainable economy, one that fosters economic growth while preserving ecological integrity. However, achieving this requires balancing conservation priorities with the need for inclusive development, using innovative financing, strong governance, and low-carbon technologies. This will ultimately require addressing the drivers of a future green economy, viz, shifting toward NBS, promoting sustainable resource-based industries, expanding renewable energy choices, and properly accounting for climate change mitigation. A holistic carbon finance model would be required to contribute to the aspirations and livelihood in the Basin while addressing climate change mitigation. By properly leveraging REDD+ mechanisms and voluntary carbon markets, countries in the Basin could generate sustainable revenue streams from forest conservation through verified carbon credits. Scaling sustainable forestry, eco-certified timber, NTFPs, and agroforestry systems that enhance biodiversity while providing income would create a vista of financial incentives to be reinvested for conservation and improvement of rural livelihoods and eco-tourism which generate jobs.

Figure 1 presents a framework for summarized solutions of global, international, regional, and national economic initiatives in the Congo Basin. As indicated, a plausible pathway to a sustainable green economy will require investing in green infrastructure to stimulate sustainable economy and trade while minimizing environmental impacts, as well as a circular economy that reduces environmental pressure while creating green jobs in urban and peri-urban areas. This must be at the behest of strengthening governance and transparency, inclusive benefit-sharing mechanisms, blended finance and risk-sharing instruments, science, technology, and innovation as well as capacity building and skills development. These would inadvertently require governments digitizing land registries, and enforce environmental impact assessments to build investor and community trust, ensuring equitable distribution of benefits from carbon finance and conservation funds to IPLCs, expanding forest monitoring systems, and adopting climate-smart technologies to strengthen sustainability outcomes and ensuring that training programs for green jobs can ensure that IPLCs are active participants in the emerging green economy.

Inherently, as shown in Fig. 1, without reliable data or information a sustainable future for the Basin will be undermined. Policy and financing should guarantee critical data requirements such as environmental data (forest cover and land-use change, carbon stocks and fluxes, biodiversity inventories, water, and climate patterns) that would be required for understanding the ecological baseline and tracking changes over time, as well as economic and market data (e.g., sustainable value chain assessments, pricing and demand trends, investment flows and financing gaps) for a complete economic intelligence. The comprehensive development of the Basin would require policy decisions on social equity that may require social and livelihood data (e.g., community livelihood profiles, land tenure and rights mapping, equity, and gender data) to account for social inclusion and local participation.

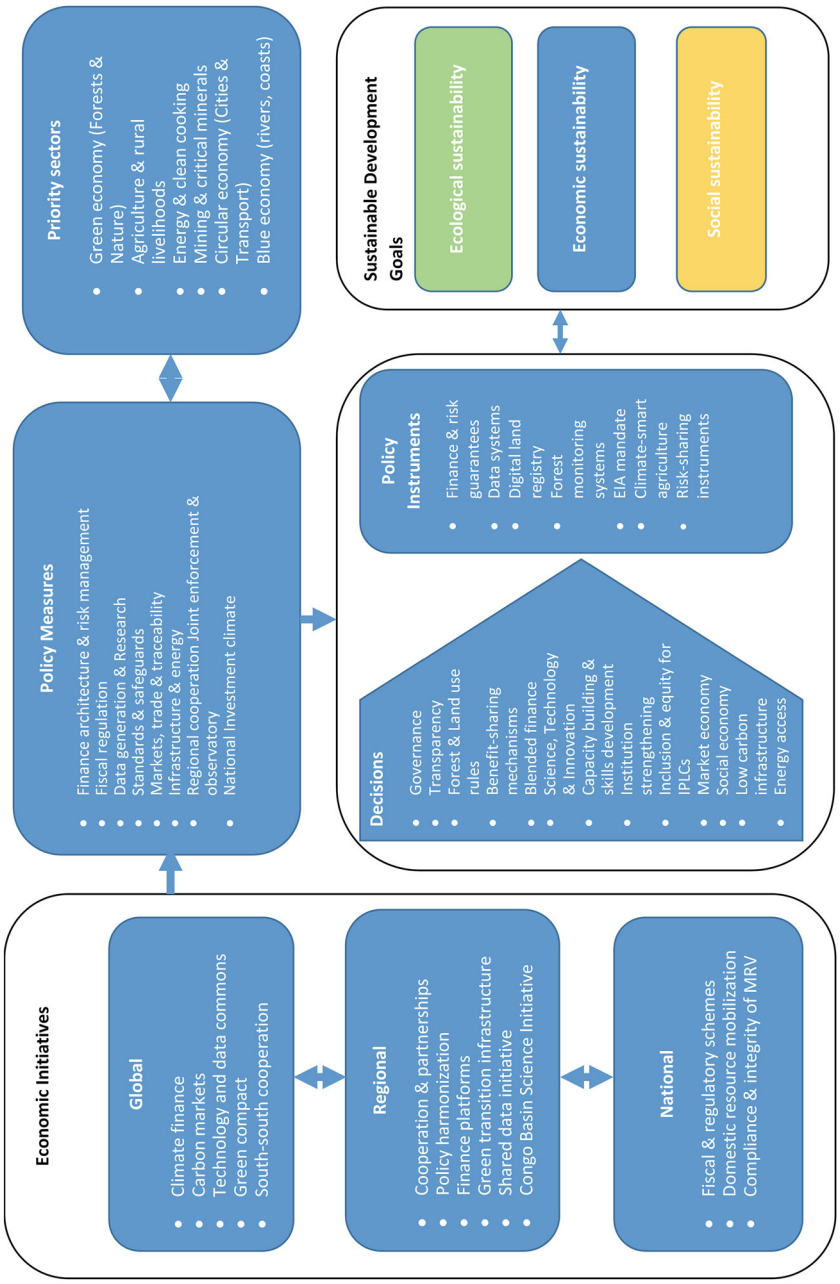

Fig. 1 Framework for solutions of global, international, regional, and national economic initiatives

Making decisions on transparency would require updated governance and institutional data (e.g., policy and legal framework databases, concession and permit maps, monitoring, reporting, and verification systems for compliance with international agreements and funding requirements) which underpin investor confidence and public trust.

In a nutshell, environmental sustainability, economic viability, and social equity remain the bedrock of a future green sustainable economy in the Basin, and this requires targeted policy decisions that balance ecological protection with socioeconomic development, such as strengthening environmental governance by harmonizing environmental laws especially standardizing forest, land, and water management policies across the Basin countries to prevent cross-border exploitation loopholes. It also requires effectively enforcing anti-deforestation regulations by scaling up satellite-based monitoring and community patrols to enforce forest protection. Better environmental governance would also require decentralized resource management which empowers local governments and IPLCs to manage forests sustainably, supported by legal rights to land and resources.

With effective policy measures, sustainable production can be incentivized via promoting climate-smart production activities as well as green taxation and subsidies. This will require introducing capacity building for climate-smart practices as well as tax breaks for eco-friendly enterprises and removing subsidies for polluting activities like illegal logging or destructive mining. Sustainable production could also be encouraged through efficient certification schemes and value addition to access premium markets, while encouraging local value addition to reduce export of raw materials. Public–private partnerships which encourage private sector investments in renewable energy, eco-tourism, and sustainable agriculture shall remain important to drive sustainable production.

The energy needs of a growing economy in the Basin would require an energy-mix which promotes renewable energy and low-carbon infrastructure by expanding hydropower, solar, and biomass energy projects tailored to rural and urban needs; and ensuring sustainable transport networks such as climate-resilient roads, river transport, and electrified mobility to minimize carbon emissions. Energy access policies should target affordable and equitable access to clean energy, particularly for rural communities. More important, investing in Research, Education, and Technology remains the foundation for greener future in the Basin. A knowledge-driven green transition needs R&D, investments in Science, Technology and Innovation (STI), as well as education and skills training and data-driven decision-making.

Since in the Congo Basin different groups of IPLCs and rural and urban dwellers confront barriers that prevent them from fully participating in political, economic, and social life, a modern economy would require ensuring social inclusion and equity for green economy policies to benefit all, especially marginalized groups. This would require clear benefit-sharing mechanisms to ensure revenues from natural resource use are shared equitably with local communities, properly articulated gender-sensitive policies to promote women's participation in decision-making

and green entrepreneurship, as well as Indigenous knowledge integration so that traditional conservation practices fit into policy frameworks.

Despite these lofty proposals, funding, nonetheless, remains a major barrier to implementation. There is need for robust financing mechanisms. To invest in modern monitoring technologies, develop open data platforms, build national and local capacity, foster public–private–community data partnerships, and ultimately align with global standards, robust financing will remain the Achilles heel to these efforts. Financing the sustainable future economy would require more than green bonds as climate funds, but a robust domestic resource mobilization (i.e., strengthening environmental taxes, royalties, and eco-tourism revenues to finance green projects), as well as properly conceived debt-for-nature swaps that effectively account for debt repayments in lieu of conservation and sustainable development.

Congo Basin countries should be encouraged to exploit domestic resource mobilization (DRM) and effective Natural Resource Valuation (NRV) to finance sustainable development in addition to international aid and private investment. Although many Basin countries struggle to raise domestic income for public service delivery, sustainable land-use, conservation, and green development should be prioritized. Strengthening DRM by raising domestic revenues through better tax design and administration and new domestic financial instruments can provide fiscal space, minimize external financing volatility, and align public incentives with sustainable forest management. The potential for DRM is couched in the low tax-to-GDP ratios relative to their resource endowments and service needs. Caution must be exercised, however, since DRM strategies require political legitimacy and safeguards; and heavy reliance on extractive-sector taxes can encourage boom-and-bust fiscal cycles and worsen environmental harm if extraction expands. More so, poorly designed taxes on forest-dependent activities risk pushing small producers into illegality.

Similarly, monetizing ecosystem services and natural capital in the Basin can create new revenue streams for sustainable development and conservation. While the economic value of its natural assets remains improperly measured, undervalued, or excluded from financial planning, a proper quantification of the full economic, social, and environmental value of these resources, and integrating them into fiscal policy, investment planning, and innovative financing instruments, could mobilize financial resources for countries in the Basin. DRM and NRV thus offer the Congo Basin an important pathway to mobilize sustainable financing, strengthen fiscal resilience, and incentivize conservation. However, to properly exploit this potential will require coordinated investment in data systems, governance reforms, and equitable benefit-sharing mechanisms.

Overall, some key policy and sociopolitical options are required to be implemented to deliver benefits that collectively and with scaling help achieve sustainable development as espoused in the 2050 CBD vision of living in harmony with nature (Palazzo et al. 2024). Some policy and sociopolitical options required would encompass combinations of voluntary or mandatory actions and policies, strategies, measures, and interventions intended, designed, and/or implemented to promote sustainable development in the Basin (Palazzo et al. 2024). These response options would include legal, regulatory, economic, and financial mechanisms,

human rights-based tools, social, behavioral, cultural, and technological approaches, and management instruments implemented by diverse actor groups (Brandt et al. 2014). As noted in IPBES (2024), some of these response options (e.g., conserving and restoring ecosystems, sustainable consumption, reduction of pollution, integrated planning and governance, rights and equity, risk management, and alignment of finance as well as global and multilateral agreements) can operate across different time scales (e.g., short, medium, or long term), different spatial scales (national, regional, local, etc.), jurisdictions, and through the involvement of a diversity of actors, and coalitions of actors such as IPLCs, researchers, members of civil society, and those representing private and public sector interests.

In sum, therefore, an action-oriented package to address the global, international, regional, and national economic efforts for a new sustainable green economy in the Congo Basin would include:

1. At the global level, reforms for climate finance for forests and nature. This would envisage establishing a dedicated Congo Basin window in GCF/GEF and Loss-&-Damage funds with simplified access, and prioritize pay-for-results on avoided deforestation, peatland protection, and mangroves. It would also require expanding Multilateral Development Banks (MDBs) guarantee capacity (Credit, Political risk and Foreign exchange guarantees) to cover losses that would attract private capital for green infrastructure and NBS, as well as facilitating technology adoption and promoting a data access for Congo Basin. This could be done through a technology and data commons initiative which should fund an open Congo Basin Earth Observation stack (satellite + LiDAR + field plots) and an open Monitoring, Reporting and Verification (MRV) protocol to cut transaction costs and verify results.
2. At the international level, there shall be need to better exploit coalitions, standards, and partnerships such as a Congo Basin Green Compact, harmonized investment standards, market access, and buyer engagement with verified deforestation-free commodities with price premium linked to landscape performance, as well as south–south platforms involving structured exchanges with the Amazon and the Borneo Basins. The Congo Basin Green Compact should be envisaged as a multipartner compact (donors, MDBs, buyers, philanthropy, and corporates) pledging 10–15-year outcome finance for intact forest protection, climate-smart commodities, clean energy and clean cooking, and resilient cities and blue economy.
3. At the regional level, the organizations of ECCAS, CEMAC, and COMIFAC should play more effective roles in policy harmonization (e.g., common forest and land-use rules with respect to concessions, community titles, MRV, and benefit sharing), finance platforms, and infrastructure provision (power-related infrastructure or road, rail, river transport of climate-resilient standards with wildlife crossings), as well as shared data and enforcement of biodiversity regulations. The finance platform would be an effective regional Green Investment Facility or a dedicated financing platform acting as a one-stop shop for climate finance blending grants with loans or guarantees to de-risk private

investment in the region in a bid to help governments, development banks, and private investors to mobilize money to finance environmentally sustainable projects. A Congo Basin Observatory 2.0 should be the foundation of the Shared data and enforcement imitative undertaking near-real-time forest alerts, peatland water-table monitoring, artisanal mining mapping, and joint wildlife crime and illegal logging task force. More important is the integration of traditional knowledge into participatory monitoring and governance system.

4. At the regional level, it would further require establishing a Congo Basin Climate Science Initiative (CBCSI), comprising of at least a $150-million, decade-long program of research. The CBCSI should focus on modeling the integrated system in the Basin, climate effect from changes in land-use function, and the sustainability of different development options. The CBCSI would speed up scientific progress by developing an overarching science program for both domestic and international funding, training scientists to scale-up successfully tested measures which are currently insufficient in scope or unreliably funded (e.g., scaling the CongoFlux tower model). The CBCSI would have to hold regular forums or enlarged meeting of scientists, politicians, and advisers from the region to facilitate discussions of the policy-relevant questions that scientists should investigate. As part of its mandate, the CBCSI should establish a scientist-led framework by exploiting south–south cooperation through regular joint-workshops with scientists from the Amazon and Borneo Forests to address crucial research questions and assess lessons from the other Basins.
5. At the national level, promoting country-based policy and investment would require enacting policies and decisions that facilitate processing, transformation, and value addition of renewable and nonrenewable assets from the Basin; policies that promote STI with respect to the assets of the Congo Basin; as well as address fiscal and regulatory measures (such as natural capital accounting integrated into budgets, or accelerate IPLCs land titles, and possibly better network, lobby, and follow-up on international finance), effectively exploit DRM (e.g., efficiently allocating royalties, carbon revenues, and green levies to a natural capital Fund, facilitate natural capital valuation and scale debt-for-nature swaps linked to measurable conservation outcomes and sovereign sustainability-linked bonds with credible indicators), project preparation facility for bankable projects, and green public procurement to promote deforestation-free and recycled commodities, as well as promote compliance and integrity with public MRV portals. Above all, it would be important to establish national data systems complete with documentation and information processing.

Conclusion

Leveraging the Congo Basin's multifaceted development potential continues to preoccupy stakeholders. If prudently managed, the Congo Basin would not only lift millions out of poverty but also become a model for green, inclusive growth in the twenty-first century. However, realizing this potential demands concerted effort

to improve governance, invest in sustainable infrastructure, protect the environment, and empower local communities. The Congo Basin's complex environmental and socioeconomic landscape demands informed and adaptive decision-making. Through the generation and strategic use of diverse data sources that would range from satellite imagery to community mapping, stakeholders would be better equipped to confront deforestation, promote conservation, and support sustainable livelihoods. To optimize the continuous critical roles of the Basin in the global environment, economy, and society, both data and effective science have to be leveraged to properly evaluate problems related to deforestation, degradation, climate change, endangered species, or vulnerability to natural disasters. In the case of the Congo Basin, notwithstanding, evidence-informed decision-making remains paramount to emphasize actions which should be informed by the best available evidence from research and other sources. Moreso, by combining public policy, concessional capital, private investment, carbon and ecosystem payments, and strong local governance, policymakers can create a durable finance architecture that rewards forest stewardship, supports equitable local development, and secures the region's priceless natural resource benefits for generations. The success of these policy decisions will not only determine local development in the Basin but also contribute significantly to global climate stability and biodiversity conservation. Overall, a sustainable green economy in the Basin will continue to depend on cooperative investment for a deliberate blend of ecological stewardship, inclusive economic growth, and robust governance.

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The Potential for Restoring and Rewilding Degraded Ecosystems Across the Congo Basin to Play a Role in Land Management and Conservation

37

Hermann Taedoumg, Rolf Gael Mabicka Obame, Nathalie van Vliet, Neil-Yohan Musadji, and Victor Aimé Kemeuze

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Abstract

The Congo Basin, home to one of the world's most biodiversity tropical forest ecosystems, is facing intensifying deforestation and ecological degradation driven by slash-and-burn agriculture, industrial logging, armed conflicts, and expanding urbanization. While much of its forests cover remains comparatively "intact" relative to other major tropical regions, mounting anthropogenic pressures accelerating habitat fragmentation and faunal decline. Safeguarding remaining forests landscapes, establishing ecological corridors, and advancing sustainable resource governance are urgent conservation priorities. However, ecological restoration and rewilding efforts—with its potential to reverse degradation—remain limited in scope and implementation. Current initiatives are frequently constrained by insecure land tenure, inadequate financial mechanisms, weak private sector engagement, and challenges in achieving long-term local participation. Emerging integrative approaches that combine community-based restoration, technological innovation, species reintroduction (e.g., pilot efforts involving gorillas and bonobos) demonstrate potential, yet remain at an early stage. Looking forward, key challenges include strengthening scientific research— particularly on seed viability and forest regeneration dynamics—enhancing monitoring frameworks, and mobilizing innovative, durable financing models. Drawing on international best practices and fostering cross-sectoral collaboration will be critical to embedding restoration and rewilding within broader sustainable management strategies for the Congo Basin. Addressing these gaps offers a unique opportunity to position the region not only as a biodiversity stronghold, but also as a global leader in ecological resilience and climate mitigation.

Keywords

Congo Basin · Deforestation · Ecological restoration · Rewilding · Biodiversity conservation · Forest conservation · Community-based management · Wildlife corridors

Introduction

The Congo Basin stands out as one of the world's greatest reservoirs of biodiversity, sheltering a remarkable array of plant and animal life. Many species found here are endemic, with a significant proportion threatened with extinction (Job 1994; Taedoumg 2020; Beekmann et al. 2024). Spanning six Central African countries, the basin supports approximately 10,000 plant species (Thompson 2024), 1000 bird species (BirdLife International 2021), and emblematic mammals such as gorillas and forest elephants

(IUCN 2020). This exceptional diversity underscores the region's ecological importance and highlights the urgent need for effective conservation and management strategies.

Between 1990 and 2000, the Congo Basin experienced a net deforestation rate about 0.09% per year, which increased to 0.17% per year between 2000 and 2005—a relatively low rate compared to other tropical forest regions at the time (Tchatchou et al. 2015). However, more recent studies reveal a sharp rise in forest loss: from 1990 to 2020, the Congo Basin lost over 352,000 km^2 of forest cover, representing approximately 8.5% of its total forest area. In the Democratic Republic of the Congo (DRC), which contains around 60% of the basin's forests, deforestation rates have significantly increased, with projections estimating a loss of 33% of intact tropical forests by 2050 if current trends persist (WWF 2025; World Bank 2023). Key drivers of deforestation in the Basin include slash-and-burn agriculture, commercial farming, infrastructure development, and forest degradation from fuelwood collection and logging (Megevand and Mosnier 2013; De Wasseige et al. 2015; Tchatchou et al. 2015). Over 80% of the population depends on fuelwood, exacerbating forest loss (FAO 2024). In the DRC, conflicts exacerbate deforestation by forcing people to relocate and enabling illegal resource exploitation (Global Forest Watch 2025). Rapid population growth and urban expansion further increase pressure on remaining forests (World Bank 2023). The forests of the Congo Basin are perceived as relatively less degraded compared to other forest basins. However, the entire basin has experienced severe deforestation. Widespread elephant poaching and intense hunting have led to the phenomenon of "intact but empty" forests.

At the 2014 Global Climate Summit, and through the New York Declaration on Forests, land degradation was recognized as a major challenge for sustainable development and climate change mitigation. The reduction of natural habitats and declines in wildlife populations negatively impact biodiversity, the environment, and the livelihoods of communities dependent on these resources (Nasi et al. 2012; Bele et al. 2015). Globally, around 410 million people—including 60 million Indigenous peoples—live in or near tropical forest ecosystems and rely on them for their subsistence (Wiersum et al. 2005). Biodiversity loss and habitat degradation reduce ecosystem resilience to climate variations and undermine vital ecosystem services, such as climate regulation, water purification and crop pollination (Sharma and Birman 2024). The preservation and restoration of degraded ecosystems are essential to mitigate climate change impacts and conserve biodiversity (Millennium Ecosystem Assessment 2005; Bele et al. 2015).

To reverse current trends, efforts must prioritize adopting effective restoration and rewilding strategies in already degraded areas. Although the area under protection in the Congo Basin has significantly increased in the past few years and is set to continue to increase (IUCN and ICCN 2012; PFBC-CBFP 2021), available data reports a growing deforestation rates and widespread declines in large fauna, stressing the need to emphasize protection, restoration, and rewilding strategies (Pyhälä et al. 2016). The private sector has a key role to play in conserving the Congo Basin forests. While industries such as logging, mining, and oil extraction contribute to deforestation and associated environmental challenges, forging strategic partnerships with businesses can create meaningful opportunities to mitigate

these impacts. Nonetheless, private sector engagement remains limited and must be significantly strengthened to achieve a sustainable balance between economic development and forest conservation (Arce 2019).

The restoration of degraded ecosystems aims to re-establish the structure, function, and biodiversity of degraded habitats. According to Hobbs and Harris (2001), "ecological restoration goes beyond tree planting; it requires a holistic approach that considers the complex interactions among species, their habitats, and ecological processes." Reforestation, assisted natural regeneration, species reintroductions and the protection of protected areas must be combined with the engagement of local communities and the private sector to achieve sustainable outcomes (Le et al. 2012; Thomas et al. 2010). The active involvement of Indigenous and local populations in resource management is widely recognized as a cornerstone of successful conservation initiatives (Schmitt and Mukungu 2019; Castro and Nielsen 2001). Restoration projects play a vital role in rehabilitating ecosystems, preserving biodiversity, and combating climate change. Globally, the positive impacts of ecological restoration on biodiversity are well documented (Crouzeilles et al. 2017; Ndangalasi et al. 2021; Newton et al. 2021). For instance, Rey Benayas et al. (2009) conducted a meta-analysis revealing that restoration increased biodiversity by an average of 44%. Another meta-analysis reported that forest restoration enhanced biodiversity and vegetation structure by 15–84% and 36–77%, respectively (Crouzeilles et al. 2016). In tropical forests, Crouzeilles et al. (2017) reported that natural regeneration produced greater benefits for plants, birds and invertebrates. Ndangalasi et al. (2021), in forest restoration study in Tanzania, found notable colonization of native animal-dispersed tree species in fragmented and disturbed tropical forests surrounded by farmland.

Rewilding, either through the reintroduction of locally extinct native species or through strategies that enhance wildlife abundance also holds considerable promise. This process can restore ecosystem balance and bolster resilience to environmental changes (Hobbs and Cramer 2008; Brown et al. 2011). Reintroduction programs, however, require careful planning and long-term monitoring to ensure the survival and adaptation of re-established populations (Kemp and Alexander 2021). Establishing ecological corridors to facilitate species movement is another promising strategy, with encouraging results observed in other regions (Beier and Noss 1998).

In the vast and diverse landscapes of the Congo Basin, conservation and restoration success depend on cooperation among governments, non-governmental organizations (NGOs), scientists, local communities, citizens, and the private sector (Brown et al. 2010, 2014; Sewell et al. 2016; Poulsen et al. 2020). Achieving lasting impact will require mobilizing financial resources, integrating scientific knowledge with traditional practices and fostering active participation by businesses and communities.

While inclusive approaches are often essential, there are contexts where they may not be appropriate. In some remote protected areas with few or no permanent inhabitants, and which are sometimes only visited mainly by poachers or illegal miners' conservation strategies must be adapted (Poulsen et al. 2020). The Basin encompasses diverse settings: from PAs near capital cities to remote forests, and

from territories inhabited by Indigenous hunter-gatherers to regions settled by Bantu farming communities.

This chapter explores the opportunities and challenges of ecosystem restoration and rewilding in the Congo Basin. It highlights the importance of these strategies for preserving biodiversity and enhancing climate resilience, offering a comprehensive analysis of rewilding by examining its potential benefits and inherent challenges. Given the relatively limited restoration and rewilding to date, the chapter also looks at how the Congo Basin can draw lessons from global experiences, particularly those from other tropical regions. Through selected case studies, it presents key successes, setbacks and insights, concluding with the identification of critical knowledge gaps and practical recommendations to promote restoration and rewilding as integral components of land management and conservation in the Congo Basin.

Importance of Ecosystem Restoration in the Congo Basin

The primary drivers of forest degradation in the Congo Basin include slash-and-burn agriculture, illegal logging, mining, and fuelwood collection. Shifting cultivation-largely fueled by population growth and a heavy reliance on fuelwood results in substantial tree cover loss (Besisa Nguba et al. 2025; Global Forest Watch 2025). Unregulated logging and infrastructure development further amplify forest exploitation and fragmentation (WWF 2001). Additionally, mining activities and conflict-related displacement exacerbate degradation, with commercial farming and urban expansion also contributing, albeit to a lesser extent (World Bank 2023).

To address these issues, ecosystem restoration was identified as a key solution at the Rio Summit in 1992. The commitment of most Congo Basin countries under the Bonn Challenge—a global initiative aiming to restore 350 million hectares of forests by 2030—seeks not only to support national priorities such as water access, food security, and rural development, but also to help countries meet their climate change, biodiversity and land degradation commitments. However, many Congo Basin countries have not yet met these restoration commitments. For example, the Republic of Congo (ROC) committed to restore two million hectares but has so far achieved only around 50,000 hectares, primarily in the Bateke savanna and mainly through the planting of exotic Eucalyptus species. Moreover, international frameworks such as the Bonn Challenge do not differentiate between restoration using native species and the establishment of exotic monoculture plantations, which can undermine ecological outcomes (Lewis et al. 2023).

During its ninth Ordinary Session in 2016 in Kigali, Rwanda, the Council of Ministers of COMIFAC (Commission des Forêts d'Afrique Centrale) endorsed the AFR100 (African Forest Landscapes Restoration Initiative), which aims to assist member states in meeting their commitments to reverse forest and land degradation by restoring 15% of degraded forests by 2020 and 25% by 2025 in Central Africa (COMIFAC 2016). Despite these strong political commitments and growing pledges, actual restoration implementation on the ground remains limited, constrained by insufficient financial resources, limited private sector engagement,

and the need for stronger monitoring and reporting mechanisms (PFBC-CBFP 2021; Guizol et al. 2022). For instance, Cameroon's restoration efforts face challenges due to funding shortfalls and poor coordination, leading to slow progress despite ambitious goals (FAO 2024). Similarly, in the Democratic Republic of Congo (DRC), restoration initiatives are hindered by ongoing conflict and insecure land tenure, while private sector participation remains minimal, limiting both investment and innovative approaches to restoration (Guizol et al. 2022; World Bank 2023).These examples illustrate the persistent gap between political commitments and tangible restoration outcomes, underscoring the need to increase funding, enhance private sector involvement, and improve monitoring systems.

Restoring ecosystems in the Congo Basin can enhance ecosystem services such as biodiversity conservation, hydrological regulation and climate stabilization, while also stimulating economic growth. A meta-analysis of studies across diverse ecosystems, including forests, found that restoration activities increased biodiversity and ecosystem service provision by an average of 44–25%, respectively, compared to degraded systems (Rey Benayas et al. 2009).

Forest restoration can also substantially reduce greenhouse gas emissions and improve ecosystem resilience to weather disturbances (Thompson et al. 2009; Mala 2011; Rogers et al. 2022). Indeed, restored ecosystems are often better able to withstand climate change impacts, providing essential protection for biodiversity and natural resources (Suding et al. 2015; Fuchs and Noebel 2022).

Local communities—whose livelihoods are directly tied to natural resources—are particularly vulnerable to forest degradation. Environmental destruction leads to economic and food insecurity for these populations (Nellemann 2009). Ecosystem restoration can enhance access to renewable resources such as water and non-timber forest products, improve livelihoods and promote sustainable resource management. Moreover, restoration efforts play a crucial role in soil conservation. A study by FAO (2018) demonstrated that practices such as agroforestry can reduce soil erosion and improve fertility, thereby supporting sustainable and resilient agriculture. By improving soil health, ecosystem restoration can also enhance food security for communities dependent on agriculture. Finally, restoration strengthens ecosystem resilience, enabling ecosystems to better absorb and recover from both natural and anthropogenic disturbances (Moberg and Rönnbäck 2003).

By reestablishing ecological interactions, restoration fosters dynamic and stable ecological communities within ecosystems. In conclusion, restoration in the Congo Basin is essential not only for environmental protection but also for securing a sustainable future for populations reliant on these ecosystems. Restoration efforts are important for maintaining ecological balance and advancing sustainable development in the region. By mobilizing resources and actively involving local communities in restoration initiatives, it is possible to create a long-long-lasting positive impacts on biodiversity, climate, and livelihoods (Alcamo 2003). Achieving synergy between nature conservation and human well-being is crucial to ensure the Congo Basin remains a rich and vital region for future generations.

Case Studies of Ecosystem Restoration Experiments in the Congo Basin

Various case studies illustrate ongoing restoration initiatives in the Congo Basin. While some of the projects described below do not fully align with the conventional definition of ecological restoration, they primarily focus on enrichment planting and agroforestry. These methods are increasingly recognized as effective strategies for advancing ecosystem recovery, enhancing carbon sequestration, supporting biodiversity and climate change mitigation efforts (Eba'a Atyi et al. 2022).

Mangrove restoration projects have been implemented in selected coastal areas to improve marine biodiversity and protect coastlines from erosion (Kaly and Jones 1998). For example, two partners, "Planète Urgence" and the company "Orange," launched the CAMERR project (Cameroon Mangrove Ecosystem Restoration & Resilience), which aims to restore 1000 hectares of mangrove forests of Cameroon and Ntem in the estuaries over a 30-year period. This project contributes to global carbon neutrality and the United Nations Sustainable Development Goals, aiming to enhance marine biodiversity and strengthen the resilience of coastal communities dependent on these resources in the face of climate change (Akbar and Yudiatmaja 2021).

Numerous reforestation initiatives have also been launched to restore areas affected by both legal and illegal logging. Notably, "Nature Plus" has worked in forestry for over 20 years, establishing nurseries and implementing reforestation and forest enrichment projects while monitoring forestry practices within logging concessions in the region. These projects aim to revitalize forests while involving local communities in the sustainable management of these resources (Megevand and Mosnier 2013).

In the Central African Republic, the "Participatory Reforestation" project, implemented by FAO and local NGOs, focused on five pilot sites in the country's southwest—Bangui, Berbérati, Mbaïki, Bayanga, and the North of Mambélé—to restore degraded ecosystems through community engagement. This project has led to the replanting of thousands of hectares of forest and has had a positive impact on local biodiversity (PFBC-CBFP 2021; FAO 2025). In Cameroon, the "Conservation and Community Development" initiative, supported by IUCN and BirdLife International, aims to raise awareness of sustainable agricultural practices among local populations. These efforts have resulted in reduced deforestation and improved livelihoods, illustrating the importance of integrated approaches that combines conservation and community engagement (Karsenty and Gourlet-Fleury 2006).

Another notable initiative is the "Restoration of Degraded Forests" project in the Democratic Republic of the Congo, managed by the Rainforest Foundation. This program seeks to rehabilitate forests degraded by unsustainable agricultural practices. Through agroforestry techniques, communities are trained in sustainable farming while reforesting affected areas, thereby contributing to the resilience of local ecosystems.

In Cameroon and Kenya, the Alliance Bioversity-CIAT implemented an innovative approach by launching the "The Restoration Challenge Grant Platform for

Smallholders and Communities, with Blockchain-Enabled Crowdfunding" based on blockchain technology (Giacomini et al. 2023). Supported by the Global Environment Facility (GEF), his initiative facilitates greater engagement and investment by smallholder farmers and rural communities in restoration efforts across the wet savannahs of western Cameroon and the humid forests of the south. The platform leverages mobile technology and payment transfer services to provide small grants for restoration activities. Mobile technology ensures efficient and reliable verification of activities and payments, while blockchain technology throughout the restoration value chain guarantees transparency, trust, real-time monitoring, and effective mobilization of funds.

The COBALAM project (Reducing Barriers to Biodiversity Conservation, Land Restoration, and Sustainable Forest Management through Community-Based Landscape Management), established by Rainforest Alliance in 2020 in Cameroon, targets the restoration of 53,000 hectares of degraded forests and agricultural lands in the Western Highlands and around the Dja Reserve (Rainforest Alliance 2020). Using a community-based landscape management approach, COBALAM engages local populations in biodiversity conservation, promotes sustainable agricultural practices, and creates priority zones to preserve forests with high conservation value. It also seeks to strengthen the skills of communities, particularly rural women, by giving them a central role in land governance and resource management, thereby contributing to effective and equitable ecosystem restoration.

AFR100 is a major initiative dedicated to restoring forest landscapes across Africa, aiming to rehabilitate 100 million hectares of deforested and degraded land by 2030. However, much of the restoration pledges, particularly in the Congo Basin region, target drier forest areas located outside the core humid tropical forest zone. Furthermore, many restoration projects rely heavily on planting fast-growing exotic species—such as *Eucalyptus* and *Acacia*—rather than focusing on restoring native forest biodiversity. Although not all Congo Basin countries have committed to restoring their landscapes (Table 1).

AFR100 aligns with the Bonn Challenge, the African Union's Agenda 2063, and the Sustainable Development Goals, providing sustainable solutions to environmental and socio-economic challenges. By supporting reforestation and sustainable land management, the initiative promotes food security, job creation, and the strengthening of local livelihoods.

Table 1 Commitments of Congo Basin countries to AFR100

Country	Surface area of the country (Mha)	Committed Area to restore by 2030 (Mha)	Country Forest Cover (%)	Landscapes to restore relative to the country's surface (%)
Cameroon	47.5	12	27	25
Republic of Congo	34.2	2	33.2	6
DRC	234.5	8	59	3
CAR	62.3	3.5	36.3	6

Source: https://afr100.org/fr/countries

The Restoration Initiative (TRI) brings together the knowledge and skills of IUCN, FAO, and UNEP, in partnership with ten countries, including three from the Congo Basin (Cameroon, Central African Republic, and Democratic Republic of the Congo) where significant restoration opportunities exist. This flexible approach addresses common barriers to restoration and, through this unprecedented partnership fosters knowledge exchange among Southern countries, builds capacity and reduces costs associated with restoration efforts.

Negative Lessons from Past Restoration: Insights for Improving Future Efforts

Ecosystem restoration initiatives in the Congo Basin, while achieving positive results, also offer significant negative lessons that can inform and improve future efforts.

One of the primary shortcomings observed is the insufficient involvement of local communities (Höhl et al. 2020). The success of restoration projects is closely linked to the engagement and active participation of local residents. Early and meaningful consultations with communities is essential to ensure that their needs, knowledge, and perspectives are considered. Frequently, there is a misalignment between community and priorities and the objectives of restoration managers (Höhl et al. 2020; Taedoumg and Manga 2024). Moreover, many projects have applied uniform, one-size-fits-all solutions, failing to account for local biodiversity, cultural practices, and socio-economic contexts (Kuria 2019; Stanturf et al. 2019). This highlights the importance of adopting a customized approach that addresses the unique ecological and social characteristics of each area.

Financial sustainability also represents a major challenge. Many projects have been hampered by a lack of long-term funding, compromising their viability and impact (Sewell et al. 2016). To ensure the success of restoration efforts, it is imperative to explore sustainable funding sources, whether through grants, public-private partnerships, or carbon offset mechanisms (Sapkota et al. 2018), and to promote community engagement to reduce operational burdens.

Land tenure insecurity poses another major obstacle. In the Congo Basin, access to land and the establishment of secure land rights are often problematic, especially in areas with prevalent land use conflicts (Awono et al. 2023; ProFEC 2024; Taedoumg and Manga 2024). The absence of clear property rights in the Congo Basin often leads to tensions not only between local communities and project managers but also involves government authorities, complicating the implementation of restoration and conservation initiatives (Guizol et al. 2022). Overlapping land claims and permits, coupled with poor coordination among different government ministries responsible for forestry, agriculture, mining, and conservation, often result in conflicts over land use (PFBC-CBFP 2021). Restoration projects must therefore integrate strategies to address land tenure issues and establish clear equitable land-use agreements.

The quality of seeds is another crucial determinant of ecological restoration success. Seed collection in the Congo Basin is commonly disorganized and conducted without consideration of genetic diversity, leading to the planting of seedlings that cannot ensure a viable vegetative cover or resilience to long-term climate change. It is now increasingly proven that the quantity and genetic quality of native tree seeds are key to meeting ambitious global restoration targets, especially in developing countries where restoration efforts must address both ecological and local livelihood needs (Fremout et al. 2021; Giacomini et al. 2023). A limited gene pool from a small number of mother trees can cause inbreeding, making seedlings more vulnerable to diseases, pests, and environmental stressors (Fischer and Matthies 1998; Vergeer et al. 2003).

Inadequate monitoring and lack of long-term impact assessment are also common, limiting the ability to adapt interventions based on empirical evidence (Ferraro and Pattanayak 2006). Integrating robust monitoring systems from the outset of projects is essential to enable adaptive management and ensure continuous improvement based on real-world data.

Moreover, many projects fail to account for external stressors such as illegal logging and climate change, both of which can undermine restoration efforts (Höhl et al. 2020). Effective restoration strategies must incorporate measures to mitigate these pressures. A widespread misconception of restoration as merely tree planting further constrains effectiveness, as it overlooks the restoration of ecological functions, processes, and species interactions essential for long-term resilience (Rey Benayas et al. 2009; Höhl et al. 2020). A more holistic and ecosystem-based approach to restoration is thus necessary.

Conflicts of interest among stakeholders including governments, NGOs, and the private sector can undermine the success of restoration projects. Transparent, inclusive governance structures are crucial to align stakeholders objectives and build trust (Omba 2010). Lastly, the lack of training for local actors in sustainable land management and the benefits of restoration can limit the reach and durability of project outcomes (Gornish et al. 2024). Integrating awareness-raising and training programs is essential to build local capacity and foster long-term stewardship.

By incorporating these lessons learned, future restoration initiatives in the Congo Basin can be better designed to navigate the region's complex challenges, ensuring more sustainable and beneficial outcomes for both the environment and the communities that depend on it.

Success Stories, Effective Models, and Replicable Innovations for Restoration

Several initiatives of restoration have been implemented worldwide, successfully revitalizing degraded environments and offering valuable lessons and hope for future efforts (Rey Benayas et al. 2009; Dudley and Alexander 2017; Newton et al. 2021).

A notable forest restoration project took place in the coastal and sub-montane forest of northeast Tanzania, where only 10% of the forest cover remained

(Ndangalasi et al. 2021). Conducted by WWF and its local partner, the Tanzania Forest Conservation Group (TFCG), the project ran from 2004 to 2014, aiming to prevent biodiversity loss, improve local livelihoods, and restore and sustain the multiple forest functions (Mansourian et al. 2019). The project achieved an 88% reduction in forest clearance and fragmentation, and forest fires declined by 97% in village land forest reserves. By its conclusion, local communities were actively engaged in forest stewardship, with over 1326 individuals participating in beekeeping and camphor basil, resulting in a 239% increase in household incomes.

The ReforesTerra project, co-developed by Reforest'Action and the NGO Rioterra in Brazil, aims to restore 2000 hectares of secondary forests in the Baixo Rio Jamari watershed on degraded former pastures. Validated under the international VCS and CCB standards in November 2023, the project follows the ARR (Afforestation, Reforestation & Revegetation) typology and employs innovative techniques such as Framework Tree Planting, planting a dense mix of over 90 native species on 75% of the area to establish forest structure and encourage natural regeneration, and nucleation on 25% of the land to accelerate succession by strategically planting trees planting trees. Local communities, especially landowning farmers, are directly involved in all phases, receiving technical support from Rioterra for soil preparation, planting, and tree maintenance over 2 years before assuming autonomous management of their plots, with annual monitoring by Rioterra. Expected impacts include restoring forest cover, improving regional hydrology, enhancing native biodiversity, and strengthening community well-being through active participation (Reforest'Action 2023; Rioterra 2023).

New tools are increasingly being developed to improve seed system organization and monitoring. In Cameroon, the Alliance of Bioversity-CIAT is helping shift from reliance on exotic, unsuitable, or ineffective planting material toward restoration approaches that leverage the genetic resources of native tree species. These efforts enable foresters and nurseries to collect, document, and trace seed sources, produce seedlings with accurate traceability, and meet the growing demand for high-quality planting material for restoration. As part of these activities, modular applications have been developed, including MyGeoTree Collector [1], MyGeoTree Nursery [2], MyGeoFarm [3], now available online (Eitzinger et al. 2023). Additionally, Diversity for Restoration (D4R) is a decision-support tool created by the Alliance Bioversity-CIAT, aids scientists, planners, restoration practitioners, policymakers, investors, and donors in selecting appropriate species and sourcing seeds based on restoration objectives and site conditions. D4R [4] is especially valuable where improved decision-making and data sharing among stakeholders are crucial (Fremout et al. 2021). Initially designed for Colombia's dry tropical forest, D4R has been expanded to Peru, Ecuador, Burkina Faso, and Cameroon.

The Restoration Opportunities Assessment Methodology (ROAM), by IUCN and WRI, has emerged as a key resource for identifying and prioritizing restoration areas, particularly in the Congo Basin (IUCN and WRI 2014). By engaging diverse stakeholders in a collaborative process, ROAM supports the creation of national plans aligned with international frameworks such as the Bonn Challenge and the Convention on Biological Diversity (AFR100 2022). ROAM facilitates mapping

opportunities, estimating carbon and biodiversity benefits, and anticipating institutional challenges. However, ROAM's effectiveness depends heavily on data availability quality, and requires continuous adaptation to fit complex local conditions. Despite these limitations, ROAM remains a cornerstone for planning large-scale restoration in the Basin.

In 2019, Rainforest Alliance, Conservation International, and Verra launched LandScale [5], a platform designed to assess sustainability at the landscape scale (Rainforest Alliance 2021). LandScale enables public and private stakeholders to measure, track, and communicate ecological and social impacts, with forest restoration as a key area of focus. The platform supports the identification of degraded areas, monitors forest regeneration, and assesses benefits for local communities (Vergara-Asenjo and Potvin 2014). For instance, in Chiapas (Mexico), LandScale contributed to the restoration of forests associated with coffee cultivation, enhancing biodiversity and improving farmers' incomes (Rainforest Alliance 2023). Through collaborative processes and transparent indicators, LandScale ensures rigorous monitoring and long-term impact (Sayer et al. 2013).

Rewilding in the Context of the Congo Basin

Rewilding is the process of rebuilding a natural ecosystem after major human disturbance, by restoring natural processes and the complete or near complete food web at all trophic levels as a self-sustaining and resilient ecosystem with biota that would have been present if the disturbance had not occurred (Carver et al. 2021).

In the context of the Congo Basin, rewilding is not a universal solution and should be prioritized only after two critical steps: first, the protection and sustainable use of existing wildlife populations; and second, the maintenance and restoration of wildlife corridors. Rewilding efforts should be implemented selectively, in carefully chosen areas where they can achieve clearly defined objectives. These objectives include restoring ecosystem functions that benefit rural populations, enhancing ecosystem services in agricultural landscapes, reversing extensive habitat degradation from activities such as mining and logging, and supporting the re-establishment of key species that have become locally extinct.

Rewilding may focus on keystone species that have a disproportionate impact on ecosystem dynamics despite their low abundance or on locally extinct species with significant ecological or charismatic value. Within protected areas, reintroduction can serve as a valuable conservation strategy for endemic species that are already locally extinct or are at high risk of extinction, provided that the original drivers of their decline—such as habitat fragmentation and overhunting—are effectively controlled.

The concept of rewilding should not be limited to the artificial reintroduction of charismatic species. It should also encompass the restoration of wildlife populations of common or vulnerable species to pre-disturbance levels without active reintroduction. In such cases, rewilding may involve creating conditions that enable natural population recovery, for example through seasonal hunting bans, restrictions

on hunting gear, or spatial zoning to manage hunting pressure more effectively. This approach, often termed sustainable wildlife management, represents a practical and impactful form of rewilding.

Examples of rewilding in the Congo Basin remain rare. Notable cases include the reintroduction of Gorillas into protected areas in Central African (Pearson et al. 2008) and the release of Bonobos back into the wild in the Democratic Republic of Congo (Bowie et al. 2021).

Gorilla re-introduction: The Aspinall Foundation established the first gorilla orphanage in Congo-Brazzaville in 1989 and has since rescued over 100 orphaned gorillas. In partnership with national governments, the foundation runs two western gorilla reintroduction projects in the Republics of Congo and Gabon under the Projet Protection des Gorilles (PPG) and is a founding member of the Pan-African Sanctuary Alliance (PASA). The program's primary objective is to re-establish self-sustaining populations of western gorillas within their former range. In Gabon, reintroduction efforts mainly involve wild-born orphans rescued from the illegal bushmeat trade, along with some captive-born individuals breeding programs in the United Kingdom. Rescued orphans undergo a two-month stabilization phase before entering long-term rehabilitation. A subsequent 15-month soft-release process enables the gorillas to acclimate to their natural habitat with comprehensive psychological, social, and medical support. Two groups comprising 29 gorillas have completed this process, achieving an 85% post-release survival rate. Post-release monitoring includes GPS tracking, health assessments, and supplementary feeding for up to 23 months. The reintroduced gorillas have expanded their home ranges and successfully adapted to wild diets. The first recorded birth among the reintroduced population occurred in 2007. Compared to other primate reintroduction programs, this initiative has achieved notably higher survival rates, particularly for captive-born gorillas (86% post-release), with lessons from early releases improving long-term success.

Releasing Bonobos back into the wild (Democratic Republic of Congo): In 1994, "Amis des Bonobos du Congo (ABC)" established Lola ya Bonobo, a sanctuary near Kinshasa, to care for bonobos orphaned by the illegal wildlife trade. In 2009, ABC created Ekolo ya Bonobo, a protected reintroduction site near Basankusu in Équateur Province, DRC. The site was chosen due to its prime bonobo habitat and lack of existing wild bonobo population. In 2019, Ekolo ya Bonobo was designated a Community Forest Reserve, covering 117,412 acres of swamp forest. As of May 2019, 27 bonobos had been successfully reintroduced. Since then, one bonobo died of a suspected snake bite in 2011, and three others have not been observed for several years—possibly having integrated into wild populations or perished. Notably, five bonobos have been born to reintroduced females, marking the first natural reproduction within the reserve. The current bonobo population at Ekolo stands at 29 individuals.

Lessons learned from rewilding efforts elsewhere in Africa highlight several critical factors. Foremost among these is that reintroductions are only meaningful when the underlying factors for the decline or extinction of the species have been addressed (or are being controlled). These factors often include overhunting or

habitat fragmentation, which compromise landscape connectivity (Soulé and Noss 1998).

Another key consideration is the importance of reserve size. Larger reserves are essential for maintaining viable populations of wide-ranging species, particularly carnivores, while smaller reserves remain highly susceptible to human impacts such as hunting and agricultural conflicts. Species-specific spatial requirements further underscore this point; for example, African wild dogs require a minimum habitat area of approximately 3606 km^2 to support sustainable populations (Wolf and Ripple 2018).

A stable and sufficient prey base is also fundamental to the success of reintroduction efforts. Restoring or maintaining abundant prey populations is crucial for supporting reintroduced predators. For instance, successful leopard reintroductions depend not only on the availability of extensive protected areas but also on the recovery of prey species populations to sustain them (Henschel 2009).

Post-release monitoring is essential for evaluating the initial success of reintroduction efforts, particularly through the assessment or tracking of survival and reproduction rates (King et al. 2014). This is especially important for long-lived species, where estimating demographic parameters can be challenging but critical to gauging success. For example, a reintroduction project for the critically endangered western lowland gorilla (*Gorilla gorilla gorilla*) on the Batéké Plateau in the Republics of Congo and Gabon provided valuable insights into survival and reproductive performance (King et al. 2014). Among the 51 released gorillas, the annual survival rate was 97.4%, while 9 females produced 11 infants with a first-year survival rate of 81.8%. These outcomes are comparable to those observed in wild gorilla populations, suggesting initial success in both survival and reproduction. Population models derived from such data are invaluable for predicting long-term viability and informing future reintroductions.

Moreover, effective communication and robust community engagement are essential components of successful rewilding projects. Conflicts often emerge when project objectives diverge from community expectations, particularly when local residents feel excluded or insufficiently recognized as stakeholders in initiatives that directly affect their livelihoods. In the case of a gorilla reintroduction project in Congo, inconsistent communication resulted in misunderstandings about the project aims and undermined relations with local communities (Cartwright et al. 2012). Tensions were further exacerbated when local priorities, such as economic development opportunities, did not align with the conservation-centric goals of the project.

While the biological aspects of rewilding often receive primary attention, the social dimensions—including community involvement, education and empowerment—are equally critical for ensuring long-term success. Rewilding initiatives must address local aspirations and foster genuine engagement so that communities feel included and invested in the process (Cartwright et al. 2012; Henschel 2009; Bowie et al. 2021). For example, Bonobo reintroduction programs in the Democratic Republic of Congo underscore the importance of understanding the psychology and perspectives of local communities, who play a pivotal role in

the conservation of great apes. Conservation programs like Ekolo ya Bonobo must continue to promote positive human-wildlife relationships, advance conservation education, and encourage cultural attitudes supportive of long-term wildlife protection (Bowie et al. 2021).

Knowledge Gaps and the Emerging Priority of Restoration and Rewilding

Persistent Knowledge Gaps in Restoration and Rewilding Science and Practice

Although the concepts of restoration and rewilding have received increasing attention in recent years, several critical knowledge gaps remain that limit the effectiveness of restoration efforts. One recurring challenge lies in the inherent complexity of the ecological interactions in the Congo Basin and the still limited understanding of the natural processes driving ecosystem regeneration within such a vast and diverse tropical environment (Clay 2016; Buwani 2017; Bauters 2018). Effective ecological restoration and rewilding require a systemic approach that accounts for interactions among species, habitats, and ecological processes (Hobbs and Harris 2001; Aerts and Honnay 2011). However, applying this approach specifically to the Congo Basin remains challenging, as the region's high biodiversity and heterogeneous local conditions complicate the planning and execution of restoration strategies.

A major knowledge gap is the lack of research on the effectiveness of specific natural regeneration techniques in the context of the Congo Basin forests (Peltier et al. 2014; Nghonda et al. 2024). The role of local communities in forest management, particularly in promoting natural regeneration, also remains underexplored (Ichikawa 2017; Ota et al. 2021). Although reforestation and natural regeneration programs have been initiated in parts of the Congo Basin, relatively little is known about their capacity to restore long-term ecological functions, such as biodiversity conservation or climate change regulation (De Wasseige et al. 2015). Additionally, research on gene flow and genetic diversity prior to seed collection and distribution of native species during restoration projects is scarce. There is a pressing need for research to guide the development of seed supply guidelines as the Congo Basin scale, especially to ensure that restoration objectives align with genetic principles, as emphasized by Giacomini et al. (2023).

Current understanding of soil degradation and restoration processes in tropical ecosystems also remains limited, hindering the design of effective interventions. As highlighted by Megevand and Mosnier (2013) and reaffirmed by more recent studies—the impacts of human activities, such as logging and agriculture, on soil quality and the natural regeneration capacity of forests are still poorly understood (Burger and Kelting 1999; Picchio et al. 2020).

Regarding rewilding through reintroduction of wildlife in Congo Basin, despite attempts to reintroduce endangered species such as the okapi and the mountain

gorilla, the procedures and consequences remain poorly documented (Farmer and Courage 2008; Henschel 2009). The success of such projects depends heavily on meticulous planning and sustained monitoring of reintroduced populations; yet, long-term data necessary to assess species adaptation and their impact on the dynamics of restored or regenerating ecosystems regenerating (King et al. 2014).

Moreover, habitat fragmentation and the absence of functional ecological corridors further complicate species reintroductions, as many species struggle to establish viable populations without secure migration pathways (Beier and Noss 1998). The ecosystems of the Congo Basin also face persistent anthropogenic pressures, including illegal logging and hunting, which exacerbate the challenges of rewilding and restoration (Hanson 2018).

Effective cooperation among government agencies, scientists, local authorities, NGOs, and communities remains another significant challenge. Although research highlights the importance of community engagement for the success of most conservation programs (Schmitt and Mukungu 2019; Höhl et al. 2020), institutional and social barriers frequently hinder collaboration efforts. Studies indicate that participatory management approaches often encounter conflicts of interest among stakeholders, particularly between long-term goals of conservation and the immediate resource needs of local populations (Omba 2010; Huge et al. 2020). In general, the sustainable management of tropical ecosystems must integrate these human factors to achieve meaningful results (Höhl et al. 2020), yet collaborative governance mechanisms in the Congo Basin remain underdeveloped.

Thus, despite the existence of a few pilot rewilding projects in the Congo Basin, substantial gaps persist—particularly regarding region-specific methods, the integration of empirical knowledge, and the implementation of rigorous monitoring systems. Future research should address these gaps through long-term data collection and multidisciplinary approaches that integrate ecological complexity, social realities, and the region's political challenges.

Conservation and Sustainable Management: Conditional Emerging Role of Restoration and Rewilding

While the Congo Basin remains one of the most "intact" ecosystems on Earth, the region is experiencing a rapid and alarming surge in deforestation, forest degradation, and fragmentation—trends that are particularly severe in countries such as the Democratic Republic of Congo (DRC) and Cameroon. These pressures are not only reducing forest cover but are also leading to "empty forests," characterized by the loss of wildlife, with key species such as the forest elephant already extirpated from vast areas. This ongoing decline in biodiversity and the weakening of ecosystem functions underscore the urgent need to address the root causes of deforestation and degradation, including agricultural expansion, infrastructure development, and unsustainable resource extraction.

Given this context, the immediate priorities for the Congo Basin must be:

1. The conservation and sustainable management of the remaining "intact" forests
2. The establishment and maintenance of ecological corridors to prevent further fragmentation and support wildlife movement
3. The integration of restoration and rewilding—not as a primary focus at this time, but as an essential component of regional land management and conservation strategies, particularly in carefully selected, highly degraded areas

Restoring degraded ecosystems and re-establishing wildlife in the Congo Basin requires a thorough understanding of the extent and severity of ecosystem degradation. Research indicates that only certain areas are so heavily altered that they won't naturally recover or rewild without targeted interventions (Shapiro et al. 2021; Guizol et al. 2022). This situation contrasts with the Amazon Basin, where widespread forest damage has prompted ambitious restoration commitments, such as the goal to restore 15 million hectares of natural forests. In the Amazon, these large-scale efforts are implemented through coordinated national and regional action plans, substantial public funding mechanisms like as the Amazon Fund, and restoration programs that emphasize the use of native species, agroforestry, and the active involvement of Indigenous communities (WWF 2025).

Meanwhile, in the Congo Basin—unlike in other African regions such as the Lake Chad Basin—where large-scale ecosystem restoration is an urgent priority—the primary focus should remain on halting ongoing loss and degradation and addressing the most severely affected areas and tackling the underlying drivers of deforestation and ecosystem.

Restoration and rewilding in Congo Basin should be strategically targeted to:

1. Restore ecosystem benefits for rural populations
2. Optimize ecosystem services in agricultural landscapes
3. Reverse large-scale habitat destruction from activities such as mining and logging
4. Conserve or reintroduce key species that have been locally extirpated

Nevertheless, as deforestation and environmental degradation accelerate, the importance of restoration and rewilding is likely to grow. Being prepared and committed to implementing these approaches will be crucial for rehabilitating damaged areas and preventing further ecosystem deterioration.

Synthesis

The Congo Basin, spanning six Central African countries, is a globally significant biodiversity hotspot, home to thousands of plant and bird species as well as iconic wildlife such as gorillas and forest elephants. Although deforestation rates were relatively historically low, recent decades have witnessed a sharp acceleration, with over 352,000 square kilometers of forest lost between 1990 and 2020—representing approximately 8.5% of the basin's total area. The Democratic Republic of Congo,

which contains the largest share of the basin's forests, has been particularly affected; projections suggest that up to one-third of intact forests could be lost by 2050 if current trends continue. The main drivers of this deforestation include slash-and-burn agriculture, commercial farming, infrastructure development, fuelwood collection, illegal logging, mining, and displacement caused by conflict.

It is important to emphasize, however, that compared to other tropical regions such as the Amazon or the Lake Chad Basin, restoration and rewilding are not currently top priorities in the Congo Basin. This is primarily because the forest remains relatively "intact," making the immediate priority the prevention of ongoing forest loss and the mitigation of its underlying drivers. Consequently, the region's conservation agenda is centered on the protection and sustainable management of remaining "intact" forests, along with the establishment of ecological corridors to prevent further fragmentation and maintain wildlife connectivity.

While the need for restoration and rewilding is acknowledged—especially in already degraded areas or where key species have been lost—these strategies are not yet at the forefront of policy or practice in the region. Restoration and rewilding are seen as important complementary tools that may become increasingly relevant as pressures on the forest intensify. For now, targeted restoration efforts are mostly confined to specific, severely degraded sites rather than being implemented on a large scale across the basin.

This contrasts sharply with the Amazon, where widespread forest degradation has prompted ambitious commitments to restore 15 million hectares of natural forests through coordinated action plans, public investment, and extensive community involvement. In the Congo Basin, restoration initiatives remain limited by insufficient financial resources, weak private sector engagement, governance challenges, and ongoing instability. Even though countries have made international restoration pledges—such as under the Bonn Challenge or AFR100—progress on the ground has been slow, with efforts often focused on monoculture plantations of exotic species rather than true ecological restoration.

Looking ahead, as deforestation and environmental pressures intensify, the importance of restoration and rewilding in the Congo Basin is expected to grow. Preparing for this shift will require strengthening financial mechanisms, advancing scientific research, enhancing community engagement, and learning from successful global restoration experiences. For now, however, conservation and sustainable management of "intact" forests remain the region's most urgent priorities, with restoration and rewilding recognized as emerging, but not yet central, strategies.

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Natural Resource Management Policies in the Congo Basin

38

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Abstract

Policies on natural resources were assessed both nationally and regionally to identify areas where there are still policy gaps, gaps between policies and their implementation, and areas where countries of the Congo Basin have progressed over the last decades. New emerging economic patterns were also rapidly screened. Significant progress in legislations has been made in all the countries of the Congo Basin, but there were also some inadequacies between enacted policies and legislations and their enforcement. Limited capacity, poorly paid personnel, and inadequate resourcing for enforcement explained many of these inadequacies and were linked to the overall poor governance, lack of transparency, limited freedom of speech, limited inclusion, and inequalities in the redistribution of the wealth generated by natural resources in the Congo Basin. Political and financial conditionalities imposed by western-based international financial institutions pushed the countries of the Congo Basin to search for less politically arrogant and financially less conditional economic cooperation alternatives and opened up the new scramble for Africa, whereby China, India, and South Africa have invested a lot of resources, followed by other countries such as Brazil, Lebanon, Morocco, Pakistan, Russia, and Turkey. There are new types of economic cooperation, including bartering natural resources for infrastructure or for security. Consequences of these new dynamics are not yet well documented and should be a priority for investment in science.

Keywords

Congo Basin · Policy · Governance · Participation · Law enforcement · Natural resources

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Introduction

Participation in the Governance of natural resources in the Congo Basin is heavily skewed in favor of state authorities against other stakeholders. Studies suggest that in light of artisanal timber harvesting, artisanal mining, biodiversity conservation, deforestation, habitat degradation, and poverty alleviation, collaborative approaches are necessary as a means for governance (e.g., Laporte and Justice 2001; Massardier 2003; Sonwa et al. 2011; Kakelengwa 2013, 2023; Kakelengwa and Maindo Monga Ngonga 2016; Mizaba et al. 2023; Tabena et al. 2023). Unfortunately, the politics of personal interests and the struggle for political power have prevailed over public interests for more than a quarter of a century in all countries of the Congo Basin, after the 1990s liberalization of the political space (Stéphane and Fankem 2018; Jackson and Rosberg 2023). The representational democracy, imported into the region around the 1990s, has shown its limits in most countries (e.g., Guèye 2009). Public space, defined by Habermas (1997) as a place for the construction and manifestation of power relations, where ordinary citizens express themselves on how power is managed, has shrunk back to very narrow margins, limiting the social process of constructing decisions to just a few powerful people. Although new people joined the dominant groups in all the Congo Basin countries, the dominated groups increased proportionally to the growth of human populations overall, creating large numbers of marginalized people with little access to natural resources.

The deployment of coherent policy and regulatory frameworks at different scales (subnational, national, regional, and international) for effective and transparent forest governance remain a challenge in the countries of the Congo Basin (Gizachew et al. 2017). Institutional capacities and institutional arrangements for sustainable forest management are minimal in the Congo Basin, noted challenges of institutional capacities to monitor, report, and verify (MRV) and insisted that knowledge transfer must happen before effective governance can become operational in several countries. Secured land tenure, effective stakeholder representation, and participation in the decision-making processes and minimal social inclusion were also identified as hurdles to effective transparent management of natural resources in the Congo Basin (Cadman et al. 2017). Pirker and Carodenuto (2021) argued that governance challenges are ultimately linked to political will, to which should be added social and political stability (Castro-Nunez et al. 2016).

While international and regional initiatives (CAFI, REDD+, FCPF, etc.) and international civil society organizations have been pointing out the poor governance, lack of capacity, multiplicity, and incoherence of legal instruments and policies, it is also true that in many instances they have failed to provide resources to support activities to improve weaknesses they have identified with national institutions in the Congo Basin.

Historical Perspectives on Natural Resource Management in the Congo Basin

The history of natural resource management in the Congo Basin has been marked by dynamics of exploitation, appropriation, and conflicts of interest that have influenced the development of the region (Harms 1987). Between ca 1885 and ca 1960, the

European colonizing powers reorganized the traditional societies of the Congo Basin to maximize the exploitation of natural resources for the benefit of colonial metropolises. This period was marked by intensive, often violent extraction practices geared to the needs of the colonizers, notably for timber, wild rubber, game, ivory, and minerals (Stengers 1966).

Between the 1960s and ca 1980s, newly independent Central African states continued to export raw materials to former colonizing countries in order to earn hard currency and to sustain their economies (Brasseul 2016). Biodiversity conservation and natural resource management followed the same patterns. For example, in DRC, the first wave of protected areas was created using the same methods as previously used by the Belgians, while countries of the former Afrique Francophone Equatoriale (Cameroon, CAR, Gabon, and ROC) retained hunting reserves as an essential part of their protected areas.

The single party regimes that emerged after independence and elites coalesced around one strong leader, capturing not only the political power but also the wealth generated by natural resources in a monopolized state system and redistributing the wealth among themselves, their cronies, and the international networks they created (Bayart 1989; Bierschenk et al. 2000). Bayart (1989) described this period, in a metaphor that gained popularity across the region, as "*La politique du ventre*" (the politics of the belly), which essentially meant that the elites captured wealth to maintain their grip on political power, through predation and monopolization of the state resources, redistributing them to the networks of their local and international clients to ensure they remained in power as long as possible.

In the decade following independence, some countries nationalized companies extracting and trading renewable and nonrenewable natural resources (Barbier 1995). The most extreme case was that of DRC, whose Zaireanization led to catastrophic economic results (Young and Turner 1985); Gabon went through a gradual "Gabonization" that targeted only some key enterprises (Didzambou 2010), with better results. In ROC, all enterprises passed into state management when the country became a communist regime between 1969 and 1992 (M'Paka 2005); in CAR, enterprises were supported by the government rather than being nationalized after independence (e.g., Banque Mondiale 2019). An exception in the region was Cameroon, which continued with private enterprises working alongside some state investments (Noumba 1996; Brunel 2003). Shifts in management and ownership of export-driven companies were challenging in governance because of lack of preparedness in entrepreneurship and economic policies became unpredictable as politics became instable.

Gabon and ROC emerged as oil producing countries in the 1970s, with their economies becoming largely dependent on oil exports (Johnson and Wilson III 1982) and performing better than other countries in the region. Countries such as Cameroon, CAR, DRC, and Equatorial Guinea remained largely dependent on other natural resources, whose prices declined as a result of the 1979 oil crisis, drastically deteriorating their terms of trade (the purchasing power of imported goods and services they could bear as compared to their exports) (Boughton 2001). Boughton (2001) argued that the oil crisis and deterioration of terms of trade it caused precipitated countries into a debt crisis, which had devastating effects on the nonoil

Congo Basin countries, which were poorer, faced more deep-seated structural problems, and were much more dependent on official rather than commercial credits.

This resulted in a period marked by structural adjustments (1980s–1990s), which saw the International Monetary Fund (IMF) making economic policies, prescribing administrative measures, laws, and regulations that the Congo Basin countries had to follow, if they were to receive funds and to achieve greater economic growth (Bekolo-Ebe 1985). This crisis affected all the countries of the Congo Basin. Between 1960 and the 1980s, the new political leadership in Congo Basin countries had presided over the policymaking for their own economies, even though they all had a myriad of technical advisors from former colonial powers. The ability of the IMF to make resource management policies during the structural adjustments in countries such as Cameroon (Ndongko 1993) and DRC (Lututala et al. 1993) was felt as an inacceptable interference into the sovereignty by many countries. For Moosa (2021), the ten commandments grouped in four major areas, including fiscal reform, interest and exchange rate policies, liberalization of trade and foreign direct investment, and privatization and deregulation (including property rights) (aka the Washington Consensus), were indiscriminately implemented throughout the world by the IMF. In the countries of the Congo Basin, implementing the Washington Consensus strangled investment in social capital (education, health, etc.) and other economic sectors (e.g., Inogwabini 2022). Herbst (1990), Adejumobi (1996), and Ibhawoh (1999) suggested that inadequate investments in social capital and the well-being of citizens weakened the political basis on which political leaders in the Congo Basin drew their legitimacy. Even though the countries of the Congo Basin were also hit by the wave of democratization that swept the world in the 1990s following the fall of the Berlin Wall, the hardships imposed by structural adjustments were a driver of political change, although in Cameroon and Gabon the country leaders remained in place (e.g., Mehler 1997). Mitterrand's speech at La Baule, which broke the cooperation protocol that had hitherto been established between France and the French-speaking countries of Africa, linking France's support to countries with the efforts toward greater freedom (Laloupo 2022) found a fertile environment to thrive on. People in Central Africa created conditions for democratization or rather the dawn of multiple party regimes, although Lejeal (2022) is right that attributing all the merit for the democratization to external factors would equate to condescension.

Democratization and the Management of Natural Resources in Congo Basin

From the 1990s onward, the Congo Basin entered the era of democratization, civil society organizations emerged, and citizen participation in the policymaking process greatly increased with its consequent greater demands on accountability, transparency, and equity in sharing natural resources. It is with this background that policies governing natural resource management in the Congo Basin are assessed below, with additional elements including the new economic globalization, and the heightened conscience of environmental issues, as stipulated in the Rio de Janeiro agreement

(Convention on Biological Diversity, CBD). Democratization in the countries of the Congo Basin came about as a conjunction of multiple factors; political scientists fiercely critiqued the regimes across the region, which lent strong support to the then underground opposition (e.g., Nzongola-Ntalaja 1986; Hamos 1988; Bayart et al. 1992; Nzongola-Ntalaja 1997; Kissita 2021). As suggested by Stroup and Zissimos (2014) and Reinsberg et al. (2023), economic conditions resulting from IMF adjustments contributed to the undermining of support for the single-party system of the Congo Basin countries; the 1990 international context provided the conditions for people to express their long-suppressed voices wherever they were, to demand greater political participation and genuine distributive justice.

An Appraisal of the Congo Basin Natural Resources Legislations from the 1990s Onward

The Rio de Janeiro meeting in 1992 led to the creation of the CBD, whose provisions cover a wide range of topics, including sustainable development, rights to development, inclusion of political and social minorities, and transparency in the management of natural resources (e.g., Morgera and Tsioumani 2011). These have been widely endorsed by governments and integrated into national legislations across the world (Chandra and Idrisova 2011), including in the countries of the Congo Basin. As Table 1 shows, all but one country (Equatorial Guinea) signed the convention the very same year the convention was voted; they all ratified it before 2000.

The early ratification of the CBD by the countries of the Congo Basin showed their willingness to implement its provisions. Even though there is no evidence to directly link the CBD ratification and the political will to include biodiversity and the environment in the legislations of the Congo Basin, it is a fact that shortly after 1992, care for the environment became part of national legislations. The right to a healthy environment became a right for the citizens of ROC in its 1992 constitution's article 46, which also obliges the government to protect the environment (now article 41 of the 2015 ROC's constitution, as emended in 2022) (Présidence de la République du Congo 1992, 2015, 2022). Other constitutions of the countries of the Congo Basin integrated the same provisions shortly thereafter. This is the case of the DRC's article 30 of the transitional constitution of 1994 (Présidence de la République du Zaïre 1994) and article 53 of the 2006 DRC constitution, as amended in 2011 (Présidence de la République Démocratique du Congo 2006, 2011). The preamble of the 1996

Table 1 Countries of the Congo Basin and dates they signed and ratified the CBD

Country	Date of signature	Date of ratification
Cameroun	14 June 1992	19 October 1994
CAR	13 June 1992	15 March 1995
DRC	11 June 1992	03 December 1994
Equatorial Guinea		06 December 1994
Gabon	12 June 1992	14 March 1997
ROC	11 June 1992	01 August 1996

Cameroonian Constitution, as amended in 2008, followed suite with the same provisions (Présidence de la République du Cameroun 1996, 2008). The Gabonese Republic included the right to a healthy environment in its constitution as amended in 2011 (Présidence de la République Gabonaise 2011) whereas in CAR, similar provisions appeared in the 2016 constitution and, subsequently, in 2023 (Présidence de la République Centrafricaine 2016, 2023). To show how important this inclusion of the right to and duty to care for the environment in the constitutions of several countries of the Congo Basin is, it is worth recalling that the environment was only included in the constitution of France (Article 1) in 2021.

To implement the above constitutional provisions, countries of the Congo Basin adopted policies that would enable them to conserve their biodiversity globally. That explains the promulgation by countries of laws to govern mining (▶ Chap. 15, "Mining and Ecosystem Functions and Services in the Congo Basin"), biodiversity conservation (▶ Chap. 19, "History, Development, and Politics of Protected Areas in the Congo Basin Countries"), and the management of forests and timber extraction (▶ Chap. 14, "Timber Production and Ecosystem Functions and Services in the Congo Basin"). Some of these laws are listed below (Table 2). A quick reading of some of the most important provisions included in them reveals that biodiversity conservation and environmental laws, and those on extraction of natural resources, were carefully crafted to allow for accountability, transparency, and better and sustainable usages by national communities and to stop illegal activities (Katz-Lavigne 2020; Gerner et al. 2023).

There are commonalities in all of these policies including the proclaimed strong will to conserve biodiversity and environment; to extract natural resources in accountable, better, sustainable, and transparent ways; to combat illegal activities; and to share the wealth generated by natural resources equitably among citizens. There are, however, differences in practices, as well as legal and political traditions. This is why it was deemed necessary to harmonize different policies across the Congo Basin, which was achieved in 2025, following a long process.

Regionalizing Natural Resource Management Policies in the Congo Basin

A central mechanism in the harmonization of natural resource policies in the Congo Basin is Commission des Forêts d'Afrique Centrale (Central African Forest Commission) (COMIFAC). In the spirit of its creation, COMIFAC is specialist organism of the Economic Community of Central African States (ECCAS); it is governed by a treaty signed in 1999 by 11 member states, expanding beyond the core nations of the Congo Basin (Cameroon, CAR, DRC, Equatorial Guinea, Gabon, and Republic of the Congo), to include Angola, Burundi, Chad, Rwanda, and São Tomé and Príncipe. It took until February 2005, when the member states adopted a "Convergence Plan," for COMIFAC to become functional, with a mandate to harmonize policies and help improve management of natural resources across the Congo Basin (COMIFAC 2020).

Table 2 Some of the most important policies in natural resources per countries of the Congo

Country	Laws	Year signed	Amended in	Policy area covered
Cameroun	Law No. 74-1	1974		Land rights
	Law No. 94/01	1994		Forest, fauna, and fish
	Law No. 2023/014	2023		Mining
CAR	Law No. 63-441	1964		Land rights
	Law No. 20.026	2020		Wildlife, protected areas
	Law No. 08-022	2008		Forest code
	Loi No. 24008	2024		Mining
DRC	Law No. 66-33	1966	1981	Land rights
	Law No. 011/2002	2002	2020	Forest
	Law No 007/2002	2002	2018	Mining
	Law No. 11/022	2011		Agriculture
	Law No. 14/003	2014	2020	Wildlife, protected areas
Gabon	Law No. 016/2001	2001	2002, 2008, and 2010	Forest
	Law No. 003/2007	2007		Protected areas
	Ordinance No. 5/2012	2012		Land rights
	Law No. 002/2014	2014		Sustainable development
	Law No. 007/2014	2014		Environment
	Law No. 37/2018	2019		Mining code
	Law No. 002/2019	2019		Hydrocarbon
	Law No. 18/2022	2022		Climate change
ROC	Law No. 003/91	1991		Environment
	Law No. 4-2005	2005		Mining
	Law No. 21-2018	2018		Land rights
	Law No. 33-2020	2020		Forest

As a Central African regional mechanism, COMIFAC shares best practices, experiences, and knowledge between the different countries of the region to help regional actions and initiatives to converge toward the efficient conservation and sustainable management of the Congo Basin forests. It does so through providing policy and institutional advice to the political leadership of the Congo Basin nations so that they can promote sustainable forest management in the Congo Basin and across Central Africa as a whole. With harmonized policies and practices, the countries of the Congo Basin expect to have a stronger position at international biodiversity, climate, and natural resources discussions and negotiations.

An example of how solidarity and concerted action can produce greater benefits for the countries of the Congo Basin is the role Gabon played to ensure that other Congo Basin countries were admitted to the World Bank Forest Carbon Partnership

Facility (FCPF) funding mechanism. Gabon was the first country in the world to be selected for FCPF funding, but in solidarity with the other countries of the Congo Basin, the Gabonese authorities refused to take any funds from other Congo Basin countries until they had all been selected. Several years later, all Congo Basin countries were admitted even though, by then, Gabon had decided to develop its own REDD+ program alongside a self-funded sustainable forest economy plan. Subsequently, in 2022, Gabon was the first African nation (and one of only two to date, along with Uganda) to validate REDD+ results on the UNFCCC Lima hub.

Paradox Between Policies and Their Enforcement

As indicated above, political history has influenced policymaking, policies, and their implementation in the Congo Basin, but laws framing national policies have common elements across the countries of the Congo Basin. For example, laws on biodiversity conservation (fauna, fish, wildlife, and protected areas; Table 2) have elements related to law enforcement ranging from payment of simple fines, confiscation, and destruction of materials used to commit the offenses, up to and including imprisonment of the offenders. However, implementing these policies has been difficult for several reasons, chief among them being weak management by states of their borders, which are very porous in most of the Congo Basin (e.g., Chauvin 2018; Ndong 2018). Porous borders have often been seen as a factor that enables wildlife trade beyond sustainable levels. The other important impediment in enforcing wildlife laws and policies across the Congo Basin is that the law enforcement personnel are limited in numbers, lack basic equipment and training, and are poorly and often irregularly paid (e.g., Inogwabini et al. 2005; Ngimbog 2002; FMI 2023). Because they are not adequately paid, they often turn to corruption, weakening law enforcement (Ngimbog 2002; FMI 2023). Poorly screening their borders and poorly equipping and paying the law enforcement personnel are an indication that states are, at minimum, conceptually and materially poorly equipped to address some of the most important issues.

Several studies have been suggested that the criminalization among the elites has nurtured a political culture whereby administrative agents as well as politicians capture the resources necessary for providing civil and public services such as security, clean drinking water, descent sanitation, good education, and affordable healthcare (e.g., Bayart et al. 1997; Justesen and Bjornskov 2014; Andersen et al. 2020). This statement may need to be nuanced, but the performance of all the Congo Basin countries in terms of corruption, as measured by the indices of perception of corruption (CIP) for each of them (Fig. 1), lends support to the idea that corruption is widespread and it swallows significant portions of income that could, otherwise, support countries in their efforts to develop. With the highest values being those of countries with less corruption, Fig. 1 shows that none of the countries of the Congo Basin fairs well in indices of corruption; all of them are below 50%. For comparisons, the best performing nations worldwide over the same period were Denmark (CIP = 90), Finland (CIP = 88), Singapore (CIP = 84), New Zealand (CIP = 83),

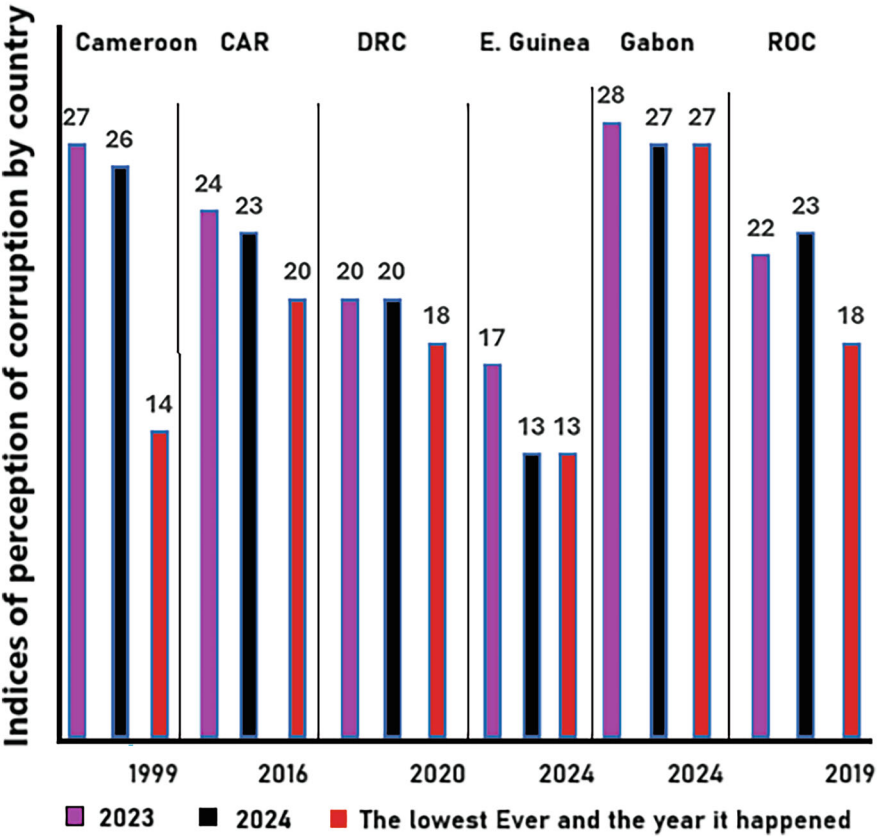

Fig. 1 Corruption perception indices per country of the Congo Basin. (Source https://www.transparency.org/en/cpi/2024)

and Luxemburg, Norway, and Switzerland (CIP = 81). A light improvement has been observed only in ROC over the last 2 years (2023–2024); conditions in all five other countries have worsened though DRC remained at the same position between 2023 and 2024 after a deep downfall in 2020. The worst drop in score occurred for Equatorial Guinea. This trend is worrisome as most of the Congo Basin Governments pledged and have been trying to fight corruption and its adverse economic effects over the two last decades, at least.

The explanations as to why law enforcement personnel are poorly paid and equipped and why corruption indices are so low are complex. However, lack of management skills and undemocratic institutional arrangements are one line of argument suggested by different researchers for nearly two decades now to explain the existence of such conditions (e.g., Himmelstrand 1994; Calderisi 2007; Inogwabini 2007). Calderisi (2007) suggested that ignorance (or willingness to ignore) of the ethical requirements for any public action; attachment to an obsolete, useless, cumbersome administrative culture; poor political competence at the highest

levels of government; and lack of a culture of governance were causes of the poor economic performances of countries of the Congo Basin, suggesting that due to the blurred line between the private and public spheres state resources were taken that could otherwise have been used for sustainable development. Whereas Mitterrand's "La Baule speech" introduced political conditionality to aid and cooperation (Laloupo 2022), theories of governance have been put forward and generated a second set of cooperation and aid conditionalities, which center around management skills, with two key conceptions. The first dimension is around accounting traceability, which has been promoted by international financial institutions. The second dimension is that of democratic participation, inclusiveness in decision-making processes, as well as the promotion of freedom. As a decision-making process, governance provides a comanagement framework that seeks to satisfy private and public interests by means of public action (Gaudin 2004), which is, itself, a joint construction between state and nonstate actors (Thoenig 1998). Both the accounting traceability and the democratic participation conceptions are packaged as good governance, which has become a measure of how well governments work to ensure inclusive growth in their countries (Smith 2008). They are measured yearly through the corruption index and the Random House Freedom Rating. Apart from their respective weak performances in perception of corruption (Fig. 1), countries of the Congo Basin also poorly perform in the other indices of good governance, including that given by the Freedom House Freedom Rating (FR). Over the last years, most countries of the Congo Basin showed very limited progress for this index, all being classified as countries that are not free (Fig. 2). For comparisons, the best performing nations worldwide over the same period were Finland (FR = 100, a totally free state), New Zealand and Sweden (FR = 99), Canada and Denmark (FR = 97), Belgium, Estonia, and Switzerland (FR = 96), and Australia, Chile, and Germany (FR = 95).

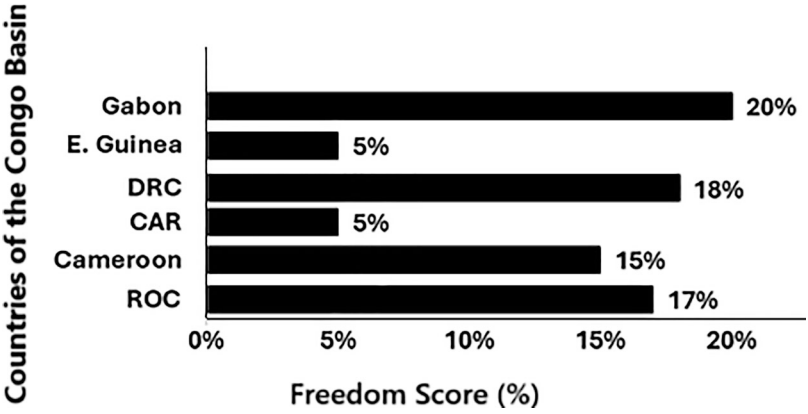

Fig. 2 Freedom House Freedom Rating for the Congo Basin. (Source Freedom House, https://freedomhouse.org/country/scores?type=fiw)

There are differences between countries but these are not so significant. Factors explaining this weak performance in the region are often discussed; they include destructively perverting effects of international aid (Himmelstrand 1994; Randel et al. 1999; Moyo 2010), which has created fatalism now ingrained in the minds of many people and led to self-pity and expectation of pity from others (Lugan 2015); confusion between crooked maneuvering in private affairs and politics (e.g., Lugan 2015; Trefon 2016); and misconception of the idea and role of the modern political leader and the traditional chief, to whom everything was owed and who deserved all (e.g., Souop 2015; Jackson and Rosberg 2023).

"*La politique du ventre*" (Bayart 1989) seems to also eat a lot of resources and prevents social inclusion, as it has been consistently supported by the Gini coefficient (GC) (Fig. 3), which describes levels of inequalities in the redistribution of the wealth each nation creates.

As per Fig. 3, no country of the Congo Basin was among the most equitable in 2024, which supports the feeling that the elite captured the majority of wealth coming from natural resources in the Congo Basin. DRC and Gabon, whose performances were very bad in 2019, had dropped down the scale indicating higher efforts toward equality by the end of 2024, as was the case for Cameroon, while a degradation has been documented in CAR and ROC. Equatorial Guinea remained at the same position while taking over from CAR as the most equal society in the Congo Basin. For comparisons, the worst performing nations worldwide over the

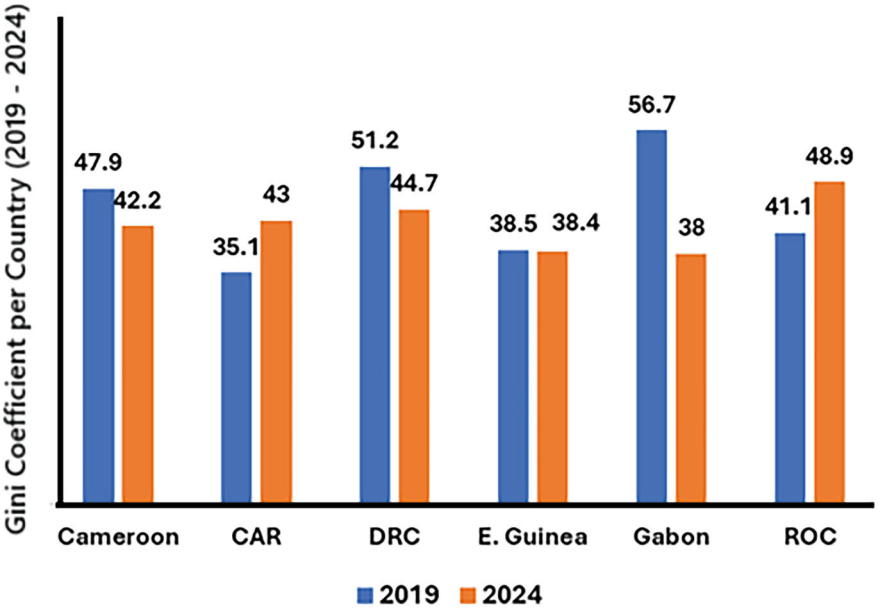

Fig. 3 The evolution of Gini coefficient in the Congo Basin (2019–2024). (Source https://worldpopulationreview.com/country-rankings/gini-coefficient-by-country)

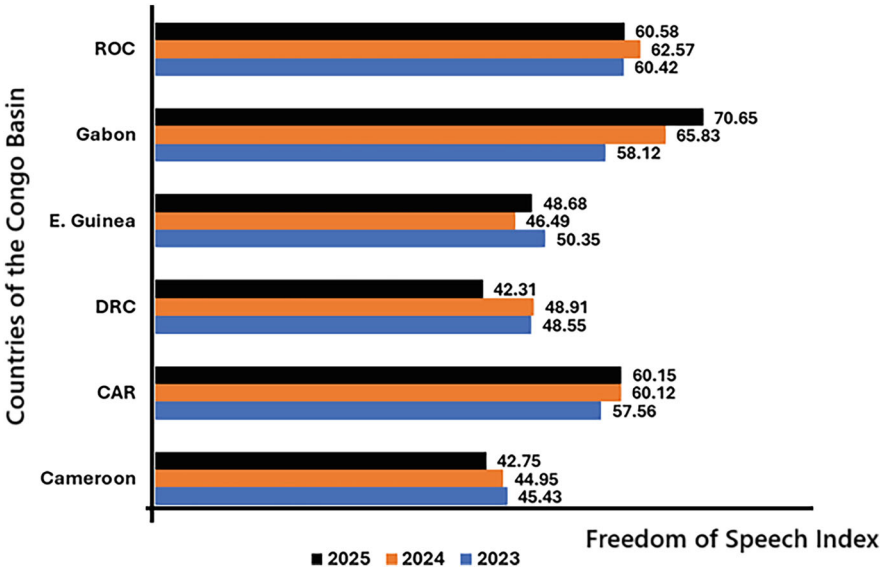

Fig. 4 Freedom of Expression Rating for the Congo Basin. (Source Reporters without Borders 2025: https://rsf.org/en/index?year=2023)

same period were South Africa (GC = 63.0), Namibia (GC = 59.1), Botswana (GC = 54.9), Eswatini (GC = 54.6), and Colombia (GC = 53.9).

Modern lawmaking requires active participation of local communities and interest groups. Figure 4 presents a measure of freedom of speech (FS) in the countries of the region. In this case, not all the countries fair too badly over the last 3 years although the two countries with the largest populations (Cameroon and DRC) still have limited scope for community participation. For comparisons, the best performing nations worldwide by the end of 2024 were Norway (FS = 92.31), Estonia (FS = 89.46), the Netherlands (FS = 88.64), Sweden (FS = 88.13), and Finland (FS = 88.18).

The Implementation of National Natural Resource Policies

Implementing national natural resource management policies under circumstances of high levels of perceived corruption (Fig. 1) and mild (or lack of) progress in good governance has been difficult. Good natural resources policies have often contradicted the reality on the ground in some countries (Tabagan and Ortance 2023). For example, in DRC, implementing policies often fails because laws are made sector by sector, making their implementation problematic and leading to interinstitutional conflicts. The conservation law coexists with the mining laws, which often conflict in their allocation of space, for example, this lack of legislative coherence has led the country to lease oil exploration permits on areas overlaid over

legally protected areas (Lawson et al. 2022), posing a serious challenge to sustainable forest management, livelihoods of local communities, and ecological services forests and waters of the country provide globally (Earth Insight 2025).

Assembe-Mvondo (2009), De Wasseige et al. (2014), and Djiegni et al. (2016) suggested that the adoption of conflicting land allocations was a regional trend. In some cases, reforms were adopted that are poorly adapted to local realities and/or are incomplete, sometimes imported by international organizations. However, improvements have been noted starting by the mid-2010s for some countries. For example, the commitment to adhere to forest certification and voluntary partnership agreements (VPAs) have had some successes in Gabon and Cameroon but have been less successful in CAR, DRC, and Equatorial Guinea (Eba'a Atyi et al. 2022). Furthermore, the effects of logging on wildlife species are varied; while in Gabon and ROC they have been reported to have minimal impact on wildlife species, in countries such as CAR and DRC they are thought to result in defaunation. Another policy area where progress has been observed is the process to create protected areas in the Congo Basin. While almost all the pre-1990 protected areas were created in the colonial style and with the insistence and assistance of the international community and without involving local communities (e.g., Tshimanga 2006; Van Schuylenbergh 2009), all the post-1990 policies (Table 2) have featured community consultations, local agreements, and land right assessments to ensure that communities are not ejected from their ancestrally owned land (see also ▶ Chap. 19, "History, Development, and Politics of Protected Areas in the Congo Basin Countries"). Barume (2000) suggested that countries of the Congo Basin faced challenges such as corruption, influence of multinationals, land conflicts, conflicts, and violence.

Inadequacies and Gaps in Regulating Resources in the Congo Basin

Although progress is undeniable, the legal arsenal in the countries of the Congo Basin does still have gaps or areas of inefficiencies, briefly reviewed in this section.

Artisanal Timber Production

A logging is, legally, authorized mainly to supply domestic markets (Chervier et al. 2024); it is expected that industrial extraction should supply global markets (Lescuyer et al. 2014). All the States of the region have well-fleshed laws and policies for industrial logging, while there are loopholes in the informal sector to point that some artisanal logging activities are nearly illegal; most do not to pay any taxes in countries such as DRC, except when they pay for authorizations to operate.

Nontimber Forest Products (NTFPs)

Exploitation of NTFPs often constitutes a large portion of the assets communities in the Congo Basin use for their livelihoods (MECNDD 2014; FAO 2017). They are

covered by national legislations throughout the Congo Basin, but policies to manage them remain poorly developed.

Artisanal Mining

Artisanal mining, unlike artisanal logging, sells its products to the global market. As is the case for industrial logging, the nations of the Congo Basin heavily legislated on mining, while the artisanal mining sector lurks mostly in the shadows of the rule of law, with most activities being illegal, paying no taxes and developing illicit transboundary trade circuits in many cases (e.g., Trefon 2016).

Freshwaters

Management of cross-polity river waters are often hotly debated (World Bank 2010), which is why the 1945 UN Charter introduced the concept of hydro-diplomacy, to ensure cross-border cooperation around shared water resources. UN-Water/Africa (2014) argued that if better water management approaches are not put in place, an African water crisis will likely be unavoidable and its potentially disastrous consequences will be difficult to mitigate. The 1992 Dublin Declaration clearly enshrined the principle that water resource management and development must involve users, planners, and decision-makers at all levels. In the Congo Basin, it is difficult to know whether local populations have participated effectively in management decisions. Participation works better in countries where freedom of speech is both guaranteed by legal instruments and effective (Habermas 1997), and this is not always the case in the Congo Basin (Fig. 4).

National water management institutional frameworks across the Congo Basin attribute *de jure* prerogatives to national governments that have the authority over water resources within their borders (Tchakossi 2024). Nevertheless, States of the Congo Basin agreed in 1999 to establish the Commission Internationale du Bassin du Congo-Oubangui-Sangha (CICOS), with the mandate to ensure a uniform river navigation regime throughout the Congo River and its main tributaries. In 2007, CICOS was given a further mandate to achieve the Millennium Development Goals for the people of the Congo Basin for access to safe drinking water and sanitation (CICOS, 2007), in line with the 1997 New York Convention (the Law of the Non-Navigation of International Watercourses), which stipulates that particular attention must be paid to provision of drinking water or water for food production (article 10). In practice, however, water is provided to citizens of each country of the Congo Basin by a national agency, which has little or no relationship with CICOS and no regionally coordinated action.

A major gap in the legislations of countries of the Congo Basin is that of legal provisions to implement their engagements to the RAMSAR Convention. As presented in ► Chap. 19, "History, Development, and Politics of Protected Areas in the Congo Basin Countries," there are Ramsar sites in all Congo Basin countries. However, a thorough assessment of legislation country by country shows that no

national legislation provides for the existence of the Ramsar Convention in their legal frameworks. This is a big caveat, although it can be explained by the fact that the tacit jurisprudence in these countries is that international agreements they have signed supersede national laws. Despite this, the need exists to translate the provisions of the Ramsar convention into nationally appliable policies.

Transhumant Use of Waters in the Congo Basin Resulting in Conflict

The UN Water Conference (1977) established the principal, endorsed by the Congo Basin countries, of the human right to water, whether in normal periods or in times of crisis. Long dry seasons and the droughts they cause in other regions of Africa have led to tensions over water resources over the last decade. These tensions are now felt in the Congo Basin, where transhumant cattle-raising communities are coming in search of water sources (Nagabhatla et al. 2021). Countries of the Congo Basin have not included influxes of transhumant communities in their laws; in consequence, to date the situation has been addressed using a security lens (Vircoulon 2020), falling short of the right to water.

Conflicts, Political Instability, and Natural Resources in the Congo Basin

Exploiting natural resources has fueled conflicts and instability in some countries in the Congo Basin (e.g., Marysse and Tshimanga 2009; De Koning 2011; UNEP 2015), rather than catalyzing economic prosperity (Olanrewaju et al. 2020; Sini et al. 2021; Okoi 2024). Indeed, there is a clear link between governance of natural resources and peace and security. Conversely, conflicts and insecurity impact the sustainable management of natural resources and, as a consequence, hold, prevent, or slow responses to climate change (Busby et al. 2013; Rüttinger et al. 2015; Wig and Tollefsen 2016; Witmer et al. 2017). People internally displaced because of conflict often deforest and degrade the environment. This has been the case in the Anglophone part of Cameroon where Wandia (2024) documented the conflict to have increased reliance on forest resources for fuelwood and income, resulting in deforestation; weakened state capacity caused by the armed conflict led to a surge in illegal activities (Wandia 2024). Similar patterns have been described in CAR and in eastern DRC (e.g., Dalby 2015; Ahmed 2018), where large numbers of internally displaced people camps have used forests as the sole source for energy.

Brown (2017, 2021) suggested that some conflicts may have protected forests and biodiversity as they constrain business development in the forest. However, relationships between natural resource abundance, governance, and conflicts are complex and interconnected (Okoi 2024). In some cases, political instability leading to armed conflicts results from the will to own and to control natural resources. Exclusive ownership of resources by governments can lead to conflicts between *de jure* and *de facto* use regimes (Brown 2017; Okoi 2024); restricted political and economic freedoms increase the likelihood of civil unrest. When governments fail to address the

basic needs of the majority of their citizens for equity (Sini et al. 2021), inclusion, and equal political participation in the decision-making process and in wealth sharing, they create tall-order hurdles before they approach broader issues such as sustainable natural resource management and climate change (Scheffran et al. 2014; Witmer et al. 2017; Olanrewaju et al. 2020; Okoi 2024). While variable in some degrees, metrics to assess equity, inclusion, and equal political participation in decision-making process and in the wealth sharing used (Figs. 1, 2, 3, and 4) indicate that the Congo Basin has a long way to go to become a region of stability, shared peace, and prosperity and subsequently an ecologically and economically sustainable region.

The Role of the Civil Society in the Management of Natural Resources

Civil Society comprises a large group of stakeholders, essentially located outside of state and political power (Sandler 2004); it comprises nongovernmental organizations (NGOs), pressure groups, churches, think tanks, private sector entrepreneurs, and youth movements (Smith 2008). They constitute groups of interest and, as such, are not as neutral as they seem to appear and are often (positively) ideology-driven (Mana 2015).

Both national and international civil society organizations and local communities play an important role in the sustainable management of natural resources; they are involved in implementation of ecosystem protection projects. Many NGOs work to empower local communities. Their collaboration can be essential to address the challenges of deforestation, biodiversity conservation, and land management. NGOs, mostly international, assist the governments of the Congo Basin in the management of natural resources, intermediating between local communities, governments, and international donors, raising awareness, building local capacity of stakeholders, and monitoring and managing forests (OFAC 2020).

However, despite the acknowledged roles civil society organizations play, their actions are often taken as adversarial by the governments of the Congo Basin. Reduced space for global freedom (Fig. 2), limited freedom of speech (Fig. 4), and sometimes plain ideological clashes with the views and wills of the strong man in power explain situations where actions of NGOs and other civil society organizations are objected to by institutions vested with the public authority to manage natural resources (Cohen 2016).

Despite some ideological clashes, legal inclusion and official recognition of the rights of traditional communities have evolved positively over the last two decades (e.g., Oyono 2004). Laws in Table 2 such as Law No. 2023/014 (Cameroon), Law No. 08-022 (CAR), Law No. 14/003 as amended in 2020 (DRC), Law No. 003/2007 (Gabon), and Law No. 33-2020 (ROC) have specific provisions on inclusion and rights of Indigenous people and local communities. Effective inclusion and participation are still rudimentary and will need time to take roots in the political practices of the Congo Basin before they are applied in the management of natural resources (Inogwabini 2024); participation is, first and foremost, a democratic exercise that

needs time to infuse the political thinking and practices. One-off consultations, as often practiced by NGOs, are not enough. This point is also valid for implementing the principles of the Free, Prior and Informed Consent that today are taken as the backbone of any consultation on inclusion or participation.

Emerging New Economic Paradigms in the Congo Basin

Tired of political democracy and economic lessons pontificated by western countries (Gassama 2008), such as the La Baule speech, and the governance and financial conditionalities the international financial institutions impose (Larsen and Fold 2008), the countries of the Congo Basin have been working to diversify their economic partners, entering, in their turn, into the new Scramble for Africa (Southall and Melber 2009). China (e.g., Brautigam 2011), India (e.g., Naidu 2009), and South Africa (e.g., Daniel and Bhengu 2009) have taken some significant weight in the new economic space in the Congo Basin; Brazil, Lebanon, Morocco, Pakistan, Russia, and Turkey are also economic stakeholders with increasing importance.

From the Bandung Conference to Stadium diplomacy and Palace diplomacy: Congo Basin countries openly appreciate economic cooperation with China, because the political conditionalities China imposes are lighter compared to heavy conditionalities of IMF and other western-based financial institution (Brautigam 1998). Modern relationships between African countries and Congo Basin countries, specifically, date back to the 1955 Bandung Conference where the anticolonial nationalist and anti-imperialist agendas developed in many African and Asian countries. The Chinese political leadership at that time saw an opportunity to invest to further the long-term political interests of their country (Chang and Halliday 2007). China's first interventions in the Congo Basin were part of its "*Stadium diplomacy programme*" through which stadia and other state buildings were constructed in countries such as Cameroon, Congo, DRC, and Gabon, to serve the Chinese state's diplomatic policies (e.g., Xue et al. 2019).

Resources-for-Infrastructure Barter Economic Cooperation

From Stadium diplomacy and Palace diplomacy, China has steadily engaged in wider infrastructure development and varied economic investment in the countries of the Congo Basin since the late 1990s (Putzel et al. 2011; Mazwi et al. 2024). For Putzel et al. (2011), Chinese investment and aid is often politically motivated; it targets projects identified by the heads of State. Congo Basin Governments negotiate large deals with China (Putzel et al. 2011). Recently, DRC secured a large deal with China through a "*Resources—Infrastructures Barter Economic Cooperation*," consisting of a pledge by China to invest US$ 6 billion to develop major infrastructure in return for rights to nine major copper deposits (Putzel et al. 2011; Muhire 2024). Cameroon, CAR, Gabon, and ROC also have similar Resources-for-Infrastructure projects. The Chinese invest in timber production, mining, and agricultural

development and are compensated with roads, railroads, and hydroelectric dams. Putzel et al. (2011) found that there were also many small Chinese businesses operating in the mining sector throughout the Congo Basin; these were thought to harm the environment more than large-scale mining operations, because they operate in the margins of environmental best practices.

"Resources-for-Security Barter Cooperation"

Faced with deep security problems, some countries of the Congo Basin have tried to get support from external powers to impose the rule of law within their territories in exchange for access to their resources. In ROC, France provided security support to one of the fighting factions in the 1997 war to secure access to oil by Elf (e.g., Yengo 2007); CAR agreed with Russia to receive Russian military support, while allowing them to access natural resources as compensation (e.g., Okafor 2025; Ahmed 2018); and Russia has a 60-year long cooperation history with ROC, which continues unabated and provides access to Congolese natural resources in exchange for, among other things, security materials and diplomatic support (Duarte and Thibaud Kurtz 2025). DRC is wishing to barter its enormous resources for the provision of security support from the USA in the hope this support will enable it to end its three-decade-long war (Kabasele and Tshibambe 2025). While Congolese politicians expect this minerals-security barter agreement to help them take back the control of their national space, other observers fear that it will backfire in several ways, including direct clashes with China over mining sites (e.g., Hendrix 2025).

The extent to which these deals are favorable to the Congo Basin nations is not yet well understood and should be a priority for future research, as should the economics of natural resource concessions and exploitation generally.

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Trends Protected Areas Will Take in the Context of 30 × 30 Congo Basin Engagements

39

Bila-Isia Inogwabini, Florence Palla, and Donald Jomha

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Abstract

Options available to the Congo Basin's countries to fulfill their engagements to implement the Kunming-Montreal Framework's target 3 by protecting 30% of each of their national land and inland waters and marine space were reviewed. At its face value, Congo Basin would need to increase its land and inland water protected areas network by 583,975-km^2 (or an additional 14% of the 4,081,143 km^2 of the entire region). Increasing protected areas by this magnitude is economically, socially, psychologically, and managerially problematic. Gazetting new protected areas using recent history's methods is likely to meet resistance and would require enormous conceptual and material resources.

Possible ways to address these problems include identification of existing potentials and mechanisms to be used to increase the geographic extent of

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protected areas without necessarily creating new strict protected areas. Sound corridors, sacred sites, community conservation areas, and high-value conservation areas within extractive concessions offer such possibilities, if they are democratically and officially recognized. Creating new protected areas to preserve currently underrepresented ecosystems remains a necessity. If corridors, sacred sites, and other mechanisms are recognized, secured, and managed adequately in addition to existing protected areas, Congo Basin countries can go beyond the Kunming-Montreal Framework by 2030.

Lack of sustainable financial capacity is the chief impediment to increasing protected areas networks; lack of internal financial resources and the reluctance of the global community to financially support biodiversity conservation are the most difficult problems to solve for the Congo Basin to achieve its goals.

Keywords

Sacred areas · Corridors · Kunming-Montreal Framework · Sustainable finances

Introduction

Dinerstein et al. (2019) proposed an idea to expand the territory to conserve nature for humanity to be able to cope with climate change and conserve levels of biodiversity that would be viable enough to sustain life on earth. This idea launched a process that culminated in the endorsement of the Kunming-Montreal Global Biodiversity Framework (hereafter Kunming-Montreal Framework) by more than 100 countries on 18 December 2022. A flagship resolution of the Kunming-Montreal Framework is the 30 × 30 provision whereby parties agreed to put 30% of their lands and marine territories within their protected areas networks by 2030. One of the framework's targets (target 3) stipulates [that governments engage to] "*ensure and enable that by 2030 at least 30 per cent of terrestrial, inland water, and of coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem functions and services, are effectively conserved and managed through ecologically representative, well-connected and equitably governed systems of protected areas and other effective area-based conservation measures, recognizing indigenous and traditional territories, where applicable, and integrated into wider landscapes, seascapes and the ocean, while ensuring that any sustainable use, where appropriate in such areas, is fully consistent with conservation outcomes, recognizing and respecting the rights of indigenous peoples and local communities, including over their traditional territories*" (UNEP 2022).

Acknowledging the role the Congo Basin plays in both addressing issues related to biodiversity conservation and climate change globally, countries of the Congo Basin endorsed the agreement and pledged to protect 30% of their lands and marine territories. This chapter takes up the current status of that engagement, analyzing possibilities and hurdles the countries of the Congo Basin might face before achieving that pledged goal. The chapter uses some examples from the history of

biodiversity conservation in the Congo Basin to identify possible problems and to propose potential pathways to solving them, paving the way for a successful implementation of the provision of target 3 in the future.

Current Spatial Occupation of Protected Areas Network in the Congo Basin

Doumenge et al. (2021) described Central Africa to have a total of 800,000 km^2 made of protected areas of different categories. But that figure also includes protected areas of Burundi, Chad, Rwanda, and Sao Tome and Principe, which are not part of this assessment report. Taking figures from different recent assessments, about 705,974 km^2 (ca. 16%) of the Congo Basin are land and inland water protected areas (Table 1).

One thing that needs to be emphasized in this report is that countries in the Congo Basin have significantly augmented the number and size of protected areas in the last 20 years. Indeed, looking at the history of the creation of protected areas (▶ Chap. 19, "History, Development, and Politics of Protected Areas in the Congo Basin Countries"), one sees that, for example, in Gabon most protected areas are new creations and are dated back to the early 2000s. Indeed, comparing data from Proces et al. (2020) and those provided by OFAC (2024), one sees a significant increase in number of protected areas across the region globally. Even in countries like Democratic Republic of Congo (DRC) where protected areas have been part of a relatively long history, new protected areas such as the Itombwe, Tumba-Lediima, Ngiri Triangle, and Lomako Forest Natural Reserves were created in the early 2000s and the Lomami-Lualaba National Park was created relatively recently. These examples show that the willingness of the Congo Basin countries to increase the

Table 1 Total land and inland water areas per country of the Congo Basin, total land of protected areas, and gaps remaining to achieve the 30 x 30 biodiversity conservation objective in 6 years from now

Country	Total areas	30% land area	Protected land (km^2)	Percentage protected	Gap to 30 x 30 (km^2)
DRC[a]	2,345,000	703,500	350,578	14.95%	352,923
Congo[a]	342,000	102,600	41,024	12.00%	61,576
Cameroon[b]	475,440	51,055	40,412	10.74%	91,578
CAR[b]	622,984	132,126	110,891	21.21%	54,769
Gabon[a]	267,668	80,300	60,413	22.57%	19,888
Equatorial Guinea[b]	28,050	5174	5862	18.45%	3241
Totals	4,081,142	1,224,343	705,974		583,975

[a]Data from the presentation by Melissa de Kock, on behalf of UNEP-WCMC, to the Bezos Foundation Meeting in July 2024, Kinshasa (DRC), but OFAC (2024) suggested a lower figure of 323,109.20 km^2 or 13,78% of the national territory
[b]OFAC (2024)

size of their protected area network existed before their commitment to the Kunming-Montreal Framework targets. Indeed, DRC has been increasing its pledged willingness to increase its protected areas network several times, going from 10% (e.g., Inogwabini et al. 2005a; IUCN 1989, 1992; Sayer 1992) to 15% (e.g., Inogwabini 2014), and it is now embracing the 30 × 30 Kunming-Montreal Framework after nearly achieving the 15% pledge (Table 1). As of early 2025, a decree (N°. 25/1 of 15 January 2025) was signed by the country's prime minister and created the Kivu-Kinshasa Green Corridor. The Kivu-Kinshasa Green Corridor has been designated a community reserve. However, the map of this 544,270 km^2 large area includes large cities such as Butembo, Beni, Kisangani, Bumba, Mbandaka, and Kinshasa and crosses many multiuse zones including those used for agriculture, logging, and with the recent auction for oil exploration, oil drilling areas (e.g., Shah 2025). Conceptualizing how this massive protected area will be managed is challenging, especially considering DRC's weak financial and human capacities to govern it properly. Nevertheless, adding 544,270 km^2 to the 350,578 km^2 already protected areas leads to 894,848 km^2 or 38.15% of the DRC National territory falling within the country's network of protected areas. With the 38.15% figure, DRC may be said to have already surpassed the requirements of the Kunming-Montreal Framework for its inland water and terrestrial habitats, albeit with some question about the manageability of the additional protected area.

Expected Spatial Occupation of Protected Areas Network in the Context of 30 × 30 Engagements

Table 1 also shows that to reach its 30 × 30 objective for the land and inland waters; the Congo Basin has to put an additional area of 583,975 km^2 (ca. 14% of its land) under some biodiversity conservation measures. To put this figure in its geographic perspective, 583,975 km^2 is 1.7 times larger than Republic of Congo (RoC) and more than 1 time the size of Cameroon; it is also almost the double of Gabon and 18 times larger than Equatorial Guinea. This suggests gigantic efforts needed to achieve the commitments of 30 × 30 in the Congo Basin. If the huge 544,270-Km^2 corridor above is excluded from this analysis because of problems its management raises, DRC will have to extend its network of protected areas by more than 15% of its territorial land, an area larger than the entirety of Gabon. The magnitude of the efforts committed to by the countries of the Congo Basin is enormous, but the results, if realized, will benefit not only the Congo Basin but also the entire world.

In Gabon, protected marine and terrestrial areas account for 25.1% of the country's total area, with marine areas representing 28.8% and terrestrial areas 22.4% of the national territory (WWF 2023a, b). These figures are complemented by efforts to identify and recognize Other Effective area-based Conservation Measures (OECMs), notably through the protection of sacred forests such as the Massaha forest, governed by local communities and aligned with CBD Decision 14/8 criteria (ICCA Consortium 2022; RRI, 2024). Cameroon, aware of its contribution to the 30 × 30 target of the Kunming–Montreal Global Biodiversity Framework, is actively

engaged in conserving and restoring its ecosystems. Measures already implemented include the creation of protected areas covering 22% of its territory—above the Aichi target of 17%—as well as combating desertification, restoring mangroves, and planting thousands of tree seedlings (CBD 2021; Tiokeng et al. 2024). Additionally, several sacred forest sites and community forests are under review for OECM recognition, supported by ethnobotanical evidence and local governance structures (Tiokeng et al. 2024).

As indicated above, in January 2025, a decree (No. 25/1 of 15 January 2025) signed by the Prime Minister created the Kivu–Kinshasa Green Corridor in the DRC, designated as a community reserve. This proposed 544,270 km^2 area spans major urban centers such as Butembo, Beni, Kisangani, Bumba, Mbandaka, and Kinshasa and overlaps with zones currently used for agriculture, logging, and—following recent oil exploration auctions—hydrocarbon extraction. This raises complex challenges for zoning, governance, and ensuring biodiversity outcomes. Adding the Kivu–Kinshasa Green Corridor to the 350,578 km^2 already protected area would bring the DRC's protected area network to 894,848 km^2, or 38.15% of its territory—surpassing the Kunming–Montreal 30 × 30 target. However, as highlighted in recent analyses (RFUK 2016; Jonas et al. 2024), the effective management of such large, multiuse areas requires substantial financial resources, robust governance frameworks, and community engagement to avoid the pitfalls of "paper parks" or "paper OECMs."

From a spatial ecology perspective, achieving and sustaining the 30 × 30 target in Central Africa will require not only quantitative expansion of protected and conserved areas but also functional ecological connectivity between them. Connectivity ensures that species can move between habitat patches, maintain genetic diversity, and adapt to climate change (Assis et al. 2021; Hilty et al. 2020). In Gabon, linking terrestrial protected areas with coastal and marine ecosystems through ecological corridors could enhance resilience of both forest-dependent and marine species. In Cameroon, integrating sacred forests and community-managed landscapes into broader ecological networks could strengthen north–-south and east–west habitat linkages, essential for migratory species and forest elephants (Bele et al. 2019).

For the DRC, the proposed Kivu–Kinshasa Green Corridor offers an unprecedented opportunity to operationalize large-scale connectivity between eastern montane forests, central basin lowland rainforests, and the Atlantic coastal ecosystems via riparian corridors along the Congo River and its tributaries. Such spatial integration can transform isolated conservation units into a cohesive regional network, reducing edge effects and enhancing ecosystem services provision (Bertzky et al. 2012; UNEP-WCMC 2023). To avoid the trap of isolated "islands" of biodiversity, OECM recognition processes should incorporate explicit connectivity metrics—such as habitat permeability indices, least-cost path modeling, and functional connectivity scores—into site evaluations. This aligns with the CBD's call for well-connected and equitably governed systems of protected and conserved areas (CBD 2022).

Possible Drawbacks of the 30 × 30 Political Engagement in the Congo Basin

One drawback of the Kunming-Montreal Framework in the Congo Basin is the geographic extent of the 30 × 30 provision relative to the region's rapidly growing human populations. Indeed, DRC's population, for example, is growing at alarming rates, having multiplied by six since the 1960s and expected to maintain a growth rate as high as 3% between 2020 and 2030 (Franco-Henao et al. 2018). Consequently, the process of establishing traditional or community-protected areas is likely to become increasingly important yet less straightforward. Population growth rates raise the question of the rationality of extending protected areas networks across the Congo Basin when many people are in need of land to exercise their rights to livelihood activities. As discussed in ▶ Chap. 19, "History, Development, and Politics of Protected Areas in the Congo Basin Countries," protecting biodiversity has often faced the dilemma of ensuring that it is done without jeopardizing the needs for local sustainable livelihood and development (Inogwabini 2024). Indeed, one of the problems that the concept of landscape conservation met at its initial stages was that of mapping out large areas that crisscrossed countries of the Congo Basin, giving the impression that most of the lands in each country were under the aegis of the protected areas authorities. In fact, 30% of the land area of Congo Basin (1,224,343 km^2; Table 1) roughly represents 52% of the entire DRC (2,345,000 km^2; Table 1). Or, if one wants this much scale expressed in other terms, 30% of the land of the Congo Basin represents more than the half of the Western Europe, including the British Islands. Picturing the 30 × 30 provisions in this way clearly explains the psychological effects it could have in people residing in the Congo Basin, should everything get down to traditional protected areas.

The second drawback that might impede the efforts to achieve the 30 × 30 Kunming-Montreal Framework is the regional capacity to actually conduct the work needed to properly classify protected areas. This includes the capacity to carry out field biological surveys to identify appropriate areas. After identifying the appropriate areas to be protected, those areas need to be delineated, ideally by a multidisciplinary team of social scientists, legal and mapping experts, biologists, etc. Once delineated, the areas will need sound and ongoing institutional presence to mitigate potential threats and do research to inform adaptive management plans. Moreover, despite years of efforts to build local scientific and governance capacities in the Congo Basin, capacity remains low in most areas (e.g., Inogwabini 2024; White et al. 2021; Abernethy et al. 2016) leading to management and governance failures in established protected areas (e.g., Adams et al. 2020; Abernethy et al. 2016).

To build such capacities, significant financial resources are needed. White et al. (2021) estimated that for the Congo Basin to build its scientific muscles it has to invest US$ 150 million in science over a 10-year period. This amount does not include the financial resources needed to train law enforcement personnel and protected areas managers and does not include the daily costs of paying conservation operatives including administrators, logistics, and law enforcement personnel.

According to a study by Inogwabini et al. (2005a), if each government of the Congo Basin was to invest just 100$ per year in each km^2 of its protected lands (30% or ca. 1,224,343 km^2; Table 1), it would cost US$ 122,500,000 annually (rounded up). Unfortunately, despite the willingness of countries of the Congo Basin to protect the biodiversity and ecological functions the Congo Basin shelters, poverty in these countries means governments do not have the financial resources to invest the called-for $125 million, adding the approximate estimate of 120 million above and 1.5 million for scientific research per year (as per White et al. 2021) to invest yearly in biodiversity conservation. Countries of the Congo Basin have more vexing economic, human, and social demands (Chia et al. 2016; Tutin 2002), including providing food and clean drinking water, medical services, clean energy, etc. to impoverished communities.

That is why, given the importance of the biodiversity and ecological services the Congo Basin provides the world globally (e.g., Dezfuli 2022; Dargie et al. 2017), governments have been asking for financial payments to help cover the needs for the sustainable management of natural resources (e.g., De Anguita et al. 2014; Nelson et al. 2010). It has been known for long that biodiversity conservation will be sustainable only if and when its measures are financially viable (Lapeyre 2015; Humavindu and Stage 2014). Taxes levied from forest assets such as exported timber logs do not generate sufficient resources to cover the financial expenses necessary to conserve the biodiversity of the Congo Basin (Cerutti et al. 2010), due mostly to lack of transparency in the financial management, and in some cases caused by the plain corruption in the administration of the countries of the Congo Basin (e.g., Assembe-Mvondo 2015). Tourism has been often put forward as a mechanism to generate long-term sustainable funding to support biodiversity conservation and local development (Bhatia 2006; Eagles et al. 2002). Examples from East African countries such as Kenya (e.g., Hassan et al. 2019; Mayaka and Prasad 2012; Irandu 2006) and Rwanda (Hannah and Spenceley 2010) substantiate the claim that eco-tourism can generate conservation funding. In the Congo Basin, mountain gorilla tourism offers an example of how such an industry could generate revenues to support biodiversity conservation and local sustainable development (e.g., Maekawa et al. 2013; Ando et al. 2008). However, impediments to a lucrative tourism in the Congo Basin abound; not only is the infrastructure nearly inexistent in many countries, but also political instability, opaque visa policies, banditry, and burglary in public spaces (e.g., Inogwabini et al. 2005a) all undermine the creation of a reliable tourism industry. Also, even if tourism was significantly developed, its ecological footprint (Ozturk et al. 2016) has been questioned (Müller 1994) for the environment (e.g., Zolfani et al. 2015) and some species such as gorillas (Costa et al. 2023a, b). National budgets in the Congo Basin being meagre as measured against the vastness of need, there remains one viable option: international investment in and funding of conservation in the Congo Basin, recognizing the critical role the region plays in maintaining global equilibrium. Unfortunately, internationally, the long-term trend that has been observed throughout the Congo Basin is that there is little willingness from the global world community to invest adequate funding levels to ensure optimal biodiversity conservation (e.g., Wilkie et al. 2001).

Existing market mechanisms for promoting and funding conservation efforts such as REDD+ (Karsenty et al. 2014) have not yet been shown to be effective in the Congo Basin. REDD + raised the hopes of providing sustainable funding that could ignite the virtuous biodiversity conservation—sustainable Development—Biodiversity Conservation circle. Such sustainable funding mechanism would have, then, ensured that the Congo Basin remains on the climate trajectory it pledged (e.g., Abernethy et al. 2016). However, caveats (not discussed in this chapter) that emerged when implementing the REDD+ mechanisms in the Congo Basin show how difficult achieving the Kunming-Montreal Framework will be financially. Suffice it to be said at this level that mechanisms such as REDD+ are difficult to implement (Kengoum et al. 2020; Samndong 2018; De Anguita et al. 2014; Somorin et al. 2012); REDD+ has not worked very well in the Congo Basin thus far. This implies that it is unlikely to expect other market-based mechanisms to be more successful; counting solely on them to boost the financial capacities to conserve biodiversity in the Congo Basin may likely be another wishful thinking that characterizes the negotiations around biodiversity conservation, climate change, and sustainable development for several decades now.

Possible Routes to Avoid the Drawbacks in Implementing the 30 × 30 Engagements in the Congo Basin

Despite the multiple challenges discussed above, countries of the Congo Basin can achieve their international commitments to the 30 × 30 Kunming-Montreal Framework. This is particularly so if one considers that the 30 × 30 framework is a global goal; there is a need to examine how these global goals translate at the local and national levels, particularly for communities that depend on nature (Bezeng et al. 2025). To do this, they will have to get around some of the difficulties mentioned above. The first and most apparent difficulty that the 30 × 30 Kunming-Montreal Framework is likely to face is the question about locking areas when people actually will need more space. The solution to this problem, however, is to be found in the language of the 30 × 30 Kunming-Montreal Framework itself in combination with other options. Indeed, the language of the 30 × 30 Kunming-Montreal Framework is that the areas to be included by countries in their commitments to protect 30% of their lands and inland waters should be *ecologically representative*. In addition, throughout the Congo Basin, biodiversity conservation is now not just an environmental goal but includes provisions to leverage economic and social development for local populations; which, in return, would have strong support from local communities.

However, being *ecologically representative* offers also the possibilities to include areas that connect these ecologically representative areas as part of the 30%. This means that the Congo Basin countries do not have to create new protected areas everywhere; they may increase their networks with ecological corridors linking existing protected areas where possible. Ecological corridors ensure the spatial continuity of habitats and are an important piece of the gamble to protect biodiversity

because they keep not only the physical movements of species in their natural range but also keep pathways open for genes to flow freely (e.g., Chen et al. 2024; Ding et al. 2023; Salviano et al. 2021).

The Kunming-Montreal Framework is open to including *traditional territories of Indigenous peoples and local communities as part of the extension of protected areas networks.* These areas, now called community forests in Congo Basin countries, with their biodiversity conservation areas, have the potential to preserve biodiversity without having to impede on the rights of local communities, provided that communities receive skills to manage biological resources residing in these areas. Countries in the Congo Basin have recently included legal provisions to support the rights of local communities to conserve their titles on geographic spaces (forest, inland waters, and lands) they hold by heritage from their ancestors. In DRC, for example, despite appearing cumbersome in its processes, the 2014 Conservation law (n° 141003–11 February 2014) has provisions on the process to secure spaces owned by local communities. These community forests are to be partitioned in zones of diverse activities, including areas where no extractive activities are allowed. Some provisions of such laws are so highly technical that they may become hurdles for communities to use them meaningfully; there is need to build local capacities to get to the point where communities can grasp the legal intricacies in the laws to be able to affirm their rights and to optimize the benefits of managing their community forests. Local capacities are also needed to build processes that are weaned from being NGO-dependent and from project-supported, which they are currently.

Community forests and community reserves have different meanings in the legislations of the Congo Basin countries. There are differences, for example, between DRC and RoC, two neighboring countries in what it is meant by community reserve. For example, the Lake Telé—Likouala Community Reserve in RoC is managed like an IUCN category VI protected area with protected area personnel in charge of law enforcement (e.g., Twagirashyaka and Inogwabini 2009); in DRC, the idea of community forest is essentially about community-based natural resources managed (CBNRM), in that local institutions, customary practices, and knowledge systems become central in management, regulatory, and enforcement processes of community areas (e.g., Robinson et al. 2021). In this sense, community forests are areas which management is meant to be left totally to local communities. This difference in legal status comes from difference legal tradition and differentiated philosophical and political evolution in each Congo Basin country, most likely created by colonial history. These differences warrant to be accounted for in the implementation of the Kunming-Montreal Framework regionally; one way out of this situation is to further harmonize the nomenclature and the content of protected areas across the Congo Basin. Also, as Robinson et al. (2021) found out, community-managed areas have their own challenges and should not be taken as a panacea but rather as one part of the protected area equation in the Congo Basin.

Along with community forests, sacred forests (▶ Chap. 19, “History, Development, and Politics of Protected Areas in the Congo Basin Countries”) would also increase proportions of protected areas in the Congo Basin, albeit with totally different management authority and policies. Community conservation forests

(areas) seem to be a key component in implementing the 30 × 30 by the countries of the Congo Basin. In fact, beyond traditional IUCN's Protected Areas, there are a lot of areas in each Congo Basin country, which need to be recognized as being part of crucial protected areas network and will provide some additional security and perhaps access to funding. Viewed from this angle, the real gap today is to take new concepts of protected areas in the existing national frameworks and to ease the classification process in each country. All countries are engaged; some of the Congo Basin's countries have already identified such potential areas but will need to fill the gaps in their legal framework on land tenure and enforcement laws for these new types of conservation areas (Doumenge et al. 2024). For example, Equatorial Guinea is committed to aligning its National Biodiversity Strategy with the objectives of the Global Framework, including the 30 × 30 target; it aims to use innovative solutions and integrated approaches, combining the creation of protected areas and sustainable resource management, while meeting the needs of local communities.

As discussed in ▶ Chap. 19, "History, Development, and Politics of Protected Areas in the Congo Basin Countries," most sacred sites are not known; this means that to include the sacred sites (forests) in their protected areas networks, each country of the Congo Basin needs to inventory all of its such sites. Then, each country should discuss with traditional authorities in charge of sacred sites to agree on the management type they would have to put in place. Of course, it is suggested that governments across the Congo Basin should desist from the temptations to bring those sites under the management of their park authorities for sites located outside of national parks or reserves. Indeed, these sites have been preserved throughout history without being managed by central governmental authority; it would be unwise to replace the existing work of local communities with new, top-down policies and management practices. Likely the best option for such sites is being fully recognized as areas that are officially protected for beliefs and spiritual reasons. The role of the governments of the Congo Basin in this case might be as simple as taking their inventory, mapping them, and offering sustained support to traditional management authorities. The value of adding sacred sites to the list of protected areas is that they will be guarded from other exploitative usages. Being located on national maps and benefiting from the status of officially and internationally recognized protected areas, sacred sites will not fall prey to extractive activities other than those allowed by local traditions.

Buffer zones around protected areas are another way that the Congo Basin countries can use to increase their land areas falling in the category of protected areas. Indeed, one way to interpret the Kunming-Montreal Framework's wording about having protected areas that are "*integrated into wider landscapes, seascapes and the ocean"* is to consider the buffer zones between protected areas and other land use modes or practices. Buffer zones have been acknowledged to be a key strategy to increase the conservation performance of protected areas globally (De Almeida-Rocha and Peres 2021), and as a means to integrate protected areas in wider landscapes, they offer the theoretical possibility of integrating human needs and biodiversity conservation (Inogwabini 2020; Salafsky and Wollenberg 2000). The concept of buffer zone is already present throughout the Congo Basin, with

multiple contextual nuances. In DRC, for example, the idea of buffer zones around protected areas dates back to 1969 when the conservation legislation empowered park authorities to enforce to record offenses up to 50 km beyond the boundaries; within this radius, all actions likely to cause direct harm to ecosystem components are prohibited (UICN 2010); the 2014 Conservation law has not formally abrogated that notion but redefined the buffer zones around protected areas to be essential to the development of local communities and their activities (land rights and use rights); with its management being compatible with the conservation objectives and management plans of protected areas, they are to cushion against other forms of land usages. The same 2014 Conservation law enjoined the Central government and the provincial authorities, ensuring the promotion of ecological development within the zones around protected areas. Strictly speaking, if the buffer zones were adequately managed, they would correspond to the IUCN Category VI protected areas. Indeed, IUCN defines Category VI protected areas as protected areas with sustainable use of natural resources (Philipps 2004); that is why, Category VI protected areas are sometimes called managed resource protected areas where the pursued aim is to protect and preserve biological diversity in the long term while ensuring that needs of local communities are taken care of, with the large capitalist international commercial activities excluded (Philipps 2004).

If buffer zones around protected areas were considered as IUCN's category VI protected areas as per the provision above and if they were adequately managed, DRC would not necessarily need to increase its protected areas network; with its large buffer zones (50 km beyond any contour-point of any current protected areas) the sizes of each would, in several cases, double. This could account for more than 30% of the Congolese land and inland water within any category of protected areas. Unfortunately, studies suggest that many buffer zones are not adequately managed, which means that they are not playing the role they are theoretically thought to play (e.g., De Almeida-Rocha and Peres 2021; Robinson et al. 2013). Even in Democratic Republic of Congo, a country with generous legislation on buffer zones, IUCN (2010) found their poor management to be generating conflict between local communities and protected area managers.

The option to increase the coverage of protected areas by considering buffer zones as category VI protected areas may be promising but will depend on where these protected areas are located. Indeed, for areas where human densities are so high, this may not be an option at all. Where human densities are low, including the buffer zones in the management of protected areas will need to start a new process where local communities shall be brought to grasp what buffer zones are both for biodiversity conservation and their own livelihood activities, some legal changes in the ways of law enforcement will be needed, which may include some practices of comanagement. Above all, adequate management of buffer zones will need increased managerial capacities, skills to manage large areas, and financial support.

Ecologically sensitive management of logging concessions whereby zoning concessions in such a way that high-valued habitats for wildlife species to thrive are set aside offers another way for the Congo Basin countries to accrue their protected area networks. Efforts to conserve biodiversity in logging concessions

have shown that they can benefit wildlife species; and Nouabalé-Ndoki National Park, in North-Western RoC, is an example that eloquently illustrates the possibilities that better management of logging concessions can support biodiversity conservation in the Congo Basin. A 1993 initiative tested this model where over 15,000-km2 of the peripheral ecosystems of the core Nouabalé-Ndoki protected zone were managed in collaboration with a logging company (Morgan et al. 2024a). Three decades later, the area adjacent to the Nouabalé-Ndoki National Park holds some of the most important populations of critical species like gorillas and forest elephants (Morgan et al. 2024b). This approach will need not only total shift of the mindset that opposes biodiversity conservation and logging activities but also to envisage new partnerships and inventing new ways in which logging concessions can make benefits of forest areas they leave standing in their concessions to conserve biodiversity. Benefits could include CO_2 and biodiversity credits.

Finally, it is important to recognize that increasing the total coverage of the Congo Basin's land and inland waters to 30% will require creating new protected areas. This will likely occur where major habitat characteristics are still unrepresented among the existing protected areas networks. For example, a study by Inogwabini et al. (2005b) on the habitat gaps in the protected area networks identified that freshwater swamps and related aquatic vegetation were, at that time, the least represented biome within the then protected area network of Democratic Republic of Congo; it suggested that 14% of swamps and associated freshwaters be protected. With all the new protected areas created since that paper was published, a similar analysis should be carried to move on with creating new protected areas in Democratic Republic of Congo and in the Congo Basin more broadly.

If all the options explored above are implemented, the percentage of new protected areas to create will be less than what Table 1 expresses as the gaps remaining to achieve the 30 × 30 biodiversity conservation objective in 6 years from now. However, to create more new protected areas in countries where that will be necessary, there will first need to be a thorough habitat gap analysis conducted to identify areas where the new area can be created. Then, because growing human populations require increasing land on which to carry out livelihood activities, the process of creating new protected areas must be paired with increasing collaboration with and participation of local communities. This means that creating new protected areas has to become part of a democratic exercise (e.g., Inogwabini 2007), shifting several governance practices that prevail throughout the Congo Basin (i.e., the dominance of government-owned national parks, militarized and top-down management, and opaque management of biodiversity conservation funds).

Funding Mechanisms for an Enlarged Protected Area Network in the Congo Basin

One of the most difficult problems of the implementation of the Kunming-Montreal Framework's target 3 is the lack of financial resources. The governments of the Congo Basin have limited funds and many problems to solve, and this will remain so

even for the next decades. Hence, the Kunming-Montreal Framework's target 3 comes as an additional financial burden. Some paths to explore in trying to improve this situation have been piloted in the Congo Basin, including ecological and cultural tourism programs, CO_2 markets (REDD+ included), trust funds, and private-public joint ventures. Tourism is often thought of as being able to generate significant resources. However, as discussed above, its success depends on many other conditions beyond a site's natural assets: the site's management regime and other sociopolitical and economic factors including regional political stability and security, infrastructure, and political culture (Inogwabini et al. 2005a). The very image countries project internationally also affects tourism flow (Inogwabini et al. 2005a): If a country projects a negative image of itself externally, it will attract less tourists. Most of these conditions are poor in Congo Basin countries, posing impediments to the creation of successful tourism projects. This is unlikely to change within the next decade, leading us to other mechanisms for achieving the Kunming-Montreal Framework's target 3.

The CO_2 market, as described above in the case of REDD+, is also a difficult mechanism to engage widely as a solution to the problems facing Congo Basin countries in their efforts to achieve 20 x 30 (Kengoum et al. 2020; Samndong 2018; De Anguita et al. 2014; Somorin et al. 2012). Without adequate scientific capacity already developed, nations will not be able to easily access these mechanisms. Building capacities takes a long time; in the case of the Congo Basin, it is fair to imagine a decade, if the work begins right away. This means that the CO_2 market and other ecological services markets are, at their best, an option for the midterm future. Equally, trust funds have tried to provide safe and sustainable funding mechanisms for protected areas in the Congo Basin. A Democratic Republic of Congo Conservation Trust Fund was established in 2013 (Bath et al. 2020; World Bank 2013); the Sangha Tri-national Trust Fund, a regional fund covering three countries (Cameroon, Congo, and Central African Republic), was put in place in 2007; and a similar effort was developed in Gabon (Bath et al. 2020). All this shows how creative biodiversity conservation actors have been trying to find secured sustainable funds to manage protected areas in the Congo Basin. Though these mechanisms are in place, their impacts and benefits emerge slowly. These trust funds are built to generate capital that will flow into existing protected areas, not to help fund extending the current protected areas portfolio that exists in the Congo Basin. In the same vein, private-public joint ventures are being currently tested and could offer some alternative resources, should the private sector actors accept investing in the creation of new protected areas. Yet, their long-term efficiency for managing existing protected areas still needs a thorough assessment across the region. This leaves only one option to count on if the Kunming-Montreal Framework's target 3 has to be reached: more funding from international actors to support the capacity building in Congo Basin countries and nationals who can then carry out the research needed to: (1) locate where ecological corridors are needed, (2) to identify sacred sites, (3) to study how biodiversity areas can coexist with and within community-owned forests, and (4) to allocate underrepresented biomes to new protected areas.

The most important funding initiatives for biodiversity conservation in the Congo Basin began when the former USA International Development Agency created its Central African Regional Program for Environment (CARPE) providing multi-annual financial support for biological landscapes and protected areas throughout the Congo Basin. Currently, peatlands receive investments, including the $100 million the Bezos Earth Fund contributes to the Congo Basin biodiversity, forest, and climate research, the French One Forest Initiative, and the British Government Fund that supports the Congo Basin Science Initiative to train the next generation of Congo Basin experts. However, the above analysis on the financial capacities for the Congo Basin to sustain its biological diversity over long term applies even though the above initiatives currently invest significant amount of cash in helping the Congo Basin to tackle its biodiversity conservation problems; this is because, as indicated above, with just 100$ to conserve 1 km^2, the cost to manage the Congo Basin protected area network after it achieves its 30 × 30 commitment is enormous, calling for a need to imagine other ways to fund the conservation. Maybe, the benefits such as the moisture that is generated by forests of the Congo Basin and transferred to other African regions (e.g., Gebrehiwot et al. 2018) should be paid for by the African Union. This suggestion is a tall-order proposal but has the value of provoking a discussion to think about a different way to ensure the ecological sustainability of the Congo Basin on which other African regions depend.

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The SPCB Vision for the Congo Basin in 2050

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Abstract

The current ecological, socioeconomic, and governance status of the Congo Basin is profoundly influenced by its historical dynamics, including the significant impacts of colonialism, postcolonialism, structural adjustments, globalization, and the emergence of a multipolar world. These historical contexts, alongside national agendas and realities, must be considered when devising optimal management strategies for the Congo Basin.

We suggest that despite significant progress since the Rio Conference in 1992, a business-as-usual model will not generate sufficient development opportunities for the Congo Basin's young, growing population to facilitate sustained development, environmental governance, and to ensure peace and security. There is a need for improved governance, a postcolonial economic model based on transformation not simply extraction and which sustains ecosystems and the services they provide, rather than degrading and destroying them. Given its natural resources and human potential, the region can and must lead the world toward a sustainable development model that promotes environmental and social resilience.

Keywords

Governance · Sustainable development · Economy · Ecosystem services · Postcolonial model · Leadership

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Introduction

The Congo Basin and equatorial Africa more widely are both the cradles of humanity and the only tropical ecosystems on our planet where intact large mammal communities continue to range in relatively undisturbed ecosystems (▶ Chaps. 9, "Critical Interconnections Between Cultural and Biological Diversity in the Congo Basin," and ▶ 10, "The Ecological Functions of Congo Basin Ecosystems and Basin-Wide Carbon Cycle"). Perhaps it is because hominins have lived in the Congo Basin for at least 650,000 years and traditional communities have been custodians of nature for thousands of generations that man and nature have coexisted more easily here than on other continents (▶ Chaps. 7, "Central African Rainforest Archaeology," and ▶ 8, "Human Occupation of the Congo Basin").

However, the Atlantic trade that exploded in the mid- to late-1500s, expanding dramatically in the seventeenth century, had a catastrophic ecological and social impact on coastal communities. Natural resources were plundered, plagues of new diseases wiped out whole tribes, and the brutal trade in human beings saw an estimated six million slaves displaced from the Congo Basin, principally to Brazil, with smaller numbers to the Caribbean and what became the USA (▶ Chap. 8, "Human Occupation of the Congo Basin"). The period of formal colonial rule, which emerged after the Berlin conference of 1884–1885 and lasted until the 1960s (most Congo Basin nations) and 1970s (Angola), undermined traditional governance systems and treated the Congo Basin's natural resources as European assets, exporting huge quantities of cheap raw materials to be processed in Europe, allowing the colonial powers to accumulate vast wealth (▶ Chaps. 8, "Human Occupation of the Congo Basin," and ▶ 29, "Mining Influence on the Future of the Congo Basin"). During this period, the people of the Congo Basin were treated as subjects with no rights, to be moved around at will and serve as forced labor. Even though the Congo Basin nations have now been independent for almost as long as they were under colonial rule, the shadow of this dark period is only just starting to fade.

The influence of the colonial powers on the region remained strong for several decades after independence and authoritarian postindependence leaders perpetuated the economic model of "stripping the Congo Basin's natural resources and exporting them to Europe for processing," creating wealth and jobs outside the African continent (e.g., ▶ Chap. 38, "Natural Resource Management Policies in the Congo Basin"). It was not until the 1990s, with the emergence of multiparty democracies, the emergence at the Rio 1992 Earth Summit of the need for a new sustainable model of development, and the massive arrival of Asian investors, that the political and economic emancipation of the region began, all be it timidly at first (▶ Chap. 38, "Natural Resource Management Policies in the Congo Basin"). In 1992, the President of the Gabonese Republic stated in his address to the plenary of the Rio Earth Summit that "all too often in Africa we have been forced to develop at no matter what cost" ["in our rush to catch up with the rest of the world"]. He was referring to the willingness to see natural resources plundered to generate jobs and revenues, often resulting in huge environmental damage that will handicap future generations. The President of the Republic of Congo also spoke out on this theme.

After Rio, in 1993 Gabon adopted its first environment law, while in 1994, Cameroon finalized a new forestry law, instituting the principals of sustainable logging, creation of community forests, revenue sharing, wildlife protection, and protected area creation and management. CAR, Congo, DRC, and Gabon also initiated reforms of their forestry laws, and in 1999, the Congo Basin presidents attended the Yaoundé Summit on the "Conservation and Sustainable Management of Tropical Forests," signing the Yaoundé Declaration that established COMIFAC (Commission des Forêts d'Afrique Centrale/Central African Forest Commision), a regional policy and coordination body, unique among the tropical rain forest regions (▶ Chaps. 14, "Timber Production and Ecosystem Functions and Services in the Congo Basin," and ▶ 38, "Natural Resource Management Policies in the Congo Basin").

After the Yaoundé Summit, in 2000 Equatorial Guinea created a national park network covering 20% of Equatorial Guinea. In 2002, at the World Summit on Sustainable Development ("Rio plus 10"), Gabon announced the creation of 13 national parks covering 3 million hectares (11% of Gabon). This involved the cancellation (with compensation) of almost 2 million hectares of logging concessions (▶ Chap. 19, "History, Development, and Politics of Protected Areas in the Congo Basin Countries"). The Congo Basin heads of state were showing environmental leadership on the international stage for the first time, and this marked a turning point for natural resource governance in the region (▶ Chap. 38, "Natural Resource Management Policies in the Congo Basin").

In 2009, Gabon discovered that only 15% of Gabon's wood was being processed in-country, while the forestry law adopted in 2001 required 60% local transformation before export; the government went on to completely ban the export of unprocessed timber in 2010 (▶ Chap. 14, "Timber Production and Ecosystem Functions and Services in the Congo Basin"). The French government tried unsuccessfully to persuade the Gabonese authorities to reverse their decision, which would impact the French economy and jobs. Similarly, when the Gabonese Government later announced in Tokyo and Brussels the intention to ban the export of all unprocessed raw materials, developed nations were not supportive. Their economies still depended partly on Africa as a source of cheap raw materials, and this announcement was seen as a threat to the status quo. Despite the rhetoric that dominates the communications channels of the International Monetary Fund (IMF), the World Bank, and other multilateral and bilateral agencies, Official Development Assistance (ODA) has not developed the Congo Basin, nor the African continent at large, since its inception in the postcolonial era (▶ Chaps. 26, "How Could Agricultural Policies and Practices Influence the Future of the Congo Basin's Biodiversity and Ecosystems?," and ▶ 36, "Solutions of Global, International, Regional, and National Economic Initiatives").

One telling example comes from the various "REDD+ readiness programmes" financed through the World Bank and UN Agencies. This saw upward of $100 million spent by donors preparing the Congo Basin countries to claim results-based payments from developed countries, on the basis of reducing their carbon emissions due to deforestation; as defined in Article 5 of the Paris Agreement. The Congo

Basin nations that accepted the funding, and all the developed-nation consultants that they paid to help them, are still not "ready." However, Gabon, which chose not to take the funds but instead to develop its own local capacity, was the first African nation (one of only two to date!) to register their emissions reduction and carbon sequestration results on the UNFCCC's Lima Hub (▶ Chap. 38, "Natural Resource Management Policies in the Congo Basin"). If Africa is going to emerge from its economic doldrums, it will have to fight, tooth and nail, for market share and access to capital. None of its "partners" will do this in the place of its own governments and business leaders (▶ Chap. 23, "Opportunities and Potential for Sustainable Development in the Congo Basin from an Environmental Sustainability Perspective").

In the 2022 and 2024 African Youth Surveys (IFF, 2022, 2024), which surveyed the attitudes of over 11,000 young people across 21 African countries, including Cameroon, Congo, DRC, and Gabon, several key findings emerged that are highly relevant to this final chapter, in which we attempt to bring together the contributions of all the authors who contributed to the SPCB 2025 report and make recommendations for the future. The most important are:

- There is a strong degree of Afro-optimism among the youth, suggesting that we are at an inflexion point, looking forward to a prosperous future rather than backward to the ills of the colonial period.
- Seventy percent of African youth are concerned about the influence of foreign powers on the continent, especially China and the USA. They are particularly worried about the foreign ownership of natural resources, which they perceive as the perpetuation of a neocolonial system.
- There is a strong appetite for the emergence of an African form of democracy and good governance, founded on the principals of equality of citizens, freedom of speech, fair elections, and fighting corruption.
- Environment is a key concern, particularly access to clean drinking water and fighting climate change. Eighty percent of African youth feel that their governments should be doing more to fight climate change. They are frustrated at the slow progress of international negotiations and impatient to see investment in reducing carbon emissions, green energy, and mitigation of the effects of climate change on food production and water availability.
- There is a high degree of concern about the threat of terrorism, and an average of 53% of the people questioned said their lives had been impacted by terrorism, insurgency, or conflict.
- In the digital age, there is consensus that universal access to the Internet is a basic human right.

Around 60% of Africa's population is under 25, and 75% is under 35 (the figures for the Congo basin are approximately 65% and 80%, respectively, ▶ Chaps. 8, "Human Occupation of the Congo Basin," and ▶ 18, "Urbanization, Biodiversity, Ecosystem Functions and Services in the Congo Basin"). This will either be the key to the continent and the Congo Basin's success in a prosperous future, or a human tragedy on a scale never before seen, if Africa's leaders fail to seize the opportunity offered by

the continent's abundant renewable and nonrenewable resources to construct a prosperous future for the continent's young population. Having a young population in a global context of aging work forces is a competitive advantage, but if jobs are not created then dissatisfaction, resentment, and resignation could provoke civil disobedience and conflict. The most serious and imminent threat to a prosperous future is climate change (▶ Chap. 17, "Climate Change and Ecosystem Functions and Services in the Congo Basin"). The Africa Progress Panel, chaired by the seventh secretary-general of the United Nations, Kofi Annan, wrote in its 2009 report that: "23 African countries will face a high risk of violent conflict when climate change exacerbates traditional security threats. A further 14 African countries face a high risk of political instability" (African Progress Panel, 2009).

The scientists that have contributed to this report are in agreement that finding a solution to climate change and preserving the ecosystem services provided by the Congo Basin ecosystems locally, regionally, continentally, and globally is not only critical to the future of the African continent and its people but also to the global community (e.g., ▶ Chaps. 5, "The Hydrology of the Congo Basin," ▶ 6, "Hydrology of the Ogooué and Sanaga Watershed Systems: Critical Case Studies in the Context of the Congo Basin Forest," ▶ 10, "The Ecological Functions of Congo Basin Ecosystems and Basin-Wide Carbon Cycle," ▶ 17, "Climate Change and Ecosystem Functions and Services in the Congo Basin," ▶ 20, "Ecosystem Functions and Services in the Congo Basin," ▶ 23, "Opportunities and Potential for Sustainable Development in the Congo Basin from an Environmental Sustainability Perspective," and ▶ 24, "The Future of Biodiversity in the Congo Basin"). Creating economic models whereby all the nations of the Congo Basin can ensure quality livelihoods for their growing, youthful populations while preserving the ecosystems that represent a vital life support system is the key to a prosperous future (▶ Chap. 23, "Opportunities and Potential for Sustainable Development in the Congo Basin from an Environmental Sustainability Perspective"). Shifting away from the colonial model of extracting value from the Congo Basin, to one that captures that value by transforming locally and uses it to create jobs and prosperity in the region is fundamental (▶ Chaps. 23, "Opportunities and Potential for Sustainable Development in the Congo Basin from an Environmental Sustainability Perspective," and ▶ 25, "What Might Influence Economic Forecasts for the Congo Basin?"). Coming together with, and providing leadership and vision to, the international community on the issues of our time, particularly the triple threat of climate change, biodiversity loss, and pollution, is a fundamental enabler of this brighter future.

While much has been achieved, business as usual, the first scenario we will consider below, is not a viable option. The people of the Congo basin live in a world where developed nations are competing against Africa for resources and wealth, on an uneven playing field, strongly tipped in their favor. It is often stated that the Congo Basin Forests are of global importance, alongside the Amazon, but investment flows, be they in funding for scientific research, education, social development, or private sector investment, continue to be feeble (White et al., 2021). The scientific capacity and therefore the profound knowledge needed to understand and chart a future for the Congo Basin ecosystems is lacking, and while the Science

Panel for the Congo Basin has for the first time brought together most of the scientists active in the ecosystem and synthesized the knowledge that does exist, many glaring gaps in baseline data and understanding have been identified. Are the developed nations of the world to be held responsible for the lack of investment in fundamental scientific research in our region, or does the reality lie with the political leaders and governments of the region? It is probably fair to argue that both parties share a common responsibility for a region whose ecosystems should be considered both as strategic national assets and a critical global common.

When Gabon registered 187 million tonnes of REDD+ results on the UNFCCC Lima hub, for the period 2010–2018, of the developed nations, who have adopted Article 5 of the Paris Agreement by consensus, promising results-based payments, no nation was willing to pay, although Norway did pay for 3.4 million tonnes of results based on its own methodology (▶ Chaps. 23, "Opportunities and Potential for Sustainable Development in the Congo Basin from an Environmental Sustainability Perspective," and ▶ 38, "Natural Resource Management Policies in the Congo Basin"). The fact is that the forests, and nations, of the Congo Basin have net absorbed upward of 30 billion tons of CO_2 since the Rio Conference in 1992 (▶ Chap. 10, "The Ecological Functions of Congo Basin Ecosystems and Basin-Wide Carbon Cycle"), but the world seems not to place any value on that service. And worse, the international community seems content to stand by as deforestation increases because poor rural people have no alternative other than to slash and burn the Congo Basin forests. This seems, at best, extremely short-sighted.

We propose a vision for a prosperous, sustainable future for the Congo Basin peoples and forests, founded on sound scientific knowledge, wise international agreements, and thriving equitable economies that maximize returns of the transformation of the regions' abundant natural resources for the nations and people of the Congo Basin while maintaining its precious ecosystems. Some will say this is a panacea, others, an impossible dream. As scientists, we are agonizingly aware of the tragedy that is playing out hidden in the gloom of the forest and intensely frustrated that the solutions we have to offer have not yet convinced the World's leaders of their merit. But we agree collectively that the evidence clearly indicates the need for a new development model, evolving out of the progress we have seen since the vital Rio Earth Summit in 1992.

Building Blocks for a Prosperous Congo Basin

The authors of various chapters of this report have identified key building blocks for a prosperous future in the Congo Basin. Here we summarize the main features of a sustainable development model for future prosperity.

1. New, More Inclusive, Equitable, and Sustainable Economic Models

   If the Congo Basin nations continue to accept the colonial model, where natural resources are exploited at minimum cost, with maximum environmental damage, and exported to all corners of the Earth other than the African continent

to be processed, creating wealth and jobs elsewhere, the status quo will never change (▶ Chaps. 25, "What Might Influence Economic Forecasts for the Congo Basin?," and ▶ 36, "Solutions of Global, International, Regional, and National Economic Initiatives"). The exploitation model can be made slightly more appealing by enforcing high environmental standards and avoiding the flight of tax revenues via criminal accounting and other illegal activities (▶ Chap. 25, "What Might Influence Economic Forecasts for the Congo Basin?"), but it will never result in more than about 10% of the potential economic and social returns staying within the Congo Basin.

To develop, the Congo Basin nations will have to maximize the local transformation of renewable and nonrenewable natural resources and export mostly finished and semifinished products (▶ Chap. 23, "Opportunities and Potential for Sustainable Development in the Congo Basin from an Environmental Sustainability Perspective"). Gabon has been an early mover, banning the export of unprocessed timber in 2010 (▶ Chaps. 14, "Timber Production and Ecosystem Functions and Services in the Congo Basin," and ▶ 25, "What Might Influence Economic Forecasts for the Congo Basin?"), with promising results, and of raw manganese ore in 2025 (▶ Chap. 29, "Mining Influence on the Future of the Congo Basin"). A more coordinated, regional approach might be more effective. ▶ Chapter 29, "Mining Influence on the Future of the Congo Basin" suggests that the Gabonese economy would be over $400 billion larger today, if timber processing in-country had been implemented at Independence. If we apply this same model to the natural resources extracted from the Congo Basin since the colonial period, it would be measured in multiple trillions.

2. An Agricultural Revolution

Agriculture is the main source of livelihoods for over half of the population of the Congo Basin, although the percentage of people who depend on it varies from 10–15% in oil-rich Gabon and Equatorial Guinea to 30–35%, 40–45%, 55–60%, and 70–75% in Republic of Congo, Cameroon, DRC, and CAR, respectively (▶ Chap. 12, "Agriculture, Ecosystem Functions, and Services in the Congo Basin"). Farming typically continues to use the slash and burn technique that has continued, little changed, for more than two millennia, while nature-based solutions (NbS) fostering sustainable development and resilience are weakly implemented across the Congo Basin (▶ Chaps. 26, "How Could Agricultural Policies and Practices Influence the Future of the Congo Basin's Biodiversity and Ecosystems?," and ▶ 35, "Nature-Based Solutions in the Congo Basin"). Modern forms of tropical agriculture practiced in SE Asia and Central and S America can be 10–20 times more productive and stabilize farming activities on the same piece of land through soil fertility methods, avoiding the need for annual deforestation (▶ Chap. 26, "How Could Agricultural Policies and Practices Influence the Future of the Congo Basin's Biodiversity and Ecosystems?,").

Over the last two decades, DRC has shifted from being a High Forest Low Deforestation country that was net absorbing around 500 million tons of CO_2 annually to losing between 500,000 and 1,000,000 (or more) ha of forest annually, making it a net CO_2 emitter. The majority of these emissions are a result of

subsistence agriculture by poor rural populations (► Chap. 20, "Ecosystem Functions and Services in the Congo Basin"). Each family cuts around 1 ha of forest every year, releasing approximately 500 t CO_2. Typically, they will earn the equivalent of $100–200, while releasing the equivalent of €37,500 of CO_2, if we apply the current price on the European Emission Trading System (ETS). One year's worth of emissions from DRC are worth €37.5 billion, in an equivalent quantity of reduced emissions within the EU, which is half of DRC's GDP in 2024. If we were to create a Green Bond worth the equivalent of 1 year of DRC's deforestation emissions to fund the modernization of its agriculture, we could make it ten times more productive, a net contributor to DRC's exports and carbon positive. The know-how and technology to do this exist.

3. Natural Capital and Nature-Based Solutions

As the President of the Gabonese Republic stressed over three decades ago in Rio, most development in the Congo Basin in the past has had catastrophic environmental consequences that we are only today beginning to quantify. In a planet suffering from the consequences of climate change and in the throes of its sixth biodiversity extinction crisis, development that destroys the natural capital and ecosystem services of the Congo Basin is nothing more than a short-term dead end. Despite the ever-rising pressures, the Congo Basin is one of the planet's last surviving major undisturbed ecosystems and the environmental services it provides are critical to the integrity of Africa and the world at large (► Chap. 10, "The Ecological Functions of Congo Basin Ecosystems and Basin-Wide Carbon Cycle"). Despite the failure of the global community to agree to effective mechanisms to preserve these ecosystem services, the first to suffer if we lose them will be the people of the wider Congo Basin. A development model that does not preserve the Congo Basin's natural capital will not be sustainable (► Chaps. 10, "The Ecological Functions of Congo Basin Ecosystems and Basin-Wide Carbon Cycle," ► Chap. 23, "Opportunities and Potential for Sustainable Development in the Congo Basin from an Environmental Sustainability Perspective," and ► 25, "What Might Influence Economic Forecasts for the Congo Basin?").

The good news is that this is possible. Both subsistence and industrial agriculture can be carbon and biodiversity positive (► Chap. 26, "How Could Agricultural Policies and Practices Influence the Future of the Congo Basin's Biodiversity and Ecosystems?"); mining operations may destroy relatively small areas, but by applying best environmental practices to avoid pollution and offsetting any negative impacts, they can make an important contribution to the economic and social development of the region (► Chap. 29, "Mining Influence on the Future of the Congo Basin"). When managed properly, forestry can be sustainable and carbon-positive, and similarly certified concessions may qualify as effective conservation areas (► Chaps. 19, "History, Development, and Politics of Protected Areas in the Congo Basin Countries," ► 29, "Mining Influence on the Future of the Congo Basin," and ► 25, "What Might Influence Economic Forecasts for the Congo Basin?"). With time, it seems unlikely that global mechanisms for carbon and biodiversity credits will not apply to the Congo Basin, and as and when this is the case they may provide additional resources, or make debt less prohibitively

expensive (▶ Chaps. 35, "Nature-Based Solutions in the Congo Basin," and ▶ 36, "Solutions of Global, International, Regional, and National Economic Initiatives")

4. Climate Resilience and Mitigation

   The severe impacts of increased drought stress on the wider continent are already tragically visible, such as in the horn of Africa where upward of 50 million people experienced food insecurity related to drought in 2023. The Congo Basin is relatively unaffected to date, although localized heat stress, flooding, droughts, and other impacts are becoming more frequent (▶ Chap. 17, "Climate Change and Ecosystem Functions and Services in the Congo Basin"). However, the forest ecosystem is starting to show signs of climate stress, with temperatures at the few long-term monitoring stations up a degree since Rio, rainfall showing increased seasonality, stronger and more frequent storm events, and a drying trend. While the Congo Basin forests seem to be more resilient than the southern Amazon, decreased fruit productivity and consequent loss of body condition by rain forest mammals is perhaps an early warning of the changes that are underway (▶ Chap. 17, "Climate Change and Ecosystem Functions and Services in the Congo Basin"). The combined impacts of increased deforestation and climate change represent a threat to the vital ecosystem services provided by the Congo Basin to other regions in Africa, such as the Ethiopian Highlands and the Sahel, which are dependent on atmospheric circulation of moisture evaporating from the Central African forests for part of their rainfall (▶ Chaps. 2, "Geology and Geodynamics Evolution of the Congo Basin," and ▶ 10, "The Ecological Functions of Congo Basin Ecosystems and Basin-Wide Carbon Cycle"). Put simply, the Congo Basin forests are the green heart of the African continent, helping fill the Blue Nile, pumping water all the way to Egypt, where it irrigates the agriculture that feeds over 100 million people.

   Despite increasing emissions linked to deforestation and forest degradation, the Congo Basin remains one of the vital terrestrial carbon sinks, removing around 600 million tonnes of CO_2 from the atmosphere every year (▶ Chap. 20, "Ecosystem Functions and Services in the Congo Basin"). Reducing deforestation, especially in DRC, and restoring degraded ecosystems in the Congo Basin has the potential to more than double current carbon sequestration levels.

5. The Role of Science

   Put simply, you cannot manage a system you do not understand. Without the collective efforts of the scientists who have maintained the Lopé and phenology database and weather station over four decades, we would be unaware of the early warning signs that the Congo Basin trees are beginning to feel the heat, and that wildlife is becoming stressed, and potentially more susceptible to disease and punctual climate shocks (▶ Chap. 17, "Climate Change and Ecosystem Functions and Services in the Congo Basin"). Today we cannot say with certainty what proportion of the waters of the Blue Nile are generated in the Congo Basin and how deforestation will impact its flow, but we do know that it is significant and it will result in less water entering the Grand Ethiopian Renaissance Dam and being available for irrigation in Egypt (▶ Chap. 10, "The Ecological Functions of Congo Basin Ecosystems and Basin-Wide Carbon Cycle"). Perhaps the uncertainty of the relationship is why there has not been more solidarity between the nations that

depend on the Blue Nile for their existence and the Congo Basin countries, its atmospheric but not its classically defined hydrological source. Should we redraw river basins to include their sources of atmospheric humidity, to better influence policy and international relations? We can only do this if we undertake more research on the complex relations between hydrology, climate, and forests. The Science Panel for the Congo Basin (SPCB) and the Congo Basin Science Initiative (CBSI) were founded at the One Forest Summit in Libreville in 2023, following the publication of a commentary in the journal *Nature* coauthored by the forest and environment ministers of the region alongside leading scientists, calling for massive investment in scientific research and capacity, along the lines seen in the Amazon 30 years ago (White et al., 2021). CBSI was launched at the Three Basins Summit in October 2023 in Brazzaville and SPCB at COP28 in Dubai in December 2023. The international response to that paper is promising, but still lacking in ambition. There remains a threat that we will lose much of this critical ecosystem before we fully appreciate its local, regional, and global importance or understand the complexities of the ecological, hydrological, climatological, and socioeconomic processes it supports.

6. Governance

   Global indices of democracy and governance paint a dark picture of the Congo Basin countries. Sound political and economic governance are critical to the development of the region, just as sound environmental governance is vital for sustainable development, resilience, health, peace, and security. Weak political systems, corruption in government, and illegality in exploitation of natural resources are drivers for short-term economic models that tend to maximize extraction and minimize investment (▶ Chaps. 22, "Human Influence on Current Status of Biodiversity of the Congo Basin," ▶ 25, "What Might Influence Economic Forecasts for the Congo Basin?," and ▶ 38, "Natural Resource Management Policies in the Congo Basin").

   Strengthening of governance is the fundamental foundation of any sustainable development model that can attract longer-term capital and investment. Imposing a Western model on the young democracies in the Congo Basin nations is not viable. There is a need for the emergence of an African democratic model which integrates some of the principals of traditional governance that were eroded during the colonial period while adapting them to the social and economic challenges and principals of the modern world.

Business as Usual Scenario

In the immediate postcolonial period, intensified export of unprocessed natural raw materials continued to be the norm, resulting in the flight of natural capital, principally to Europe and later to Asia (▶ Chap. 25, "What Might Influence Economic Forecasts for the Congo Basin?"). Decisions by the Congo Basin nations in the post-Rio decades saw the creation of extensive networks of protected areas, adoption of sustainable forestry, and wildlife protection policies, including the concepts of participatory management and community natural resource management. However, the majority of the oil, minerals, and timber continued to be exported in their unprocessed form,

severely limiting the development impact of these industries (▶ Chaps. 14, "Timber Production and Ecosystem Functions and Services in the Congo Basin," ▶ 15, "Mining and Ecosystem Functions and Services in the Congo Basin," and ▶ 16, "Hunting, Fishing, and Ecosystem Functions and Services in the Congo Basin"). With populations increasing rapidly, resulting in increased deforestation and wildlife harvest and in the light of generally weak environmental and political governance, poaching pressures and environmental degradation increased (▶ Chaps. 16, "Hunting, Fishing, and Ecosystem Functions and Services in the Congo Basin," ▶ 18, "Urbanization, Biodiversity, Ecosystem Functions and Services in the Congo Basin," and ▶ 22, "Human Influence on Current Status of Biodiversity of the Congo Basin"). The loss between 1970 and 2015 of 90% of the forest elephants to organized poaching by criminal gangs is an indication of the environmental pressures felt during this period (▶ Chap. 19, "History, Development, and Politics of Protected Areas in the Congo Basin Countries"). Elephants are slaughtered illegally for the commercial gains that can be obtained through illegal trade of their ivory. Rampant poaching is an indicator of loss of the rule of law, and in most countries, when they lost their elephants they went on to lose their forests, often descending also into civil strife (e.g., Côte d'Ivoire, Nigeria, Sierra Leone, and Liberia). Similarly, illegal exploitation of timber, gold, diamonds, coltan, and other minerals has undermined governance systems and resulted in severe environmental degradation, pollution, and civil insecurity in many areas.

From 2010 onward, there was a gradual shift toward in-country processing, which generates significantly more economic benefits and jobs for the Congo Basin nations. The development of in-country timber processing in Cameroon, Congo, and Gabon and the development of special economic zones through public-private partnership agreements have seen forest economies increase significantly. The majority of the capital firing this change has come through new economic partnerships with countries such as Singapore, China, India, and Malaysia, rather than with traditional (e.g., colonial, Lebanese) sources (▶ Chap. 25, "What Might Influence Economic Forecasts for the Congo Basin?"). However, it has proved extremely difficult to attract sufficient affordable capital to accelerate this process, and international mechanisms such as REDD+, which promised to provide free or concessional funding to preserve the Congo basin ecosystem, have failed to deliver at a meaningful scale (▶ Chap. 23, "Opportunities and Potential for Sustainable Development in the Congo Basin from an Environmental Sustainability Perspective"). Similarly, protected areas have struggled to attract investment and catalyze development in surrounding communities, with the notable exception of mountain gorilla tourism in Rwanda and Uganda. Indeed, most Congo Basin nations currently struggle to provide adequate management budgets to protected areas and natural resources management authorities, in some cases devolving management authority to NGOs through public-private-partnership arrangements (▶ Chap. 19, "History, Development, and Politics of Protected Areas in the Congo Basin Countries").

The post-Rio gains remain fragile and vulnerable to reversals, not least because inevitably the development of industries in the Congo Basin will result in economic

and job losses in other parts of the world, that have developed on the back of cheap raw materials from Africa and are reluctant to surrender their competitive advantage. Change through business as usual is extremely hard to kick-start and unlikely to prove sustainable. The increased deforestation pressure in Cameroon and DRC are early warnings of the growing threat of environmental degradation, threatening the viability of the ecosystem services provided by the Congo Basin ecosystems (► Chap. 24, "The Future of Biodiversity in the Congo Basin").

Furthermore, if the global community fails to cut carbon emissions and limit the severity of climate change, there is also a significant threat that the Congo Basin will hit a tipping point at which increased temperature, water stress, and the resulting fires turn it into a net carbon source and initiate the transition from humid tropical forest to drier, more open ecosystems, as seems to be happening in the southern Amazon (► Chap. 17, "Climate Change and Ecosystem Functions and Services in the Congo Basin"). Paleoecology and archaeology studies demonstrate that massive forest loss occurred at the beginning of the first millennium and act as a warning that we cannot take the current resilience of the Congo Basin forests for granted (► Chaps. 4, "The Evolution of Congo Basin Ecosystem Diversity," and ► 7, "Central African Rainforest Archaeology"). The majority of the Congo Basin forests, which are mostly relatively low-lying, are unlikely to be viable in a 3-degree world (► Chap. 17, "Climate Change and Ecosystem Functions and Services in the Congo Basin").

Finally, there is a severe risk that sustainable economic development will not keep pace with the demands and aspirations of a growing, young population and that environmental gains will be threatened if this results in growing frustration and eventually civil strife analogous to the Arab Spring.

Theory of Change: A Possible Future

The current situation in the Congo Basin is that of galloping demography, increasing levels of poverty, declining wildlife and fish abundance, increasing land degradation and deforestation, intensive uncontrolled artisanal and industrial extraction and export of unprocessed minerals, and poor governance. This Theory of Change lays out the building blocks for an economically thriving and inclusive and ecologically sustainable Congo Basin for future generations.

Rich natural resources, including their agricultural potential, timber, oil, and minerals, humid equatorial climate, and dynamic young population mean that the Congo Basin nations have many of the building blocks necessary to develop thriving sustainable economies that nurture, rather than destroy, natural capital and critical ecosystems. The key enablers required to achieve this transition include:

- Governance is the lynchpin—weak institutions will facilitate illegality and inevitably undermine the natural potential of the region, leading to collapse, while development of robust, inclusive governance will enable prosperity. There is a need to develop strong democracies and governments based on an African model

of society, rather than simply transposing Western systems, which are themselves showing signs of stress. The colonial and postcolonial extractive economic models that have prevented the development of thriving economies need to be banished in favor of equitable partnerships between Central African nations, former colonial powers, and other partners. It is only through the development of strong institutions and the elimination of corruption that the region will be able to fight illegal extraction of natural resources and reassure investors that a longer-term economic model is possible.

- To fully take advantage of the development potential of a young population, it is critical that health care and education is improved and that appropriate birth control is put in place before populations become a burden rather than a competitive advantage.
- Technological innovation through embracing the transformative potential of modern digital tools, renewable energy, and AI and training the new young generation of Congo Basin citizens to adopt them is a key to success. Already the region has good access to mobile phones, Internet, and mobile banking, but these need to be further developed. If harnessed effectively, technology could revolutionize forest management, enhance transparency, and generate inclusive economic opportunities—though capacity gaps remain a challenge.
- Climate resilience and adaptation are critical to the long-term sustainability of the Congo Basin economies and human populations in a world where climate change seems close to being out of control. The region should aim to emerge as a global leader in ecosystem-based resilience strategies through the development of nature-based solutions, national adaptation plans, and integrated climate observatories. The region also needs to strengthen its collective voice in international negotiations and to create alliances with other comparable regions so as to put pressure on the international community to uphold its commitments to emission reductions. Unless developed and emerging nations respect the scientifically determined pathways to zero carbon emissions, the viability of the Congo Basin region risks being significantly compromised.
- Sustainable development and conservation should be considered as a fundamental foundation for long-term economic prosperity. Unlike most of the developed world, which has lost its natural ecosystems and natural capital, the Congo Basin remains relatively intact and is in a position to create a new development model that guarantees both human and ecosystem prosperity. This balanced model where biodiversity preservation, economic diversification, and strong governance reinforce one another could be a "win-win" pathway where local communities benefit from ecotourism, green finance, and forest-based economies, similar to successful models seen in Costa Rica and Kenya, while nations profit fully from their natural resources. Key components of this vision include the following: the development of models of industrial, smallholder, and subsistence agriculture that harness the environmental resources of the region but are carbon and biodiversity positive, through implementation of modern principals of tropical agriculture and soil husbandry; well-managed, sustainable use of forest resources, including timber, nontimber products, wildlife, and fish, both in industrial concessions and community-managed areas such that ecosystem services are preserved

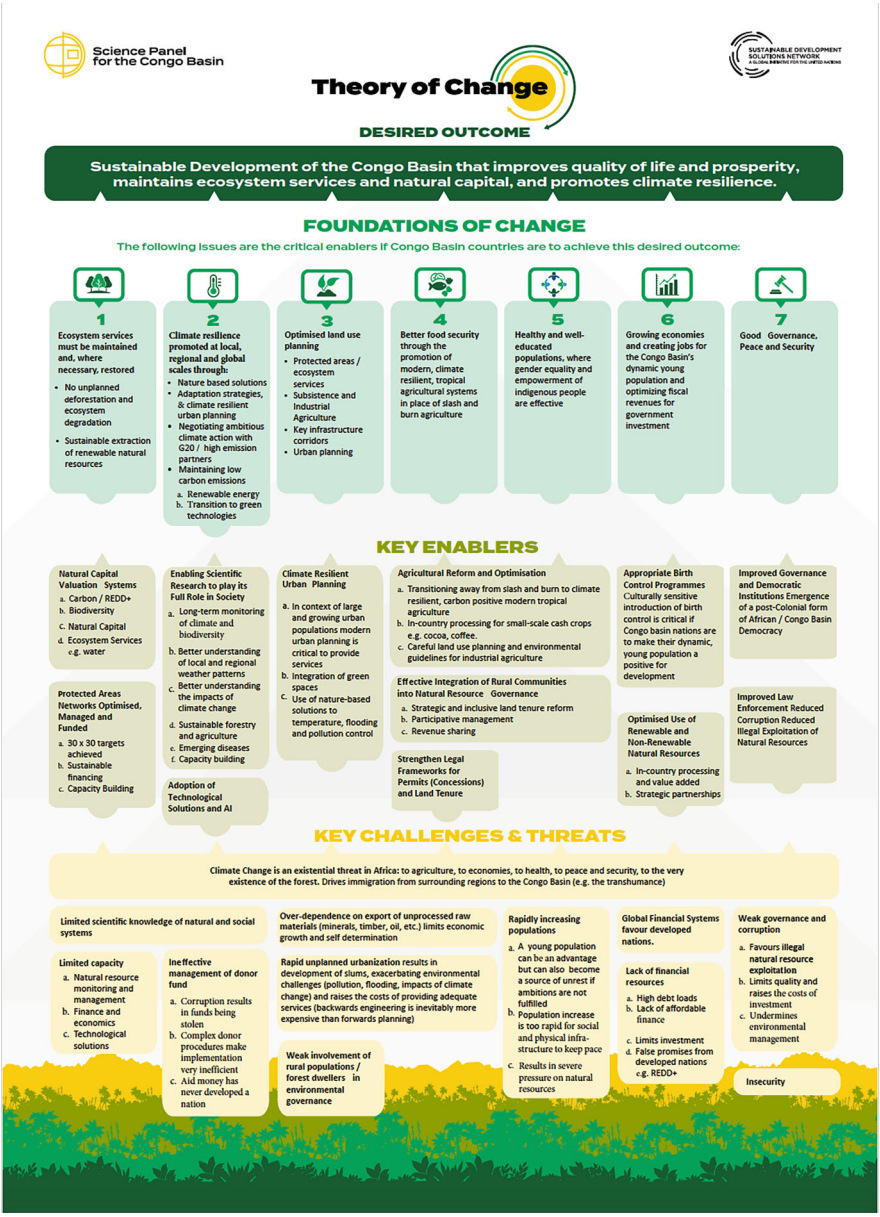

Fig. 1 Theory of change to guide the sustainable development of the Congo Basin, improving quality of life and prosperity, maintaining ecosystem services and natural capital, and promoting climate resilience

through a principal of exploit to conserve; and conservation of representative examples of the varied ecosystems found in the Congo Basin and of those that provide critical ecosystem services.

- Science and research must guide policy and decision-making. Targeted investments in research, monitoring, and innovation are needed if we are to understand the complexities of the Congo Basin forests and to optimize and monitor the impacts of management decisions, and to develop new socioeconomic models that are appropriate in the region.

Figure 1 presents a theory of change diagram that attempts to summarize the foundations on which change can be built, the key enablers that will facilitate the emergence of resilient economies while preserving the natural capital of the Congo Basin, and the challenges that will need to be overcome if this vision is to become a reality.

The Congo Basin stands at a crossroads. The choices made today will determine whether it becomes a cautionary tale of missed opportunities or a global model for sustainable development and environmental leadership by 2050, or 2063. The region's development partners and the multilateral banks and agencies can and should play an active role in this transformation, which will benefit the global community as much as the region, if it is successful, but only leadership from within the region can make it a reality.

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