ESA Contract No.	4000135758/21/I-EF
Project Name	BIOMONDO
Towards Earth Observation supported monitoring of freshwater biodiversity	

Deliverable	D1.1 Requirement Baseline (RB)
Short description	A detailed analysis of the scientific and policy biodiversity priorities and challenges.
Work package No.	WP1
Lead Partner	BG
Distribution	ESA, Project team, AB, BEs
Version	V2.1
Submission date	2022-03-22
Contributors	Petra Philipson (Brockmann Geomatics) Susanne Thulin (Brockmann Geomatics) Jelle Lever (Eawag) Daniel Odermatt (Eawag) Carsten Brockmann (Brockmann Consult) Kerstin Stelzer (Brockmann Consult) Jorrit Scholze (Brockmann Consult) Miguel Dionisio Pires (Deltares) Marieke Eleveld (Deltares) Jan Janse (PBL) Tamara Keijzer (PBL) Aafke Schipper (PBL)

Table of Contents

1 Summary

BIOMONDO aims to support freshwater biodiversity monitoring through Earth Observation (EO), which is the gathering of information about the physical, chemical, and biological systems of the planet Earth through remote sensing or ground-based techniques.

Observing and monitoring biodiversity changes should adhere to a range of different types of requirements, some of which are very specific for freshwater ecosystems. First, relevant variables must be identified across different levels of structural, compositional and functional diversity. Second, their choice must be aligned with different implementation targets, such as the improvement, preservation or restoration of biodiversity. And third, monitoring anthropogenic drivers of declining biodiversity should also be considered, because they are often anticipatory and controllable. Such direct drivers include habitat change, climate change, invasive species, overexploitation, and pollution and nutrient enrichment.

Current biodiversity policies and strategies as well as assessments of progress towards set targets acknowledge, point out that there has been a general failure to halt the negative trend of biodiversity loss and that different approaches that includes transformative change is needed to reverse the situation. This includes revision of targets and the indicators that inform the targets and a greater emphasis on the links between biodiversity, ecosystems and their services and people.

Despite the detailed goals of the biodiversity policies and strategies for the last twenty-five years the negative trends have continued in response to direct human-caused drivers. The reasons are many and interlinked but the main areas that have been highlighted are a lack of legally binding agreements and conservation legislation, especially on national and local levels where implementations of actions to protect and restore biodiversity take place. In addition, lack of funding and imprecise goals, targets and indicators are mentioned. Close involvement and cooperation between all sectors of society, including actual economic valuation of ecosystems and their services including biodiversity, have been deficient, as well as in some cases, a lack of will to achieve goals.

There is general agreement on the five drivers of environmental change although a better understanding of their interaction is required to be able to develop improved mitigation measures. Intense work is being directed towards the development of the new CBD Post-2020 Global Biodiversity Framework (GBF) to try to ensure that it can facilitate radical change and really lead to "bending the curve" of biodiversity loss. The knowledge gaps highlighted by the IPBES 2019 assessment cover several areas that need to be addressed but the main gaps where EO data can be of support are the ones where better spatial data is required, especially when it comes to ecosystem processes and condition.

Policy goals and targets need to have sound scientific base with possibilities for simple tracking of progress. Essential biodiversity variables (EBVs) have been developed to support the link between primary observations including remote sensing and in situ data and indicators of biodiversity change used for monitoring of achievements. The aim is to ensure that global assessments can be made more easily also when indicators change, and new data becomes available. In recent years efforts have been made to identifying those EBVs for which satellite data and remote sensing can enable improved in-

formation that is consistent, scalable and continual that addresses key knowledge gaps, so called RS enabled EBVs. Also, integration of EO in ecosystem services modelling is developing.

Several international biodiversity networks (GEO BON, bioDISCOVERY, Biodiversa+) are now operating and try to bring the work of the different science communities closer to the priorities of the policy sectors. The systems for monitoring, modelling and assessment of biodiversity are storing and creating a multitude of data but there is substantial difference in the coverage of different parts of the earth and there is a bias towards temperate regions. The challenges facing the networks and the development of information systems are several: access to appropriate biodiversity data (spatial coverage, consistency, etc), difficulties in translating raw observation data into essential variables that can facilitate indicator development to support monitoring of progress towards policy targets and improving communication between the science and policy sectors.

Models are critical tools to generalize, interpret and extrapolate links between drivers of change and the ecological state, including biodiversity composition of ecosystems. There are basically two types of model approaches to describe this link, correlative models linking environmental conditions to species composition and/or abundance based on empirical data and process-based models based on physiological and ecological mechanisms. The future is in combination of different modelling approaches, model intercomparison projects and clear communication of uncertainties. In BIOMONDO, we will use GLOBIO as an example of the empirical approach (for the fish species indicator), and BLOOM as an example of the process-based model (for the phytoplankton indicator).

Over the last decades several biodiversity observing, or observation, systems have been developed by different global and regional partners and organisations to try to collate biodiversity related data. The main facilities are the Global Biodiversity Information Facility (GBIF) that collect biodiversity data for all ecosystems and data on freshwater biodiversity that are collated by the Freshwater Information Platform. The Data Portal behind the Living Planet Index, and the UNEP Biodiversity Data Lab can be used to access, analyse and provide key information on targets and goals based on global data from many different providers including satellite data. Together with the European Knowledge centre for biodiversity (KCBD) with the biodiversity Information System for Europe (BISE) they all strive to collate relevant biodiversity data and connect research communities and policy makers.

Freshwater biodiversity, with its richness of species and ecosystems and provision of many essential ecosystem services, has in the past not been specifically prioritised despite its disproportional decline compared to terrestrial and marine biodiversity. Freshwater habitats are experiencing 2-3 times the rate of biodiversity loss. The urgency to increase the focus is now being highlighted by many scientists and biodiversity networks. The CBD Post-2020 GBF presents a great opportunity (and challenge) for a radical improvement of the situation by developing actions for implementation that are explicit for the Freshwater realm and that lead to recovery.

Although the knowledge gaps that need to be filled to revert the negative trend of global biodiversity loss such as data gaps, effects of interacting drivers including climate change are common to all ecosystem groups there are specific needs pertaining to freshwater biodiversity that are different, mainly because freshwater ecosystems link land and sea and supply ecosystem services that sometimes are in conflict. The main knowledge gaps relate to uneven biodiversity data coverage (spatial, temporal and for different organism groups), structure of freshwater ecosystems, with ecosystem condition less well represented than ecosystem extent. Also, better overview and access to data are called for including better methods for monitoring freshwater biodiversity. Effects of changes in land use can vary depending on what components of freshwater ecosystems are studied and effects of ecosystem protection and restoration of environmental flows and connectivity are understudied. Action priorities to improve freshwater biodiversity include restoration of river flows and improved protected area networks that incorporate the connectivity between terrestrial, freshwater and marine systems.

In practice, it is difficult to obtain the information needed to determine biodiversity on a global or even regional scale through field work, because it depends on sample size, sampling efforts differ between species, some regions and ecosystem types are difficult to investigate and because there simply are too many species. Upscaling, therefore, requires remote sensing enabled proxies that are more easily detectable on a global scale, and biodiversity models to extrapolate from field observations at point locations to a regional or global scale. For many metrics of biodiversity (including Essential Biodiversity Variables, EBVs) it is not clear how this should be done, highlighting a huge knowledge gap. For each of the pilot objectives and associated pilot sites as described in BIOMONDO's Science Policy Traceability Matrix (see section 5.3), as well as for each Candidate Earth System Science Pilot (see Chapter 7), we therefore assess the potential to transfer the developed solutions to other areas and upscaling to a large-scale regional or global monitoring system.

Even though considerable obstacles need to be overcome to achieve global monitoring of freshwater biodiversity, the major drivers affecting their condition are quite clear and, for the most part, easier to assess and monitor (see Revenga et al. 2005). To monitor freshwater ecosystems, we may thus have to rely on global, relatively easily detectable proxies, in particular those measuring changes of environmental conditions. Monitoring such environmental changes is highly effective because 1) they can be used as proxies of change in biodiversity, 2) change in environmental conditions can precede biodiversity loss by several decades, and 3) they can be used to set targets for policy making (i.e. because they are anthropogenic). BIOMONDO, therefore, takes off from the five main threats of global environmental change to freshwater ecosystems, i.e. 'Water pollution and eutrophication', 'Habitat change (hydrological disturbance)', 'Invasive species', 'Climate change', and 'Overexploitation', and aims to assess their impact on different aspects of biodiversity (including Essential Biodiversity Variables, EBVs) and ecosystem services (including Essential Ecosystem Service Variables). Remote sensing can contribute to such a monitoring approach through estimates of the concentrations of several optically active constituents inside freshwater bodies (e.g. chlorophyll concentrations, dissolved organic matter, total suspended matter), other inherent optical properties (e.g. vertical light attenuation), and changes in, for example, the extent, connectivity, retention time, and hydroperiod, of water bodies.

The analysis of the EO potential for assessing and monitoring the main drivers of global environmental change demonstrates that satellite observations are increasing our understanding of the dynamics of freshwater systems, their riparian borders and catchment. Satellite remote sensing is crucial to getting long-term global coverage and allows for time series analysis and change detection. It can rapidly reveal where to reverse the loss of biological diversity on a wide range of scales in a consistent, borderless and repeatable manner. Future satellite missions will enhance the potential to use EO data for biodiversity assessment and monitoring with increasing technical advancements and the continuous extension of the observation period.

The future of biodiversity assessment and monitoring relies on a compact development of IT solutions covering diverse requirements and objectives. Various available IT solutions already cover aspects of a comprehensive biodiversity assessment and monitoring, e.g. handling big data processing or monitoring EBVs on regional scale. These IT solutions show great potential but need to be developed further to cover the challenging requirements for biodiversity assessment and monitoring.

In this precursor study, we include three candidate Earth System Science freshwater biodiversity pilots that are of particular relevance within the context of monitoring the impact of changing environmental conditions on biodiversity and for which results can be obtained within the two-year time frame of this project. The scientific objectives of these pilots provide the basis for WP3 and WP4 in which the scientific and policy impact of these pilots is assessed and maximised, and should contribute to the development of a Science Agenda and Scientific Roadmap (WP5) for the implementation phase of the EC-ESA Biodiversity Flagship Action.

To develop a broad outlook on ongoing changes in freshwater biodiversity and how these changes can be monitored using EO data, these pilots each address objectives and knowledge gaps corresponding to one of the following three drivers of global environmental change in freshwater ecosystems: ‘pollution and nutrient enrichment’ (pilot 1), ‘climate change’ (pilot 2), and ‘habitat change’ (pilot 3). More specifically, in **BIOMONDO pilot 1** we explore the possibilities of integrating EO data into Delft3D. Delft3D is a world leading 3D modelling suite to investigate hydrodynamics, sediment transport and morphology, and water quality for fluvial, estuarine and coastal environments, and is used on many places around the world, such as the Netherlands, USA, Hong Kong, Singapore, Australia, Venice. In **BIOMONDO pilot 2** we explore the possibilities of using a combination of EO data on SWT and thermal tolerance of freshwater fish species in order to quantify the impacts of increases in temperature and heat waves on freshwater fish diversity. And in **BIOMONDO pilot 3** we explore the possibilities for combining EO data and biodiversity modelling for monitoring and assessing the impact of dam construction and removal on biodiversity, including the effects on: 1) Habitat fragmentation and dispersal routes, 2) Changes in habitat extent, and 3) water quality.

The BIOMONDO Showcases will demonstrate how novel Earth Observation and Biodiversity modelling products can be integrated to enhance decision support systems for biodiversity monitoring and address policy priorities such as the EU Biodiversity Strategy for 2030. Three showcases will be developed based on the three pilots mentioned above and demonstrate and assess the policy utility and impact of the results from these pilots. The assessment will be made together with relevant Early Adopters. Each show case will address specific biodiversity policy goals by presenting information that is easy to act on and has clear potential to lead to enhanced biodiversity management.

BIOMONDO aims to develop a broad outlook on ongoing changes in freshwater biodiversity and how these changes can be monitored using EO data in combination with models. Our Freshwater Biodiversity pilots will address pilot objectives corresponding to some of the main drivers of global environmental change and ultimately, these pilots should contribute to the development of a Science Agenda and Scientific Roadmap for the implementation phase of the EC-ESA Biodiversity Flagship Action.

2 Introduction

Biological diversity (biodiversity) is the variety of life on Earth and depends on the many different aspects that make organisms and the communities within which they coexist unique. For monitoring biodiversity, a single, objective metric of biodiversity does not exist. But it can be determined on different levels of organisation, i.e. varying from *genetic diversity* within and between populations of the same species, *species diversity* within and between ecosystems, to the *diversity of different ecosystem and/or habitat types* on a regional or global scale. In addition to this, species have different roles and functions within ecosystems. In a well-functioning ecosystem, i.e. in which species appear to coexist over longer time periods, there typically are large differences between the number and diversity of species within different functional and/or taxonomic groups. There are, for example, typically few top predators relative to the number of species on lower trophic levels e.g. relatively few bird species when compared to the number of insect species. Rather than determining the total species richness of entire ecosystems, we may therefore want to determine *the biodiversity of different functional or taxonomic groups* separately and/or to determine an ecosystem's *functional diversity*, i.e. the extent to which species are different or do different things. In an attempt to identify the major components of biodiversity, Franklin *et al.* (1981) recognized three primary attributes in ecosystems: composition, structure, and function. Composition has to do with the identity and variety of elements, e.g. genes, species, and landscape types, in a collection. Structure is the physical organization or pattern of a system, from habitat complexity to patterns in the networks of interactions between species. Function involves ecological and evolutionary processes, including gene flow, disturbances, and nutrient cycling (Figure 1, Noss, 1990)

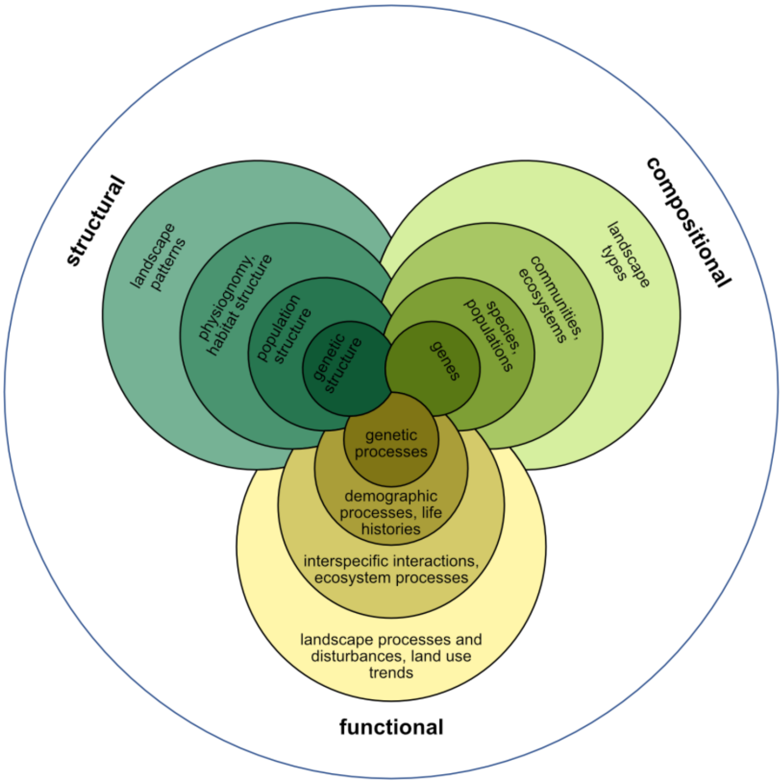

Figure 1: Compositional, structural, and functional biodiversity, shown as interconnected spheres, each encompassing multiple levels of organization. This conceptual framework may facilitate selection of indicators that represent the many aspects of biodiversity that warrant attention in environmental monitoring and assessment programs (redrawn from Noss, 1990).

Measurable, objective metrics of biodiversity cannot capture all these different aspects of biodiversity simultaneously, simply because the development of such metrics requires subjective choices on how much we value one aspect of biodiversity relative to the others. Compound metrics of the value or quality of natural areas used in national or regional government policies exist that take a variety of factors into account (e.g. different aspects of biodiversity as well as a landscape's cultural and historical value), but there is no globally accepted metric of biodiversity that can capture the broadness of this concept in a single, measurable value.

Still, the scientific community knows broadly accepted, measurable metrics of diversity for most of the aforementioned aspects of biodiversity. This means that the question of *which aspects of biodiversity to monitor* is most crucial (see further Chapter 3). Ecologists, for example, usually define species diversity in a way that takes the number, i.e. *species richness*, as well as the evenness of the relative abundances of species into account. Taxonomic groups with more species and/or more even abundance distributions are considered to be more diverse (Shannon and Weaver, 1949; Simpson, 1949). Other metrics describe biodiversity on different levels, e.g. within an ecosystem, between ecosystems, and on a landscape level (Whittaker, 1972).

A key question to answer when deciding which aspects of biodiversity to monitor, is which aspects we value as most important for nature conservation, which is a question for policy makers. Methodological issues, i.e. some aspects of biodiversity are easier to monitor than others, come second to this. When it comes to policy targets, we are – in addition to this - confronted with the question of whether we want to *increase, preserve*, or *restore* biodiversity. To trace an increase in biodiversity, monitoring simple metrics of biodiversity might be sufficient. But environmental policies are more commonly mandates to preserve or restore biodiversity relative to a desired reference state, rather than simply to increase biodiversity. This can mean to safeguard ecosystem services, avoid biotic homogenization or protect rare species of specific habitat types that may often have a relatively low biodiversity. So, the reason *why we want to monitor biodiversity* may influence the way in which we have to do this (see Chapter 0).

In addition to the previously discussed questions of *why* and *which aspects* of biodiversity we want to monitor is *what* we want to do with the information we obtain when monitoring biodiversity. Usually, this involves mitigation of the effects of changing environmental conditions that are leading to a change in biodiversity (e.g. relative to a reference state). It is, perhaps for that reason, that the important global assessments of biodiversity change focus on the impact of these drivers on biodiversity rather than on monitoring or describing a change in biodiversity per se (e.g. MEA 2005; IPBES 2019 – Regional Reports). Scientifically, there are also reasons for such a focus. First of all, drivers of global environmental change usually affect most or all of the above described aspects of biodiversity simultaneously. As such, they thus come as close to a compound proxy for change in (the many different aspects of) biodiversity as we can get. And, secondly, a change in environmental drivers may precede biodiversity loss by several decades. Monitoring a change in environmental drivers thus gives us an early outlook on future changes in biodiversity to come. The key to a biodiversity monitoring system that provides useful scientific and policy output is, in our view, therefore a system that assesses impacts and trends of drivers of global environmental change on (different aspects of) biodiversity. BIOMONDO, therefore, takes off from these drivers, and explores how Earth observation techniques can be used to assess these drivers and their impacts on freshwater ecosystems (Figure 2).

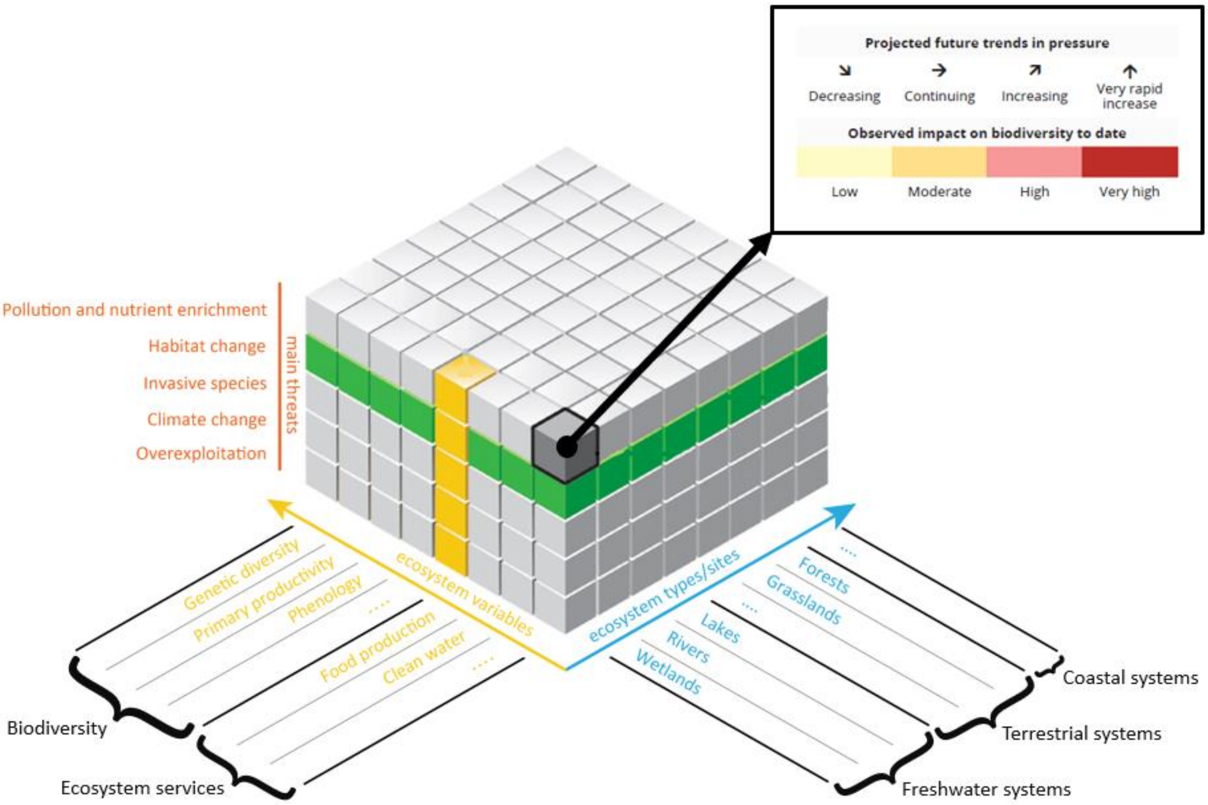

Figure 2: Monitoring biodiversity is a three-dimensional problem. Objectives when monitoring biodiversity are usually of the type: We monitor the effect of threat X on ecosystem variable Y for ecosystem type/site Z. Ultimately, these monitoring efforts help to assess observed impacts on ecosystem variables, or to project future trends. Key threats to biodiversity usually, if not always, belong to one of the five main classes 'pollution and nutrient enrichment', 'habitat change', 'invasive species', 'climate change', and 'overexploitation'. Ecosystem variables either describe a change in a particular aspect of biodiversity (see Figure 1 and Chapter 0) or a change in an ecosystem service (see Chapter 3). Ecosystem types belong to the three broad classes 'freshwater ecosystems', 'terrestrial ecosystems', and 'coastal systems. In BIOMONDO we focus freshwater ecosystems.

3 International policies and assessments

3.1 Frameworks and drivers for policy change

Global and regional biodiversity and sustainability policies, strategies and assessments comprise a suite of regular updates by different bodies of the United Nations, namely the General Assembly (GA), the United Nations Environment Programme (UNEP), the Secretariat of the Convention on Biological Diversity (CBD), and the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES). The biodiversity strategy of the European Union (EU) is closely linked to this development. In addition, almost 200 countries have developed National Biodiversity Strategies and Action Plans (NBSAP) in response to Aichi target 17[1]. An overview of major documents published by these organizations is shown in Figure 3. Two additional IPBES assessments were launched in early 2022 as part of the work programme 2030, one is the nexus assessment between biodiversity, water, food, energy and health in the context of climate change, and the other aims to assess the causes of biodiversity loss and the determinants of transformative change.

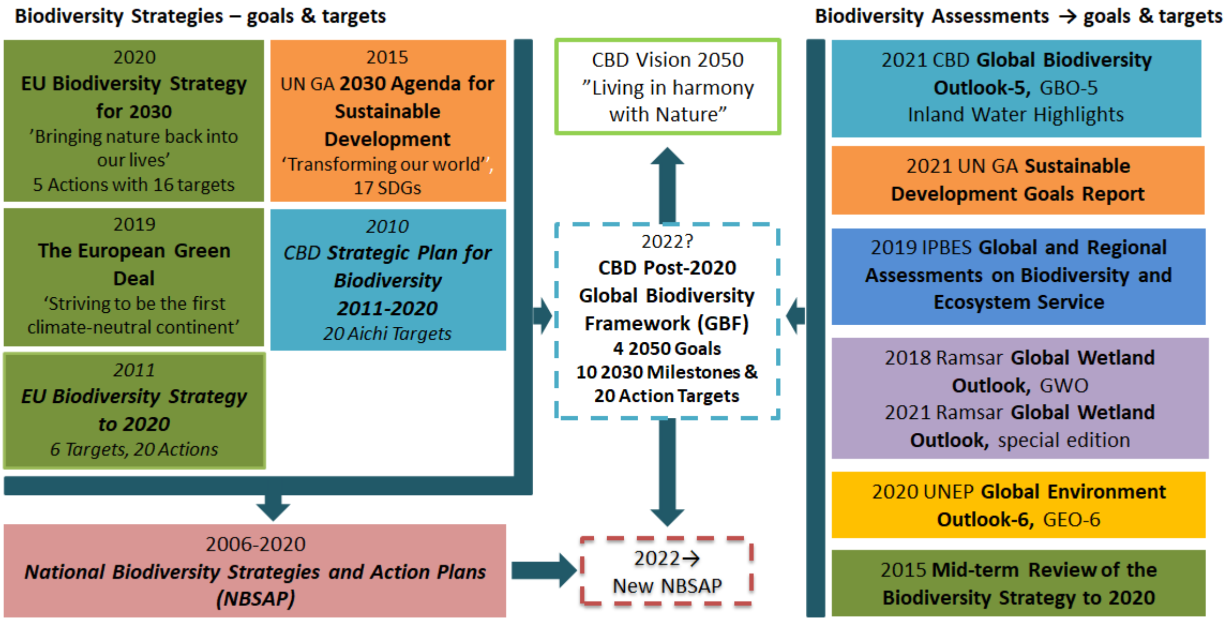

Figure 3: Overview of policy documents released by UN GA (orange), UNEP (yellow), CBD (light blue), IPBES (blue), the EU (dark green) and individual countries and parties of the CBD (red). The new CBD Post-2020 GBF and new NBSAPs are marked with a dashed frame to set them apart from adopted strategies and plans. The dashed line symbolises that the steps for adoption are not complete. Policies in italics indicate replacement by revised versions.

The CBD Strategic Plan for Biodiversity 2011-2020, including Aichi Biodiversity Targets, has currently (November 2021) been developed into the First draft of the post-2020 global biodiversity framework (GBF), including a declaration of main intents at the UN Biodiversity Conference and COP 15 – the Kunming declaration 2021. National Biodiversity Strategies and Action Plans (NBSAPs) for 2006-2020 will be reviewed because of the new GBF. These will be of crucial importance as it is on national and local levels that policies need to be implemented and actions take place. Ongoing policies and strategies include the UN GA 2030 Agenda for sustainable development (2015) with its Sustainable Development Goals (SDGs) and is of key importance for policies and strategies for biodiversity as many of its goals contain aspects that directly relate to biodiversity, ecosystems and their services.

In addition, the UN GA has proclaimed the UN Decade 2021-2030 as the Decade for Restoration (https://www.decadeonrestoration.org/), following a proposal for action by over 70 countries from all latitudes. It is "*a rallying call for the protection and revival of ecosystems all around the world, for the benefit of people and nature. It aims to halt the*

[1] By 2015 each Party has developed, adopted as a policy instrument, and has commenced implementing an effective, participatory and updated national biodiversity strategy and action plan.

degradation of ecosystems, and restore them to achieve global goals." It is led by UNEP and FAO and aims to empower a global movement through a strategy with ten actions including building political momentum for restoration, capacity building and thousands of initiatives on the ground.

At the 2010 Nagoya COP 10, the CBD framed the vision of *Living in Harmony with Nature* by 2050, which calls for transformative societal change and aims to *mainstream* biodiversity appreciation. Several related concepts support this vision. *Bending the curve* of biodiversity loss means that multiple efforts such as reduced consumption, sustainable production, the mitigation of climate change, conservation and restoration must be combined to halt biodiversity loss (see for example, WWF Living Planet Report, 2020, CBD GBO-5, 2020, Tickner et al. 2020, Leclère et al. 2020, van Rees et al., 2020). This transition is motivated by IPBES' concept of *Nature's Contributions to People* (NCP), which builds on ecosystem services and incorporates cultural values and specifically indigenous and local knowledge (Diaz et al., 2018). A number of tools have been developed to help the policy implementation of these visionary concepts. The *Nature Future Framework* by IPBES is a heuristic tool to develop scenarios with positive futures for nature and to inform assessments of policy options across multiple scales, and across natural, societal and cultural value perspectives (Kim et al., 2021; Pereira et al. 2020, Scholenberg et al. 2018).

Natural Capital Accounting (NCA) is an umbrella term for the use of an accounting framework to measure and report on stocks and flows of natural capital in a systematic way. It supports policy decisions on a set of unbiased data describing material natural resources, such as forests, energy and water. The System of Environmental Accounting (SEEA) is the standard for environmental-economic accounting and its framework was adopted in 2012 by the UN Statistical Commission of the System of Environmental Economic Accounting. The SEEA Ecosystem Accounting (SEEA-EA) complements the central framework of the SEEA and was adopted in March 2021. It is built on five core accounts: ecosystem extent, ecosystem condition, ecosystem flow accounts (physical and monetary) and monetary ecosystem asset. Compliant with the SEEA-EA is the European accounting system INCA (Integrated Natural Capital Accounting), that is now being further developed to provide support in the form of data and tools for decision making at different stages of the policy cycles (INCA21, 2021-2023, a Eurostat funded project) INCA concepts are closely linked to the Mapping and Assessment of Ecosystem and their services (MAES, Maes et al. 2020). *Nature Based Solutions* are recommended in policies and strategies (e.g. the EU Biodiversity strategy for 2030, UN WWAP (United Nations World Water Assessment Programme)/UN-Water (2018)) and defined as "actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (IUCN, accessed 2022). According to (Lafortezza et al. 2018) EO data has potential to support measurement of the viability of nature-based solutions and assessment of projects aiming to protect and restore natural ecosystems.

To achieve the 2050 vision and a transformative change to business as usual both the direct and indirect drivers of biodiversity loss need to be addressed in combination (see section 3.3.1 and CBD, 2022).

3.2 Current biodiversity policies and strategies

In addition to the EU 2030 Biodiversity Strategy, ongoing policies and strategies relevant to freshwater biodiversity include the UN 2030 Agenda for sustainable development and the Ramsar Convention on Wetland Strategic Plan (2016-2024).

The **EU Biodiversity Strategy for 2030** (EC, 2015) builds on earlier strategies such as the EU Biodiversity Strategy to 2020, (EC, 2011) and assessments, Mid-term review of 2020 targets, (EC, 2015), and the key goals are to protect and restore European nature. A mid-term review is planned for 2024. To address the five known drivers of declining biodiversity (Figure 2) the strategy commits to establishing a larger EU-wide coherent network of protected areas on land and at sea, to launching an EU Nature Restoration Plan, to introducing measures to enable the necessary transformative change and to introducing measures to tackle the global biodiversity challenge

The EU Nature Restoration Plan includes legally binding EU nature restoration targets to be proposed in 2021. By 2030, significant areas of degraded and carbon-rich ecosystems should be restored. Habitats and species shall no longer show deterioration in conservation trends and status, and at least 30% reach favourable conservation status or at least show a positive trend. The decline in pollinators shall be reversed. The risk and use of chemical pesticides must be reduced by 50%, and at least 10% of agricultural area must be under high-diversity landscape features. At least 25% of agricultural land shall be under organic farming management, and the uptake of agro-ecological practices is significantly increased. Finally, three billion new trees should be planted in the EU and at least 25,000 km of free-flowing rivers should be restored.

In relation to pollution, the EU 2030 strategy furthermore states that the Commission will promote the goal of zero pollution from nitrogen and phosphorus flows from fertilisers through reducing nutrient losses by at least 50%, while ensuring that there is no deterioration in soil fertility. This will result in the reduction of use of fertilisers by at least 20%. To this end, the Commission will work with Member States to develop an Integrated Nutrient Management Action Plan in 2022. It will also develop a set of indicators for the progressive reduction of pollution and will establish baselines to help monitor progress.

The strategy recognises that the fight against biodiversity loss must be based on sound science. To support this the Horizon Europe programme has been launched, which includes a long-term strategic research agenda for biodiversity. The Commission will promote and facilitate partnerships, including a new dedicated European Biodiversity Partnership: Biodiversa+ (see section 4.1.3), to make the bridge between science, policy and practice and make nature-based solutions a reality on the ground. The Commission has in 2020 established a new Knowledge Centre for Biodiversity (KCBD) in close cooperation with the European Environment Agency (EEA). Hopefully, it can support a change to a less piece-meal approach to improving freshwater ecosystem and address the entire pollution chain from source to impacts. On the KCBD web site, the EC has in December 2021, launched an online actions tracker that will provide up-to-date information on the state of implementation of the many actions of the Biodiversity Strategy. A Targets Dashboard will complete the picture by showing progress to the quantified biodiversity targets set by the Strategy, both at the EU level as well as in the Member States.

The dashboard is in its prototype phase, with a current set of seven indicators that will be complemented with additional ones in 2022.

The EU Biodiversity Strategy also recognises that protecting biodiversity is a global challenge and the next decade will be decisive. In this spirit, the EU is ready to lead all efforts – working with like-minded partners in a high-ambition coalition on biodiversity – to agree an ambitious new global framework for post-2020 at the upcoming 15th Conference of the Parties to the Convention on Biological Diversity. With the strategy, the Commission proposes ambitious commitments for the EU to bring to the table.

The **UN GA 2030 Agenda for sustainable development (2015) with its Sustainable Development Goals (SDGs)** is of key importance for policies and strategies for biodiversity as many of its goals contain aspects that directly relate to biodiversity, ecosystems and their services. The 2030 Agenda is a framework of universal and indivisible goals and targets to address a range of global societal challenges. It is a data and evidence driven agenda, consisting of a framework of the 17 SDGs and 169 targets, supported by 232 indicators. The indicators are intended as a management tool for countries to implement development strategies and report on progress towards the SDG targets. Many of the SDGs require conservation of freshwater and the most relevant SDGs for Freshwater ecosystems and biodiversity are (Harper et.al. 2021, Weise et.al. 2020, Turak et.al. 2017):

- SDG 3 Ensure healthy lives and promote well-being for all at all ages
- SDG 6/6.6 Clean water and sanitation/Protect and restore water-related ecosystem (indicator 6.6.1 "Proportion of water basins experiencing high surface water extent changes" is especially important for wetlands)
- SDG 12 Ensure sustainable consumption and production patterns
- SDG 14 Life Under Water
- SDG 15.1 Life on land/Conserve and restore terrestrial and freshwater ecosystems

Also, SDG 6.4, the target for increasing water use efficiency, is closely related to freshwater biodiversity because of links to both water extent and flow, and water quality. The assessment of indicators 6.4.1 *Change in water-use efficiency over time* and 6.4.2 *Level of water stress: freshwater withdrawal as a proportion of available freshwater resources* can provide tools to help manage issues related to balancing different resources needs.

Through the SDGs the UN Member states have agreed to address the goals and national governments can use reporting on progress towards the goals as a tool to achieve their goals and identify data gaps.

The Convention on Wetlands, or the Ramsar Convention, as it is often called (https://www.ramsar.org/), is the intergovernmental treaty that provides the framework for the conservation and wise use of wetlands and their resources. Established in 1971 in Ramsar, Iran (and in force in 1975) it has now been signed by 172 contracting parties. Under the "three pillars" of the Convention, the Contracting Parties commit to:

- work towards the wise use of all their wetlands
- designate suitable wetlands for the list of Wetlands of International Importance (the "Ramsar List") and ensure their effective management
- cooperate internationally on transboundary wetlands, shared wetland systems and shared species

The **Ramsar Strategic Plan for 2016-2024** was approved at COP12, 2015 in Uruguay, and lays out a new vision with three strategic goals, one operational goal and 19 specific targets which are designed to support, Parties, partners and other stakeholders in preventing, stopping and reversing the global decline of wetlands (Ramsar Convention Secretariat, 2016). The goals involve addressing drivers of wetland loss and degradation, conserving and managing the Ramsar Site network, wisely using all wetlands, and enhancing implementation of the Convention on Wetlands.

All Parties are required to regularly report the status and change in the ecological character of wetlands and on a three yearly basis progress on national implementation including challenges, difficulties and future priorities as well as specific actions relating to the goals and targets. Additional information relating to the Ramsar sites can also be added. Implementation of the Strategic plan should contribute to the achievement of several SDGs and targets but are based mainly on reports on the SDG indicator 6.6.1. However, non-compliance relating to the reporting requirements might be jeopardise the gathering of adequate information for the SDG reporting on change in the extent of water-related ecosystems over time (Davidson et al. 2020).

3.3 Global biodiversity assessments

3.3.1 IPBES Global Assessment report

The 2019 IPBES Global Assessment on Biodiversity and Ecosystems Services (IPBES, 2019) is the first global assessment of ecosystems and biodiversity since the Millennium Ecosystem Assessment 2005 (MEA, 2005), and it refers to the same direct drivers (Figure 4). It is based on 15,000 scientific publications, including local and indigenous knowledge as well as feedback on IPBES regional reports such as the IPBES regional assessment report for Europe and Asia (IPBES, 2018). It is a critical assessment "of the status and trends of the natural world, the social implications of these trends, their direct and indirect causes, and, importantly, the actions that can still be taken to ensure a better future for all." <u>Direct drivers</u> are land and sea use change, exploitation, climate change, pollution, invasive alien species and "Others" which include interaction between drivers. <u>Indirect drives</u> include demographic and sociocultural, economic and technological, institutions and governance, and conflicts and epidemics (Figure 4). The Global Assessment report also outlines specific findings for freshwater ecosystems, for which land use change dominates followed by direct exploitation and pollution (see also Section 4.3.2). Inland waters and freshwater ecosystems show among the highest rates of decline (see also section 3.3.3). According to IPBES (2019) and Ramsar Convention on Wetland (2018) only 13 per cent of the wetland present in 1700 remained by 2000 and recent losses have been even more rapid (0.8 per cent per year from 1970 to 2008) ("established but incomplete").

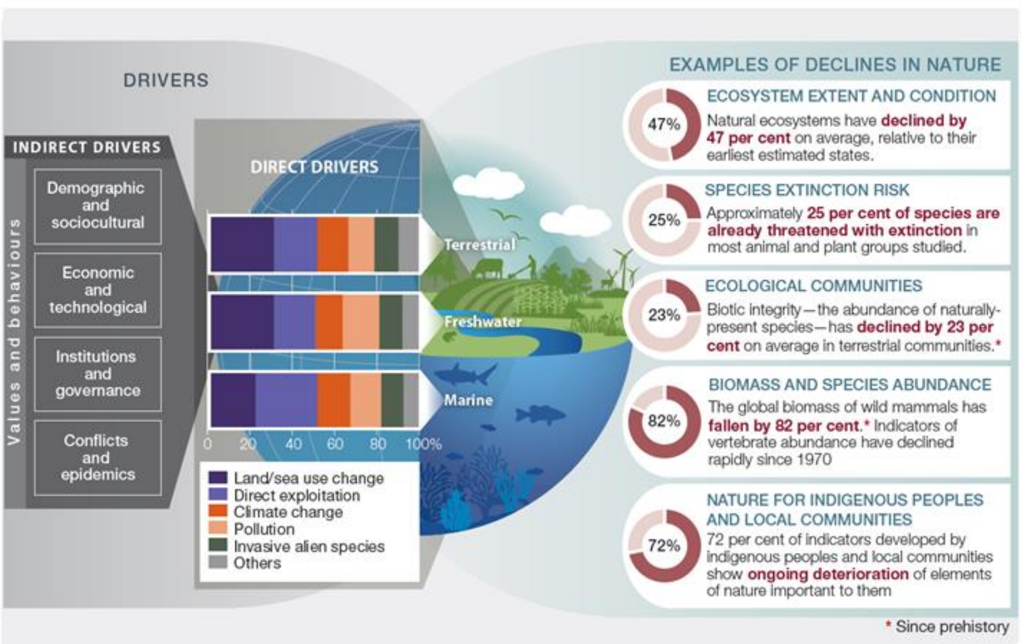

Figure 4: Direct and indirect drivers of change including examples of declines in nature (based on studies since 2005). It shows the relative global distribution for terrestrial, freshwater and marine ecosystems in colours. From IPBES Global Assessment, 2019, SPM2, p XXIX.

A tentative list of knowledge gaps is included in the Global Assessment report as Appendix 4, several of which are specific for freshwaters and could be addressed by further activities in BIOMONDO (see also section 4.3.2, Appendix 1 and Appendix 2, Table 9). The gaps in monitoring of nature and the drivers of change represent potential observables for satellite earth observation, and the gaps concerning specific biomes and units of analysis emphasize that freshwater ecosystems are particularly understudied. But needs for quantitative, global data and indicators that can potentially be sourced from Earth observation recur in all sectors.

3.3.2 CBD Global Biodiversity Outlook 5

The CBD Global Biodiversity Outlook 5 (CBD GBO-5, 2020a) is the most recent report on progress towards the Aichi biodiversity targets, which were a part of the CBD Strategic Plan for 2011-2020. The assessment is based on indicators, research studies and assessments (including IPBES GA BES and national implementation reports). It describes in detail the eight transitions considered to be needed to reach the overarching 2050 goal of *Living in Harmony with Nature*. The GBO-5 also specifically contains a final assessment of the Aichi biodiversity targets in inland and freshwater systems and transitions needed for sustainability. The outcomes are also summarised in a separate publication called GBO-5 Inland Waters Highlights (CBD, 2020b). The main findings from the assessment of the progress towards these Aichi Targets indicate a doubling of manmade wetlands at the expense of natural wetlands, an extensive fragmentation of most of the World’s rivers, a missing protection status for 60% of 15,000 Key Biodiversity Areas (KBA) and faster decline in freshwater than all other species. See 0 for the point-by-point assessment of Aichi Targets for inland waters.

The GBO-5 key components of the Sustainable Freshwater Transition (or actions) are closely related to the key drivers of biodiversity loss of freshwater ecosystems and these need to be implemented across all levels of society. They have been selected as starting points for the BIOMONDO pilot objectives and are included in the Science and Policy Traceability Matrix (SPTM). Difference to note are that climate change effects on freshwater ecosystems is not specifically mentioned in the GBO-5 Inland Water Highlights but integration of environmental flows into water management is included as a key component. With respect to Target 15, dam removals for river flow restoration have increased exponentially since 1950s. There is potential for EO to support this specific restoration target by improving the status of current dam datasets as well as monitor effects of restoration actions. This has been added as a potential pilot objective for BIOMONDO.

3.3.3 Other relevant assessment reports

The UN Sustainable Developments Goals Reports (UN, 2020, UN, 2021) assess the progress towards the SDGs. The progress towards these goals shows a similar failure to the progress towards the Aichi targets, and the 2021 update due to the COVID-19 crisis reveals devastating impacts. Specifics for freshwater ecosystems relate mainly to SDG 6 Clean Water and Sanitation and SDG 15 Life on Land. In the 2021 SDG report section on Target 6 Clean Water and Sanitation there is specific focus on the dramatic change in freshwater ecosystems including loss of inland wetlands. The need for urgent response in the form of upscaling and acceleration of restoration and protection efforts is highlighted. Naturally, the overlap of the SDG and Aichi targets are high (Schulz et al. 2016), and so are the results of the assessments, including the loss of natural wetland area, the lack of protected freshwater KBA etc.

Two recent Ramsar assessment reports, Global Wetland Outlook (Convention on Wetlands, 2018) and its 2021 special edition (Convention on Wetlands, 2021a) are of high relevance for the Freshwater ecosystem theme of BIOMONDO. They highlight that outside the Ramsar list of wetlands of international importance (13-18% of the global wetland area) wetland loss is ongoing and fast, and they emphasize the need for actions, such as improvement of national wetland inventories, tracking of wetlands' extent and identification of and measurement of drivers of change. These actions can all be supported by approaches integrating remote sensing with field assessments (and citizen science). Furthermore, in the Ramsar global guidelines for peatland rewetting and restoration (Convention on Wetlands, 2021b) it is stated that "remote sensing should be developed as a near real-time and cost-effective method for monitoring large-scale restoration projects". This objective will be considered in BIOMONDO depending on the final choice of Pilots and Pilot sites.

The 2020 World Wildlife Fund (WWF) Living Planet Report (WWF, 2020) refers to the Living Planet Index (LPI) to track the abundance of populations. It indicates a 68% decrease in population sizes of mammals, bird, amphibians, reptiles and fish between 1970 and 2016. But the Global LPI does not give the entire picture as biodiversity declines at different rates in different places. Based on the five IPBES regions the decline is for example 94% for South America compared to 24 % for Europe. But overall, the report supports the relevance of the BIOMONDO approach using EO data in combination with biodiversity modelling such as GLOBIO and its output "Mean Species Abundance (MSA)" to potentially support improvements in calculating scenarios based on different land-use models.

Global Environment Outlook reports are published by the UN Environmental Programme (UNEP). The most recent, GEO-6 Global Environment Outlook (UNEP, 2019), provides an assessment of recent scientific information and data, analysing current and past environmental policy, and identifying future options for achieving sustainable development by 2050. The results include four key messages with 31 detailed descriptors/points of needed actions and aims to help policy makers and society achieve environmental goals, such as the SDGs and other internationally agreed environmental goals. The report includes a specific chapter (No. 7) on Global environmental state of Freshwater and (No. 16) Freshwater Policy.

3.4 Post-2020 Global Biodiversity Framework

Based on the CBD Strategic Plan for Biodiversity 2011-2020 that included the Aichi Biodiversity Targets (2010) a new framework, the Post-2020 Global Biodiversity Framework (GBF), is now under development. The First draft (CBD, 2021a) included a declaration of main intents that were presented at the UN Biodiversity Conference and COP 15, in Kunming, China – the Kunming declaration 2021. The UN Biodiversity Conference marks the close of Aichi targets. The second meeting at Kunming to endorse the finals version of the GBF is planned for April/May 2022. The GBF describes updated goals for 2050 and it also recognises a close mutually enabling relationship with the SDGs of the 2030 Agenda for Sustainable Development. The 2050 Vision as set out in the 2011-2020 Strategic Plan (CBD, 2010) remains the same but the 2030 Mission is revised, simplified and made more concise compared to the 2020 Mission. There are four main long-term goals for the 2050 vision, each with 2-3 milestones and several targets for the 2030 Mission. The progress towards the 2050 vision will be assessed in 2030 but monitored along the way.

The key targets of the proposed GBF correspond mostly to the drivers listed in Figure 2. First, to stop *habitat change* by ensuring that at least 30% globally of land areas and of sea areas, especially areas of particular importance for biodiversity and its contributions to people, are conserved through effectively and equitably managed, ecologically representative with well-connected systems of protected areas and other effective area-based conservation measures, and integrated into the wider landscapes and seascapes. Second, to take action against *invasive species* by reducing the rate of introduction and establishment of invasive alien species by 50%, and control or eradicate such species to eliminate or reduce their impacts. Third, to reduce *nutrient enrichment and pollution* by reducing nutrients lost to the environment by at least half, pesticides by at least two thirds, and eliminate discharge of plastic waste. Fourth, to mitigate *climate change* by means of ecosystem-based approaches that contribute at least 10 Gt CO_2 per year to mitigation and ensure that all mitigation and adaptation efforts avoid negative impacts on biodiversity. Fifth, overexploitation is addressed by redirecting or eliminating incentives harmful for biodiversity in a just and equitable way, by at least $500 billion per year. Ultimately, and in support of these five targets, it requires to increase financial resources from all sources to at least US$ 200 billion per year, including new, additional, and effective financial resources, increasing by at least US$ 10 billion per year international financial flows to developing countries, leveraging private finance, and increasing domestic resource mobilization, considering national biodiversity finance planning.

A comparison of the Aichi Targets and the proposed post-2020 GBF targets are shown in Figure 5. In the Aichi targets Biodiversity (BD) and Ecosystem (ES) and Ecosystem Services (ESS) issues were included in every goal, whereas in the GBF goals and target these issues are distilled into specific themes. As the draft GBF is under revision and the definition and description of the goals keep changing further comparison between the Aichi targets and the new GBF targets is difficult. However, the targets associated with Goal A, that relate to status and change trends of ecosystems are those where EO data and remote sensing inputs can provide essential support.

Aichi 5 Goals – 20 Targets (2020)	GBF 2022 4 Goals – 12 Milestones/20 Targets (2030)
A. Causes of BD loss adressed – mainstreaming BD, impl in plans B. Reduced direct pressures – BD loss reduced, sust man (..invasive species, climate ch) C. Improved BD status (safeguard ES and genetic diversity) D. Benefits fr BD & ES shared, impr. ES restoration for essential ESS, & ES resilience E. Enhanced implementation, integration of indigenous and local knowledge in plans	A. Enhanced integrity of all ES i. Area, connectivity, integrity ->5% ii. Extinction rates reduced iii. Gen. diversity safeguarded B. Natures contribution to people NCP i. Fully accounted and informing decisions ii. Contributing to SDGs C. Benefits shared – utilisation of genetic resources D. Gap closed btw finances and other means needed and those necessary to achieve 2050 vision

Figure 5 Comparison of the Aichi goals and the proposed GBF goals. BD = biodiversity, ES = Ecosystems, ESS = Ecosystem Services.

For Goal A, which focuses on the extent, integrity and connectivity of ecosystems (A.0.1 and A.0.2), the GEO BON Species Habitat Index (SHI) can give measurements of changes to losses and gains. The SHI is enabled by EBVs and is calculated and validated using species occurrence data combined with environmental change data informed by remote sensing (CBD/WG2020/3/INF/6, 2021[2]). There are also other "goal monitoring elements" where remote sensing data can inform indicators, such as "Trends in fragmentation and quality of inland waters" and "Trends in wetland extent" as outlined by GEO BON[3]. For Goal A, remote sensing products can support derivation of EBVs and indicators to inform on status and progress towards GBF targets, both at a global scale but also to support national biodiversity observation systems.

The GBF recognises that to galvanise action and create change, a new framework must be fundamentally different to previous approaches and has therefore built it around a Theory of Change (Figure 6). It recognises that "*urgent policy action globally, regionally and nationally is required to transform economic, social and financial models so that the trends that have exacerbated biodiversity loss will stabilize in the next 10 years*" and assumes that "that a whole-of-government and society approach is necessary to make the changes needed…". As part of the Mission and Means of implementation Tools and Solu-

[2] https://www.cbd.int/doc/c/2397/5133/3ce87fa6c735a7bf1cafb905/wg2020-03-inf-06-en.pdf
[3] https://www.cbd.int/doc/c/60fe/c885/c309aa2a521eb0fec8f892c4/sbstta-24-item3-geobon-technical-support-en.pdf

tions are highlighted which includes using new techniques such as those intended to be developed within BIOMONDO that can contribute information to implement actions to reduce threats and meeting people's needs. We see remote sensing products integrated with biodiversity modelling as a means to achieve the transparency and responsibility needed and these novel approaches can help development of appropriate and globally valid indicators to inform on biodiversity status and trends. The Theory of Change of the GBF is in line with the IPBES identified solution to reverse the current trajectory of human impact on nature and its negative consequences: "Transformative Change" and the third chapter of the EU Biodiversity Strategy 2030, which outlines steps to enable transformative change by establishing a new European biodiversity governance framework, stepping up implementation and enforcement of EU environmental legislation and building on an integrated and whole-of-society approach. In preparation for the Geneva meetings in March 2022, a document prepared by GEO BON and bioDISCOVERY program of Future Earth (CBD, 2022), has been circulated that emphasises the importance of transformative actions and provides "an updated synthesis and assessment of how the actions implied by the proposed targets in the first draft of the post-2020 global biodiversity framework and a comprehensive monitoring framework could contribute to achieving the biodiversity milestones and goals (Goal A) of the framework." Furthermore, it states that "to achieve a transformative change we must also address the indirect social and economic drivers of biodiversity loss."

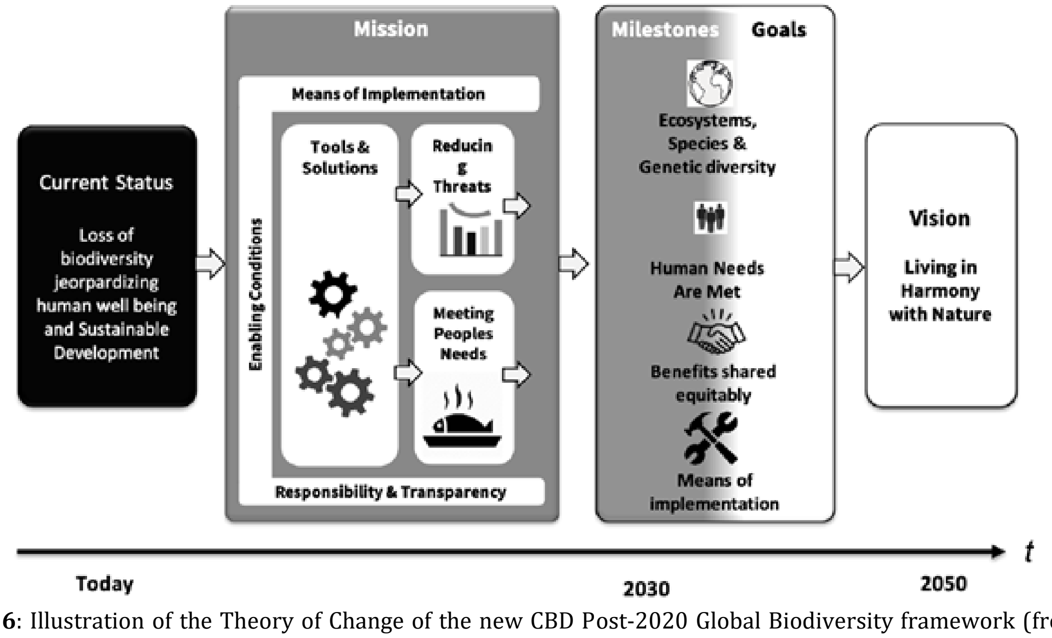

Figure 6: Illustration of the Theory of Change of the new CBD Post-2020 Global Biodiversity framework (from CBD (2021a)).

A main challenge for the CBD development of a new post-2020 framework is to ensure that the negotiations leading up to the GBF arrive at assessments, new milestones and targets that are more than lowest common denominators of the participating nations and that a stringent monitoring system for progress is put in place to ensure that deviations from the strategy/plan can be addressed swiftly and effectively along the way, although the problem might not be unambitious targets but rather failure to achieve any targets... Developments towards a truly different post-2020 global biodiversity framework is further outlined in (CBD, 2020c) and it is highlighted that it needs to be accompanied by a rigorous monitoring framework, which currently is in draft form (CBD, 2021c).

It is also becoming more and more evident that climate change is not only an increasingly relevant driver of biodiversity loss, but there is also a climate change - biodiversity nexus which requires careful consideration of actions that do not play the two issues off against each other, and in the best case deliver mutual benefits. From an Earth observation perspective, the emerging collaboration between IPBES and IPCC means that the two scientific communities may move towards joint action, and shared platforms or observation systems (O'Connor et al. 2020).

Despite the detailed goals of the biodiversity policies and strategies for the last twenty-five years the negative trends have continued in response to direct human-caused drivers. The reasons are many and interlinked but the main areas that have been highlighted are increasing pressure from direct drivers, a lack of legally binding agreements/binding conservation legislation, especially on national and local levels where implementations of actions to protect and restore biodiversity take place, lack of funding and imprecise goals, targets and indicators. Close involvement and cooperation between all sectors of society including actual economic valuation of ecosystems, their services including biodiversity, have been deficient as well as in some cases the actual will to achieve goals.

4 Scientific frameworks and challenges

4.1 International networks and projects

Several international biodiversity networks (GEO BON, bioDISCOVERY, Biodiversa+) are now operating that try to bring the work of the different science communities closer to the priorities of the policy sectors. The systems for monitoring, modelling and assessment of biodiversity are storing and creating a multitude of data but there is substantial difference in the coverage of different parts of the earth and there is a bias towards temperate regions. The challenges facing the networks and the development of information systems are several: access to appropriate biodiversity data (spatial coverage, consistency, etc), difficulties in translating raw observation data into essential variables that can facilitate indicator development to support monitoring of progress towards policy targets and improving communication between the science and policy sectors.

4.1.1 GEO BON

The Group on Earth Observations Biodiversity Observation Network (GEO BON) makes suggestions for *which aspects of biodiversity to monitor* by developing the concept of Essential Biodiversity Variables (EBVs) that could form the basis of biodiversity monitoring programs worldwide. They comprise of six classes that correspond either to a particular aspect of biodiversity or to a measure of the extent to which species are disturbed (see Table 1). A lack of global consensus on which key aspects of biodiversity to monitor however remains, with several EBVs often missing in national or regional monitoring programs. GEO BON is currently closest, and making rapid progress, towards reaching a global agreement around the concept of EBVs. See also Section 4.2.1.

Table 1: The six classes of Essential Biodiversity Variables (EBVs) as defined by the Group on Earth Observations Biodiversity Observation Network (GEO BON) (Turak et al. 2017, Pereira et al. 2013).

EBV class	EBV name
Genetic composition	Genetic diversity (richness and heterozygosity)
	Genetic differentiation (number of genetic units and genetic distance)
	Effective population size
	Inbreeding
Species populations	Species distributions
	Species Abundances
Species traits	Morphology
	Physiology
	Phenology
	Movement
Community composition	Community abundance
	Taxonomic/phylogenetic diversity
	Trait diversity
	Interaction diversity
Ecosystem functioning	Primary productivity
	Ecosystem phenology
	Ecosystem disturbances
Ecosystem structure	Live cover fraction
	Ecosystem distribution
	Ecosystem vertical profile

In addition, and as part of the development of the CBD Post-2020 Global Biodiversity Framework (GBF) and its emerging monitoring framework, GEO BON has proposed a Global Biodiversity Observation System (GBiOS), (GEO BON 2022). It will be part of the March 2022 Geneva discussions on the proposal to be presented to the COP and negotiated in step 2 in Kunming in May 2022 (see CBD 2021d). GBiOS is described as a network of networks, not to replace any existing monitoring systems but to support alignment of the information gathered globally by local, national and regional systems through guidelines including templates for reporting.

4.1.2 bioDISCOVERY

bioDISCOVERY is an international research programme fostering collaborative interdisciplinary activities on biodiversity and ecosystem science. The programme was launched by DIVERSITAS, an international research programme on biodiversity science. bioDISCOVERY became a core project of Future Earth in 2015. The international project office (IPO) of bioDISCOVERY has been hosted by the University of Zurich (Remote Sensing Laboratories) since January 2017. The mission of bioDISCOVERY is to advance and integrate science to better observe and predict biodiversity and ecosystem change. Using a network approach, the pro-gramme seeks to mobilise the scientific community to make use of observations, modelling, indicators and scenarios to support policy and decision-making for informed glob-al environmental management, including activities to overcome barriers that impede the uptake of new approaches and methodologies.

Part of the activities of bioDISCOVERY is to use Earth observations to obtain measures of taxonomic, functional and structural diversity at various spatial and temporal scales. Remote sensing is further used for the assessment of ecosystem properties that underpin the supply of ecosystem services, and will help to close gaps in observation data collected on the ground and provide global spatial assessments of select traits."

4.1.3 Biodiversa+

Biodiversa+ is the new European biodiversity partnership supporting research on biodiversity with an impact for society and policy. It is part of the EU Biodiversity Strategy 2030 and evolved from Biodiversa, which was a project supported by the ERA-NET instrument under H2020. Biodiversa has developed a database that holds information on funding programs and associated calls for research proposals on biodiversity and associated ecosystem services in Europe, research projects on biodiversity and associated ecosystem services funded through these programmes, and research institutes and other organisations (including stakeholders) that are involved in the projects funded, and researchers leading the projects. The new Partnership aims to connect science, policy and practice for transformative change. The first call for preproposals for "Supporting the protection of biodiversity and ecosystems across land and sea" (2021-2022 Joint Call) closed on November 30, 2021.

Biodiversa+ objectives highlight that biodiversity dynamics will be correlated with environmental changes assessed by Earth observation programs such Copernicus and utilisation of related research and other relevant infrastructures. Future plausible dynamics will be explored with scenarios. Biodiversa+ will help address knowledge needs by supporting development and deployment of new technologies and approaches including remote sensing through satellites and airborne campaigns among many others whose potential needs to be explored by biodiversity research and monitoring activities. It requires a transnational level of development, transfer and use, together with better use of emerging technologies and algorithms (e.g. artificial intelligence/machine learning/deep-learning).

4.2 Informing policy with observations

4.2.1 Observations, essential biodiversity variables and indicators

Indicators are essential to obtain policy-specific information from scientific data. According to the Biodiversity Indicators Partnership (BIP), indicators are successful if they are scientifically valid, based on available data, responsive to change, easily understandable, relevant to users' needs, championed by an institution responsible for its continued production and communication, and used (https://www.bipindicators.net/national-indicator-development). A lot of indicators refer to the driver, pressure, state, impact, response (DPSIR) scheme, which enable linking up of human activities, ecological dynamics, and social goals (Lévrel et al. 2009).

The EBV concept (see also Section 0) builds on the experience and successful development and use of the UN Essential Ocean Variables and the Essential Climate Variables by the Global Climate Observing System. EBVs form the basis for biodiversity monitoring services and has recently been extended to also include Essential Ecosystem Services Variables, that are being further developed by an expert group of GEO BON. In a recent publication, a minimum set of core variables needed to identify key changes in the interactions between nature and society that contribute to human well-being through ecosystem services are identified (Balvanera et al. 2022). All these different essential variables can be considered an integral complement that many indicators will be based on to track progress towards targets from national to global scales (CBD 2020c). The links between the essential variables are described further by Balvanera et al. (2022), who also highlight that global monitoring is needed of the way healthy ecosystems support thriving communities, that EESVs can track changes in human-nature interactions and that proof-of-concept testing of the EESV classes confirms their readiness for monitoring.

The relationship between primary observations, EBVs and biodiversity change indicators, including biodiversity models, is succinctly illustrated by Navarro et al. (2017) and here shown in Figure 7. In this example, integrated data from different primary sources of observations (in situ, remote sensing) are combined within biodiversity models to produce layers of spatial and temporal variation in ecosystem extent and species distribution EBVs. In some cases, one EBV can be an input for a model to produce another EBV. This information is then integrated and summarised within reporting units ((1) and (2) in the figure) to calculate an indicator of biodiversity change, which can then be used, for instance, for reporting progress towards an Aichi conservation target. Note that this indicator can be processed within any spatial unit (e.g. from an ecoregion, to a country, or an entire biome). EBVs and models can also be used to project changes in the indicator using scenarios. Although both raw observations and indicators might change in the future, including with the development of new observation techniques and the expression of new user needs, the EBVs should, by definition, remain the same.

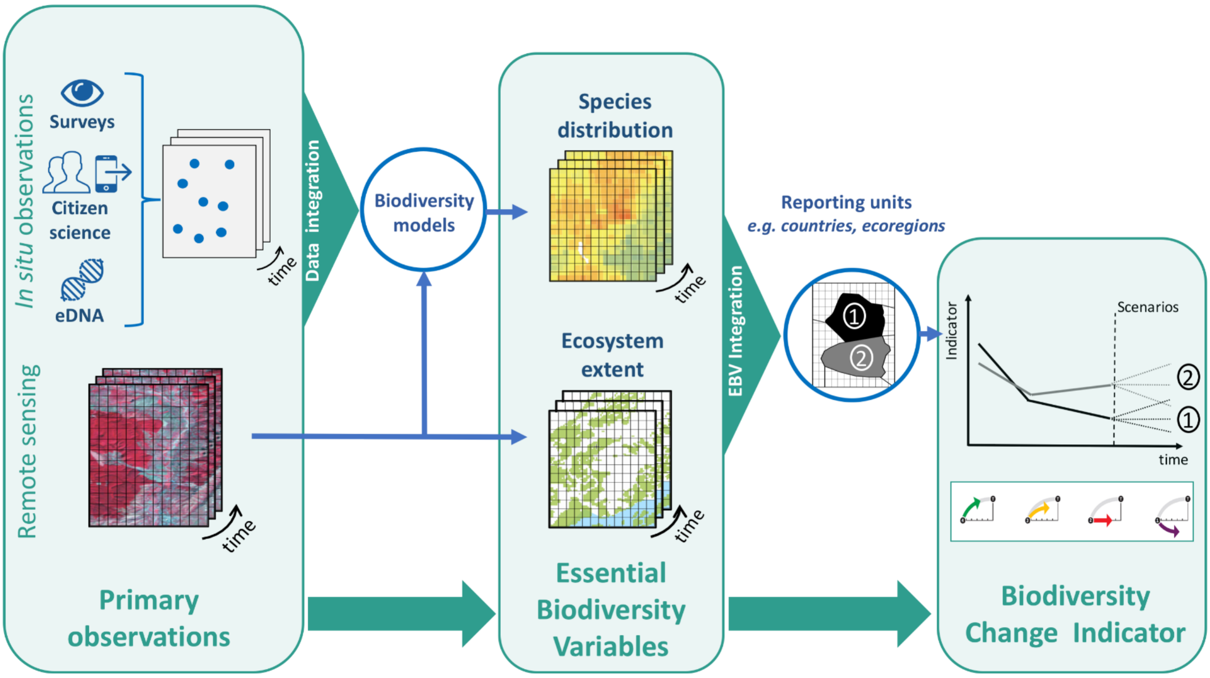

Figure 7: Relationship between primary observations, BD models, EBVs and BD change indicators. From Navarro et al. (2017).

Several other indicators useful for tracking biodiversity change have been mentioned as part of the policy and strategy review above, for example the WWF Living Planet Index, IUCN Red List Index, GEO BON Species Habitat Index, modelled indices such as Mean Species Abundance (MSA, used by GLOBIO (Alkemade et al., 2009) Index and the Biodiversity Intactness Index (BII), (Scholes & Biggs, 2005). The SEBI process to streamline European biodiversity indicators (EEA 2012) has also contributed to better align indicators with changes to goals and targets. This process is continuing in the development of the proposed indicators for the monitoring framework of the CBD Post-2020 GBF (www.post-2020indicators.org. An issue that has been raised is that many indicators in use, especially at national levels, are not portable to global levels and may need to be translated for global reporting on biodiversity change (Guerra et al. 2019, Bhatt et al. 2019).

In recent years quite some work has gone into identifying those EBVs for which satellite data and remote sensing can enable improved information that is consistent, scalable and continual with sound scientific basis, and that addresses key knowledge gaps, so called RS enabled EBVs (Pettorelli et al. 2017, Skidmore et al. 2015, O'Connor et al. 2015). Also, integration of EO in ecosystem services modelling is developing (Ramirez-Reyes et al. 2019). In doing so, ensuring that EBVs and indicators are aligned appropriately to policy objectives, close communication between policy makers and the scientists is required. Lock et al. (2021) describes the inherent problems in these relationships and ideas for how they can be solved. One such idea is for these communities to agree on what geographic extent (area size and scale) to monitor and which biodiversity attributes should be covered.

4.2.2 Biodiversity models

Models are critical tools to generalize, interpret and extrapolate links between drivers of change and the ecological state, including biodiversity composition, of ecosystems (IPBES, 2016). There are basically two types of model approaches to describe this link (Brotons et al., 2016):

a. Correlative models, linking environmental conditions to species composition and/or abundance based on empirical data; examples are species distribution models (SDMs).
b. Process-based models, based on physiological and ecological mechanisms to understand the way ecosystems and species respond to environmental drivers. Examples are dynamic vegetation models, lake food web models and eco-hydrological models.

Some hybrid models also exist that combine the two approaches. Within both types, there are (1) 'spot models', describing the relationships in (representative) ecosystems assumed homogeneous; and (2) Spatial models, that include the spatial relations between (eco)systems, such as catchment-scale models (Teurlincx et al., 2018) and connectivity models (e.g. meta-community models). Models also differ in the biological levels addressed (from organisms via species and populations to communities) and in level of complexity.

All these types of models are useful, and may complement each other (IPBES, 2016). Generally speaking, process-based models cover biota in terms of physiological/functional groups, based on traits of more or less comparable species. Available physiological knowledge often sets a limit to extend to the species level, apart from some well-known examples. These models are in principle better suited for extrapolation. Correlative models can cover the species level if the underlying data are there but are less prone for extrapolation outside the domain of the data. As ecological knowledge expands, the two types tend to move toward each other; e.g. trait-based models are increasing their number of functional groups. The future is in combination of different modelling approaches, model intercomparison projects and clear communication of uncertainties (IPBES, 2016).

Earth-system models and integrated assessment models (IAMs) are widely-used process-based and spatially explicit models. They serve as 'background models' to describe the earth's environment and may go as far as ecosystem extent (depending on climate, hydrology, land-use, etc.), on which the biotic models are superimposed. In this way they are used for global ecosystem and biodiversity assessments and projections.

Examples of empirical models are GLOBIO (Alkemade et al., 2009; Janse et al., 2015; Schipper et al., 2020) and PREDICTS (for terrestrial systems). They use a reference-based indicator (MSA or BII) representing biodiversity intactness, based on data on several species groups, but also modules based on the SDM approach are being developed for fish (Barbarossa et al., 2020). PROTECH (Elliott, 2021), is a well-known phytoplankton traits model.

The process-based model BLOOM (Los, 2009) covers three phytoplankton groups (cyanobacteria, green algae and diatoms. The cyanobacteria consist of eight genera) each divided in different physiological states. It calculates the relative abundance of these phytoplankton groups based on the availability of nutrients and light. BLOOM is part of the Delft3D software suite which allows it to be connected to the hydrodynamics module (Delft3D-FLOW) so that calculations are done at the level of the entire water system (in 3D). There are also several aquatic macrophytes models. PCLake+ (Janse et al., 2008; Janssen et al., 2018) is a model that combines the two within an ecosystem context. The Madingley model (Harfoot et al., 2014) is a so-called 'General ecosystem model' (GEM) based on physiological properties covering many biotic groups but does not yet cover freshwater ecosystems. With respect to fish, besides the empirical models mentioned, there are models for fish production, and habitat connectivity models for specific species.

In the BIOMONDO, we will use GLOBIO as an example of the empirical approach (for the fish species indicator), and BLOOM as an example of the process-based model (for the phytoplankton indicator).

4.2.3 Biodiversity observation systems

Over the last decades several biodiversity observing, or observation, systems have been developed by different global and regional partners and organisations to try to collate biodiversity related data. Closely related to these systems are different networks that aim to facilitate sharing of tools and latest scientific results as well as enabling communication between different sectors and procure information for policy. Most facilities now operate under the FAIR principle and are committed to making data Findable, Accessible, Interoperable and Reusable.

Common goals of biodiversity observation systems are to gather and make accessible species records and derived indices and other spatial and temporal aggregates. The main facilities are the Global Biodiversity Information Facility (GBIF), an international network and data infrastructure funded by the world's governments and aimed at providing anyone, anywhere, open access to data about all types of life on Earth, e.g., species occurrence data, and the Ocean Biodiversity Information System (OBIS), a global open-access data information clearing-house on marine biodiversity. Together they contain millions of species records, however 79% of GBIF data comes from ten countries, and 37% from USA (Hughes et al. 2021). The authors' analysis represents a comprehensive global analysis of both marine and terrestrial data, their spatial and taxonomic coverage, the biases encountered and the drivers of these biases. The Living Planet Index (LPI) is "a measure of the state of the world's biological diversity based on population trends of vertebrate species from terrestrial, freshwater and marine habitats.", (https://livingplanetindex.org/home/index). The data behind the LPI also show, despite being based on thousands of population time series, spatial bias towards temperate regions (Proenca et al. 2017).

Data on freshwater biodiversity are collated by the Freshwater Information Platform (www.freshwaterplatform.eu), including species distributions, pressure maps and strives for a comprehensive overview and links to the results of European and global projects on freshwater biodiversity. The Global Lake Ecological Observatory Network (GLEON) facilitates sharing of networked sensor data for lakes (sites) with its members around the world with the objective to support interdisciplinary science and interpret data to understand, predict and communicate the role and response of lakes in changing global environment (GLEON, 2013).

Organisations such as GEO BON, UNEP (WCMC), IUCN (Red List of Threatened Species and Key Biodiversity areas), Ramsar and GEO support such observation systems and they also in their own right gather data for sharing, assessment, monitoring and reporting. For example, the UNEP Biodiversity Data Lab can be used to access, analyse and provide key information on targets and goals based on global data from many different providers including satellite data (Figure 8).

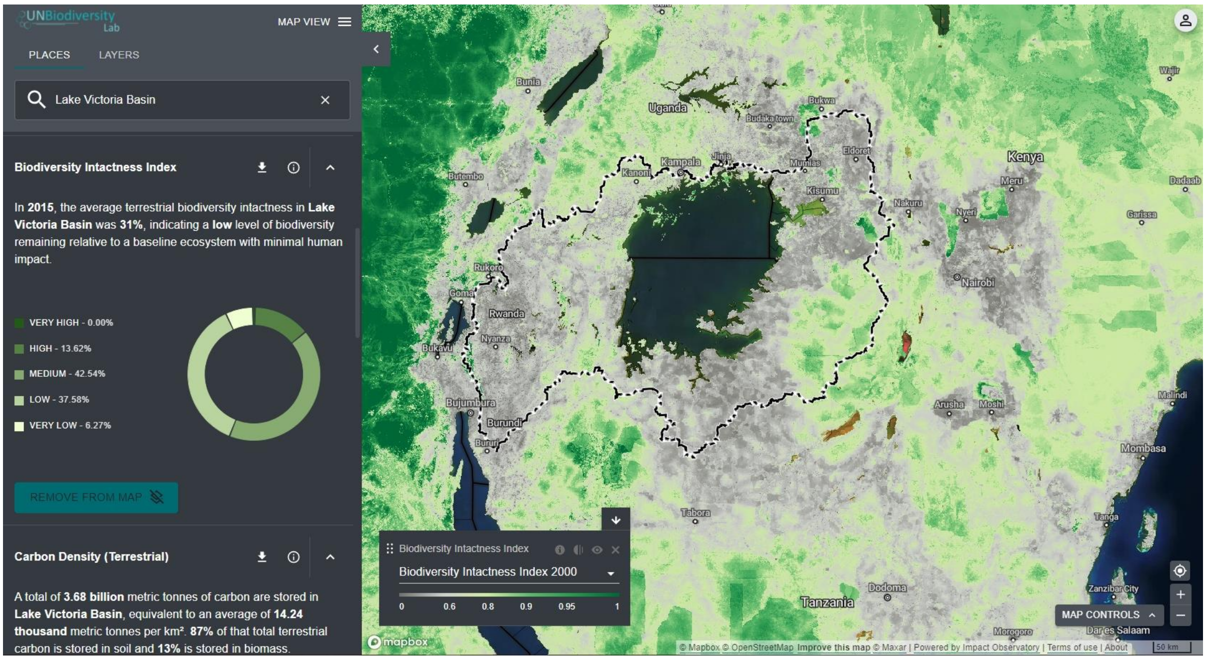

Figure 8: Biodiversity Lab map of the Lake Victoria Basin with values from the Biodiversity Intactness Index 2000 in green and a satellite image as background (https://unbiodiversitylab.org/).

Other knowledge centres and partnerships try to facilitate access to and the sharing of data for biodiversity monitoring on regional levels and include the EC KCBD (Knowledge Centre for Biodiversity) which supports policy making by developing tools and making structured information more accessible. The KCBD was launched in 2020 and is supported by the biodiversity Information System for Europe (BISE) as a single-entry point for biodiversity data in Europe and includes comprehensive statistics on a country basis. Support in the form of tools and services for networking and information sharing, and data collection (including water quality), is also provided by the European Environment Information Observation Network (EIONET, https://www.eionet.europa.eu/). EKLIPSE (https://eklipse.eu/) and Alternet (http://alterneteurope.eu/) are two other networks of biodiversity and ecosystem experts in Europe who together aim to improve the science-policy interface by knowledge integration.

4.3 Challenges and Knowledge Gaps

4.3.1 Missing the biodiversity targets

Recent assessments of progress towards biodiversity and sustainability goals and targets show generally little or no progress. This seems mostly like a consequence of the large gap between the policy driving visions (Section 3.1 *Living in Harmony with Nature*) and today's thriftless socio-economic standards in most of the World.

The actual reasons for the lack of progress are manifold and interlinked but the main challenge areas that have been highlighted are a lack of legally binding agreements/binding conservation legislation, especially on national and local levels where implementations of actions to protect and restore biodiversity take place, lack of funding and imprecise goals, targets and indicators. Close involvement and cooperation between all sectors of society, economic valuation of ecosystems and their services including biodiversity, have been deficient, as well as in some cases, the actual will to achieve goals .

The continued failure to meet global targets for reversing the course of biodiversity loss have also been attributed to the lack of appropriate biodiversity observation data (Gill 2020, Bhatt 2020). Recent assessments (IPBES 2019, UN 2021, Convention on Wetlands 2021) suggest that EO data, biodiversity modelling and integrated earth science approaches have the potential to improve these shortcomings if properly aligned with policy objectives (IPBES, WWF, UN GA etc). BIOMONDO aims to make a contribution on this modest level, and by focusing on the application cases outlined in Chapter 7.

4.3.2 Policy and scientific knowledge gaps relating to freshwater biodiversity

Although the knowledge gaps that need to be filled to revert the negative trend of global biodiversity loss such as data gaps, effects of interacting drivers including climate change are common to all ecosystem groups there are specific needs pertaining to freshwater biodiversity that are different, mainly because freshwater ecosystems link land and sea and supply ecosystem services that sometimes are in conflict. The main knowledge gaps relate to uneven biodiversity data coverage (spatial, temporal and for different organism groups), structure of freshwater ecosystems, with ecosystem condition less well represented than ecosystem extent. Also, better overview and access to data are called for including better methods for monitoring freshwater biodiversity. Effects of changes in land-use can vary depending on what components of freshwater ecosystems are studied and effects of ecosystem protection and restoration of environmental flows and connectivity are understudied. Action priorities to improve freshwater biodiversity include restoration of river flows and improved protected-area networks that incorporate the connectivity between terrestrial, freshwater and marine systems.

The IPBES assessments (2018, 2019) highlight knowledge gaps that need to be addressed to achieve transformative change in the way we approach actions to revert the negative trends in global biodiversity. The key information needs, or knowledge gaps, are divided into eight sectors and relate mainly to data gaps, indicators, inventories and scenarios (see Appendix 1 for full list). The first sector is "Data, inventories and monitoring of nature and the drivers of change" and the second is "Gaps on biomes and units of analysis". These two are the main ones of importance for BIOMONDO developments but contributions could also be linked to the fourth one "Links between nature, nature's contributions to people and drivers with respect to targets and goals" that calls for better quantitative data. Several other sources point (Gill 2020, Bhatt 2020) to the issue of biodiversity data scarcity including reviews of the data in GBIF and LPI databases (section 4.2.3).

The knowledge gaps in the IPBES assessment are often quite generally expressed, and only some are specific or include references to freshwater biodiversity. Examples are listed in **Table 2**.

Table 2 Examples of general knowledge gaps from IPBES Global Assessment, Appendix 4 (2019).

Sector	Knowledge gaps
Data, inventories and monitoring on nature and the drivers of change	• Data on ecosystem processes (including rates of change) that underpin nature's contributions to people and ecosystem health • Data from monitoring of ecosystem condition (generally less well represented than ecosystem extent) • Data on changing interactions among organisms and taxa • …
Gaps on biomes and units of analysis	• Inventories on under-studied ecosystems: freshwater, arctic, marine/ocean, seabed, and wetlands • Inventories in soil, benthic and freshwater • … • Data gaps in key inventories: World Database on Protected Areas, the World Database of Key Biodiversity Areas™, red lists of threatened species and ecosystems, and the Global Biodiversity Information Facility • …

The gaps described also often refer to all ecosystem groups together or to terrestrial or marine ecosystems or qualitative notions of availability of data/information for these groups in contrast to freshwater, i.e., "less than", "greatly underrepresented", "few" etc.

However, some of the knowledge gaps in Table 2 and knowledge gaps described in the running text do specifically mention freshwater ecosystems:

- There are few indicators for the structure of freshwater ecosystems, with ecosystem condition less well represented than ecosystem extent.
- There are no available indicators on interaction among organisms and taxa. Freshwater together with marine assemblages are greatly underrepresented compared to terrestrial.
- There is low degree of confidence related to impact of climate change in freshwater ecosystems, but it is thought to be dominated by effects on ecosystem function.

- Only a few metrics of biodiversity and ecosystem function have been explored deeply enough to draw conclusions on their interactions in a globally changing environment.
- Unknown or uncertain effects of climate change, i.e. projections but changes will occur from change in: temperature, water availability, flow regimes through changes in precipitation and/or temperature.
- Future impacts of habitat fragmentation on freshwater biodiversity and ecosystem function. Uncertain effects of dam building (e.g. species extinction risks – blocked migrations and/or reduced population size and gene flow) and spiralling interacting changes due to altered flow regimes, more dam building and population increases)
- Unknown effect of competition between non-native and native species leading to (e.g. disease spread, degraded ecosystem services and economies as well as biotic homogenization of aquatic ecosystems
- Understanding of links between biodiversity and ecosystem function on a global level – i.e., global modelling tools to explore in different systems (marine, terrestrial and freshwater) the futures of bd/ecosystem function are disconnected. Gap reflects need for connecting model developments across disciplines.

Because of the steep loss of freshwater biodiversity in the last fifty years and a tendency in policies and assessments to not treat freshwater ecosystem as a proper third realm (the other two being terrestrial and marine) several scientific papers have tried to summarise the research needed to address freshwater biodiversity declines (Maasri et al. 2022, Harper et al. 2020, van Rees et al. 2020). These research needs stem from different knowledge gaps and needs and build on the those outlined by Mace et al. (2018) and Tickner et al. (2020), who made specific attempts to identify those, that if filled, will protect and restore freshwater biodiversity rather than only halt the loss.

Maasri et al. (2022) identified through an extensive global consultation process 15 priority needs grouped into five major areas to advance research and support informed stewardship of freshwater biodiversity: Data infrastructure, Monitoring, Ecology, Management and Social ecology. The priorities were further allocated to challenges, either Knowledge gaps (limited research, disparity in access to information or both), Miscommunication (insufficient communication and exchange among scientists, practitioners, managers and policy makers), or Inadequate policy (deficient policy, lack of political will or the decoupling of current policy from demonstrated best practices for preserving and recovering freshwater biodiversity and the services it provides).

The freshwater biodiversity research priorities for the five major areas linked to Knowledge gaps were:

- **Data infrastructure**
    - Establish a comprehensive overview of freshwater data outlets
- **Monitoring**
    - Identify and tackle gaps in biodiversity knowledge
    - Develop new innovative methods for biodiversity monitoring
- **Ecology**
    - Understand mechanistic relationships between biodiversity and ecosystem services,

    - Study the response of biodiversity to multiple stressors,
    - Investigate the ecological and evolutionary responses of organisms, communities, and ecosystems to global change
- **Management**
    - Thoroughly evaluate restoration measures
- **Social ecology**
    - Strengthen integration of social science in biodiversity research

Similarly, Harper at al. (2020) identified six themes based on urgent research questions related to knowledge gaps and barriers that if addressed can be used to advance action for bending the curve of freshwater biodiversity loss. These were:

1. Learning from Successes and Failures
2. Improving Current Practices
3. Balancing Resource Needs
4. Rethinking Built Environments
5. Reforming Policy and Investment
6. Enabling Transformative Change

These six themes contain very specific research questions (see also Appendix 2, Table 9). The freshwater knowledge gaps identified from (IPBES 2019, Maasri et al. 2022 and Harper et al. 2020) have been collated in Table 9 for use as reference for the further advancement of the BIOMONDO Pilots and associated SPTM and the assessments of scientific and policy impact (WP3 and WP4) as well as for the development of the Roadmap (WP5).

4.3.3 Specific priorities for freshwater biodiversity

Tickner et al. (2020) outlined an emergency framework with six priority actions for freshwater biodiversity that are needed to *bend the curve* of biodiversity loss. They are:

- to accelerate the implementation of environmental flows,
- to improve water quality,
- to protect and restore critical habitats,
- to manage exploitation of species and riverine aggregates, and
- to prevent and control non-native species invasions and to safeguard and restore freshwater connectivity.

These priority actions are closely related to the five main direct drivers of biodiversity loss/change in general (section 3.3.1) but it is important to consider the differences compared to the terrestrial biodiversity situation. According to the IPBES GA (2019), for freshwater ecosystems, land use change is the direct driver with the largest negative impact. However, Tickner et al. (2019) emphasise that to achieve necessary improvements to freshwater biodiversity mitigating measures must extend beyond improved land management or enhanced protected area coverage and condition because freshwater ecosystems especially rivers are not area based in the same way as terrestrial but rather linear. Therefore protected-area networks also need to incorporate the connectivity between terrestrial, freshwater, and marine systems to successfully protect freshwater ecosystems.

4.3.4 Transferability and Upscaling

Even though consensus around the question of which aspects of biodiversity to monitor is emerging, and despite many local initiatives that collect data on different aspects of biodiversity, local sampling schemes and agreement on which essential variables to monitor will not be enough to monitor biodiversity on a global scale. In practice, it is difficult to obtain the information needed to determine biodiversity on a global or even regional scale through field work, because it depends on sample size, sampling efforts differ between species, some regions and ecosystem types are difficult to investigate and because there simply are too many species.

Estimates of global biodiversity, therefore, are based on expert opinions, use changes in the rates at which new species or higher taxa are discovered, or are obtained through extrapolation from well-studied to other taxa, or by extrapolation of macroecological patterns, from the better sampled temperate regions to the tropics (Mora et al. 2011). With the exception of a few taxa, for example birds (Bebber et al. 2007) and fishes (Mora et al. 2008), all methods to estimate biodiversity on a global scale are either quite novel or highly contested. Despite 250 years of taxonomic classification and over 1.2 million species already catalogued, an estimated 86% of the existing species on Earth still awaits description (Mora et al. 2011) and even this estimate has a high degree of uncertainty.

New technologies to determine genetic diversity may speed up this process, but it remains unlikely that the full variety of life on Earth will be described within the centuries to come. Even for well-defined metrics of specific aspects of biodiversity we thus must rely on estimates and approximations when monitoring biodiversity on a global or regional scale. A comprehensive measurement of ecosystem functioning, community composition, and most other EBV classes is feasible only locally. Upscaling requires remote sensing enabled proxies that are more easily detectable on a global scale, and biodiversity models to extrapolate from field observations at point locations to a regional or global scale. For many EBVs it is not clear how this should be done, highlighting a huge knowledge gap. For each of the pilot objectives and associated pilot sites as described in BIOMONDO's Science Policy Traceability Matrix (see section 5.3), as well as for each Candidate Earth System Science Pilot (see Chapter 7), we therefore assess the potential to transfer the developed solutions to other areas and upscaling to a large-scale regional or global monitoring system.

5 Earth Observation for Freshwater Biodiversity monitoring

Freshwater ecosystems, including rivers, lakes, and wetlands, provide home to a rich diversity of species and habitats. Over 125,000 freshwater animal species are described to date which corresponds roughly to 10% of the number of species described globally (Balian *et al.*, 2008). When considering that rivers and lakes together take up only about 0.01% of the water on earth and cover approximately 2.3% of the land surface area, it becomes clear that those systems are extremely diverse and of special concern when monitoring biodiversity. In addition to this, freshwater ecosystems are of key importance for terrestrial biodiversity as a source of freshwater and food; e.g. because terrestrial animals are (indirectly) dependent on fatty acids produced in freshwater ecosystems (Twining *et al.* 2016). It is perhaps for this reason that wetlands – in between terrestrial and aquatic environments – belong to the world's most biodiverse ecosystem types as well, and that changes in the diversity and dynamics of freshwater ecosystems are likely to affect global terrestrial biodiversity when cascading through aquatic-terrestrial food webs. Wetlands are estimated to approximately cover 5.4-6.8% of the world's land surface (e.g. Lehner & Doll, 2004; Reid *et al.* 2019). Definitions of what constitutes a wetland, however, may vary affecting these estimates.

As discussed in section 4.3.4 it is impossible to monitor (changes in) all the different aspects of biodiversity on a global scale directly. When determining biodiversity, we thus have to rely on estimates and approximations. In an influential review, Revenga *et al.* (2005) however wrote that "Considerable obstacles need to be overcome to achieve global monitoring of the extent and condition of freshwater ecosystems, but the major drivers affecting their condition are quite clear and, for the most part, easier to assess and monitor. […] For example, using data on the extent of agriculture in a watershed, or the size and location of dams, we can draw some conclusions about the relative degree of alteration or stress affecting a system. These geospatial indicators are often called proxies or surrogates, because they are indicators of current threat and give only indirect information about actual ecological integrity." To monitor (change in) freshwater ecosystems, we may thus (have to) rely on global, relatively easily detectable proxies, in particular those measuring changes of environmental conditions, and biodiversity models that use these proxies to extrapolate from local field observations to a regional or global scale.

BIOMONDO aims to support biodiversity monitoring through Earth Observation (EO), which is the gathering of information about the physical, chemical, and biological systems of the planet Earth through remote-sensing or ground-based techniques. Remote sensing is done from a distance, being it drones, aircrafts or satellites and involves, in most cases, the analysis of radiation reflected and emitted by the earth. Remote sensing can be done over large areas (e.g. the entire globe), including remote areas, and at a relatively high temporal resolution (e.g. daily, of course at the expense of spatial resolution which is typically in the order of several hundreds of meters for global daily observations). As such, remote sensing techniques are thus ideal when monitoring changes over time and across space, where proxies are "visible[4]" at a certain spatial scale. It should be clear that today, almost no species can be "seen" directly, but proxies indicating change of the environmental condition can: for example, a change in land cover/land use affecting the ecosystem with potential consequences for certain species or change in the phytoplankton abundance in a water body which can indicate eutrophication. In some cases, it is possible to monitor relevant biodiversity variables directly from space, e.g. 'phenology', which is an RS-enabled EBV (see Skidmore et al. 2021). Integration into ecologi-

[4] **visible here is meant in the sense of detectable by a sensor measureing electromagnetic energy at a certain wavelength or frequency.**

cal/ecosystem models is necessary in other cases. This may be particularly true for freshwater ecosystems where life happens to a great extent under water.

Deriving information about the surface (land cover or phytoplankton) from space borne measurements is a complex and error prone process. In the domain of optical remote sensing, the solar radiation is the energy source, and the solar energy is modified and absorbed by the atmosphere and partially reflected by the land or water surface, see Figure 9. Correction needs to be applied in order to derive the parameter of interest. Thus, data derived from remote sensing needs to be validated with ground measurements. In this way, remote sensing can be used to estimate information about the surface (land and water), and in particular about the concentrations of several optically active constituents inside freshwater bodies, of which the following are the most important (descriptions taken from Dekker and Hestir, 2002):

1) *Chlorophyll (CHL):* an indicator of phytoplankton biomass, trophic and nutrient status; the most widely used index of water quality and nutrient status globally.
2) *Cyano-phycocyanin (CPC) and cyano-phycoerythrin (CPE):* indicators of cyanobacterial biomass common in harmful and toxic algal blooms.
3) *Coloured dissolved organic matter (CDOM):* the optically measurable component of dissolved organic matter in the water column, which can be used as an indicator of organic matter and aquatic carbon.
4) *Total suspended matter (TSM) and non-algal particulate matter (NAP):* important for assessing the quality of drinking water and controlling the light environment of aquatic environments.

In addition, the following conditions can also be estimated:

1) *Vertical light attenuation (Kd) and turbidity*: measurements of the underwater light field that are important for assessing the degree of light limitation, rates of primary production, species composition and other ecosystem responses.
2) *Emergent and submerged macrophytes:* down to depth of visibility, important indicators of wetland and aquatic ecosystem health and function.
3) *Bathymetry:* if the bottom or bottom cover of a water body reflects a measurable amount of light through the water column to above the surface then the water depth can be estimated.

The sum of all optically active constituents represents the inherent optical properties of a water body (Odermatt *et al.*, 2012).

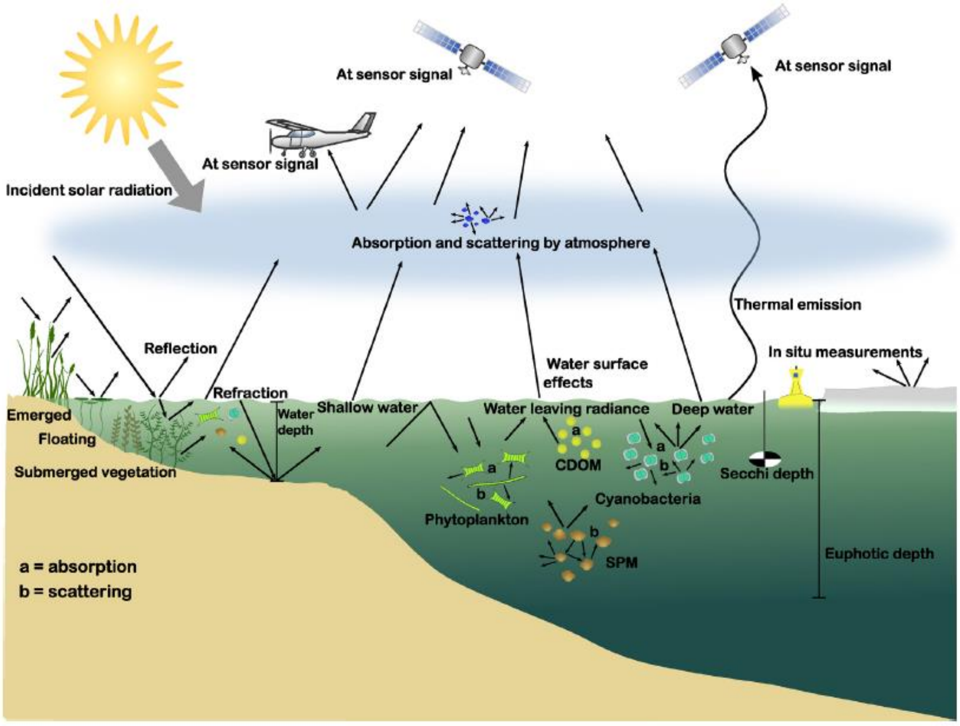

Figure 9: Interaction between radiation, remote sensing indicators of lake ecology, and sensors (taken from Dörnhöfer and Oppelt, 2016).

Many changes in water bodies that are of importance for biodiversity can be monitored through remote sensing as well. Among those, the most important ones are:

- Changes in *the* extent and *location* of freshwater systems
- Changes in the *connectivity* of freshwater systems
- Changes in *retention time*
- Changes in the *hydro period*

Eventually, as already mentioned before, the *land use and land cover* changes *in the watershed* can indicate that conditions relevant for species abundance for a freshwater system is changing with the risk of losing biodiversity (or vice-versa). The terms land cover and land use are often used interchangeably, however, they are distinct from each other. Land cover describes the biophysical composition of the Earth's surface. Land use describes the anthropogenic use of the Earth's surface. The differentiation of both terms is crucial in remote sensing as satellites provide imagery of land cover, whereas information on land use is mostly based on additional human interpretation. Both parameters can be relevant for changes affecting biodiversity. Land Cover and Land Use are derived from optical remote sensing measurements by fully or semi-automated interpretation of temporal evolution of the spectrum throughout a year, and by combining this temporal colour pattern with additional information, such as biomes allowing only certain classes (see e.g. Wyatt 2000).

5.1.1 Monitoring drivers of global environmental change

As discussed in chapter 2, monitoring a change in drivers of global environmental change is highly effective because 1) they themselves can be used as proxies of change in biodiversity, 2) change in environmental conditions can precede biodiversity loss by several decades and may thus give an early indication of upcoming biodiversity losses, and 3) they can be used to set targets for policy making (i.e. because they are anthropogenic). Most central questions in the scientific community also revolve around the impacts of drivers of environmental change on biodiversity and ecosystem functions as well, in particular within the fields of ecology and environmental science. In what follows, we give a brief overview of the historical assessment of five main drivers of global environmental change to freshwater ecosystems, i.e. 'Water pollution and eutrophication', 'Habitat change (hydrological disturbance)', 'Invasive species', 'Climate change', and 'Overexploitation'. These drivers are highly akin to the main drivers assessed in global and regional biodiversity assessment reports (e.g. MEA 2005; IPBES 2019 – Regional Reports, see Chapter 2 and Figure 2), as well as in scientific reviews of biodiversity change in freshwater systems (Revenga et al. 2005; Carpenter et al. 2011; Dudgeon, 2006; Reid et al. 2019). A comparison between these reviews (e.g. between Dudgeon, 2006 and Reid et al. 2019) suggests that impact of these drivers and, consequentially, the biodiversity crisis in freshwater ecosystems has deepened. In a deviation from previous reviews, Reid et al. (2019) report 12 emerging threats; i) changing climates; ii)e-commerce and invasions; iii) infectious diseases; iv) harmful algal blooms; v) expanding hydropower; vi) emerging contaminants; vii) engineered nanomaterials; viii) micro-plastic pollution; ix) light and noise; x) freshwater salinisation; xi) declining calcium; and xii) cumulative stressors. Most of those, however, can be categorized under the above mentioned five key drivers with the exception of cumulative stressors which we discuss under a sixth category 'Multiple/unknown drivers'. Alarmingly, indicators are revealing rapid population declines and a large extinction risk in freshwater organisms. The World Wide Fund for Nature (WWF) Living Planet Index (LPI) disclosed that the index for populations of freshwater species fell more steeply from 1970 to 2012 than either the index for marine or terrestrial populations (Collen et al., 2009; WWF, 2016; Reid et al. 2019).

In addition to this, we will review the potential for EO to monitor change in these drivers and particular areas that are of concern when monitoring a change in those drivers. When describing these areas of concern, we take into account that biodiversity is not distributed equally over the world (see Figure 10, Abell *et al.* 2008; Tisseuil *et al.* 2013; IPBES 2019). We will continue to further develop this *baseline* review in preparation for the roadmap (WP 5).

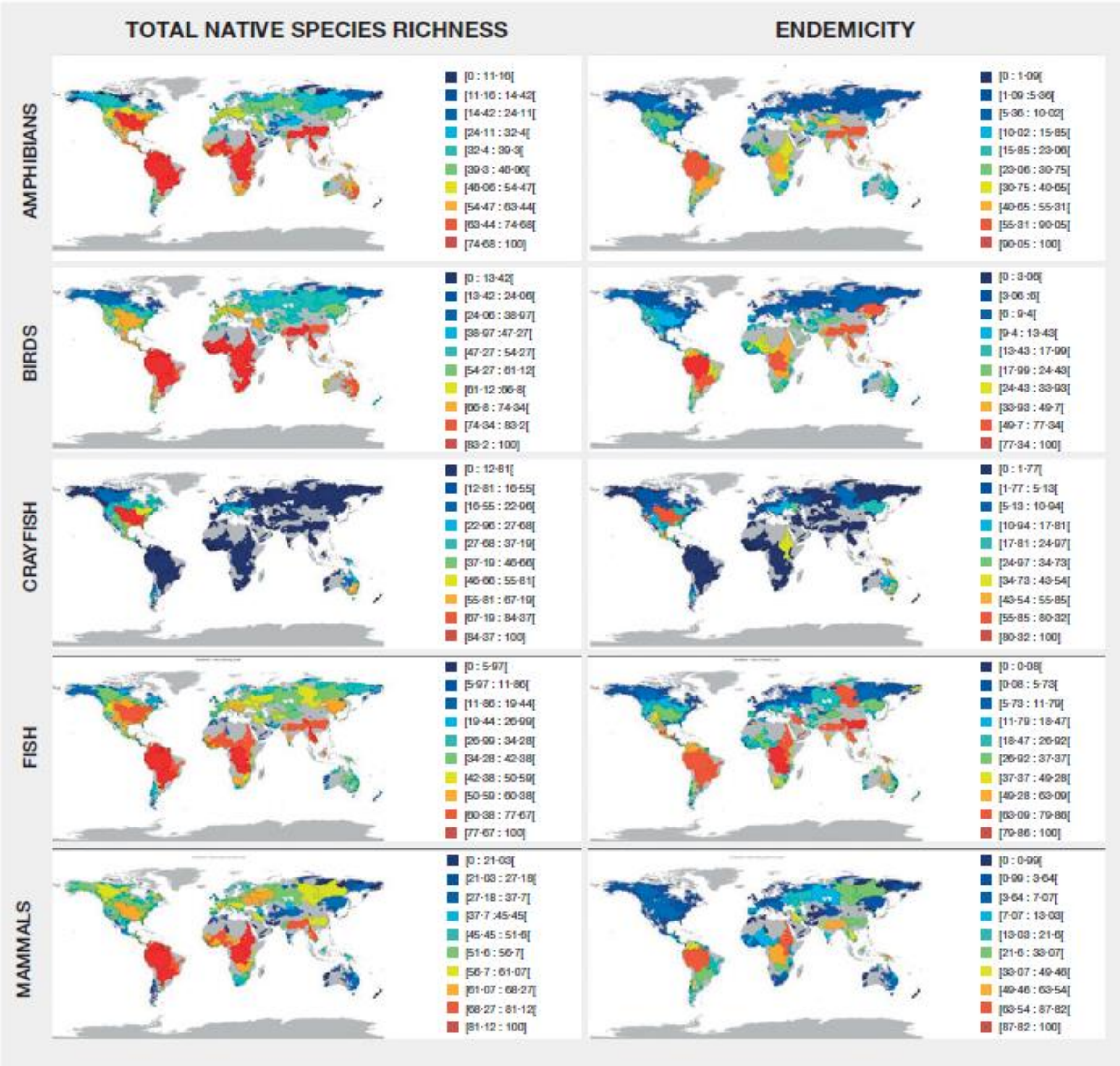

Figure 10: Global diversity maps (species richness and endemicity) for freshwater fishes, aquatic amphibians, aquatic mammals, crayfish and aquatic birds. (taken from IPBES 2019; after Tisseuil *et al.* 2013)

5.1.2 Water pollution and eutrophication

Nutrient concentrations have increased substantially in rivers and lakes throughout the world (Heathwaite et al. 1996; Revenga et al. 1998; Revenga et al. 2005; Carpenter et al. 2011; Dudgeon, 2006; Reid et al. 2019), resulting in eutrophication, harmful algal blooms, loss of submerged macrophytes, biodiversity loss in lakes and rivers, and high levels of nitrate in drinking water. Pollution by hazardous substances has undermined water quality across the world. Of particular concern are pesticides, ammonia, PCBs, polyaromatic hydrocarbons, and metals, while transport is an important source of oil pollution (IUCN 1992). And 'new' emerging substances like microplastics and pharmaceuticals. Microbiological contamination by pathogenic bacteria, viruses, and protozoa is an important water quality problem in many regions of the world, and diffuse discharges from agriculture are important sources of micro-pollutants for both surface and groundwaters.

Potential for EO to improve the monitoring of this driver

Various studies have shown that satellite data can be used to quantify cyanobacterial blooms in lakes and coastal waters (including Kutser 2004, 2009, Kahru et al. 2007, Simis et al. 2005, Alikas et al 2010, Matthews et al. 2012, Lunetta et al 2014). These approaches include the detection of blooms and floating cyanobacteria (Kahru et al. 2007), the estimation of phycocyanin (Ruiz-Verdú et al. 2008; Simis et al., 2005) or the identification of cyanobacteria blooms and their chlorophyll-a concentration (Matthews et al. 2012) or the cell counts (Hunter et al. 2010, Lunetta et al. 2014). Phycocyanin is the blue pigment that also gives the cyanobacteria their name blue-green algae or blue-green algae.

Also, high biomass blooms of phytoplankton are indicators for eutrophication. They can be detected by a number of different chlorophyll retrieval algorithms and also turbidity can indicate such blooms with high concentrations. the evolution of such high biomass blooms, their extent and duration are indicators that can be used for assessing eutrophication of a system. Many processing chains and services provide information about chlorophyll concentration.

Areas (sites) of concern

Areas of concern are any specific examples are available for inland water systems (e.g. Malmqvist and Rundle 2002; Tockner and Stanford 2002). For instance, the agricultural sector contributes an average of 50% of the total load of nitrogen and phosphorus to the Danube River in Europe, domestic sources contribute about 25%, and industry or atmospheric deposition 25%.

5.1.3 Habitat change (hydrological disturbance)

Clearing or drainage for agricultural development is the principal cause for wetland loss worldwide (MEA, 2005). By 1985 it was estimated that 56–65% of available wetland had been drained for intensive agriculture in Europe and North America, 27% in Asia, 6% in South America and 2% in Africa—a total of 26% loss to agriculture worldwide (OECD 1996; IPBES 2019). In China, some of the most extensive peatland areas (5,000 km^2) occur at 3,500-meters elevation on the Tibetan Plateau, the source of the Yellow and Yangtze Rivers. Large networks of drainage canals were constructed there in the 1960s and 1970s to increase the area for livestock grazing, leading to a dramatic drop in peatland area and a subsequent degradation and loss of the peat, desertification, and loss of water retention capacity (UNDP/GEF/GOC 2003).

Water regimes of inland waters have been modified by humans for centuries, with the last 50 years in particular witnessing largescale changes in many parts of the world, often associated with drainage and infilling activities as described earlier (Brinson and Ines Malvarez 2002; Junk 2002; Malmqvist and Rundle 2002; Tockner and Stanford 2002; Revenga et al. 2005; Carpenter et al. 2011; Dudgeon, 2006; Reid et al. 2019; Grill et al. 2019). Modifications include construction of river embankments to improve navigation, drainage of wetlands for agriculture, construction of dams and irrigation channels, and the establishment of inter-basin connections and water transfers.

Potential for EO to improve the monitoring of this driver

Mapping of water extent have been undertaken for rivers, lakes, and wetlands (Donchyts et al. 2016; Yang et al. 2019) but the global extent of the area covered by these types of freshwater systems still has quite a high degree of uncertainty. This is also caused by the fact that the extent of water bodies can be highly dynamic. The Global Surface Water Explorer (GS) developed by JRC (Pekel et al. (2016) provides a tool for investigating changes in water body extent, independent if they are caused by natural (seasonal) changes or by anthropogenic influences (construction of dams). It is foreseen to integrate the tool and products into the Copernicus Global Land Service. Deltares Aqua Monitor https://aqua-monitor.appspot.com/ provides a similar visualisation. Freely available optical and SAR data are suitable to develop water extent and their changes. Information is derived from Landsat Series, Sentinel-2, Sentinel-1 and in coarser resolution also from MERIS/OLCI, VIIRS, MODIS for optical data and ERS series and ASAR.
In the Ramsar global guidelines for peatland rewetting and restoration (Convention on Wetlands, 2021b) it is stated that "remote sensing should be developed as a near real-time and cost-effective method for monitoring large-scale restoration projects". This objective might be considered in BIOMONDO depending on the final choice of Pilots and Pilot sites.
Several datasets on the locations of dams are available, e.g. the Global Reservoir and Dam (GRanD) database (Lehner et al., 2011) and the GlObal georeferenced Database of Dams (GOODD, Mulligan et al. 2020) on current dam locations (including the ones in GRanD), and the Future Hydropower Reservoirs and Dams (FHReD) dataset on future locations of dams under construction or planned. In addition, there are several regional or country-based datasets; see overview on www.globaldamwatch.org. E.g. rather extensive data sets are available for the USA and for Europe (via the AMBER project). There are also some data on dam *removal* (see www.damremoval.eu for Europe and DRIP (USGS Dam Removal Information Portal) https://www.sciencebase.gov/drip/ for the USA, and a recent overview by Habel et al., 2020. However, the datasets vary in terms of quality, coverage and definitions of dams and in the attributes provided apart from location, such as dam and reservoir dimensions, type of turbines, fish passages, flow management etc. Despite many efforts, there is still no globally consistent or complete database on the locations of dams. Such a dataset would aid the (global) analysis of the impact of dams on society and environment and impact of environmental change. The detection of dams on remote sensing imagery might be a solution. In addition to the location of current dams, it could also provide information on the time of construction of dams, dam removal or the size of the dam. Manual georeferencing from the remote sensing images would be time consuming. Machine learning approaches for the automated detection of dams on remote sensing imagery are being developed.

Areas (sites) of concern

The Aral Sea in Central Asia represents one of the most extreme cases in which water diversion for irrigated agriculture has caused severe and irreversible environmental degradation of an inland water system (MEA, 2005). The Aswan High Dam in Egypt, for

example, has led to reduced sediment transport for more than 1,000 kilometers downstream (McAllister et al. 1997). A further example of the downstream effects of dams is illustrated in the Indus delta.” (MEA, 2005).
As the world's third largest delta and one of the world's most important biodiversity hotspots, the Mekong Delta provides both ecological and food security for its inhabitants. Nevertheless, the delta has been threatened by climate change and human activities, particularly the proliferation of hydropower development across the Mekong Basin since the 1990s (Li et al. 2017).

5.1.4 Invasive species

The spread of exotic species in inland waters is increasing with the spread of aquaculture, shipping, and global commerce and affecting biodiversity. In general, this driver is, however, considered to be of lesser concern than pollution and eutrophication, habitat change, and climate change (Revenga et al. 2005; MEA, 2005; Carpenter et al. 2011).

Potential for EO to improve the monitoring of this driver
Some invasive species can be monitored from space, e.g. floating water plants such as the water hyacinth.

Areas (sites) of concern
The pan-tropical weeds salvinia (Salvinia molesta) and water hyacinth (Eichhornia crassipes) that originated in South America but are now widely distributed across the tropics. The cane toad (Bufo marinus), bullfrog (Rana catesbeiana), European domestic pig (Sus scrofa), carp (Cyprinus carpio), and zebra mussel (Dreissena polymorpha) are examples of animals that have become established outside of their native range and disrupted the inland water systems that they have invaded.

5.1.5 Climate change

The major impacts of climate change on inland waters include warming of rivers and lakes, which in turn can affect chemical and biological processes, reduce the amount of ice cover, reduce the amount of dissolved oxygen in deep waters, alter the mixing regimes, and affect the growth rates, reproduction, and distribution of organisms and species (Gitay et al. 2002; Till et al., 2019; Woolway et al., 2021). In addition, Sea level rise will affect a range of freshwater systems in low-lying coastal regions. For example, low-lying floodplains and associated swamps in tropical regions could be replaced by saltwater habitats due to the combined actions of sea level rise and extreme sea levels during storm surges or tropical cyclones (Bayliss et al. 1997; Eliot et al. 1999). Plant species not tolerant to increased salinity or inundation could be eliminated, while salt-tolerant mangrove species could expand from nearby coastal habitats. Changes in the vegetation will affect both resident and migratory animals, especially if these result in a major change in the availability of staging, feeding, or breeding grounds for particular species (Boyd and Madsen 1997; Zockler and Lysenko 2000).

In addition to this, climate change affects other drivers. In particular, drought or increased rainfall may lead to habitat change.

Potential for EO to improve the monitoring of this driver
EO can provide data on (surface) water temperature to address a lack knowledge of the extent to which a change in the occurrence of 'extreme climatic events' affects biodiversity. This can complement/replace (incomplete, point based) in-situ data, or give more (spatially/temporally) detailed estimates compared to modelling products (e.g. Wanders et al. 2019, global but 10km resolution). Landsat collection-2 Lake Water Temperature has been validated in several of our projects (e.g. DASIF) and provides valuable information. The time series of Landsat-5, Landsat-7 and Landsat-8 provides a time series of >25 years. However, the acquisition rate is 16 days and this number is even reduced by clouds so that it might be necessary to complete the time series with in-situ temperature measurements or air temperature data from nearby meteorological stations.

To monitor how climate change affects other drivers, e.g. drought or increased rainfall that may lead to habitat change/changes in the hydrological cycle we can monitor (changes in) lake surface area and (indirectly though bathymetry) depth/volume of waters could be monitored.

Ice coverage on lakes is another parameter that is detectable by EO data. From combinations of optical and SAR data, classification in ice covered and water can be retrieved. Indicators such as ice coverage yes/no, freezing time, melting point, duration of ice coverage etc. can be derived per winter season and compared in time series evolution. The Global Land Copernicus Service provides with the Ice products information about ice coverage of lakes in coarse resolution (500m, Northern Hemisphere). Data is suitable for larger lakes. The CCI+ Lakes ICE products (LIC, LIE) are providing Lake Ice Information for globally distributed lakes. From these time series, per-year or per-season indicators shall provide information about trends.

Areas (sites) of concern
Air (and likely surface water) has increased substantially more near the poles. Largest historical changes may thus be expected in e.g. Scandinavia or Canada. Further information on Lake Heatwaves can be found in Woolway et al. (2021).

5.1.6 Overexploitation

FAO's major assessment of inland fisheries (1999; 2004) reported that most inland capture fisheries rely on natural reproduction of the stocks are overfished or are being fished at their biological limit and that the principal factors threatening inland capture fisheries are fish habitat loss and environmental degradation. In addition, one of the limitations in monitoring the state and condition of inland fish stocks is that the catch from inland fisheries is believed to be underreported by a factor of two or three, due to the large volume of harvest that is consumed locally, and remains unrecorded (FAO 1999; 2004).

Potential for EO to improve the monitoring of this driver
For the assessment of inland fisheries EO data has no high potential. Nevertheless, indications on overexploitation can be studied taking EO data into account, e.g. detection of antrophogenic aquacultures and fish farming if they are observable from space (Gernez et al. 2021).

Areas (sites) of concern
Asia and Africa are the two leading regions in inland capture fisheries, accounting for 90% of the catch in 2002 (FAO 2004). China alone accounts for at least one quarter of the inland catch, followed by India (9% of the catch), Bangladesh (8%), and Cambodia (4%) (FAO 2004).

5.1.7 Multiple/unknown drivers

Drivers may act simultaneously, or drivers may be unknown. Generic patterns, e.g. in spatial or temporal variability, may indicate a loss of resilience regardless of which driver is causing this loss in resilience. The development of such indicators, however, is still in a preliminary stage in particular for (the highly dynamic) freshwater ecosystems. One member of our consortium is currently developing these indicators for terrestrial ecosystems (e.g. forests). This will be important input for the roadmap.

Potential for EO to improve the monitoring of this driver
Through the development of generic resilience indicators that can be used to detect a loss of stability that precedes biodiversity loss.

Areas (sites) of concern
Areas where it is difficult to assess the impact of drivers of environmental change, e.g. in particular areas where multiple drivers act simultaneously or when 'tipping points' may be passed.

5.2 Contributions from existing and upcoming satellite missions

The analysis of the EO potential for monitoring of the main drivers of global environmental change in 0 demonstrates that satellite observations are increasing our understanding of the dynamics of water systems, their riparian borders and catchment. Satellite remote sensing is crucial to getting long-term global coverage and allows for time series analysis and change detection. It can rapidly reveal where to reverse the loss of biological diversity on a wide range of scales in a consistent, borderless and repeatable manner. The following analysis demonstrates the potential of existing and planned EO missions and services, to lay down the basis for recommendations for extension of the activities and setting of future research agendas.

5.2.1 Experimental services/products/applications

There are various experimental data sources which address potential use for biodiversity assessment and monitoring. Nevertheless, these data sources need to be used with care due to possible discontinuation of the data source. Therefore, the use of these datasets can be critical.

Table 3 Experimental data sources, types of processing needed and resultant parameters.

Data Source	Processing	Parameters
PRISM	own processing	CHL, TUR, Algal Groups, floating vegetation,

		submerged vegetation

5.2.2 Future contributions by upcoming missions

Planned EO missions and services are the basis for recommendations for extension of the activities and setting of future research agendas. There are several relevant future data sources which have potential use for biodiversity assessment and monitoring. Some potential BD parameters need to be evaluated and determined once the data sources are open to use.

Table 4 Data sources of upcoming missions, types of processing needed and resultant parameters.

Data Source	Processing	Parameters
Sentinel Next Generation	own processing, services	CHL, TUR, submerged vegetation, floating vegetation, LULC, TBD
BIOMASS (ESA Earth Explorer)	own processing, services	Biomass, LULC
FLEX (ESA Earth Explorer)	own processing, services	TBD
EnMAP	own processing, EnMap TBX	CHL, TSM, TUR, Algal Groups, submerged vegetation, floating vegetation, LULC
Landsat-9 (commissioning phase)	own processing	CHL, TUR, submerged vegetation, floating vegetation, LULC, Temperature

5.2.3 Operational services/products/applications

There are several relevant data sources which can be obtained. Several data sources are raw EO data and need own processing steps to be used for biodiversity assessment and monitoring. A lot of work has already been done to operationalise services which provide a large variety of BD parameters already processed and ready to use. Especially the services are well validated and documented, and the use of these data sources is not critical. The data sources which need own processing steps need validation and documentation of the methods.

Table 5 Data sources of operational services/products/applications, types of processing needed and resultant parameters.

Data Source	Processing	Parameters
Sentinel 1	own processing	LCLU, dams (optional)
Sentinel 2	own processing	LCLU, dams, macrophytes, CHL, TSM, Kd, PAR, HAB, submerged vegetation, Chl phenology, bed composition
Sentinel 3	own processing	Chl, TUR, PAR, HAB (Cyanobacteria), Kd
Landsat 8	own processing	macrophytes (emerging, submerged), TUR, TSM, Temperature
CLMS PAN LCLU	Service	LCLU (Europe only)
CLMS PAN European settlement map	Service	LCLU urban class (Europe only)
CLMS PAN HR Forests	Service	forests (Europe only)
CLMS PAN HR Water & Wetness	Service	water area change (Europe only)
CLMS LOCAL Riparian Zones	Service	LCLU (Europe only)

CLMS High Resolution Vegetation Phenology and Productivity	Service	VI, ST, VPP
CGLOPS Lake Ice Extent	Service	Lake ice
CGLOPS Inland Water Products	Service	Chl, TSM, LSWT
CGLOPS Lake Water Level	Service	water level
CCI+ Lakes	Service	LSWT, LIC, LIE, Water Colour, CHL, TUR, LWE
C3S LC	Service	LC
JRC Global Surface Water Explorer	Service	water body area, temporal pattern of high and low water, inland water dynamic
Global Forest Change Univ. Maryland	Service	forests
ESA Worldcover	Service	LCLU

5.3 Science and Policy Traceability Matrix

BIOMONDO's Science and Policy Traceability Matrix (SPTM, see Figure 11 and Figure 12) is included as an appendix (.xlsx) to this document. It provides an overview of potential pilot objectives categorized according to the five key drivers of environmental change, 'Water pollution and eutrophication', 'Habitat change (including hydrological disturbance)', 'invasive species', 'climate change', 'overexploitation' and 'multiple/unknown drivers', as discussed in chapter 3 and 5.

The main objectives of the SPTM are to 1) to propose a list of candidate pilot objectives which can help addressing knowledge gaps in biodiversity monitoring, modelling, and assessment, and 2) to assess their feasibility and relevance, including the relevance of potential pilot sites. Feasibility is assessed by reading, for each pilot objective, through the matrix from left to right through the columns 'Pilot data requirements' (i.e. what we need), 'Input data' (i.e. what we have), 'Readiness/Processing' (i.e. what we need to do), up until the main columns 'Novel EO product(s)' and 'Integration into ecological/ecosystem models' that describe the main output required to address a pilot objective. Depending on the pilot objective, a 'Novel EO product' may already be an output that is relevant for biodiversity monitoring, e.g. 'phenology', which is an RS-enabled EBV. In other cases integration into ecological/ecosystem models is necessary. Further columns then continue to evaluate the relevance of this pilot objective in terms of their 'Application', e.g. contribution to environmental policy, list 'Potential pilot sites' and assess the 'Relevance of pilot sites' and the 'Potential for upscaling to a higher, e.g. regional or global level'. Feasible and relevant pilot objectives will likely become a part of BIOMONDO's selected pilots (see Chapter 7). When objectives are not yet feasible but relevant, they will be considered for the Roadmap.

Our SPTM is inspired by but is a greatly revised version of the Science Traceability Matrix used by NASA (Weiss *et al.*, 2004). When phrased as a question (see below), our drivers of environmental change correspond roughly to the 'Science objectives', and the pilot objectives to the 'Measurement objectives' in Weiss et al. (2004).

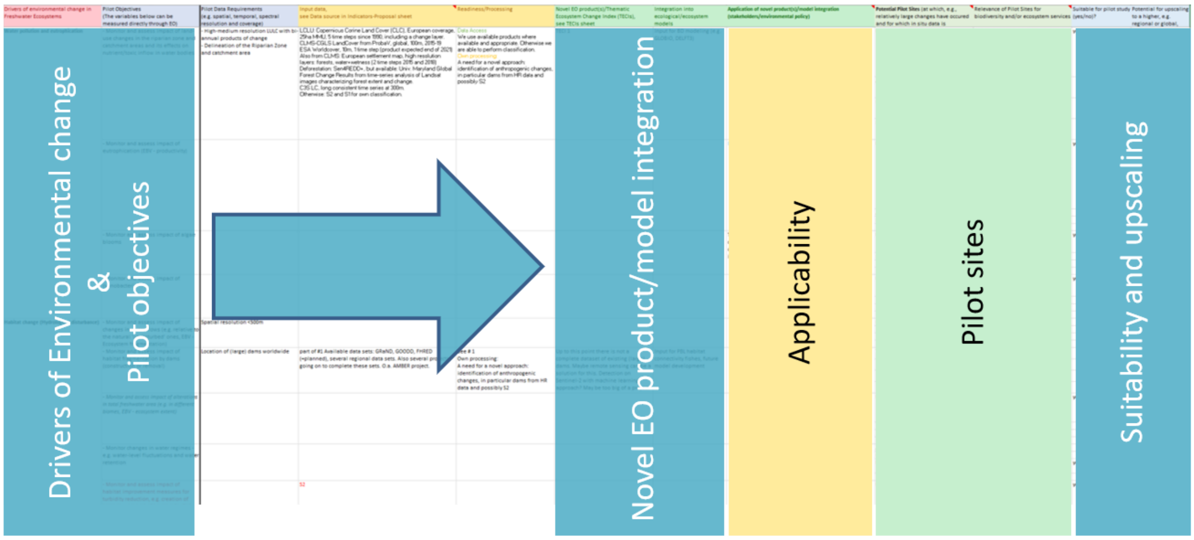

Figure 11: General setup of BIOMONDO's Science Policy Traceability Matrix. We take off from the five main drivers of environmental changes which provide us with categories within which pilot objectives are defined. We then go, from left to right, through data availability and processing steps (the arrow) until we reach the output for each pilot objective which is a novel EO product and/or novel integration of EO in ecosystem models. After this we continue to assess the applicability of this output in terms of relevance for environmental policy, the availability and relevance of different pilot sites, and the potential for upscaling. The full version of the SPTM is included as an appendix (.xlsx) to this document.

Science questions/Drivers of environmental change in Freshwater Ecosystems	Pilot Objectives (The variables below can be measured directly through EO)	Pilot Data Requirements (e.g. spatial, temporal, spectral resolution and coverage)	Input data, see also Data source in Indicators from Proposal Sheet	Readiness/Processing	Novel EO product(s)/Thematic Ecosystem Change Index (TECIs), see TECIs sheet	Integration into ecological/ecosystem models
How will the diversity of life and ecosystem services in freshwater ecosystems change with increasing water pollution and eutrophication?	- Monitor and assess impact of changes in water column trophic status, especially eutrophication and sediment load (EBV productivity) **(See section 7.2.1. in RB, pilot 1)**		Copernicus CGLOPS (produced by BC/PML). If not appropriate, we can start from S3 and S2 data. Note: a 100m S2 based product is not yet included in GCLOPS but will come.	Data Access CGLOPS inland water products at 300m Own processing for HR WQ product from S2	TECI 4	Input for Delft3D
	...	...	...	...	...	...
How will the diversity of life and ecosystem services in freshwater ecosystems change with increasing change in habitat (e.g. Hydrological disturbance or land cover and land use changes of wetlands)?	- Monitor and assess impact of river dam construction and removal on habitat fragmentation and species dispersal routes **(See section 7.2.3. in RB, pilot 3)**	Location (and changes in the presence) of large dams worldwide Location and structure of river networks worldwide	Available data river dams: GRaND, GOODD, FHRED (=planned), several regional data sets. Also several projects going on to complete these sets. O.a. AMBER project. Available data river networks: HydroRIVERS	Data Access open source databases Own processing: needed if dam databases are not sufficient	Updated dam database (when needed)	Input for geographic range connecitivty model in Barbarossa et al. (2020). Input for PBL habitat connectivity fishes, future model development, e.g. FishSuit model included in GLOBIO
	...	...	...	...	...	...
How will the diversity of life and ecosystem services in freshwater ecosystems change due to invasive species?	...	...	...	...	...	...
How will the diversity of life and ecosystem services in freshwater ecosystems change due to invasive species?	- Monitor and assess impact of changes in water temperature on fish occurrence/diversity in lakes **(See section 7.2.2. in RB, pilot 2)**	Spatial resolution: as small as possible, so the site can consist of multiple pixels (enables to study spatial differences) Temporal resolution: preferably multiple years at a daily resolution	CGLS LSWT, CCI Lakes LSWT (1000m) Landsat Collection 2 Temperature Product (100m) ERA5 Reanalysis data for surface air temperature.	Data Access All services have ready-to-use data.	TECI 4	Use remotely sensed water temperature data to study the impact of heatwaves on freshwater fish using a newly developed thermal tolerance model (as part of the GLOBIO model suite)
	...	...	...	...	...	...
How can we assess the impact of drivers of environmental change when multiple drivers act simultaneously, and/or when drivers are unknown?	- Monitor and assess the impact of a change in resilience indicators		Spatial and temporal (including phenology) variability (e.g. in Chl concentration).	Requires further development of mathematical theory on reslience indicators to match EO data.	Generic resilience indicator	
	...	...	...	...	...	...

- Application (stakeholders/environmental policy)
- Potential Pilot Sites
- Relevance of Pilot Sites for biodiversity and/or ecosystem services
- Suitable for pilot study (yes/no)?
- Potential for upscaling

Figure 12 Example of few pilot objectives and their corresponding EO products/Integration in ecological/ecosystem models as included in the SPTM. The full version of the SPTM is included as an appendix (.xlsx) to this document.

5.3.1 Scientific questions and knowledge gaps

Science Question 1
How will the diversity of life and ecosystem services in freshwater systems change with increasing pollution and eutrophication?

Knowledge gaps

- Maps of (change in) land use in the watershed can be improved (?).
- Even though we can monitor the trophic state of lakes it is not entirely clear how a change in this state affects biodiversity at all levels in the food web.
- Many types of pollution cannot be monitored with EO data, and we lack proxies that can be observed from space.

Science Question 2
How will the diversity of life and ecosystem services in freshwater systems change with increasing change in habitat?

Knowledge gaps

- Mapping exercises were undertaken for rivers, lakes, and wetlands but the global extent of the area covered by these types of freshwater systems still has quite a high degree of uncertainty.
- We lack information on the construction, removal, and impact of river dams
- We lack information on global changes in water-level fluctuations and the impact of water retention.

Science Question 3
How will the diversity of life and ecosystem services in freshwater systems change due to invasive species?

Knowledge gaps

- Many types of invasive species cannot be monitored with EO data (with the exception of example provided by Deltares) and we lack proxies that can be observed from space.

Science Question 4
How will the diversity of life and ecosystem services in freshwater systems change with increasing climate change?

Knowledge gaps

- We lack knowledge of the extent to which climate change affects the distribution and phenology of species.
- We lack knowledge of the extent to which a change in the occurrence of 'extreme climatic events' affects biodiversity.
- We lack knowledge of the extent to which changes in water temperature affect fish occurrence/biodiversity.
- Climate change is likely to affect other drivers, e.g. drought or increased rainfall that may lead to habitat alteration: we lack knowledge of how climate change affects the hydrological cycle.

- Changes in ice cover can be monitored through EO but the impacts of such a change on biodiversity are unclear.

Science Question 5
How will the diversity of life and ecosystem services in freshwater systems change with overexploitation?

Knowledge gaps
- Many types of overexploitations cannot be monitored with EO data, and we lack proxies that can be observed from space.
- Monitoring of the impacts of aqua farming is possible but we currently have no overview of its extent and impact on biodiversity.
- Each year several billion tons of mining waste (Jones & Boger, 2021) are deposited in about 18000 active tailings (ICOLD, 2018) that are subject to regular spills and dam failures with unknown effects on downstream rivers

Science Question 6
How can we assess the impact of drivers of environmental change when multiple drivers act simultaneously, and/or when drivers are unknown?

Knowledge gaps
- This requires the development and integration of generic indicators of ecosystem resilience into biodiversity monitoring systems.

Science Question 7
Which are the most appropriate methods for upscaling from local field measurements to a global scale?

Knowledge gaps
- A comprehensive measurement of ecosystem functioning, community composition, and most other EBV classes is feasible only at a few locations and requires (RS enabled) proxies that are more easily detectable on a global scale and biodiversity models to extrapolate from field observations at point locations to a regional or global scale. For many EBVs it is not clear how this should be done, highlighting a huge knowledge gap.

6 IT solutions for improving biodiversity monitoring

6.1 Evaluation of existing and upcoming IT solutions

The value of EO data for biodiversity assessment and monitoring is not questioned. Beside gaps in algorithm suitability and quality there are also barriers for stakeholders to practically use the EO based products in the daily work. These barriers are due to technical challenge

- to assess data,
- to identify the most suitable source,
- to combine satellite measurements with other data types (models, in-situ, airborne, drone, ...)
- to synthesize biodiversity relevant information,
- and to cope with the shear amount of data.

Table 6 provides a structured and comprehensive list of relevant IT services, thematic services and tools and gives an overview of ready to use technology addressing biodiversity assessments. The advantages or matches and the disadvantages or gap of each technology towards the BD community is described in the rightmost columns.

Table 6. List of relevant IT services, thematic services and tools

	Name	Description	Matches for BD community	Gaps for BD community
IT services	CEOS COVE	The CEOS COVE is a suite of tools for analyzing satellite sensor coverage for more than 100 Earth-observing satellites.	Quick overview for present and potential EO data.	Processing, management and analysis of EO data not possible.
	EuroDataCube	Euro Data Cube is a one-stop-shop for browsing, analysis and processing of EO data, from source up to the final product.	Collection, Processing, management and analysis of raster and vector data possible.	BD models and BD variables have not yet been integrated in workflow.
	Thematic Exploitation Platforms	ESA's Earth Observation Thematic Exploitation Platform (TEP) is a browser for satellite imagery and specific products on an environmental topic.	Various BD variables present.	Management and analysis of raster and vector data not possible.
	Earth System Data Laboratory	The Earth System Data Lab seeks to be a service to the scientific community to greatly facilitate access and exploitation of multivariate data sets in Earth Sciences.	Various BD variables present. Analysis and management of raster data possible. Will be continued within EuroDataCube.	Management of model and vector data not possible.
	Copernicus DIAS	The five DIAS online platforms allow users to discover, manipulate, process and download Copernicus data and information.	Processing of big EO data possible.	Management of raster or vector data not possible.
	National Platforms (CODE-DE, THEIA)	National Platforms offer high-performance access to all Copernicus data in corresponding countries.	Processing of big EO data possible.	Management of raster or vector data not possible.

	Sentinel Hub	Sentinel Hub makes satellite data easily accessible for browsing or analyzing them, within a cloud GIS or within an own environment.	Easy access to big EO data possible.	Processing, management and analysis of raster or vector data not possible.
	OpenEarthEngine	currently in development	-	-
	ADAM platform	The Advanced geospatial Data Management platform is a tool to access a large variety and volume of global environmental data	Management and analysis of raster data possible. Multiple BD variables.	Management of model and vector data not possible.
	Planetary Computer	The Planetary Computer combines a multi-petabyte catalog of global environmental data.	Easy access to big EO data and BD parameters possible.	Management of model and vector data not possible.
Thematic services	GlobWetlandAfrica Toolbox	GlobWetland Africa Toolbox was launched to facilitate the exploitation of satellite observations for the conservation, wise-use and effective management of wetlands in Africa	Toolbox developed for BD analytical purpose. Ready to use.	Toolbox is tailored to study sides in Africa.
	Ocean Virtual Lab	The Ocean Virtual Laboratory is a virtual platform to discover the existence and then to handle jointly the various co-located EO datasets and related model/in-situ datasets over dedicated regions of interest with a different multifaceted point of view.	Management and analysis of raster and vector data possible.	OVL tailored to ocean applications.
	Agriculture Virtual Lab	The Agriculture Virtual Laboratory is an integrated, user-friendly online environment that helps scientists to discover, explore, analyse, and visualize a wide variety of agricultural earth observation data.	Management and analysis of raster and vector data possible.	AVL tailored to agricultural applications.
Tools	Rasdaman	Rasdaman is an Array DBMS which adds capabilities for storage and retrieval of massive multi-dimensional arrays, such as sensor, image, simulation, and statistics data.	Tool for managing raster data (model and remote sensing data) and in situ data.	No interface for satellite data processing.
	Callisto, DeepCube, GEM, BETTER, CANDELA, EOPEN, openEO,	European R&D projects conducted under the H2020.	Development of machine learning methods analyz-	-

	PerceptiveSentinel, RapidAI4EO		ing EO data and other data.	

6.2 Requirements for future IT solutions

The future of biodiversity assessment and monitoring relies on a compact development of IT solutions covering diverse requirements and objectives. The main challenges of this evolution are to handle big data processing, develop interfaces between different data sources and satisfy various user requirement.

Big data processing

Various cloud services listed in the table above already fulfil the requirement for the ability to process large amount of EO data, e.g. the Copernicus DIAS, AWS or Google Cloud Platform. For future BD assessment and monitoring IT solutions should consider not only big data processing for EO data but also handle large amounts of modelled and in-situ data. The processing of these data sources should focus on retrieving EBVs. The deployment and operation of services on a cloud infrastructure is always associated with costs which cannot be neglected. There are the obvious costs for the Cloud service provider and there are the personnel costs on the side of the user of the cloud platform. Today the costs of the infrastructure differ, sometimes largely, but also the effort (=costs) needed by the user to achieve their goal differs. Today the effort on the user side is very relevant and hard to predict when just studying the price offers. Today the experience is that it is better to pay a higher price for a solid, robust and well tested IT infrastructure than struggling with a infrastructure which is less mature. We expect (or require) that the market of cloud providers will consolidate in the future and that own costs will become lower and better predictable.

Interfaces between different data sources

Addressing biodiversity assessment and monitoring relies currently on in-situ observations and increasingly on citizen science data. Any future IT solution supporting biodiversity stakeholders needs to be strong on integrating these data types with the EO and / or model data. This covers especially raster data and vector data. Some IT solutions already cover this requirement, e.g. the EuroDataCube has a dedicated component, the so-call geoDB which is designed for handling non-raster data. For a comprehensive BD assessment and monitoring this requirement is crucial to take advantage of all available data sources. Future IT solutions need to satisfy the need for an infrastructure which can handle and combine in-situ data, modelled data and EO data.

Satisfy various user requirement

Another important requirement for future IT solutions is to satisfy varying user requirements. The users in the biodiversity community are divers and IT solutions should potentially cover small scaled regional to global requests. The interface between the processed data, e.g. the EBVs, and the user need to address these requests. Ideally numerous EBVs are available and can be retrieved in different spatial and temporal resolutions. Tools that users are already use need to be served by data services (standards) for smooth integration into existing tools.

There is already great potential to connect the developments made by the cloud platforms, EO cloud service providers, and European R&D activities with the needs and working practice of the biodiversity community. Table 6 shows that many components of the requirements for future IT solutions are already developed. Within BIOMONDO we will use these components to build a guideline for biodiversity assessment and monitoring in freshwater systems.

GEOBON developed BON in a Box, which is a prototype of what future IT solutions may look like. It aims to serve as a technology transfer mechanism that allows countries accessing to the most advanced and effective monitoring protocols, tools and software thereby enhance or harmonize a national biodiversity observing system. Nevertheless, Bon in a Box does not cover any freshwater EBVs and the processing of big datasets is not possible with this IT solution.

A merging of the above-mentioned elements is needed to serve users of biodiversity data. Better integration and therefore a good design of interfaces is key for this.

7 ESS pilots for Freshwater ecosystems

In this precursor study, we focus on a few biodiversity pilots that are of particular relevance within the context of monitoring the impact of changing environmental conditions on biodiversity and for which results can be obtained within the two-year time frame of this project. When doing so, we use the following key definitions:

- **Biodiversity Pilots:** Biodiversity Pilots are studies investigating whether one or more Pilot Objectives, as defined in the SPTM, can be reached through the development of novel integrated EO/model/in situ products, for example the objective to "Monitor and assess impact of eutrophication (EBV - productivity)".
- **Biodiversity Pilot Sites:** Selected BD Pilots will be implemented in representative regions where biodiversity expertise and historical in situ data are available to validate the scientific utility and impact of the novel integrated products.
- **Output of Biodiversity Pilots:** Novel EO products and/or innovative integration of EO into ecological/ecosystem models.
- **Pilot Objectives:** To monitor and assess the impact of measurable metrics of a change environmental condition on freshwater biodiversity and/or ecosystem functions.

A single biodiversity pilot may thus address multiple pilot objectives and may be performed at multiple sites.

The relevance of a Biodiversity Pilot or a Pilot Site is greater when: 1) relatively large environmental changes have occurred in the time period and/or geographical area chosen for further analysis (as a minimum), or when comparison between areas or time periods with relatively large and small environmental changes is possible (preferred), 2) the study area includes sites that are of particular importance for nature conservation (BD hot spots), 3) the potential of the novel EO product for integration into ecological/ecosystem models for BD monitoring and risk assessment is high (i.e. its applicability), and when 4) upscaling to a high, preferably global, geographic scale is possible.

Rather than studying a single process in isolation, BIOMONDO aims to integrate EO in studies of the properties emerging from the interactions between humanity, the climate system, ecosystems, and biodiversity. Ultimately, our biodiversity pilots thus take an **Earth System Science (ESS)** approach and contribute to our understanding of the 'Earth System', i.e., the Earth's interacting physical, chemical, and biological processes.

7.1 Candidate ESS Freshwater Biodiversity Pilots

To develop a broad outlook on ongoing changes in freshwater biodiversity and how these changes can be monitored using EO data, our candidate ESS Freshwater Biodiversity pilots each address pilot objectives and knowledge gaps (as described in the SPTM and section 5.4.1) corresponding to one of the following three drivers of global environmental change in freshwater ecosystems: 'pollution and nutrient enrichment' (pilot 1), 'climate change' (pilot 2), and 'habitat change' (pilot 3). The scientific objectives of these pilots provide the bases for WP3 and WP4 in which the scientific and policy impact of these pilots is assessed and maximised, and should contribute to the development of a Science Agenda and Scientific Roadmap (WP5) for the implementation phase of the EC-ESA Biodiversity Flagship Action.

7.1.1 *Pilot 1: The impact of (reverse) eutrophication and habitat changes on the water quality of shallow lakes.*

As discussed in Chapter 5, nutrient concentrations have increased substantially in lakes and rivers throughout the world (Heathwaite et al. 1996; Revenga et al. 1998), resulting in eutrophication, changes in water column trophic status, harmful algal blooms, loss of submerged macrophytes affecting sedimentation and turbidity, and biodiversity loss. In addition to this, habitat changes may alter flow regimes and sediment load. Monitoring such changes in water quality should be a fundamental part of any freshwater biodiversity monitoring program. **In this BIOMONDO pilot we, therefore, explore the possibilities of integrating EO data into Delft3D. Delft3D is a world leading 3D modelling suite to investigate hydrodynamics, sediment transport and morphology, and water quality for fluvial, estuarine and coastal environments, and is used on many places around the world, such as the Netherlands, USA, Hong Kong, Singapore, Australia, Venice, etc.** Within Delft3D, the Delwaq engine simulates the far- and mid-field water and sediment quality due to a variety of transport and water quality processes. The BLOOM module describes the biogeochemical processes. State variables are phytoplankton biomass and chlorophyll-a, associated nutrient concentrations as well as oxygen. The phytoplankton is subject to gross primary production, respiration, excretion, mortality, grazing, resuspension and settling resulting in net growth (biomass increase or decrease). The phytoplankton module BLOOM includes specific formulations for these processes with the exception of excretion, grazing, resuspension and settling. The combination of Delwaq and BLOOM is often referred to as Delft3D-ECO. The model is coupled to the Delft3D-FLOW (for simulation of hydrodynamics) and Delft3D-WAVE (for simulation of waves) results and describes the fate (processes) and transport of the state variables. Within this pilot we can tackle a variety of objectives as described in the SPTM of which the most important are:

1. To monitor and assess impact of changes in water column trophic status, especially eutrophication and sediment load
2. To monitor and assess impact on algae blooms/cyanobacteria
3. To monitor and assess impact of habitat improvement measures for turbidity reduction, e.g. creation of islands, removal of barriers for fish, creation of low-wind areas for development of macrophytes improve connectivity with other wetlands in land-water interface.
4. To monitor and assess changes in seasonal dynamics (e.g. phenology of phytoplankton growth, EBV phenology)

These objectives mainly contribute to science question 1 in section 5.4.1, and will be tackled in the following way:

- Objective 1:

- EO maps for chl-a, total suspended matter (TSM) and light extinction will be produced for all the years since Sentinel-2 has been operational. Operational services including satellite missions (e.g. ENVISAT-MERIS, Sentinel-3 OLCI) will be included for coarser spatial resolution, e.g. to provide a larger historical dataset. Furthermore, the potential of primary production (PP) derived from EO data will be investigated. No operational services or PP algorithms are yet available for freshwater systems. Nevertheless, algorithm approaches will be tested and evaluated concerning their applicability.
- In situ data: phytoplankton, chl-a, light extinction, transparency and TSM data will be collected (though Rijkswaterstaat) to relate EO chl-a and TSM products. In 2022: in situ primary production measurements will be done by Rijkswaterstaat for Biomondo. These data will be compared to the EO PP products.
- Model: the Delft3D model will provide support for the observed chl-a (a.o. through modelled nutrient dynamics) and TSM (through the effects of wind on hydrodynamics and hence TSM transport) patterns.

- Objective 2:
    - EO maps with cyanobacteria indicator (in addition to the chl-a maps mentioned under Objective 1) will be produced to be able to see if cyanobacteria occurrences intensify temporally and spatially. We will investigate near future hyperspectral sensors, e.g. EnMap, to identify approaches for determining phycocyanin concentrations.
    - In situ data on phytoplankton (see Objective 1) will be used to support the EO phycocyanin indicator products.
    - Model: the Delft3D model will provide information on nutrient dynamics and hydrodynamics to help explain the observed changes in cyanobacteria concentrations.

- Objective 3:
    - EO products on especially TSM will show the effects of the Marker Wadden on (possible) turbidity reduction. These data will support the bird foraging behavior research in this area.
    - In situ data (in addition to what has been mentioned under the other objectives) on bird numbers and foraging will be provided by the bird foraging behavior program of national park Nieuw-Land.
    - The model will fill gaps between measurements (both EO and in situ)

- Objective 4:
    - The same data produced under the other objectives will serve to contribute to this objective as well. In addition, EO SWT products will be used for this objective since this is an important parameter to study changes in phenology.

If time permits, we will explore possibilities of linking Delft3D with models of change in biodiversity as well, e.g. GLOBIO, and we will explore the possibility of developing a new

EO product describing primary productivity in freshwater systems. It is likely, however, that these exercises have to become part of the Roadmap.

Pilot sites

We have chosen the IJsselmeer area as the primary site for this pilot. The IJsselmeer area (Figure 13) is an important site to study (reverse) eutrophication and habitat changes on biodiversity because 1) parts in this area have high concentrations of suspended sediments (Markermeer), 2) a shift took place from a lake, dominated by harmful algal blooms, to less harmful algae and 3) many restoration measures have been undertaken or are still in construction such as the Marker Wadden (part of the be constructed national park Nieuw-Land). The IJsselmeer area is a freshwater lake area divided in three sections: 1) the IJsselmeer itself, 2) Markermeer/IJmeer and 3) Border lakes. All three are Ramsar and Natura 2000 sites. With the closure of the Afsluitdijk in 1932, the former Southern Sea estuary was transformed in the freshwater Lake IJsselmeer. Subsequently, a string of so-called border lakes and Lake Markermeer were created by land reclamation projects and the construction of dams. These alterations serve safety, provide drinking water supplies and created agricultural land. Owing to the change in category, the lakes are by the Water Framework Directive (WFD) definition heavily modified.

Figure 13 Location of the IJsselmeer area, showing the IJsselmeer itself in the northern part of the system and the Markermeer in the southern part.

The lakes serve as a major stop for many migratory waterfowl species such as the Common Pochard or Tufted Duck. In the past, these species mainly fed on the zebra mussels which contributed almost 100% to their diet. Since the second half of the 1980's, this lake area has observed a reduction in nutrients (N, P). This ongoing oligotrophication resulted in a change of the phytoplankton composition (from large colony-forming species (mainly cyanobacteria) to smaller species (small green algae) with a high turnover rate of nutrients). The zebra mussels somehow could not survive well enough on these new species of algae and were replaced by its relatives, the quagga mussels. This species feeds on the smaller phytoplankton species but the consequence of this is that the food quality of these mussels is much lower than the zebra mussels. Because of this (though there are other hypotheses that could explain the decrease such as improved habitats elsewhere and less frozen periods in the Baltic Sea which may lead to less migration), the bird numbers are still decreasing in the area. Also, other modifications in the food web took place. For example, the European smelt has decreased in numbers, probably due to warming of the water temperature and over-fishing, and many exotic species (benthic invertebrates as well as fish species such as gobies) are now dominating the food web. Especially the Markermeer suffers from these changes also because this lake is very turbid due to the fact that suspended solids cannot leave the system. In this lake, several measures are constructed to provide sheltered habitats for the development of macrophytes, (spawning) fish, and other species at higher trophic levels. One of these measures is the creation of islands (Marker Wadden), that also aim to improve the water quality of Lake Markermeer for higher trophic levels such as red listed and other aquatic herbivorous, fish-eating, and mussel-eating waterfowl. With EO we can detect these changes in habitat type (as shown in Figure 14) to complement our analysis when needed/of interest to stakeholders.

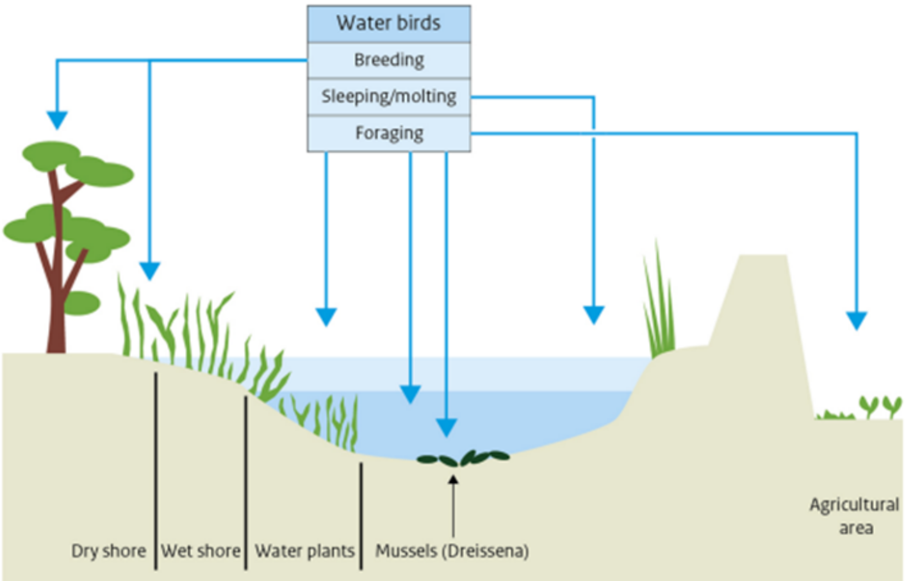

Figure 14 Different ecotopes in a lake with the ecological relation of birds in the ecosystem (Van Puijenbroek et al., 2015).

As can be seen from the described activities, we will combine earth observation data for several parameters with available in situ data coming from Rijkswaterstaat (Early Adopter) and from other sources as well (e.g. University of Amsterdam who is doing monthly cruises on the lake). The EO requirements for this pilot site are therefore products on:

- Surface water temperature (SWT)
- Light extinction
- Total suspended matter (TSM)
- Chlorophyll-a
- Phycocyanin indicator

For this pilot we will focus on the Sentinel 2 time period but will extend the EO data with previous missions and operational services which cover the time period >10 years from today. For this area, a Delft3D hydrodynamic-water quality model is available which will use the EO products either directly as input or as validation. There are separate Delft3D models available for both Markermeer and IJsselmeer. The models combine hydrodynamics (Delft3D-FLOW) with water quality processes (Delft3D-Delwaq and if necessary, expanded with the BLOOM module for primary production). For these lakes we would like to do simulations with the models in which concentrations of suspended matter/solids (TSM), chlorophyll-a and primary production are the output. We can then compare the outcome of the models for these parameters with the EO product for these same parameters. Model and EO output can then be compared to each other using the Target Value (Jolliff et al., 2009), an overall model performance metric that takes the bias, root mean square error and correlation into account. A Matlab code is available for this exercise. A specific year for this activity will be selected. As a next step, instead of using EO data only as verification of model performance, we will split EO data: a selection will be used as direct input in the model and the rest as validation of model performance (using again the Target Value metric). The improved models will be better able to assess the impact of the nature restoration measures that are taking place as well as the ones to be implemented on phytoplankton, turbidity and production.
Simultaneously, a research program around the creation of a new national park (Nieuw-Land), of which the Marker Wadden is part of, is taking place. In this project, several bird species are tracked to follow their foraging behaviour in the area, especially piscivorous bird species as common tern. One of the objectives is to see if these birds make use of (gradients of) water transparency to hunt for fish. The gradients in water transparency are influenced by wind and activities such as habitat construction and dredging. The EO products from BIOMONDO (turbidity, chl-a) will be linked to the foraging patterns of the birds. This will directly tackle the objective "Monitor and assess impact of changes in water column trophic status, especially eutrophication and sediment load (EBV productivity)" and "Monitor and assess impact of habitat improvement measures for turbidity reduction".

Upscaling and transferability
Regarding the upscaling of this pilot, our hypothesis is that water management and restoration issues for major bio-physical lake types will have certain characteristics in common. Shallow lakes are vulnerable to eutrophication because of their shallowness (limited volume) and transparency because wind-waves can resuspend sediment from the bed (Eleveld, 2012). (Seasonal) stratified deep, clear lakes, and highly absorbing "peat" lakes provide different ecotopes/habitats. These major lake types can be distinguished from EO by their optical water types, OWT (Eleveld et al., 2017). Land-water boundaries, water temperature and colour (from spectra or OWT) are indicators of: change in lake morphometry, hydrodynamics, and trophic state, and of change in its environment, hydrology, land use, ecotopes, soil and geology of the watershed, and of changes in the stressors on lake ecosystems Figure 15 indicates that the re-oligotrophication case is somewhat representative for large lakes in Central Western Europe (Jenny et al., 2020).

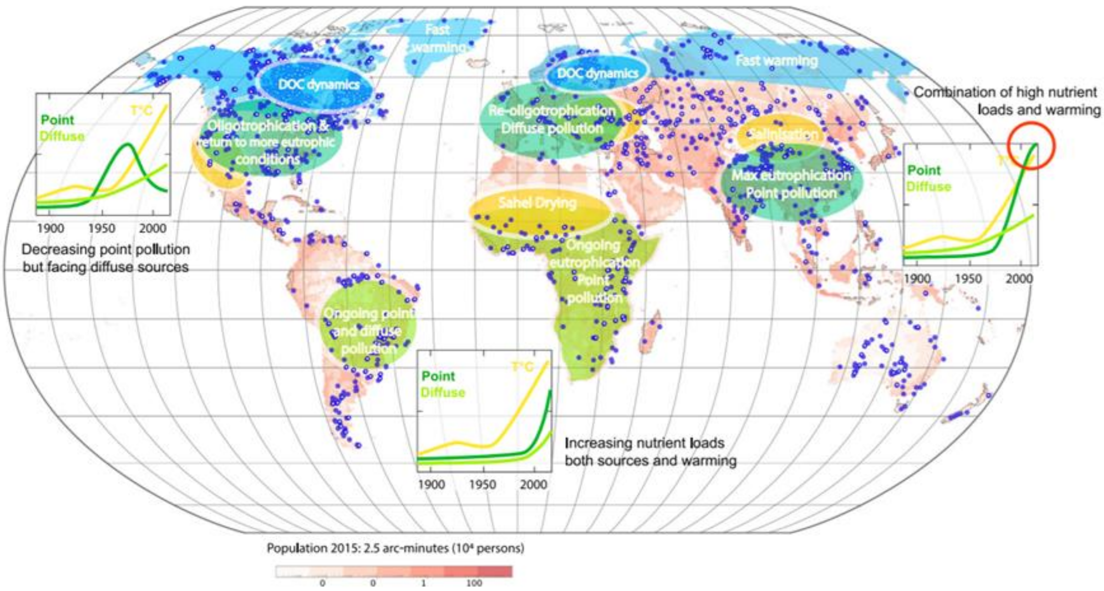

Figure 15 Stressors in large lake ecosystems of the world are represented by examples of point and diffuse nutrient pollution, and climate forcing. Note the different intensity and the accumulation of climate and warming forcing for different regional contexts. Contrasted situations are presented (for Eastern China, Europe and North America, and for Southern Hemisphere). World distribution of large lakes larger than 100 km2 (blue dots), lakes larger than 500 km2 (blue open circles) and human population density (background map, Center for International Earth Science Information Network-CIESIN-Columbia University, 2015) (taken from Jenny et al., 2020).

BIOMONDO Early Adopter Rijkswaterstaat is planning a shallow lakes community to learn from each other about the ecological challenges they face and how to tackle this. The community will cover shallow lakes from a North-South and East-West gradient. Upscaling of the Biomondo activities in the IJsselmeer areas can then later be done for some of these other lakes as well. This confluence with these Earth System Science aspects having been addressed to some extent by the EO community in the ESA Diversity II, EU GLASS, Globolakes projects.

The Delft3D software has been implemented in many lakes worldwide. Examples are several reservoirs in South America (including shallow ones like Aimorés in Brazil), Europe (e.g. Lac de Créteil in France, Lake Balaton in Hungary, Lake Constanz in Germany), Asia (Singapore reservoirs, Lake Toba in Indonesia). Because of its flexibility, it is relatively easy to apply it to other lakes in the world. Lakes that resemble the IJsselmeer area, such as Lake Peipsi, are therefore candidate areas for future pilot studies.

7.1.2 *Pilot 2: Impact of changes in water temperature and heat waves on freshwater fish diversity*

Lake surface water temperatures have been rising rapidly globally (on average 0.34 °C per decade between 1984 and 2009) (O'Reilly et al., 2015). Additionally, lake heat waves intensity and duration are expected to increase with future climate change, exacerbating the effects of long-term warming (Woolway et al., 2021). Lake ecosystems are vulnerable to these temperature changes: directly by pushing to or exceeding species and ecosystems limits of resilience, and indirectly through for example decreasing amount of oxygen in the water, altering stratification or algae blooms altering oxygen availability. Accurate data on surface water temperature (SWT) is therefore crucial for estimating impacts on biodiversity. EO data can complement or replace (incomplete, point based) in-situ SWT, or give more (spatially/temporally) detailed estimates compared to modelling products. Ideally, this data would have a daily temporal resolution in order to capture heat waves. Data covering a large temporal range would allow studying changes over longer periods of time (years/decades). If the spatial resolution is higher than the lake of interest, spatial differences can also be captured in the analysis. This would also allow avoiding the influence of mixed pixels (which include land surface temperature).

The objective of this BIOMONDO pilot is to explore the possibilities of using a combination of EO data on SWT and thermal tolerance of freshwater fish species in order to quantify the impacts of increases in temperature and heat waves on freshwater fish diversity. This objective can be found in the SPTM (see section 5.4) and contributes to science question 4 in section 5.4.1. To achieve this, we first build and evaluate a predictive model of freshwater fish species' physiological tolerance to maximum water temperature, as an extension of the existing GLOBIO-Aquatic model. (Janse et al., 2015; Barbarossa et al., 2020). We'll then apply this model to assess the impact of increases in water temperature and heat waves on freshwater fish diversity at several pilot sites using EO data on water temperature.

To model freshwater fish species' physiological tolerance to maximum water temperature, we will retrieve species-specific data on heat tolerance (critical thermal maximum) from existing databases (Comte and Olden, 2017; GlobTherm by Bennett et al., 2018; Leiva et al., 2019) and systematic literature review. Next, we establish a phylogenetic regression model that estimates the heat tolerance (critical thermal maximum) of a given species as a function of the species' morphological and ecological properties, their phylogeny and their ability to acclimate to heat. We will test the predictive ability of the models based on (block) cross-validation to evaluate how it performs for species that were not included in the model training.

We will use the resulting species-level model to assess the impact of changes in water temperature and heat waves by evaluating the potential exceedance of thermal limits for the freshwater fish species occurring in a selection of pilot sites. This requires a list of species occurring at each site, and a daily timeseries of SWT, preferably covering multiple years/decades, and with an as high as possible spatial resolution. If data availability allows, model estimates can be compared with reported heat-induced fish kills. Pilot sites were selected based on the availability of data (SWT, fish species, validation data) needed for the impact assessment (see below). The chosen pilot sites are Lake Balaton (Hungary), Lake Geneva (Switzerland), Lake Mälaren (Sweden) and Lake Victoria (Tanzania, Uganda and Kenya), as well as Lake Marken/IJsselmeer (NL) in parallel with the eutrophication pilot (7.1.1).

Obtaining remotely sensed SWT with a high resolution (both spatial and temporal) is challenging. Various satellite systems (e.g. Landsat series, Sentinel-3, MODIS, AVHRR) carry sensors that can record thermal radiation. To be able to retrieve the SWT, the emissivity of water (~0.991, Wang et al. 2015) and the atmosphere as well as other atmospheric influences (absorption, scattering, transmission) must be corrected. In the case of freshwater systems, it should be noted that the derived thermal radiation temperature corresponds to the so-called skin temperature, i.e. it originates from an approximately 500 µm thin area located at the interface between water and air (Pareeth et al. 2017). Stratification and wind on the water surface result in a skin temperature that is cooler than the in-situ measured kinetic bulk temperature. Nevertheless, various studies show that both temperatures are strongly correlated (R^2 often > 0.9), i.e. for Landsat (Simon et al. 2014).

The coarse spatial resolution of most thermal sensors (> 1 km^2 for Sentinel-3, MODIS, AVHRR etc.) is a challenge for the analysis of many freshwater systems. Only larger freshwater bodies (>100km^2) can be captured with this coarse resolution. For smaller freshwater systems, Landsat sensors, which have a higher spatial resolution but lower temporal resolution, must therefore be used. This raises the question of whether large-scale and small-scale sensors can be combined in time series. Such combinations could also reduce limitations with frequent cloud coverage.

Several SWT products are available from existing services, i.e. Copernicus Land service or the ESA Climate Change Initiative, covering the coarse spatial resolution (1 km) and the time period from 1995 to today. With these products, it is necessary to evaluate whether their spatial resolution is sufficient for biodiversity studies. To achieve the highest possible temporal resolution and to be able to go back as far as possible into the archives, these services are built on the combination of different thermal sensors. For higher spatial resolution sensors, the Landsat Collection 2 Temperature Product is available (~100m) and covers the period from 1984 to today. Nevertheless, the temporal resolution with an 8-day revisit time is rather low and potential cloud coverage is further reducing the availability of usable products.

For BIOMONDO we are aiming to combine multiple available EO-based SWT products to retrieve the highest spatial and temporal resolution possible. We will then compare the result with air temperature data (ERA5 reanalysis) as well as modelled water temperature data to check whether the spatial and temporal resolution of the SWT product is sufficient to pick up heatwaves. Modelled water temperature data with a global extent are available from the the DynWat model (Wanders et al., 2019) or Delft3D (for the Markermeer). If the resolution of the combined EO-based SWT product falls short, we may combine it either with modelled water temperature or with air temperature data. Due to high correlations of SWT to the air temperature, the high temporal resolution of the ERA5 data combined with the EO SWT data contribute valuable information for biodiversity monitoring and assessment. The novel product could be validated with in-situ surface water temperature data if available.

Pilot sites

Pilot sites for this pilot were selected based on the availability of data (SWT, fish species, validation data) needed for the impact assessment. After an assessment of data availability using search engines and our network of international collaborators, 5 pilot sites were chosen: Lake Balaton (Hungary), Lake Geneva (Switzerland/France), Lake Mälaren (Sweden), Lake Marken (The Netherlands) and Lake Victoria (Tanzania, Uganda and Kenya). Table 7 shows the data availability at those sites. For all sites EO SWT data from CCI Lakes and CGLOPS are available (temporal range >10 years). Below a description of each pilot site can be found.

It may be decided to do different or less pilot sites depending on apparent (EO) data availability or time constrains.

Table 7 Data availability in considered pilot sites. Per lake availability of in-situ data (yellow columns) and information regarding EO data (green columns).

Freshwater system	Availability of in-situ data for the suggested Freshwater System							Regarding EO data for the suggested Freshwater System	
Lake	List of fish species	Fish kills (by temperature increase)	Fish occurrence data	Description fish occurrence data	In-situ temperature data	Description in-situ temperature data (temporal/ spatial scale)	Contacts	Characteristics of the system	Potential cloud coverage
Balaton	Yes	Unknown	Yes	Surveys, representative data for 2005, 2010, 2014 and 2018.	Yes	Daily from 1975 to 2012. Between 2003 and 2021 at 5 points, with a monthly (October-May) or biweekly (June-September) frequency.	Balaton Limnological Research Institute (István Czeglédi)	Elongated, no islands, suitable for RS	Low
Geneva	Yes	Unknown	Yes	Complete survey 2012, + previous info	Yes	Real-time from April 2020 (LéXPLORE), CIPEL monthly data at two stations from 1953.	EPFL (Sébastien Lavanchy) UNIGE (Bas Ibelings) EAWAG (Ole Seehausen) CIPEL	Elongated/round, no islands, suitable for RS	Medium
Mälaren	Yes	Yes	Yes	4 stations sampled in 2016 and 2019	Yes	33 stations sampled TBD-TBD times (appr. monthly) respectively during 2016-2020.	Swedish Inst. of freshwater research and his (Alfred Sandströms)	Elongated, many islands, suitable for RS	Medium/ high
Marken	Yes	No	Yes	Per year per species using different "catching methods" (Wageningen	Yes	In situ data measured by Rijkswaterstaat (several locations in the	Deltares and Rijkswaterstaat	Round, few island, suitable for RS	Medium

				[University & Research])		lake)			
Victoria	Yes	No	Yes	Data in several sites, sampled in 2017 by Ole See-hausen's team is currently being pro-cessedYes	In situ CTD measure-ments taken in 2000–2001 and in 2008 (Pilla et al., 2021).	EAWAG (Ole Seehausen)	Round, some islands, suitable for RS	Medium/ high	

Lake Balaton (Hungary)
With its surface area of 596 km^2, an average depth of 3.2 m, and a maximum depth of 11 m, Lake Balaton is the largest shallow lake in Central Europe. It is located in western Hungary, within the Carpatian Basin. The area of Lake Balaton is part of the Balaton-felvidéki National Park, it is a Ramsar site and it is included in the Natura 2000 network. This is favorable, as Lake Balaton represents nearly half of the natural aquatic surface area in the Pannonian Ecoregion, supporting large populations of plant and animal species. Its ecological status may therefore affect biodiversity region wide. It is furthermore an important site for European wintering bird populations and provides spawning and nursery grounds for fish (Ramsar, 2017). Among its inhabitants are significant populations of Habitat Directive fish species (EC, 1992), i.e. the asp, the razor fish, the white-finned gudgeon and the bitterling. Multiple anthropogenic pressures such as alien species, eutrophication, fishing and degradation of waterside habitats affect the biodiversity of Lake Balaton (Bíró, 1997; Istvánovics et al., 2007; Specziár, 2010). Main activities at the site are tourism and related business, fishing, reed harvesting (Ramsar, 2017).
The water temperature in Lake Balaton ranges from 0 to 29°C, with an annual average of 15°C. In the winter, the lake is often covered by ice (Somogyi et al., 2020). The water rich in calcium-magnesium hydrocarbonate and oxygen gains the temperature of the air quickly due to its shallow depth (Ramsar, 2017). Water temperatures have significantly increased during the past decades. Liebherr and Wunderle (2018) studied AVHRR LSWT data from 1981 to 2016 and found significant increases in annual, spring and summer temperatures, of 0.34, 0.54 and 0.53 °C/decade respectively. The lake underwent a strong eutrophication during the 1970s–1990s due to the use of fertilizers, leading to an increase in cyanobacteria (Vörös and Nagy Göde, 1993). During the last 20 years the water quality has improved as the rate of eutrophication significantly declined.

Lake Geneva (Switzerland/France)
Lake Geneva, also known as Lac Léman, is situated between the Alps to the south and the Jura mountains to the north, and on the French/Swiss border. It is an elongated lake with a max length of 73 km, a maximum width of 14 km and a surface area of 580 km^2. As is visible in Figure 16 the western part of the lake is a small and narrow section ("Petit Lac", max. depth 76m, 4% of the water volume), while the lake is wider in the east ("Grand Lac", max. depth 310m). The lake remains stratified most of the year and the surface waters do not freeze in the main body. Mixing occurs every winter in the Petit Lac, while mixing rarely occurs in the Grand Lac (Perroud et al., 2009). Lake Geneva provides about one million surrounding area inhabitants with various services, including drinking water supply, recreation, or fisheries (CIPEL, 2014). The eastern part of the lake (Les Grangettes) is a Ramsar Site.
Lake Geneva is threatened by anthropogenic pressures and issues associated with human induced global environmental change, such as pollution, invasive species and climate change (Perroud and Goyette, 2010; Lane et al., 2019, CIPEL, 2019). From 1970 to 2010, a general warming trend was observed in and around Lake Geneva. Annual surface water temperature increased by 1.5°C during this period. Since 2012, the temperature of the lake bottom has increased by an average of 0.11 °C/year. The warming in the lake can be related to the warming in the atmospheric boundary layer (Lemmin and Amouroux, 2013; CIPER, 2021). This increase can continue, as the most significant features of climate change in the European mid-latitude region are a warming trend of the

atmosphere and an increasing extreme weather events. The former may increase lake water temperature and the latter may cause strong fluctuations in lake water temperature (Lemmin and Amouroux, 2013).

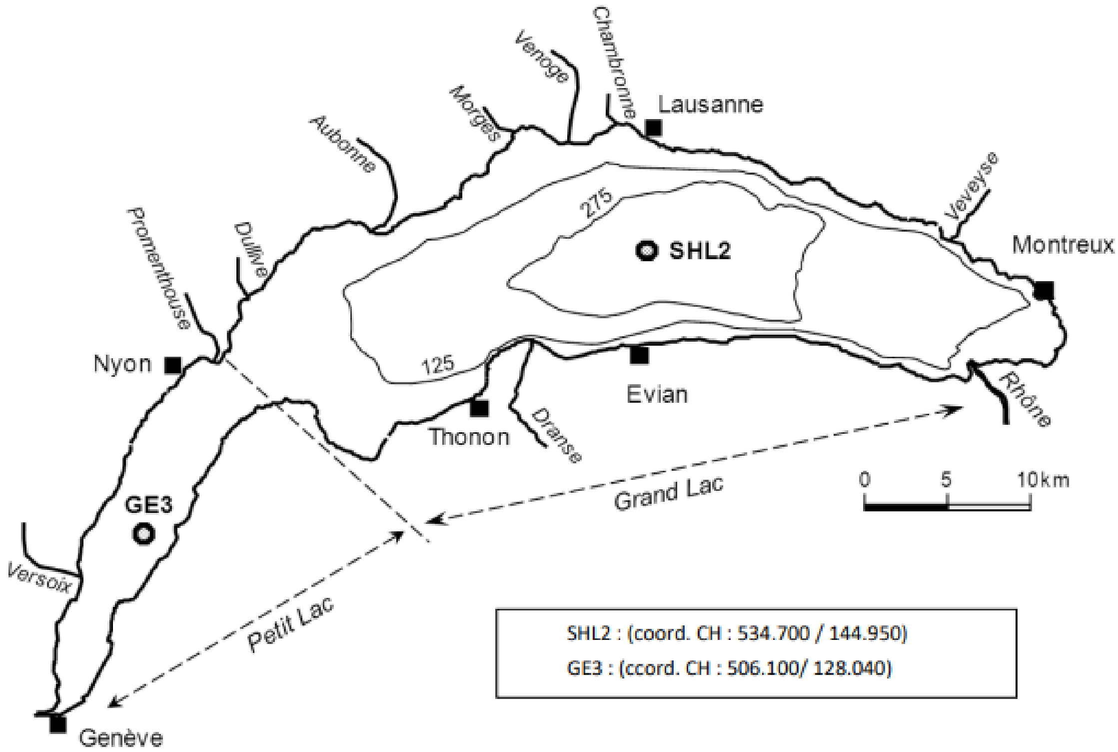

Figure 16 Lake Geneva and the location of two measuring stations (measurements include temperature) Source: CIPES (2021).

Lake Mälaren (Sweden)

Lake Mälaren is Sweden's third largest lake (1122 km^2). It has an average depth of 12.8 meters and a maximum depth of 66 meters. Several larger rivers flow into Lake Mälaren and its catchment area also includes Lake Hjälmaren, which is Sweden's fourth largest lake, as well as a number of smaller lakes. Lake Mälaren is regulated and its main outlet, which has an average water flow of just over 160 m^3/s, is trough Stockholm and into the Baltic Sea. Lake Mälaren is a typical plain lake with over 8,000 islands, islets and skerries. Its catchment area is 22,650 km^2, which corresponds to about 5% of Sweden's area. There are about eighty nature reserves around Lake Mälaren and over 40 Natura 2000 areas. In addition to these, there are also areas that have been pointed out as national interests by the Swedish regional County Administrative Boards. The area is diverse with agricultural landscapes, forested mountain areas and the archipelago. The water in Lake Mälaren is naturally nutrient-rich, which makes it sensitive to eutrophication. High levels of phytoplankton biomass have been measured, and cyanobacteria are common. During the 1960s, Lake Mälaren was heavily eutrophicated, but thanks to improved treatment plants and agricultural measures, the situation has improved. Lake Mälaren's water is very heterogeneous and the lake is divided into several administrative basins, as the conditions vary from one part to another. The lake is used for a large number of different activities, such as shipping, commercial fishing, agriculture, drinking water production and tourism. Mälaren has 34 naturally occurring fish species. The most common species are smelt, perch, roach, birch, bream and pikeperch. Smelt, which dominates the pelagic waters, plays an important role in the ecosystem as prey fish. It is anticipated that climate change will change the water level and water flows in Lake Mälaren. Climate change will also mean increasing water temperature, reduced ice cover and sea level rise which has consequences for different interests around the lakes (Eklund et. al, 2018).

Lake Marken (Netherlands)
See 7.1.1 for a description of this site.

Lake Victoria (Tanzania/Uganda/Kenya)
Lake Victoria is at 1135 m a.s.l. and by area the second largest fresh water lake in the world . Its shoreline is shared by Kenya (6 %), Uganda (45 %) and Tanzania (49 %). It lies in a shallow depression between the Great Rift Valley and the western Albertine Rift, and has an average and maximum depth of 132 m and 265 m, respectively. The lake receives 85% of all water input from precipitation, and only 15% from several small tributaries. Similarly, evaporation accounts for 85% of all water loss, and only a minor output is through its only outlet, the Victoria Nile in the north. The lake's surface level varies by up to 3 m, mostly in response to rainfall, to a smaller extent due to managed outflows (Awange and Ong'ang'a, 2006). Pelagic waters in Lake Victoria are stratified, seasonally variable and receive nutrients mainly through diffuse atmospheric deposition (Njiru et al., 2012). A comprehensive report on the freshwater biodiversity in Lake Victoria listed 651 species, whereof 204 are endemic to the lake, whereof again 76% are considered to be threatened with extinction (Sayer et al., 2018). Biodiversity in the lake is known to vary spatially, for example with increasing species richness in more transparent parts of the lake (Seehausen et al., 1997). Less is known about the impact of temporal variability and temperature.

Upscaling and transferability
Upscaling of this approach is possible, as this would only require SWT data and information on (the spatial distribution of) fish species occurring in the area of interest. If there is no local data on fish species occurrence, the use of global species distribution information can be considered (e.g. as used in Barbarossa et al., 2021). The method can therefore be applied to any place (transferability) and any scale (upscaling). The spatial resolution of the model results are equal to the resolution of SWT data used as model input. Applying the method to rivers might be problematic (present-day), as spatial resolution of EO data may be too coarse.

7.1.3 Pilot 3: Monitoring river connectivity/dams, its changes and impact on biodiversity

Obstacles such as dams and other human-made waterworks heavily alter and interrupt dispersal routes for many species, including aquatic invertebrates (Grönroos et al. 2013), fish (Barbarossa et al. 2020; Duarte et al. 2021) and plants (Merritt & Wohl 2006). In addition to this, river dams and other human-made waterworks change the natural flow regimes and habitats of aquatic and semi-aquatic species in rivers (Poff et al, 2010; Poff & Zimmermann, 2010; Janse et al, 2015) and river floodplains (Kuiper et al., 2014). Other effects of dams on biota occur via water quality deterioration and reduction of sediment transport to coastal wetlands. Consequently, removal of dams is an explicit target in the EU Nature Restoration Plan (section 3.2), which aims that at least 25,000 km of free-flowing rivers should be restored. River dams, however, also are important in the less developed countries, and are welcomed as a source of renewable energy (e.g. hydropower) when combatting climate change. These benefits come at a cost for biodiversity as, for example, discussed in Winnemiller (2016) who found that "Long-term ripple effects on ecosystem services and biodiversity are rarely weighed appropriately during dam planning in the tropics". Dam-building thus provides a real challenge when developing environmental and developmental policies and requires careful consideration of pros and cons.

The dispersal of species within and between freshwater ecosystems is limited for two reasons: 1) because there is little exchange of organisms between river basins (Leuven et al. 2009) and 2) because dispersal is constrained by the dendritic (tree-like) structure and directional flow of river networks (Hänfling & Weetman 2006; Carrara et al. 2012; Wubs et al. 2016). The limited ability of freshwater species to reach sites via dispersal as a consequence of these limitations (Shurin & Smith 2006) reduces biodiversity (Shurin et al. 2000; Irz et al. 2004), and the effects of human-induced habitat fragmentation can be expected to be particularly severe for freshwater ecosystems. In particular, because fragmentation in dendritic river networks creates habitat patches that are smaller and more varied in size when compared to terrestrial landscapes (Fagan 2002; Fuller et al. 2015; Yi et al. 2010). The multiple, simultaneous effects of river dams, e.g. on species dispersal routes, water flows and water extent, and water quality, including differences in these effects between different types of dams, however, are not well understood. Satellite Earth observation is a suitable tool to improve the inconsistent global information basis for assessments of these multiple effects and associated restoration goals (section 5.1.3).

In this pilot, we focus on the impact of river dams on freshwater ecosystems at river catchment scale and use this as the basis for formulating the requirements for upscaling to the global scale. **More specifically, the objective of this BIOMONDO pilot is to explore the possibilities for combining EO data and biodiversity modelling for monitoring and assessing the impact of dam construction and removal on biodiversity, including the effects on:**

1) **Habitat fragmentation and dispersal routes**
2) **Changes in habitat extent**
3) **water quality (e.g. through influences on sedimentation and turbidity).**

These effects correspond to three pilot objectives that be found in the SPTM (see section 5.4) and contribute to science question 2 in section 5.4.1. This, in turn, will pave the way for a further assessment of the impact of river dams on wetlands (e.g. the extent of wetlands before and behind a river dams may change considerably), and the assessment of other human-induced changes (e.g. canalization) on river biodiversity (as part of the Roadmap).

We will assess the impact of past, current, and (planned) future dams, as well as the potential for dam removal to increase connectivity, using a species-specific modelling approach. More specifically, we will model the impact of river dams on the geographic range connectivity of ~10.000 fish species living partially or exclusively in rapidly flowing freshwater (e.g. rivers) for entire drainage systems, i.e. the patterns formed by the streams, rivers, and lakes in a particular drainage basin. The impact of dams may differ between fish that complete their lifecycle in freshwater and fish species that migrate between freshwater and marine environments. Specific connectivity measures will, therefore, be adopted for driamous and nondriamous fish species, following a procedure co-developed by members of BIOMONDO and described in Barbarossa *et al.* (2020). This procedure results in an assessment of the degree of geographic range fragmentation, expressed as a connectivity index (range 0-1) where 1 represents a range that is fully connected and 0.5 results from a dam dividing a range into two equally sized fragments.

Several datasets on *the locations of dams* are available (see Section 5.1.3), including approaches where satellite observations are used. These datasets vary in terms of quality, coverage and definitions of dams, and also the attributes provided vary among them, which pose challenges on their use for global assessments and impact studies on biodiversity. At catchment level, reasonably consistent level of dam datasets, however, exist, at least for major rivers. The situation is comparable for the other parameters listed above: *land cover / land use data sets exist to monitor changes in habitat extent* but with varying quality and legends when it comes to spatial high resolution. ESA CCI provides an excellent time series at 300m with 42 internationally classes. Recently ESA has released the 10m Worldcover classification including 10 classes. The latter would have the required spatial resolution but is lacking the temporal dimension. If we find that the existing data are not suitable for our purpose, we will study options to improve existing methods, or develop a new one, in particular by facilitating latest improvements by AI/ML. *There are no operational EO data services for river water quality and turbidity*, so we need to process this on our own.

The results of this pilot may contribute to the further improvement of the GLOBIO fish habitat module, and may help quantify impacts of dam-induced changes in water flows on biodiversity intactness using the Mean Species Abundance (MSA) indicator in GLOBIO-Aquatic.

Pilot sites

We have chosen the Greater Mekong region as the as the primary site for this pilot. This region holds irreplaceable riches—ranging from rare wildlife in spectacular natural landscapes to communities with distinct cultural heritages. The vast region spans six countries: China, Myanmar, Lao PDR, Thailand, Cambodia and Vietnam. Its 809 000km^2—the combined size of Germany and Sweden—contain some of the most biologically diverse habitats in the world. This is the 'rice bowl' of Asia and at its heart lays the Mekong River. Winding almost 3,000 miles from the Tibetan plateau down to the South China Sea, the Mekong River boasts the world's largest inland fishery. It accounts for up to 25 percent of the global freshwater catch and provides livelihoods for at least 60 million people. It is second only to the Amazon River in terms of fish biodiversity. At least 1,100 freshwater species swim the waters of this mighty river including the last remaining populations of the Irrawaddy dolphin, giant freshwater stingray which can weigh up to 1,300 pounds, and the Mekong giant catfish.

Unprecedented social and economic development in the Greater Mekong makes conservation work here especially urgent and significant. The most pressing threats are hydropower development, climate change, illegal wildlife trade and habitat loss. An example of the impact of the dams in the Mekong river system on the environment and thus ecosystem services is given by Eyler, 2020 in his essay "Science shows the Chinese Dams are devasting the Mekong". This construction of the Nuozhadu dam in 2012 had a dramatic effect on the water level and the normally occurring flooding events along the river (see Figure 17).

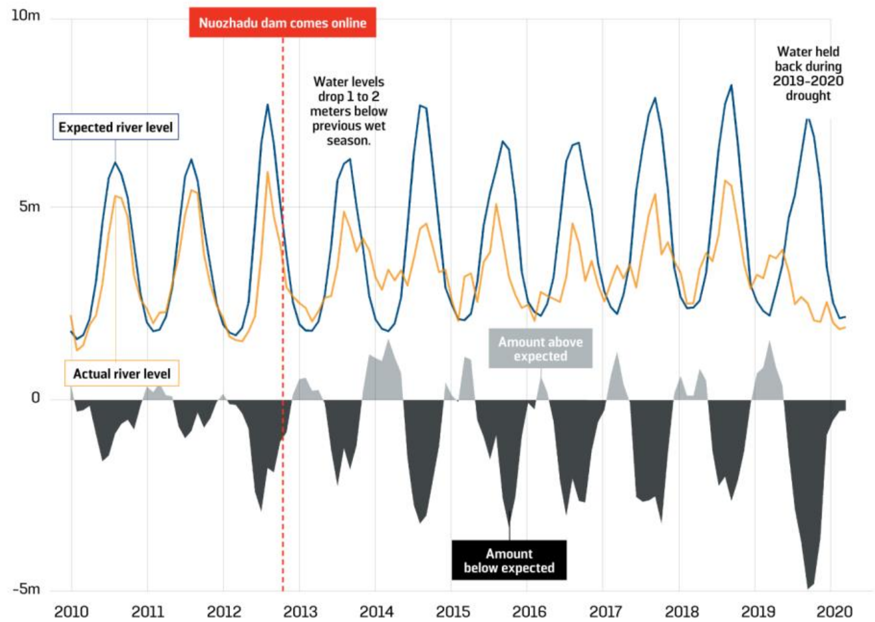

Figure 17 Impact of the Nuozhadu Dam on the Mekong River; river heights in meters. From Eyler 2020. Data source: Eyes on Earth, Mekong River Commission. The river water level is taken from NASA's Eyes on Earth system.

Wikipedia reports for 2016 a total number of 56 dams in use for hydropower energy in the Mekong river basin (i.e. for the Mekong river and its tributaries): Laos 23, China 18, Vietnam 10, Thailand 5. Another 31 dams were under construction. Most of the dams have been built after 1994, and more than 2/3 of them after 2009. Time series of when these dams were placed are available, allowing us to study changes in the connectivity of the Greater Mekong area and to assess whether critical percolation points have already been passed (see Figure 18). More specifically, landsat 5 data allows an assessment of the area in almost unregulated conditions. With ENVISAT MERIS, ASAR and AATSR, and Landsat 5 and 7, the situation before the big increase of dam constructions happened is captured. The situation after 2016 is well measured by Sentinel 2, Sentinel 3 and Landsat 8. This suite of EO sensors allows mapping of land cover / land use, water extent and water quality. With the MWR on ENVISAT and Sentinel 3 also the water level can be measured (with the known limitations for rivers). The Land Cover CCI long term time series back to 1992 allows an excellent mapping of the river basin even if at a spatial resolution of 300m only. Ready-to-use thematic data (Level 2, Level 3) are available from ESA CCI (Medium Resolution Land Cover, Lakes) and Copernicus (C3S Land Cover, CLMS Global – Hydrosphere). For some questions we may, however, need to do own processing on the satellite Level 1 data (to be studied during WP2).

The Mekong Dam Monitor[5] is an online platform which uses remote sensing, satellite imagery, and GIS analysis to provide near-real time reporting and data downloads across numerous previously unreported indicators in the Mekong Basin. Among others, it provides weekly updates of high-resolution satellite images (10-meter Sentinel imagery) of all 13 completed dams and reservoirs on the Mekong mainstream in addition to 13 tributary dams with power generation capacities greater than 200 MW, and also weekly reservoir level (meters above sea level) readings and operation curves of those dams. The platform is freely available for public use and all research inputs are public-access resources.

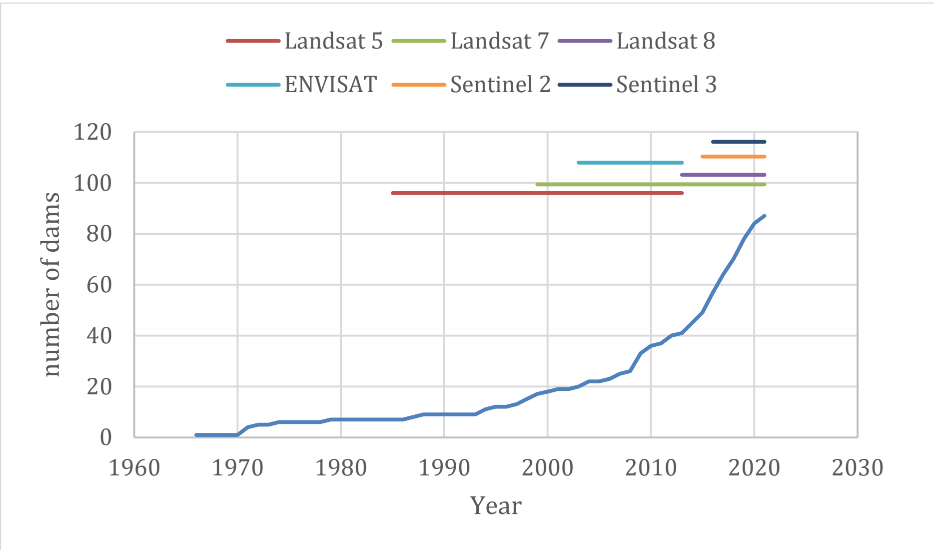

Figure 18 Timeseries of number of dams in the Mekong Basins from 1960-today and the availability of EO data for different sensors within this time period.

The Mekong basin will furthermore be one of the focus regions of the Horizon Europe project SOS-Water. This four-year project was selected in call HORIZON-CL6-2021-CLIMATE-01, and will start in the second half of 2022 with EAWAG as a partner and the Mekong River Commission's Dr. So Nam as a stakeholder. It will investigate safe operating spaces for water resource management with regards to all socio-economic and ecological values, including biodiversity.

Upscaling and transferability

Within this pilot and the Mekong basin as a pilot site we are assessing the changes on biodiversity due river connectivity changes in a densely studied region. This will help us to understand the impacts of dams on biodiversity and to validate and improve the ap-

[5] **https://www.stimson.org/project/mekong-dam-monitor/**

plied models. The aim of the pilot is to develop a method and approach that can potentially be applied to any river catchment area. Whereas EO data input, e.g. LCLU maps and water quality parameters are globally available for spatially high resolutions and the used models are not region bound, the constraint of this pilot is the availability of the dam locations. Therefore, the transferability will be currently limited to the river catchment areas with medium to larger dam sizes, because for dam detection based on EO data this is the limiting factor.

7.2 Risk Assessment

The EO datasets identified in Chapter 5 include operational services and relevant own processed datasets for the pilot sides. For those datasets the scientific and technical risk for the pilot studies can be assessed in two different levels:

Medium Risk

For Pilot 2 the technical risk **is increased** to use **EO SWT** products **with the highest spatio-temporal solutio**n as possible. Quantifying the impacts of increases in temperature and heat waves on freshwater fish diversity may need a higher temporal resolution from EO data as currently possible, e.g. to identify the effect on the SWT from heatwaves. The planned future thermal sensors, such as LSTM, will decrease this risk. Furthermore, we will look at alternatives to increase the temporal resolution, e.g. using the SWT data calculated by the Delft3D model, for minimizing this risk.

For Pilot 3 the technical and scientific risk for detecting dams with EO data is medium. Although approaches to detect dams are work in progress the methods are not yet upscaled or validated. Possible risk can be decreased by using available databases of dam locations, e.g. GRanD, GlObal, GOODD or FHRed.

Low Risk

For Pilot 1 the technical and scientific risk is low. Using operational services, e.g. Copernicus Services or CCI services, decrease any risk for the EO data due to preceding quality assessments within these services. The risk for relevant EO data processing done by the BIOMONDO team is identified as low. The intended processors used for Pilot 1 are well validated and maintained, e.g. C2RCC processor, MPH algorithm.

8 Freshwater Biodiversity Policy Showcases

The aim of the BIOMONDO Freshwater showcases is to demonstrate how novel Earth Observation and Biodiversity modelling products can be integrated to enhance decision support systems for biodiversity monitoring and address the policy priorities of the EU Biodiversity Strategy for 2030 but also the monitoring and EBV framework of the new CBD post-2020 Global Framework Directive that is under development and should be adopted in 2022 (see section 3.4), as well as, Natura 2000 assessments.

The showcases will be based on the three selected pilots presented in section 7.1 and demonstrate and assess the policy utility and impact of the results from these pilots. The assessment will be made together with relevant Early Adopters, which also will have access to the BIOMODO data cube for access to data and results. Each show case will address specific biodiversity policy goals by presenting information that is easy to act on and has clear potential to lead to enhanced biodiversity management. The showcases will be told as stories with clear illustrations to make sure the key points can be easily understood and adopted.

8.1 **Showcase 1 – Eutrophication**

8.1.1 Topic

This showcase will address the impact of eutrophication and habitat changes on the water quality of shallow lakes and demonstrate how novel EO products and model results can capture the status and the deflection of the negative trend and give guidance to mitigation measures.

The showcase is built on data from the IJsselmeer area, for which a number of restoration measures have been implemented over the last couple of years. The lakes in this area will serve as a demonstration example of shallow lakes with high risk to increase in trophic state (eutrophication) and to develop cyanobacterial blooms, and where the high turbidity in the lake reduces the underwater light field and therefore affects the submerged vegetation, macrofauna and fish. Lake management or restoration projects aim to bring such lakes from turbid to clear water state.

The EO data products to be used, and their combination with models and in-situ data, are described in detail in section 0.

8.1.2 Early Adopter

The Early Adopter for this showcase is Rijkswaterstaat (RWS), Ministry of Infrastructure and Water Environment. RWS is the manager of the national water systems in the Netherlands. This includes e.g. freshwater availability, flood protection and water quality. RWS is also responsible for the Natura 2000 management plans of national waters and responsible for the achievement of the Natura 2000 objectives. In addition, RWS is running the monitoring programs for evaluation of the different policies. Biodiversity is clearly important in different policies and gets more and more attention. RWS will support the showcase implementation and assess the possibilities and impact of using a combination of earth observation data, field products and model simulations to support measures to halt or reduce biodiversity loss.

8.1.3 Policy relevance

- The EU Biodiversity Strategy 2030 Restoration targets
- Water Framework Directive related monitoring and actions
- Assessments of EBVs (EBV productivity and EBV phenology)
- Natura2000 management plans and objectives

In *the EU Biodiversity Strategy for 2030*, the EU and its Member States have committed to implement more than 100 actions by 2030. The EU Nature Restoration Plan constitutes one part of these actions and includes "Target 13 - The losses of nutrients from fertilisers are reduced by 50%, resulting in the reduction of the use of fertilisers by at least 20%". The inflow of nutrients from the surrounding catchment area constitutes an impact on the trophic level of the lake and can significantly contribute to the eutrophication process. Heavy rain falls can cause a flush of nutrients into nearby freshwaters and coastal zones and a potential general increase in precipitation due to climate change may further increase the load of nutrients to freshwater. A loss of nutrients from the agricultural field generates a need for additional fertilization. In many countries, actions are taken to reduce the losses of nitrate and phosphorus from farmland into surface and groundwater. Several measures, such as protection zones, lime filter ditches, two-step ditches and spring cultivation can be implemented to reduce the loss. For planning, the estimated effect could be explored with models, and for follow-up data from several sources are needed. For this showcase, validated EO data products, in combination with models and in-situ data, will be used to demonstrate how e.g. Chl a can be used as a proxy for the eutrophication level in freshwaters and how changes in the level of model state variables (i.e. inflow of nitrogen and phosphorus) would affect the status of the lake.

The Water Framework Directive (WFD) was implemented in December 2000, with the goals to protect and improve all water bodies including rivers, lakes, coastal waters and groundwater and to prevent a further degradation in status of aquatic systems and wetlands. The target was ambitiously set to improve all the water bodies in Europe to "good status" before 2015, which means that the parameters for the biological quality elements should only show low levels of disturbance, as a result of human activity. This has demonstrably not been achieved and measurements should be taken to amend and plan improvements for all the water bodies that are not considered to have this status. Surface water status is assessed using biological and physical-chemical factors and several parameters. The exact implementation can vary between countries, but "Phytoplankton" is commonly one of the biological quality factors assessed and "Light condition" is a potential physical-chemical factor. Commonly, Chl a concentration, presence of cyanobacteria and Secchi Disc Depth are examples of parameters used to assess the included factors, and which also can be estimated from EO. For this showcase, validated EO data products, in combination with models and in-situ data, will be used to demonstrate how e.g. satellite based estimations of Chl a and Secchi Disk Depth can be used, as a complement to traditional measurements, to assess the biological and physical-chemical status with better spatial and temporal resolution.

The *Essential Biodiversity Variables (EBVs)* are defined as the derived measurements required to study, report, and manage biodiversity change, focusing on status and trend in elements of biodiversity, and should play the role of brokers between monitoring initiatives and decision makers. They provide the first level of abstraction between low-level primary observations and high-level indicators of biodiversity (geobon.org/ebvs). The EBV class "Ecosystem functioning" has three EBVs:

- Primary productivity - The rate at which energy is transformed into organic matter primarily through photosynthesis.

- Ecosystem phenology - Duration and magnitude of cyclic processes observed at the ecosystem level, such as in vegetation activity, phytoplankton blooms, etc.
- Ecosystem disturbances - Abrupt deviances in the functioning of the ecosystem from its regular dynamics.

For this showcase, validated EO data products, in combination with models and in-situ data, will be used to demonstrate how EO based PP, Chl a and cyanobacteria products could be used to support the assessment of the listed EBVs.

With respect to *Natura 2000* management plans and objective, the EO based products, the novel EO products, which all are linked to EBVs and BD drivers, and the output from the models could potentially be used to facilitate identification of areas that should be added to existing Natura 2000 areas. They could also be used to support regular assessments of ecosystem conditions and changes within Natura 2000 areas. A potential use could be to demonstrate inclusion of validated EO data products, in combination with models and in-situ data, in Natura 2000 SCI assessments and SCA status and change reporting. This type of application could also support the policy goals of the EU Biodiversity Strategy 2030 of "Establishment of a large EU-wide network of protected areas on land and sea". The potential showcase will be further elaborated for the Ijsselmeer region together with Rijkswaterstaat, which are responsible for the Natura 2000 management plans objectives in the Netherlands.

8.2 **Showcase 2 – Climate change**

8.2.1 Topic

<u>This showcase will address the impact of long- and short-term changes in water temperature on freshwater fish diversity. It considers the general climate change related increase in lake surface water temperatures, and occasional, but increasing in number and duration, specific lake heat waves.</u>

The showcase is built on data from five different lakes; Lake Balaton (Hungary), Lake Geneva (Switzerland), Lake Mälaren (Sweden), Lake Victoria (Tanzania, Uganda and Kenya), and Lake Marken/IJsselmeer (NL), for which data (SWT, fish species, validation data) is available. In Lake Mälaren, fish kills were observed during summer 2018 and spring 2019 and the high water temperatures are believed to be the main reason for these events.

The EO data products to be used, and their combination with models and in-situ data, are described in detail in section 0.

8.2.2 Early Adopter

Rijkswaterstaat (RWS), Ministry of Infrastructure and Water Environment will be one of the Early Adopter also for this showcase. RWS is the manager of the national water systems in the Netherlands and will work closely with the BIOMONDO team on several aspects related to Lake Marken.

For Lake Mälaren, we will collaborate with the Institute of Freshwater Research in Sweden, which is one of three divisions at the Department of Aquatic Resources (SLU Aqua), regarding the assessment of the policy utility and impact of the results from studies. The institute monitor the aquatic environment and develop methods and know-how for sustainable use of aquatic resources. The main focus is resource estimations, fisheries management and conservation of fish and its relation to the environment. They run projects dealing with the stocks in the four largest lakes of Sweden, salmon, sea trout, eel and crayfish, endangered species and eutrophic lakes and problems related to acidification and liming. The Institute of Freshwater Research is also responsible for the test-fishing data generated in national and regional environmental programs, on behalf of the Swedish Agency for Marine and Water Management.

8.2.3 Policy relevance

- Water Framework Directive related monitoring and actions

The Water Framework Directive (WFD) was implemented in December 2000, and as described in sec. 8.1.3, the surface water status is assessed using several biological and physical-chemical factors and parameters. Besides “Phytoplankton”, “Fish” is commonly one of the biological quality factors assessed and water temperature is one of the environmental factors that affect the status assessment. For this showcase, validated EO data WST products, in combination with models and in-situ data, will be used to demonstrate how this type of data can be used quantify the impacts of increases in temperature and heat waves on freshwater fish diversity and if/how it affects different species addressed in WFD.

8.3 Showcase 3 - River Connectivity

8.3.1 Topic

<u>This showcase concerns identification of dams and monitoring of the effects of dam regulations. Obstacles such as dams and other human-made waterworks heavily alter and interrupt dispersal routes for many species, including aquatic invertebrates, fish and plants, which has an effect on the connectivity and also the water quality.</u>

The showcase is built on data from the Greater Mekong region. The Mekong River boasts the world's largest inland fishery. It accounts for up to 25 percent of the global freshwater catch and provides livelihoods for at least 60 million people. It is second only to the Amazon River in terms of fish biodiversity. Unprecedented social and economic development in the Greater Mekong makes conservation work here especially urgent and significant. One of the most pressing threats is hydropower development and wikipedia reports a total number of 56 dams in use for hydropower energy in the Mekong river basin for 2016, and another 31 dams were under construction. Time series of when these dams were placed are available, which will allow us to study changes in the connectivity of the Greater Mekong area and to assess whether critical percolation points have already been passed

The EO data products to be used, and their combination with models and in-situ data, are described in detail in section 7.1.3.

8.3.2 Early Adopter

The Mekong basin will be one of the focus regions of the Horizon Europe project SOS-Water. This four-year project was selected in call HORIZON-CL6-2021-CLIMATE-01, and will start in the second half of 2022 with EAWAG as a partner and the Mekong River Commission's Dr. So Nam as stakeholder. It will investigate safe operating spaces for water resource management with regards to all socio-economic and ecological values, including biodiversity, and we will benefit from this collaboration for Showcase 3.

8.3.3 Policy relevance

- The EU Biodiversity Strategy 2030 Restoration targets
- Water Framework Directive related monitoring and actions
- UNEP GBO-5 Freshwater transition

In *the EU Biodiversity Strategy for 2030*, the EU and its Member States have committed to implement more than 100 actions by 2030 as described in section 8.1.3. The EU Nature Restoration Plan constitutes one part of these actions and includes "Target 11 - At least 25,000 km of free-flowing rivers are restored." The EU's legal framework on water is ambitious but implementation is lagging behind. Greater efforts are needed to restore freshwater ecosystems and the natural functions of rivers in order to achieve the objectives of the *Water Framework Directive*. This can be done by removing or adjusting barriers that prevent the passage of migrating fish and improving the flow of water and sediments. To help make this a reality, at least 25,000 km of rivers will be restored into free-flowing rivers by 2030 through the removal of primarily obsolete barriers and the restoration of floodplains and wetlands. For Pilot 3 (0), the specific goal is a strategy goal that this Pilot potentially can support by monitoring river connectivity issues and that can be demonstrated in Showcase 3.

The *UNEP GBO-5 key components of the Sustainable Freshwater Transition* (or actions) are closely related to the key drivers of biodiversity loss of freshwater ecosystems and these need to be implemented across all levels of society. Integration of environmental flows into water management is specifically mentioned in the GBO-5 Inland Water Highlights as a key component. With respect to Target 15, dam removals for river flow restoration have increased exponentially since 1950s. There is potential for EO to support this specific restoration target by improving the status of current dam datasets as well as monitor effects of restoration actions.

9 References

9.1 Scientific Papers

Abell, R., Thieme, M. L., Revenga, C., Bryer, M., Kottelat, M., Bogutskaya, N., ... & Petry, P. (2008). Freshwater ecoregions of the world: a new map of biogeographic units for freshwater biodiversity conservation. BioScience, 58(5), 403-414.

Alikas, K., Kangro, K. and Reinart Noorma, A. (2010). Detecting cyanobacterial blooms in large North European lakes using the Maximum Chlorophyll Index. Oceanologia 52(2). Doi: 10.5697/oc.52-2.237.

Alkemade, R., van Oorschot, M., Miles, L. et al. (2009). GLOBIO3: A Framework to Investigate Options for Reducing Global Terrestrial Biodiversity Loss. Ecosystems 12, 374–390 https://doi.org/10.1007/s10021-009-9229-5.

Awange, J.L., and Ong'ang'a, O. (2006). Lake Victoria: Ecology, Resources, Environment (Berlin, Germany: Springer Verlag).

Balian, E. V., Segers, H., Martens, K., & Lévéque, C. (2007). The freshwater animal diversity assessment: an overview of the results. Freshwater animal diversity assessment, 627-637.

Balvanera, P., Brauman, K. A., Cord, A. F., Drakou, E. G., Geijzendorffer, I. R., Karp, D. S., ... & Schröter, M. (2022). Essential ecosystem service variables for monitoring progress towards sustainability. Current Opinion in Environmental Sustainability, 54, 101152.

Barbarossa, V., Bosmans, J., Wanders, N., King, H., Bierkens, M. F., Huijbregts, M. A., & Schipper, A. M. (2021). Threats of global warming to the world's freshwater fishes. Nature communications, 12(1), 1-10.

Barbarossa, V., Schmitt, R.J.P., Huijbregts, M.A.J., Zarfl, C., King, H. & Schipper, A.M. (2020). Impacts of current and future large dams on the geographic range connectivity of freshwater fish worldwide. Proc. Natl. Acad. Sci. U. S. A., 117, 3648–3655.

Bayliss, B., Brenman, K., Elliot, I., Finlayson, M., Hall, R., House, T., Pidgeon, B., Walden B., and Waterman,P. (1997). Vulnerability Assessment of Predicted Climate Change and Sea Level Rise in the Alligator Rivers Region, Northern Territory Australia. Supervising Scientist Report 123, Supervising Scientist, Canberra, Australia 134 pp.

Bebber, D. P., Marriott, F. H., Gaston, K. J., Harris, S. A., & Scotland, R. W. (2007). Predicting unknown species numbers using discovery curves. Proceedings of the Royal Society B: Biological Sciences, 274(1618), 1651-1658.

Bennett, J. M., Calosi, P., Clusella-Trullas, S., Martínez, B., Sunday, J., Algar, A. C., ... & Morales-Castilla, I. (2018). GlobTherm, a global database on thermal tolerances for aquatic and terrestrial organisms. Scientific Data, 5(1), 1-7.

Bhatt, R., Gill, M., Hamilton, H., Han, X., Linden, H., and Young, B. (2019). Uneven Use of Biodiversity Indicators in Fifth National Reports to the Convention on Biological Diversity. Environmental Conservation, p 1-7. Doi: 10.1017/S0376892919000365.

Bíró P. 1997. Temporal variations in Lake Balaton and its fish populations. Ecol Freshw Fish 6: 196–216.

Istvánovics V, Clement A, Somlyódy L, Specziár A, Tóth GL, Padisák J. 2007. Updating water quality targets for shallow Lake Balaton (Hungary), recovering from eutrophication. Hy-drobiologia 581: 305–318.

Boswell, G. P., Britton, N. F., & Franks, N. R. (1998). Habitat fragmentation, percolation theory and the conservation of a keystone species. Proceedings of the Royal Society of London. Series B: Biological Sciences, 265(1409), 1921-1925.

Boyd, H. and Madsen, J. (1997). Impacts of global change on artic-breeding bird populations and migration. Pp. 201–217. In: Global change and Artic Terrestrial Ecosystems, W.C. Oechel, T. Callaghan, T. Gilmanov, J.I. Holten, B. Maxwell, U. Molau and B. Sveinbjoernsson (eds), Global Change and Arctic Terrestrial Ecosystems. Ecological Studies 124. Springer, New York. p. 201–217.

Brinson, M.M. and A. Ines Malvarez, (2002). Temperate freshwater wetlands: types, status, and threats. Environmental Conservation 29 (2): 115–133.

Brotons, L., V. Christensen, N. H. Ravindranath, M. Cao, J. H. Chun, O. Maury, P. L. Peri, V. Proença and B. Salihoglu, 2016: Modelling impacts of drivers on biodiversity and ecosystems. In IPBES (2016): The methodological assessment report on scenarios and models of biodiversity and ecosystem services. S. Ferrier, K. N. Ninan, P. Leadley, R. Alkemade, L. A. Acosta, H. R. Akcakaya, L.

Brotons, W. W. L. Cheung, V. Christensen, K. A. Harhash, J. Kabubo-Mariara, C. Lundquist, M. Obersteiner, H. M. Pereira, G. Peterson, R. Pichs-Madruga, N. Ravindranath, C. Rondinini and B. A. Wintle (eds.). Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany. 348 pages.

Carpenter, S. R., Stanley, E. H., & Vander Zanden, M. J. (2011). State of the world's freshwater ecosystems: physical, chemical, and biological changes. Annual review of Environment and Resources, 36, 75-99.

Carrara, F., Altermatt, F., Rodriguez-Iturbe, I. & Rinaldo, A. (2012). Dendritic connectivity controls biodiversity patterns in experimental metacommunities. Proc. Natl. Acad. Sci. U. S. A., 109, 5761–5766.

Carvajal-Quintero, J., Villalobos, F., Oberdorff, T., Grenouillet, G., Brosse, S., Hugueny, B., ... & Tedesco, P. A. (2019). Drainage network position and historical connectivity explain global patterns in freshwater fishes' range size. Proceedings of the National Academy of Sciences, 116(27), 13434-13439.

CIPEL (2014) Lake Geneva. https://www.cipel.org/en/links_en/lake-geneva/. Accessed 2019-08-16

CIPEL (Commission Internationale pour la Protection des eaux du Léman contre la Pollution). Sur les Etudes et Recherches Entreprises dans le Basin Lémanique; CIPEL: Nyon, Switzerland, 2019.

CIPEL (2021) Scientific Report 2021 - 2020 Campaign

Collen, B., Loh, J., Whitmee, S., McRae, L., Amin, R. & Baillie, J. E. M. (2009). Monitoring change in vertebrate abundance: the Living Planet Index. Conservation Biology 23, 317–327.

Comte, L. & Olden, J.D. (2018). Evidence for dispersal syndromes in freshwater fishes. Proc. Biol. Sci., 285.

Comte, L., & Olden, J. D. (2017). Climatic vulnerability of the world's freshwater and marine fishes. Nature Climate Change, 7(10), 718-722.

Davidson, N., Dinesen, L., Fennessy, S., Finlayson, M., Grillas, P., Grobicki, A., Mcinnes, R., Stroud, D. (2019). A review of the adequacy of reporting to the Ramsar Convention on change in the ecological character of wetlands. Marine and Freshwater Research, 71. DOI:10.1071/MF18328.

Dekker, A. G., & Hestir, E. L. (2012). Evaluating the feasibility of systematic inland water quality monitoring with satellite remote sensing. Commonwealth Scientific and Industrial Research Organization, Canberra, Australia.

Diaz, S., Pascual, U., Stenseke, M., Martín-López, B., … Lavorel, S., and Shirayama, Y. (2018). Assessing nature's contributions to people. Science. 359. 270-272. https://www.science.org/doi/abs/10.1126/science.aap8826

Donchyts, G., Baart, F., Winsemius, H., Gorelick, N., Kwadijk, J., & Van De Giesen, N. (2016). Earth's surface water change over the past 30 years. Nature Climate Change, 6(9), 810-813.

Duarte, G., Segurado, P., Haidvogl, G., Pont, D., Ferreira, M.T. & Branco, P. (2021). Damn those damn dams: Fluvial longitudinal connectivity impairment for European diadromous fish throughout the 20th century. Sci. Total Environ., 761, 143293.

Dudgeon, D., Arthington, A. H., Gessner, M. O., Kawabata, Z. I., Knowler, D. J., Lévêque, C., ... & Sullivan, C. A. (2006). Freshwater biodiversity: importance, threats, status and conservation challenges. Biological reviews, 81(2), 163-182.

Dörnhöfer, K. and Oppelt, N. (2016). Remote Sensing for Lake Research and Monitoring—Recent Advances. Ecological Indicators, 64, 105-122.Elliott, J.A. (2021). Modelling lake phytoplankton communities: recent applications of the PROTECH model. Hydrobiologia 848, 209–217. https://doi.org/10.1007/s10750-020-04248-4.

Eklund, A., Stensen, K., Alavi, G. and Jacobsson, K. (2018). Sveriges stora sjöar idag och i framtiden - Klimatets påverkan på Vänern, Vättern, Mälaren och Hjälmaren. Kunskapssammanställning februari 2018. SMHI report KLIMATOLOGI Nr 49, 2018.

Eliot I, C.M. Finlayson and P. Waterman, (1999) Predicted climate change, sea level rise and wetland management in the Australian wet-dry tropics. Wetlands Ecology and Management 7, 63–81.

Eleveld, M.A. (2012). Wind-induced resuspension in a shallow lake from Medium Resolution Imaging Spectrometer (MERIS) full-resolution reflectances. Water Resources Research 48(4), W04508, doi:doi:10.1029/2011WR011121

Eleveld, M.A., Ruescas, A.B., Hommersom, A., Moore, T.S., Peters, S.W.M, Brockmann, C. (2017) An optical classification tool for global lake waters. Remote Sensing 9, 420 doi:10.3390/rs9050420

European Commission 1992. Council Directive 92/43/EEC of 21 May 1992 on the con-servation of natural habitats and of wild fauna and flora. OJEC L206: 7–50.

Eyler, B., 2020, Science Shows Chinese Dams Are Devastating the Mekong. Essay in FP Foreign Policy. https://foreignpolicy.com/2020/04/22/science-shows-chinese-dams-devastating-mekong-river/

Fagan, W.F. (2002). Connectivity, fragmentation, and extinction risk in dendritic metapopulations. Ecology, 83, 3243–3249.

Franklin, J. F. (1988). Structural and functional diversity in temperate forests. Pages 166-175 in E. 0. Wilson, editor. Biodiversity. National Academy Press, Washington, D.C.

Fuller, M.R., Doyle, M.W. & Strayer, D.L. (2015). Causes and consequences of habitat fragmentation in river networks. Ann. N. Y. Acad. Sci., 1355, 31–51.

Gernez, P., Palmer, S. C., Thomas, Y., & Forster, R. (2021). Remote sensing for aquaculture. Frontiers in Marine Science, 7, 1258.

Gitay, H., Suarez, A., Watson, R.T. and Dokken, D.J. (2002). Climate change and biodiversity. IPCC (Inter- governmental Panel on Climate Change) technical paper V, 86. http://www.ipcc.chGitay.

Gill, M. (2020). Remote Sensing Applications for tracking biodiversity. Biodiversity, 21:4, 169-170, DOI:10.1080/1488386.2020.1831959.

Gillet, C., and P. Quétin (2006), Effects of temperature changes on the reproductive cycle of reach in Lake Geneva from 1983 to 2001, J. Fish Biol., 69, 518–534

Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., ... & Zarfl, C. (2019). Mapping the world's free-flowing rivers. Nature, 569(7755), 215-221.

Grönroos, M., Heino, J., Siqueira, T., Landeiro, V.L., Kotanen, J. & Bini, L.M. (2013). Metacommunity structuring in stream networks: roles of dispersal mode, distance type, and regional environmental context. Ecol. Evol., 3, 4473–4487.

Guerra, C.A., Pendleton, L., Drakou, E.G., …. Vihervaara, P., Ziemba, A., Pereira, H.M. (2019) Finding the essential: Improving conservation monitoring across scales. Global Ecology and Conservation, Volume 18, ISSN 2351-9894. https://doi.org/10.1016/j.gecco.2019.e00601.

Habel M., Mechkin, K., Podgorska, K., Saunes, M., Babinski, Z., Chalov, S.R., Podgórski ,Z. and Obolewski, K. (2020). Dam and reservoir removal projects: a mix of social-ecological trends and cost-cutting attitudes. Scientific Reports 10(19210). DOI: 10.1038/s41598-020-76158-3

Harper, M., Mejbel, H.S., Longert, D., Abell, R. … Lintermans, M., Cooke, S. (2021). Twenty-five essential research questions to inform the protection and restoration of freshwater biodiversity. Aquatic Conservation: Marine and Freshwater Ecosystems, 31. DOI:10.1002/aqc.3634.

Hasthorpe & Mount (2007) https://www.semanticscholar.org/paper/The-generation-of-river-channel-skeletons-from-HasthorpeMount/e2615926cea79533bc7c67ec8bfe4f345f5f04ea

Heathwaite, A.L., Johnes, P.J. and Peters, N. (1996). Trends in nutrients. Hydrological Processes 10, 263–293.

Hughes, A.C., Orr, M.C., Ma, K., Costello, M.J., Waller, J., Provoost, P., Yang, Q., Zhu, C. and Qiao, H. (2021). Sampling biases shape our view of the natural world. Ecography, 44: 1–11. doi: 10.1111/ecog.05926.

Hunter, P. D., Tyler, A. N., Carvalho, L., Codd, G. A., & Maberly, S. C. (2010). Hyperspectral remote sensing of cyanobacterial pigments as indicators for cell populations and toxins in eutrophic lakes. *Remote Sensing of Environment*, *114*(11), 2705-2718.

Hänfling, B. & Weetman, D. (2006). Concordant genetic estimators of migration reveal anthropogenically enhanced source-sink population structure in the river sculpin, Cottus gobio. Genetics, 173, 1487–1501.

Irz, P., Argillier, C. & Oberdorff, T. (2004). Native and introduced fish species richness in French lakes: local and regional influences. Glob. Ecol. Biogeogr., 13, 335–344.

Janse, J.H., L. N. De Senerpont Domis, M. Scheffer, L. Lijklema, L. Van Liere, M. Klinge, et al. (2008). Critical phosphorus loading of different types of shallow lakes and the consequences for management estimated with the ecosystem model PCLake. Limnologica 38: 203-219.

Janse J.H., Kuiper, J.J., Weijters M.J., Westerbeek E.P., Jeuken M.H.J.L., Alkemade R., Mooij W.M. and Verhoeven J.T.A. (2015), GLOBIO-Aquatic, a global model of human impact on the biodiversity of inland aquatic ecosystems, Environmental Science & Policy, 48: 99-114. http://dx.doi.org/10.1016/j.envsci.2014.12.007.

Janssen, A.B.G., S. Teurlincx, A. H. W. Beusen, M. A. J. Huijbregts, J. Rost, A. M. Schipper, … and J.H. Janse (2019). PCLake+: A process-based ecological model to assess the trophic state of stratified and non-stratified freshwater lakes worldwide. Ecological Modelling 2019 Vol. 396 Pages 23-32. DOI: https://doi.org/10.1016/j.ecolmodel.2019.01.006.

Jenny, J.-P., Anneville, O., Arnaud, F., Baulaz, Y., Bouffard, D., et al. (2020). Scientists' Warning to Humanity: Rapid degradation of the world's large lakes. Review. Journal of Great Lakes Research, Elsevier, 46 (4), pp.686-702. 10.1016/j.jglr.2020.05.006

Jolliff, J.K., Kindle, J.C., Shulman, I., Penta, B., Friedrichs, M.A.M., Helber, R., Arnone, R.A., (2009). Summary diagrams for coupled hydrodynamic-ecosystem model skill assessment. Journal of Marine Systems 76, 64-82.

Junk, W., (2002) Long-term environmental trends and the future of tropical wetlands. Environmental Conservation 29 (4): 414–435.

Kappes, H., Tackenberg, O. & Haase, P. (2014). Differences in dispersal- and colonization-related traits between taxa from the freshwater and the terrestrial realm. Aquat. Ecol., 48, 73–83.

Kahru, M., Savchuk, O.P. and Elmgren, R. (2007). Satellite measurements of cyanobacterial bloom frequency in the Baltic Sea: interannual and spatial variability. Marine Ecology, Vol. 343: 15–23. doi: 10.3354/meps06943.

Kim H., Peterson G. D., Cheung, W.W.L. and Pereira, H. M. (2021). Towards a better future for biodiversity and people: Modelling Nature Futures. Preprint, DOI: 10.31235/osf.io/93sqp.

Kutser, T. (2004). Quantitative detection of chlorophyll in cyanobacterial blooms by satellite remote sensing. Limnol. Oceanogr., 49(6), 2004, 2179–2189.

Kutser, T. (2009). Passive optical remote sensing of cyanobacteria and other intense phytoplankton blooms in coastal and inland waters. Int. J. Remote Sens. 30, 4401-4425.

Lafortezza, R., Chen, J, Konijendijk van den Bosch, C, Randrup T. B. (2018). Nature-based solutions for resilient landscapes and cities. Environmental Research Vol. 165, pp 431-441. https://doi.org/10.1016/j.envres.2017.11.038

Lane, S.N.; Bakker, M.; Costa, A.; Girardclos, S.; Loizeau, J.L.; Molnar, P.; Silva, T.; Stutenbecker, L.; Schlunegger, F. Making stratigraphy in the Anthropocene: Climate change impacts and economic conditions controlling the supply of sediment to Lake Geneva. Sci. Rep. 2019, 9, 1–11.

Leiva, F. P., Calosi, P., & Verberk, W. C. (2019). Scaling of thermal tolerance with body mass and genome size in ectotherms: a comparison between water-and air-breathers. Philosophical Transactions of the Royal Society B, 374(1778), 20190035.

Leclère, D., Obersteinter, M. Barrett, M. … and Young, L. (2020). Bending the curve of terrestrial biodiversity needs an integrated strategy. Nature Vol. 585, pp 551-556. https://doi.org/10.1038/s41586-020-2705-y

Lehner, B., & Döll, P. (2004). Development and validation of a global database of lakes, reservoirs and wetlands. Journal of hydrology, 296(1-4), 1-22.

Lemmin, U., & Amouroux, A. (2013). The influence of climate change on Lake Geneva. Climatic change and global warming of inland waters, 201-217.

Leuven, R.S.E.W., van der Velde, G., Baijens, I., Snijders, J., van der Zwart, C., Lenders, H.J.R., et al. (2009). The river Rhine: a global highway for dispersal of aquatic invasive species. Biol. Invasions, 11, 1989.

Li, X., Liu, J. P., Saito, Y., & Nguyen, V. L. (2017). Recent evolution of the Mekong Delta and the impacts of dams. Earth-Science Reviews, 175, 1-17.

Lieberherr, G., & Wunderle, S. (2018). Lake surface water temperature derived from 35 years of AVHRR sensor data for European lakes. Remote sensing, 10(7), 990.

Lock, M.C., Skidmore, A.K., van Duren, I., Mücher, C.A. (2021). Evidence-based alignment of conservation policies with remote sensing-enabled essential biodiversity variables. Ecological Indicators, Vol.132, 108272. https://doi.org/10.1016/j.ecolind.2021.108272.

Los, F.J. (2009). Eco-hydrodynamic modelling of primary production in coastal waters and lakes using BLOOM. PhD Thesis Wageningen University, ISBN 978-90-8585-329-9.

Lunetta, R.S., Schaeffer, B.A. Stumpf, R.P. Keith, D. Jacobs, S.A. and Murphy, M.S. 2014. Evaluation of cyanobacteria cell count detection derived from MERIS imagery across the eastern USA Remote Sens. Environ., 157 (2015), pp. 24-34. Doi: 10.1016/j.rse.2014.06.008

Maasri, A., Jähnig, S. C., Adamescu, M.C. …Wolter, C. Worischka, S. (2022). A global agenda for advancing freshwater biodiversity research. Ecology Letters, 2022;25:255–263. DOI: 10.1111/ele.13931

Maes J., Teller A., Erhard M., Condé S., Vallecillo S., Barredo J.I., Paracchini M.L., Abdul Malak D. et al. (2020), Mapping and Assessment of Ecosystems and their Services: An EU ecosystem assessment, EUR 30161 EN, Publications Office of the European Union, Ispra, ISBN 978-92-76-17833-0, doi:10.2760/757183, JRC120383.

Malmqvist, B. and S. Rundle, 2002: Threats to the running water ecosystems of the world. Environmental Conservation 29 (2): 134–153.

Matthews, M. W., and Odermatt, D. (2015). Improved algorithm for routine monitoring of cyanobacteria and eutrophication in inland and near-coastal waters, Remote Sens. Environ., 156, 374–382.

McAllister, D.E., A.L. Hamilton and B. Harvey, (1997) Global freshwater biodiversity: striving for the integrity of freshwater ecosystems. Sea Wind—Bulletin of Ocean Voice International 11(3): 1–140.

Merritt, D.M. & Wohl, E.E. (2006). Plant dispersal along rivers fragmented by dams. River Res. Appl., 22, 1–26.

Mooij, W.M., D. van Wijk, et al. (2019). Modeling water quality in the Anthropocene: directions for the next-generation aquatic ecosystem models. Current Opinion in Environmental Sustainability 2019 Vol. 36 Pages 85-95. DOI: https://doi.org/10.1016/j.cosust.2018.10.012

Mora, C., Tittensor, D. P., & Myers, R. A. (2008). The completeness of taxonomic inventories for describing the global diversity and distribution of marine fishes. Proceedings of the Royal Society B: Biological Sciences, 275(1631), 149-155.

Mora, C., Tittensor, D. P., Adl, S., Simpson, A. G., & Worm, B. (2011). How many species are there on Earth and in the ocean? PLoS biology, 9(8), e1001127.

Mulligan, M., van Soesbergen, A. & Sáenz, L. GOODD, a global dataset of more than 38,000 georeferenced dams. Sci Data 7, 31 (2020). https://doi.org/10.1038/s41597-020-0362-5

Navarro, L.M., Fernández, N., Guerra, C. … Gill, M., Pereira, H. M. (2017). Monitoring biodiversity change through effective global coordination. Current Opinion in Environmental Sustainability, Vol. 29, pp 158-169, ISSN 1877-3435. https://doi.org/10.1016/j.cosust.2018.02.005.

Newbold, T., Hudson, L.N., Phillips, H.R.P., Hill, S.L.L., Contu, S., Lysenko, I., Blandon, A., Butchart, S.H.M., Booth, H.L., Day, J., De Palma, a., Harrison, M.L.K. et al. (2014). A global model of the re-sponse of tropical and sub-tropical forest biodiversity to anthropogenic pressures. Proc. Royal Soc.B. https://doi.org/10.1098/rspb.2014.1371.

Noss, R. F. (1990). Indicators for monitoring biodiversity: a hierarchical approach. Conservation biology, 4(4), 355-364.

Njiru, M., Nyamweya, C., Gichuki, J., Mugidde, R., Mkumbo, O., and Witte, F. (2012). In-crease in Anoxia in Lake Victoria and its Effects on the Fishery. In Anoxia, P. Padilla, ed. (Rjeka, Croatia), pp. 99–128.

O'Connor B., Secades, C., Penner J., Sonnenschein R., Skidmore A., Burgess N.D. and Hutton J.M., (2015), Earth observation as a tool for tracking progress towards the Aichi Biodiversity Targets, Remote Sensing in Ecology and Conservation, Policy Forum: 19-28, doi: 10.1002/rse2.4.

O'Connor, B., Bojinski, S., Röösli, C. and Schaepman, M. E. (2020), Monitoring global changes in biodiversity and climate essential as ecological crisis intensifies, Ecological Informatics, Vol. 55, 101033, ISSN 1574-9541.https://doi.org/10.1016/j.ecoinf.2019.101033

Odermatt, D., Gitelson, A., Brando, V. E., & Schaepman, M. (2012). Review of constituent retrieval in optically deep and complex waters from satellite imagery. Remote sensing of environment, 118, 116-126.

O'Reilly, C. M., Sharma, S., Gray, D. K., Hampton, S. E., Read, J. S., Rowley, R. J., ... & Zhang, G. (2015). Rapid and highly variable warming of lake surface waters around the globe. Geophysical Research Letters, 42(24), 10-773.

Pareeth, S., Bresciani, M., Buzzi, F., Leoni, B., Lepori, F., Ludovisi, A., Morabito, G., Adrian, R., Neteler, M. and Salmaso, N., (2017). Warming trends of perialpine lakes from homogenised time series of historical satellite and in-situ data. Science of The Total Environment, 578, 417-426.

Pekel, J., Cottam, A., Gorelick, N. and Belward, A., (2016) Global Surface Water - Data Access, Na-ture. doi:10.1038/nature20584, JRC109054.

Pereira. L.M., Davies, K.K., den Belder, E., Ferrier S., …van Vuuren, C., Lundquist, J. (2020). Devel-oping multiscale and integrative nature–people scenarios using the Nature Futures Framework. People and Nature. 2020;2:1172–1195. https://doi.org/10.1002/pan3.10146.

Pereira H.M., Ferrier S., Walters M., Geller G.N., Jongman R.H.G., Scholes R.J. et al. (2013), Essen-tial biodiversity variables, Science 339: 277–278.

Perroud, M., Goyette, S., Martynov, A., Beniston, M., & Annevillec, O. (2009). Simulation of multi-an-nual thermal profiles in deep Lake Geneva: A comparison of one-dimensional lake models. Limnology and Oceanography, 54(5), 1574-1594.

Perroud, M.; Goyette, S. Impact of warmer climate on Lake Geneva water-temperature pro-files. Boreal Environ. Res. 2010, 15, 255–278.

Pettorelli N., Schulte to Bühne H., Tulloch A., Dubois G., Macinnis-Ng C., Queirós A.M., Keith D.A. et al. (2017), Satellite remote sensing of ecosystem functions: opportunities, challenges and way forward, Remote Sensing in Ecology and Conservation, 4 (2): 71–93, doi: 10.1002/rse2.59.

Proença, V., Martin, L.J., Pereira, H.M., … Tiago, P., van Swaay, C.A.M. (2016). Global biodiversity monitoring: From data sources to Essential Biodiversity Variables, Biological Conservation, Vol. 213, Part B, pp 256-263, ISSN 0006-3207. https://doi.org/10.1016/j.biocon.2016.07.014.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F. S., Lambin, E., ... & Foley, J. (2009). Planetary boundaries: exploring the safe operating space for humanity. Ecology and society, 14(2).

van Puijenbroek, P. J., Buijse, A. D., Kraak, M. H., & Verdonschot, P. F. (2019). Species and river specific effects of river fragmentation on European anadromous fish species. River Research and Applications, 35(1), 68-77.

Ramirez-Reyes C., Brauman K.A., Chaplin-Kramer R., Galford G.L., Adamo S.B. et al. (2019), Reimagining the potential of Earth observations for ecosystem service assessments, Science of the Total Environment, 665: 1053-1063.Scholes, R. J. and Biggs, R. (2005). A biodiversity intact-ness index. NATURE, Vol. 434-3, pp 45-49. www.nature.com/nature

Ramsar (2017). Ramsar Sites Information Service: Lake Balaton. Visited on 14 March 2022 via https://rsis.ramsar.org/ris/421

van Rees C.B., Waylen K.A., Schmidt-Kloiber A., Thackeray S.J., Kalinkat G., Martens, K. et al. (2020). Safeguarding freshwater life beyond 2020: Recommendations for the new global biodi-versity framework from the European experience, Conservation Letters, DOI: 10.1111/conl.12771.

Reid, A. J., Carlson, A. K., Creed, I. F., Eliason, E. J., Gell, P. A., Johnson, P. T., ... & Cooke, S. J. (2019). Emerging threats and persistent conservation challenges for freshwater biodiversity. Biological Reviews, 94(3), 849-873.

Revenga, C., Campbell, I., Abell, R., De Villiers, P., & Bryer, M. (2005). Prospects for monitoring freshwater ecosystems towards the 2010 targets. Philosophical Transactions of the Royal Socie-ty B: Biological Sciences, 360(1454), 397-413.

Ruiz-Verdu, A., Simis, S., de Hoyos, C., Gons, H.J. and Pena-Martınez, R. (2008). An evaluation of algorithms for the remote sensing of cyanobacterial biomass, Remote Sens. Environ., 112(11), 3996–4008.

Ruppen, D., Runnalls, J., Tshimanga, R., Wehrli, B., Odermatt, D. (in preparation): Optical remote sensing of large-scale water pollution impacts of mining – insights from Catoca’s tailings spill affecting Angola and the DRC.

Sayer, C. A., Máiz-Tomé, L., & Darwall, W. R. T. (Eds.). (2018). Freshwater biodiversity in the Lake Victoria Basin: Guidance for species conservation, site protection, climate resilience and sustain-able livelihoods. Cambridge, Gland: International Union for Conservation of Nature.

Schoolenberg, M., den Belder, E., Okayasu, S., Alkemade, J. R. M., Lundquist, C. J., Pereira, H. M., Chettri, N., Cheung, W., Ferrier, S., Hauck, J., Hendriks, R. J. J., Karlsson-Vinkhuyzen, S. I. S. E., Kim, H. J., Kolomytsev, G., Kuiper, J., Leadley, P., Metzger, J. P., Ninan, K. N., Palomo, G., ... van Vuuren, D. P. (2018). Report on the Workshop ‘Next Steps in Developing Nature Futures’: Meeting of the expert group on Scenarios and Models of the Intergovernmental Science-Policy Platform on Bio-diversity and Ecosystem Services, June 2018, the Hague, the Netherlands. (PBL publication; No. 3411). PBL Planbureau voor de Leefomgeving.
https://www.pbl.nl/sites/default/files/cms/publicaties/3314_Report_on_The_Hague_workshop_June_2018_V9.pdf

Schultz, M., Tyrrell, T.D. & Ebenhard, T. (2016). The 2030 Agenda and Ecosystems - A discussion paper on the links between the Aichi Biodiversity Targets and the Sustainable Development Goals. SwedBio at Stockholm Resilience Centre, Stockholm, Sweden.

Schipper, A. M., Hilbers, J. P., Meijer, J. R., Antão, L. H., Benítez-López, A., de Jonge, M. M. J., ..., Huijbregts, M. A. J. (2020). Projecting terrestrial biodiversity intactness with GLOBIO 4. Global Change Biology. https://doi.org/10.1111/gcb.14848

Seehausen, O., Alphen, J. J. V., & Witte, F. (1997). Cichlid fish diversity threatened by eutrophication that curbs sexual selection. Science, 277(5333), 1808-1811.

Shannon, C. E., and Weaver, W. (1949). The Mathematical Theory of Communication. Urbana: University of Illinois Press.

Shurin, A. & Smith, S. (2006). Room for one more? Evidence for invasibility in ecological communities. In: Conceptual ecology and invasion biology: reciprocal approaches to nature.

Shurin, J.B., Havel, J.E., Leibold, M.A. & Pinel-Alloul, B. (2000). Local and regional zooplankton species richness: A scale-independent test for saturation. Ecology, 81, 3062–3073.

Simis, S., Peters, S. and Gons, H. (2005). Remote sensing of the cyanobacterial pigment phycocyanin in turbid inland water. Limnol. Oceanogr., 50(1), 2005, 237–245.

Simon, R. N., Tormos, T. and Danis, P.A. (2014). Retrieving water surface temperature from archive LANDSAT thermal infrared data: Application of the mono-channel atmospheric correction algorithm over two freshwater reservoirs. International Journal of Applied Earth Observation and Geoinformation 30(1):247-250. Doi: 10.1016/j.jag.2014.01.005

Skidmore, A. K., Coops, N. C., Neinavaz, E., Ali, A., Schaepman, M. E., Paganini, M., ... & Wingate, V. (2021). Priority list of biodiversity metrics to observe from space. Nature Ecology & Evolution, 5(7), 896-906.

Skidmore A., Pettorelli, N., Coops N.C., Geller G.N., Hansen M., Lucas R., Mücher C.A., Paganini M. et al. (2015), Agree on biodiversity metrics to track from space, Nature 523: 403-405.Tickner D., Opperman J.J., Abell R., Acreman M., Arthington A.H., Bunn S.E., et al. (2020). Bending the Curve of Global Freshwater Biodiversity Loss: An Emergency Recovery Plan, Bioscience 70: 330-342.

Somogyi, B., Felföldi, T., Tóth, L. G., Bernát, G., & Vörös, L. (2020). Photoautotrophic picoplankton–a review on their occurrence, role and diversity in Lake Balaton. Biologia Fu-tura, 71(4), 371-382.

Specziár A, György ÁI, Erős T. 2013. Within-lake distribution patterns of fish assemblages: the relative roles of spatial, temporal and random environmental factors in assessing fish assemblages using gillnets in a large and shallow temperate lake. J Fish Biol 82: 840–855.

Stauffer, D., & Aharony, A. (1985). Introduction to percolation theory. Taylor & Francis.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., ... & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*(6223), 1259855.

Teurlincx, S., van Wijk, D. Mooij, W.M., Kuiper, J.J., Huttunen, I., Brederveld, R.J., Chang, M., Janse, J.H., Woodward, B., Hu, F. and Janssen A. BG. (2019). A perspective on water quality in connected systems: modelling feedback between upstream and downstream transport and local ecological processes. Current Opinion in Environmental Sustainability 2019, 40:21–29. https://doi.org/10.1016/j.cosust.2019.07.004.

Till, A., Rypel, A. L., Bray, A., & Fey, S. B. (2019). Fish die-offs are concurrent with thermal extremes in north temperate lakes. Nature Climate Change, 9(8), 637-641. Tockner, K. and J.A. Stanford, 2002: Riverine flood plains: present state and future trends. Environmental Conservation 29 (3): 308–330.

Tisseuil, C., Cornu, J. F., Beauchard, O., Brosse, S., Darwall, W., Holland, R., ... & Oberdorff, T. (2013). Global diversity patterns and cross-taxa convergence in freshwater systems. *Journal of Animal Ecology*, *82*(2), 365-376.

Turak, E., Harrison, I., Dudgeon, D., Abell, R. … Simaika, J.P, De Wever, A. (2017).Essential Biodiversity Variables for measuring change in global freshwater biodiversity, Biological Conservation. Vol. 213, Part B, pp 272-279, ISSN 0006-3207, https://doi.org/10.1016/j.biocon.2016.09.005.

Twining, C. W., Brenna, J. T., Lawrence, P., Shipley, J. R., Tollefson, T. N., & Winkler, D. W. (2016). Omega-3 long-chain polyunsaturated fatty acids support aerial insectivore performance more

Vörös L, Nagy Göde P (1993) Long term changes of phytoplankton in Lake Balaton (Hun-gary). Verhandlungen des Internationalen Verein Limnologie 25:682–686

Wanders, N., van Vliet, M. T., Wada, Y., Bierkens, M. F., & van Beek, L. P. (2019). High‐resolution global water temperature modeling. Water Resources Research, 55(4), 2760-2778.

Wang, F., Qin, Z., Song, C., Tu, L., Karnieli, A., & Zhao, S. (2015). An improved mono-window algorithm for land surface temperature retrieval from Landsat 8 thermal infrared sensor data. *Remote sensing*, *7*(4), 4268-4289.

Weiss, J.R., Smythe, W. and Lu, W. (2005). Science Traceability, Conference Paper in IEEE Aerospace Conference Proceedings April 2005, DOI: 10.1109/AERO.2005.1559323.

Whittaker, R. H. (1972). Evolution and measurement of species diversity. Taxon, 21(2-3), 213-251.

Woolway, R. I., Jennings, E., Shatwell, T., Golub, M., Pierson, D. C., & Maberly, S. C. (2021). Lake heatwaves under climate change. Nature, 589 (7842), 402-407.

Wubs, E.R.J., Fraaije, R.G.A., de Groot, G.A., Erkens, R.H.J., Garssen, A.G., Kleyheeg, E., et al. (2016). Going against the flow: a case for upstream dispersal and detection of uncommon dispersal events. Freshw. Biol., 61, 580–595.

Wyatt B.K. (2000) Remote Sensing of Land Cover and Land Cover Change. In: Verstraete M.M., Menenti M., Peltoniemi J. (eds) Observing Land from Space: Science, Customers and Technology. Advances in Global Change Research, vol 4. Springer, Dordrecht. https://doi.org/10.1007/0-306-48124-3_14

Zockler, C. and I. Lysenko, 2000.Water Birds on the Edge. First circumpolar assessment of climate change impact on Arctic breeding water birds. WCMC Biodiversity Series No. 11, World Conservation Monitoring Centre—World Conservation Press, Cambridge, U.K.

Yang, X., Pavelsky, T. M., Allen, G. H., & Donchyts, G. (2019). RivWidthCloud: An automated Google Earth Engine algorithm for river width extraction from remotely sensed imagery. IEEE Geoscience and Remote Sensing Letters, 17(2), 217-221.

9.2 Policy and strategy references

CBD (2022). Expert input to the post-2020 Global Biodiversity Framework: Transformative actions on all drivers of biodiversity loss are urgently required to achieve the global goals by 2050. CBD/WG2020/3/INF/11, CBD/SBSTTA/24/INF/31.
https://www.cbd.int/doc/c/5735/c241/efeeac8d7685af2f38d75e4e/sbstta-24-inf-31-en.pdf

CBD (2021a). First draft of the post-2020 global biodiversity framework, CBD/WG2020/3/3.
https://www.cbd.int/doc/c/abb5/591f/2e46096d3f0330b08ce87a45/wg2020-03-03-en.pdf

CBD (2021b). Measuring ecosystem integrity (Goal A) in the post-2020 Global Biodiversity Framework: The GEO BON Species Habitat Index, CBD/WG2020/3/INF/6.

CBD (2021c). Non-paper – Proposed monitoring framework for the Post-2020 Global Biodiversity Framework, https://www.cbd.int/doc/c/bfc9/c6c3/bcca6df9211099b1adf14947/non-paper-item3-monitoring-v1-en.pdf

CBD (2021d). Post-2020 Global Biodiversity Framework: Scientific and Technical information to support the review of the updated goals and targets, and related indicators and baselines – Draft recommendations by the Chair. CBD/SBSTTA/24/L.3.
https://www.cbd.int/doc/c/9849/459f/b9fe0e74c9e1f25dd90dee23/sbstta-24-l-03-en.pdf

CBD (2020a), Global Biodiversity Outlook 5 (GBO-5). https://www.cbd.int/gbo/

CBD (2020b), GBO-5 Inland Water Highlights, https://www.cbd.int/waters/doc/gbo5-inlandwaters-en.pdf

CBD (2020c), Post-2020 Global Biodiversity Framework: Scientific and Technical information to support the review of the updated goals and targets, and related indicators and baselines, CBD/SBSTTA/24/3.
https://www.cbd.int/doc/c/705d/6b4b/a1a463c1b19392bde6fa08f3/sbstta-24-03-en.pdf

CBD (2010), Strategic Plan for Biodiversity 2011-2020, including Aichi Biodiversity Targets, UNEP/CBD/COP/DEC/X/2, https://www.cbd.int/sp/

CBD, (2005), Millennium Ecosystem Assessment. Ecosystems and Human Well-being: Biodiversity Synthesis. World Resources Institute, Washington, DC.

EEA (2012), Streamlining European biodiversity indicators 2020: building a future on lessons learnt from the SEBI 2010 process. EEA Technical Report 11/2012. ISSN 1725-2237

EC (2020), EU Biodiversity Strategy for 2030, COM 380.
https://ec.europa.eu/environment/nature/biodiversity/strategy/index_en.htm

EC (2019), European Green Deal, COM (2019) 640.
https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

EC (2011), EU Biodiversity Strategy for 2020,
https://ec.europa.eu/environment/pubs/pdf/factsheets/biodiversity_2020/2020%20Biodiversity%20Factsheet_EN.pdf

EC (2015), The Mid-term review of EU Biodiversity Strategy to 2020. Report from the Commission to the European Parliament and the Council. Brussels, 2.10.2015 COM(2015) 478 final.

FAO, (1999) Inland Water Resources and Aquaculture Service, Fishery Resources Division, Review of the State of World Fishery Resources: Inland Fisheries, 1999. FAO Fisheries Circular, No. 942.

FAO, (2004) The State of the World Fisheries and Aquaculture 2004. FAO Fisheries Department, Rome, Italy.

GEO BON (2022). A. Gonzales presentation of GBiOS at 20220127, Webinar: Updated Monitoring Framework and associated information documents SBSTTA item 3, https://www.cbd.int/article/pre-geneva-2022-webinars/webinar-jan-27 .

GLEON, (2013). Global Lake Ecological Observatory Network, 22 May 2013. https://gleon.org/sites/default/files/pdf/GLEON_MissionValueVision_Statements_v22May2013.pdf

IPBES (2019), Global Assessment Report on Biodiversity and Ecosystem Services. https://ipbes.net/global-assessment

IPBES (2018), The IPBES regional assessment report on biodiversity and ecosystem services for Europe and Central Asia. Rounsevell, M., Fischer, M., Torre-Marin Rando, A. and Mader, A. (eds.). Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany. 892 pages. https://ipbes.net/assessment-reports/eca.

IPBES (2016), The methodological assessment report on scenarios and models of biodiversity and ecosystem services: Summary for policymaker (S. Ferrier, K. N. Ninan, P. Leadley, R. Alkemade, L. A. Acosta, H. R. Akçakaya, L. Brotons, W. Cheung, V. Christensen, K. A. Harhash, J. Kabubo-Mariara, C. Lundquist, M. Obersteiner, H. Pereira, G. Peterson, R. Pichs-Madruga, N. H. Ravindranath, C. Rondinini, & B. Wintle, Eds.). Bonn, Germany: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.

IUCN (accessed 2022): https://www.iucn.org/commissions/commission-ecosystem-management/our-work/nature-based-solutions

IUCN (World Conservation Union), (1992) Environmental Status Reports: Volume 4 - Conservation Status of the Danube Delta. Gland, Switzerland. 107 pp.

OECD (Organisation for Economic Co-operation and Development), (1996). Guidelines for aid agencies for improved conservation and sustainable use of tropical and subtropical wetlands. Paris, France.

Ramsar Convention on Wetlands. (2021a), Global Wetland Outlook: Special Edition 2021. Gland, Switzerland: Secretariat of the Convention on Wetlands.

Ramsar Convention on Wetlands. (2021b). Global guidelines for peatland rewetting and restoration. Ramsar Technical Report No. 11. Gland, Switzerland: Secretariat of the Convention on Wetlands.

Ramsar Convention on Wetlands (2018), Global Wetland Outlook: State of the World's Wetlands and their Services to People. Gland, Switzerland: Ramsar Convention Secretariat.

Ramsar Convention Secretariat (2016). The Fourth Ramsar Strategic Plan 2016–2024. Ramsar handbooks for the wise use of wetlands, 5th edition, vol. 2. Ramsar Convention Secretariat, Gland, Switzerland.

UN (2021), The Sustainable Development Goals Report 2021, New York: United Nations. https://unstats.un.org/sdgs/report/2021/The-Sustainable-Development-Goals-Report-2021.pdf

UN (2020), The Sustainable Development Goals Report 2020, New York: United Nations. https://unstats.un.org/sdgs/report/2020/The-Sustainable-Development-Goals-Report-2020.pdf

WWAP (United Nations World Water Assessment Programme)/UN-Water (2018), The United Nations World Water Development Report 2018: Nature-Based Solutions for Water. Paris, UNESCO.

UN GA (2015), Transforming our world: the 2030 Agenda for Sustainable Development, UN Resolution 70/1, 21 October 2015.
http://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E

UNEP (2019), Global Environment Outlook – GEO-6: Healthy Planet, Healthy People. Cambridge: Cambridge University Press. doi:10.1017/9781108627146

WWF (2020), Living Planet Report 2020. https://livingplanet.panda.org/

WWF (2016). Living Planet Report 2016: Risk and Resilience in a New Era. WWF International, Gland, Switzerland.

Appendix 1 IPBES GA knowledge gaps

Table **8** A selection of knowledge gaps from IPBES Global Assessment Appendix 4 (2019) with potential relevance for the development of BIOMONDO Pilots.

Sector	**Knowledge gaps**
Data, inventories and monitoring of nature and the drivers of change	Data on ecosystem processes (including rates of change) that underpin nature's contributions to people and ecosystem health
	Data from monitoring of ecosystem condition (generally less well represented than ecosystem extent)
	Indicators on the global extent and consequences of biotic homogenization, including genetic homogenization
	Global spatial datasets on key threats, e.g., data on patterns in the intensity of unsustainable exploitation of species and ecosystems
	Understanding of how human-caused changes to any EBV class (e.g., ecosystem structure) have impacts on others (e.g., community composition) and on nature's contributions to people
	Data gaps in key inventories: World Database on Protected Areas, the World Database of Key Biodiversity Areas, red lists of threatened species and ecosystems, and the Global Biodiversity Information Facility
Biomes and units of analysis	Inventories on under-studied ecosystems: freshwater, Arctic, marine/ocean, seabed, and wetlands
	Inventories in soil, benthic and freshwater environments, and the implications for ecosystem functions
NCP (ecosystem services)	Data on the status of species and nature's contributions to people linked to specific ecosystem functions
	Data and information on NCP 9: the role of nature and nature's contributions to people in mitigating or reducing vulnerability to disasters
Links between nature, nature's contributions to people and drivers with respect to targets and goals	Need for indicators for some Sustainable Development Goals and Aichi Biodiversity Targets (e.g., Aichi Biodiversity Target 15 on ecosystem resilience and contribution of biodiversity to carbon stocks and Target 18 on integration of traditional knowledge and effective participation of indigenous and local communities)
	Better quantitative data to assess the Sustainable Development Goals and Aichi Targets where qualitative indicators have been dominant (9 out of 44 targets under the Sustainable Development Goals reviewed)
Potential policy approaches	Data to analyse the effectiveness of many policy options and interventions, including 1) the comparative effectiveness of different area-based conservation mechanisms (e.g., protected areas, other effective area-based conservation measures), and 2) the effectiveness of different restoration methodologies and to assess restoration progress over time (including values)
	Better data to develop biodiversity and environmental quality standards

Appendix 2 Freshwater Biodiversity knowledge gaps

Table 9 Freshwater knowledge gaps collated from IPBES (2019), Maasri et al. 2022 and Harper et al. (2021).

Freshwater Knowledge Gaps	Research need/comment	origin
No global dataset on the extent of aquaculture, locations and area of coverage		IPBES (2019), p 206 Ch 2.2 Status and trends in nature
Only few **indicators** for the **structure** of **freshwater ecosystems**, with **ecosystem condition** less well represented than ecosystem extent.		IPBES (2019), p 233.
No available **indicators on interaction** among organisms and taxa. Freshwater together with marine assemblages are greatly underrepresented compared to terrestrial.		IPBES (2019), p 238.
No global indicators of biotic homogenization. NOT SPECIFIC FW	But may apply also to FW	IPBES (2019), p 238.
Low degree of confidence related to impact of climate change in freshwater but thought to be dominated by effects on Ecosystem function		IPBES (2019), p 254.
Lack of comprehensive global dataset on Protected Area management effectiveness. NOT SPECIFIC FW	But may apply also to FW	IPBES (2019), p 417.

Freshwater Knowledge Gaps	**Research need/comment**	**origin**
Most scenarios of biodiversity change are terrestrial or marine, while far fewer exist for freshwater. Therefore, most evidence provided in for freshwater biomes is based on local and regional studies. Only a few metrics of biodiversity and ecosystem function have been explored deeply enough to draw conclusions on their interactions in a globally changing environment.		IPBES (2019), p 625.
Unknown or uncertain effects of climate change, i.e. projections but changes will occur from change in: temperature, water availability, flow regimes through changes in precipitation and/or temperature.	Includes many more detailed examples of likely changes and interactions. Including Wetland changes and release of carbon that will cause habitat loss and reduced water quality.	IPBES (2019), p 650.
Future impacts of habitat fragmentation on freshwater biodiversity and ecosystem function. Uncertain effects of dam building (e.g. species extinction risks – blocked migrations and/or reduced population size and gene flow) and spiralling interacting changes due to altered flow regimes, more dam building and population increases)		IPBES (2019), p 650, p 652
Unknown effect of competition between non-native and native species leading to (e.g. disease spread, degraded ecosystem services and economies as well as biotic homogenization of aquatic ecosystems)		IPBES (2019), p 653
Inland fisheries are underestimated, including relationship to changes to biodiversity		IPBES (2019), p 654, 4.2.3.6 Future impacts of harvest on freshwater biodiversity and functioning

Freshwater Knowledge Gaps	Research need/comment	origin
Understanding of links between biodiversity and ecosystem function on a global level – i.e., global modelling tools to explore in different systems (marine, terrestrial and freshwater) the futures of bd/ecosystem function are disconnected. Gap reflects need for connecting model developments across disciplines.		IPBES, p. 664 4.2.5 Challenges in linking biodiversity and ecosystem functioning at the global level
Overview of data availability is lacking How to access and mobilise analogue freshwater data Lack of databases structured according to the FAIR principle	Data infrastructure – improvements are needed	Maasri et al. 2022
Knowledge gaps relating to improved/innovative methods for monitoring including monitoring programs	Monitoring	Maasri et al. 2022
Lack of understanding of mechanistic relationships btw bd and ES Lack of knowledge relating to bd response to different stressors lack of knowledge relating to ecological and evolutionary responses of organisms, communities and ecosystems to global change	Ecology	Maasri et al. 2022
Lack of knowledge from evaluation of restoration activities Lack of knowledge on how to develop NFF type strategies Lack of landscape perspective to make dam construction and operation ecologically sound	Management	Maasri et al. 2022

Freshwater Knowledge Gaps	Research need/comment	origin
Lack of knowledge relating to incorporation of social science into biodiversity research Lack of methods for assessing trade-offs among ecological, economic and social needs Lack of knowledge to systematically develop citizen science and participatory research	Social ecology	Maasri et al. 2022
Limited understanding of reasons for success or failure of past conservation efforts	1 Learning from successes and failures	Harper et al. 2021
Limited understanding of the spatial and temporal scales best suited to application of management interventions to benefit freshwater biodiversity	2 Learning from successes and failures	Harper et al. 2021
Limited understanding of characteristics of current protected areas and networks including what indigenous management lead to improved status of freshwater ecosystems	3 Learning from successes and failures	Harper et al. 2021
Limited/deficient understanding of use of flagship/umbrella freshwater species for increased restoration and protection of fwbd and public involvement	4 Learning from successes and failures	Harper et al. 2021
Deficient monitoring metrics to guide restoration, conservation and sustainable management of freshwater biodiversity	5 Learning from successes and failures	Harper et al. 2021
Limited knowledge relating to prioritisation of KBAs	6 improving current practices	Harper et al. 2021
Knowledge gap relating to best approaches to pollution reduction and remediation efforts beneficial for fwbd	7 improving current practices	Harper et al. 2021
Lack of knowledge relating to what research innovations are most needed to help restore fwbd	8 improving current practices	Harper et al. 2021

Freshwater Knowledge Gaps	Research need/comment	origin
Lack of knowledge how to incorporate climate change adaptation (resilience) into fw conservation	9 improving current practices	Harper et al. 2021
Limited knowledge how to manage fw invasive species for improvement of bd	10 improving current practices	Harper et al. 2021
Limited knowledge of what the optimal riparian management actions are that best contribute to fwbd	11 improving current practices	Harper et al. 2021
Deficient knowledge on measures that effectively address synergistic threats to fwbd	12 improving current practices	Harper et al. 2021
Limited knowledge relating to what priorities are in common for sustainable food production and fwbd conservation	13 balancing resource needs	Harper et al. 2021
Limited knowledge relating to how needs for dams and ass. Infrastructure can be balanced with connectivity, health and flow requirements of fw ecosystems and bd	14 balancing resource needs	Harper et al. 2021
Limited knowledge on how to best balance conflicting interests between human demands for natural resources and fwbd	15 balancing resource needs	Harper et al. 2021
Limited knowledge relating to what policies/programmes/activities can be implemented to turn risks with urbanisation into benefits for fw bd enhancement	16 Rethinking built environments	Harper et al. 2021
Limited knowledge on how freshwater biodiversity conservation can be better integrated into economic infrastructure planning, implementation and operation	17 Rethinking built environments	Harper et al. 2021
Limited knowledge on role of novel and designed ecosystems in conservation, and how can these systems be managed to benefit freshwater biodiversity	18 Rethinking built environments	Harper et al. 2021

Freshwater Knowledge Gaps	**Research need/comment**	**origin**
Limited knowledge on what public policy measures can most effectively promote conservation and restoration of freshwater biodiversity	19 Reforming policy and investment	Harper et al. 2021
Limited knowledge on how to scale up and optimise financial investments from all society sectors to create a step change in funding for fw cons and rest. efforts	20 Reforming policy and investment	Harper et al. 2021
Limited knowledge relating to what social and natural science investments are needed to implement environmental flows that benefit fwbd	21 Reforming policy and investment	Harper et al. 2021
Limited knowledge relating to what type of investments in *ex situ* conservation (e.g. captive breeding, reintroduction, managed relocation) are most effective for imperilled biodiversity	22 Reforming policy and investment	Harper et al. 2021
Limited knowledge relating to how to develop management frameworks and evidence bases that gain greater traction with stakeholders and managers	23 Enabling transformative change	Harper et al. 2021
Limited knowledge relating to what steps to take to better communicate and share evidence and knowledge about the science of freshwater biodiversity among stakeholders	24 Enabling transformative change	Harper et al. 2021
Limited knowledge relating to how to increase public engagement to change mindsets and build social licence and political will to 'bend the curve' of biodiversity loss	25 Enabling transformative change	Harper et al. 2021

Appendix 3 GBO-5 Aichi Target assessment for inland waters

Target 5 "*Habitat loss halved or reduced*"

- Wetland Extent Trends (WET) reduced 35 % between1970-2015. The area covered by human made wetlands more than doubled.
- Fragmentation of rivers remains a critical threat to freshwater biodiversity and loss of wetlands. According to 2019 connectivity assessment only 37% of all rivers longer than 1000 km are still free-flowing and 23% flowing free to the ocean.
- Loss of surface water - 9 million hectares 1984-2015

Target 6 "*Sustainable management of aquatic living resources*"

- Inland water ecosystems are under synergistic pressures requiring effective management to conserve freshwater biodiversity.

Target 8 "*Pollution reduced*"

- Pollution including excess nutrients and pesticides remain major drivers of biodiversity loss in freshwater ecosystems. Pollution levels including excess nutrients remain detrimental despite increasing mitigating efforts.

Target 11 "*Protected areas*"

- A significant proportion of the most important areas for freshwater biodiversity remains without formal protection (of 15000 Key Biodiversity Areas (KBA's) only 40% were protected in 2019).
- Ensuring or improving connectivity remains a problem.

Target 12 "*Reducing risk of extinction*"

- IUCN Red List index and Living Planet Index show over 60% decline between 1970 and 2016.
- Index for Freshwater species is less than one-fifth of 1970 level.
- Freshwater species show greatest decline of all species populations.

Target 14 "*Ecosystem services*"

- Continued decline of capacity of ecosystems to provide services.
- Deforestation and land degradation have had negative impact on Freshwater quantity and quality.
- Protected areas provide freshwater (20% of global runoff) to two-thirds of global population.

Target 15 "*Ecosystem restoration and resilience*"

- Limited progress towards restoring degraded ecosystems although restoration programmes provide potential for increase.