Mangroves

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Fast facts

- Salt-tolerant, mainly arboreal, flowering plants growing in the intertidal zone of tropical and sub-tropical shores.
- Global area of 157,000 km^2 to 160,000 km^2.
- Global carbon burial of approximately 18.4 Tg C yr^{-1} .
- Mangrove forests are estimated to have occupied 75% of the tropical coasts worldwide, but anthropogenic pressures have reduced the global range of these forests to less than 50% of the original total cover.
- These losses are largely due to over-harvesting for timber and fuel-wood production, reclamation for aquaculture and saltpond construction, mining, oil spills, pollution and damming of rivers that alter water salinity levels.
- Rehabilitation/restoration or plantation of mangrove forests are not only to be encouraged based on ecological or socio-economical considerations, but also have the potential of providing an efficient sink of CO_2.

Definition and global occurrence

Mangrove forests are a dominant feature of many tropical and subtropical coastlines, but are disappearing at an alarming rate. The main causes for the rapid destruction and clearing of mangrove forests include urbanization, population growth, water diversion, aquaculture and salt-pond construction (e.g. Farnsworth & Ellison 1997). On a global scale, mangrove plants are found throughout the tropical and subtropical regions of the world, and two species of *Avicennia* have penetrated into the warm temperate areas of both hemispheres. The global distribution of mangroves generally matches the winter 20°C isotherm. Mangroves are trees, shrubs, palms or ground ferns which normally grow above mean sea level in the intertidal zone of marine, coastal, or estuarine environments. Thus, mangrove plants do not form a phylogenetically related group of species but are rather species from very diverse plant groups sharing common morphological and physiological adaptations to life in the intertidal zone, which have evolved independently through convergence rather than common descent. The most recent global data compilation suggests a current global areal extent of about 152,000 km² (FAO 2007), with Indonesia and Australia together hosting about 30% of this area.

Mangrove goods & services

Besides the role mangroves play in the carbon cycle, mangrove ecosystems have a wide range of ecological and socio-economical functions.

For many communities living within or near to mangrove forests in developing countries, mangroves constitute a vital source of income and resources, providing a range of natural products such as wood (for firewood, construction, fodder, etc), medicines, and as fishing grounds. They are known to provide essential support for a wide range of intertidal and aquatic fauna, and act as nursery habitats for many commercial (and non-commercial) aquatic species such as crabs, prawns and fish (Nagelkerken et al., 2008). Whether this link is due to the provision of habitat, protection or predation, or via a direct trophic link is still under debate, but the value of mangroves in supporting coastal fisheries is unquestionable (see e.g., Mumby et al. 2004).

Furthermore, the presence of mangroves has been demonstrated to provide an efficient buffer for coastal protection: their complex structure attenuates wave action, causing reduction of flow and sedimentation of suspended material. This topic has received a great deal of attention following the 2004 Tsunami which hit SE Asia (e.g., Dahdouh-Guebas et al., 2005; Alongi, 2008; Yanagisawa et al., 2009; Das & Vincent, 2009), although demonstrating the causal link between mangroves and coastal protection is not always straightforward (e.g., see Vermaat & Thampanya 2005). This function of mangrove forests is also likely to act as an important buffer against sea level rise.

Finally, mangrove ecosystems have been shown to be effective as nutrient traps and 'reactors', thereby mitigating or decreasing coastal pollution. The feasibility of using (constructed rather than natural) mangrove wetlands for sewage or shrimp pond effluents has recently been demonstrated (e.g., Boonsong et al., 2003; Wu et al. 2008) and could offer a low-cost, feasible option for wastewater treatment in tropical coastal settings.

Productivity of mangroves

Mangrove forests are considered as highly productive ecosystems. Most data on their productivity are in the form of litter fall estimates, obtained by regularly collecting all litter in litter traps suspended below the canopy. Unfortunately, much less information is available on their biomass production in terms of wood and belowground production. When estimating overall global net primary production for mangroves, we therefore need to rely on relationships between litter fall and wood or belowground production to upscale the data on litter fall. Using a global area of mangroves of 160,000 km², the net primary production was recently estimated at 218 ± 72 Tg C yr^{-1} (Bouillon et al. 2008), with root production responsible for ~38% of this productivity, and litter fall and wood production both ~31%. There is a general latitudinal gradient in the productivity of mangroves, being significantly higher in the equatorial zone compared to higher-latitude forests – a pattern recognized for a number of decades (Twilley et al. 1992, Saenger & Snedaker 1993) and confirmed by new data compilations (Bouillon et al. 2008).

Carbon sinks in mangrove systems

Biomass produced by mangrove forests can ultimately have a number of different destinations (i) part of the biomass produced can be consumed by fauna, either directly or after export to the aquatic system, (ii) carbon can be incorporated into the sediment, where it is stored for longer periods of time, (iii) carbon can be remineralized and either emitted back to the atmosphere as CO_2, or exported as dissolved inorganic carbon (DIC), (iv) carbon can be exported to adjacent ecosystems in organic form (dissolved or particulate) where it can either be deposited in sediments, mineralized, or used as a food source by faunal communities.

In the context of CO_2 sequestration, the relevant carbon (C) sinks to consider are:

- the burial of mangrove C in sediments – locally or in adjacent systems,
- net growth of forest biomass during development, e.g. after (re)plantations.

The first process represents a long-term C sink, while the second should be considered relevant only on the shorter (decennial) term.

Three different global estimates for **carbon burial** within mangrove systems all converge to a value equivalent to ~18.4 Tg C yr^{-1} (when applying a global area of 160,000 km^2). These estimates are derived either from sedimentation estimates combined with typical organic carbon concentrations in mangroves (Chmura et al. 2003), or from mass-balance considerations – despite a number of uncertainties in these estimates there are insufficient data available to better constrain these values.

The amount of carbon stored within sediments of individual mangrove ecosystems varies widely, from less than 0.5% (on a dry weight basis) to <40%, with a global median value of 2.2 % (Kristensen et al. 2008 – see Figure 1) – extrapolations to carbon stocks on an areal basis are difficult to make due to varying depths of sediments and the paucity of concurrent data on sediment densities (i.e. volumetric weight of the sediment). Furthermore, carbon accumulating is not necessarily all derived from the local production by mangroves – organic matter can be brought in during high tide and can originate from rivers, or from adjacent coastal environments. Both the quantity and origin of carbon in mangrove sediments appear to be determined to a large extent by the degree of 'openness' of mangroves in relation to adjacent aquatic systems: mangroves with low tidal amplitude or high on the shoreline have little opportunity to export organic matter produced, and also little other material is brought in: such systems or sites typically have high carbon contents, and the organic matter accumulating is locally produced. In contrast, in low intertidal sites or systems with high tidal amplitude, a larger fraction of the organic matter produced can be washed away, and sediment with associated organic matter from adjacent systems is imported during high tide and is deposited within the system (Twilley 1995). These patterns are observed not only in mangroves (Bouillon et al. 2003) but also in salt marshes (Middelburg et al. 1997).

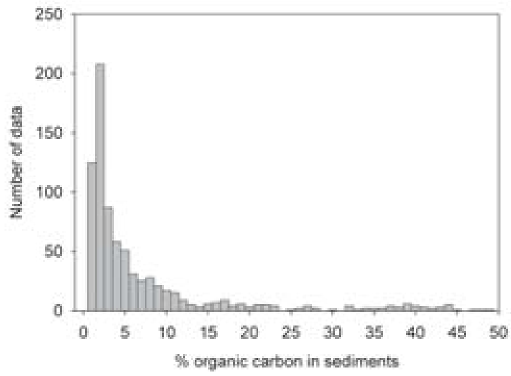


Figure 1: Compilation of literature data on sediment organic carbon concentrations in mangrove sediments (from Kristensen et al. 2008).

Irrespective of the origin of carbon in mangrove sediments, the presence of mangroves clearly has an impact on sediment carbon storage, by (i) direct inputs of mangrove production to the sediment pool, and (ii) by increasing sedimentation rates (e.g., Perry & Berkeley 2009). Conversely, clearing of mangroves can rapidly result in significantly reduced C stores in sediments (e.g., from up to ~50% over an 8 yr period in the study by Granek & Ruttenberg 2008), indicating that the carbon pool lost through deforestation substantially exceeds that of simple removal of standing biomass.

An overview of current quantitative estimates of carbon flow in mangrove systems is presented in Table 1.

Two important aspects emerge: (i) carbon burial in mangrove sediments represents a relatively small

Net primary production	**218 ± 72**
Litter fall	68 ± 20
Wood production	67 ± 40
Root production	82 ± 57
Fate of mangrove production	
CO_2 efflux	42 ± 31
Export as POC and DOC	45 ± 31
Burial	18.4
Unaccounted	**112 ± 85**

Table 1: Overview of current global estimates of net primary production and carbon sinks in mangrove systems (from Bouillon et al. 2008). All rates reported are in Tg C yr^{-1}.

fraction (<10%) of the overall net primary production, and (ii) current literature estimates of CO_2 efflux from sediments and water, export as organic carbon and burial in sediments together only explain <50% of the primary production estimate. This large discrepancy may in part be solved by a large and previously unaccounted flux of dissolved inorganic carbon towards adjacent systems (see Bouillon et al. 2008).

Woody debris and carbon accumulation in mangrove forests

Mangrove wetlands support less woody debris than upland forests (Allen et al. 2000, Krauss et al. 2005). Hydrological conditions of mangrove wetlands, which include a diversity of tide, precipitation, and river-flow regimes, can complicate direct comparisons with upland forests. Polit and Brown (1996) showed that lowered stocks of woody debris could be partially explained by the higher decomposition rates of woody debris in wetlands. Also, decay of fallen mangrove wood may be quick at first, relative to most temperate systems, due in part to consistently higher temperatures, a prolonged wet season, and a combined terrestrial and marine fungal community in mangroves (e.g., Kathiresan & Bingham 2001).

Woody debris values in mangrove forest after major disturbances (i.e., massive mortalities due to changes in hydrology, hurricanes) are scarce, making it difficult to determine their role in carbon storage in the long term. However, some studies indicate the potential role of wood components in nutrient cycling and carbon flux. For example, Rivera-Monroy et al. estimated a range of 16.5-22.3 Mg ha^{-1} of woody debris in a mangrove forest affected by hypersalinity conditions in a deltaic environmental setting in the Caribbean Sea (Cienaga Grande de Santa Marta, Twilley et al. 1998, Rivera-Monroy et al. 2006). As result of increasing salinity of up to 90 ppt, 271 km^2 of mangrove area were lost in a period of 40 years (Simard et al. 2008). A current estimate of live above ground biomass for this forest (using radar interferometry and Lidar data) ranges from 1.2 to 1.7 (±0.1) Tg over the total area, whereas estimated dead biomass was 1.6 Tg, which represent 0.72 Tg of carbon (assuming a 48% carbon content) input for decomposition and export to adjacent ecosystems. This carbon value is a conservative estimate since no information of belowground biomass (coarse roots) is available for this site and in mangrove forests overall (Bouillon et al. 2008).

Krauss et al. (2005) estimated woody debris in subtropical mangrove forest 9-10 yr after the impact of hurricane Andrew in South Florida. The total volume of woody debris for all sites sampled in this study was estimated at 67 m^3/ha and varied from 13 to 181 m^3/ha depending upon differences in forest height, proximity to the storm, and maximum estimated wind velocities. Large volumes of woody debris were found in the eye wall region of the hurricane, with a volume of 132 m^3/ha and a projected woody debris biomass of approximately 36 Mg ha^{-1}; this value is lower that the 59 Mg ha^{-1} dead biomass estimated in the CGSM, Colombia (Simard et al 2008). Smith et al. (1994) in a large spatial survey study immediate to hurricane Andrew, estimated a total woody debris of up 280 Mg ha^{-1} (135 Mg carbon) including 0.6 and 0.18 Mg of nitrogen and phosphorous.

Rehabilitation and Restoration: biomass production in planted/replanted mangrove forests

As result of the extensive loss of mangrove area and the recognized ecological and economic values of mangrove-dominated ecosystems, there has been an increasing effort to rehabilitate and restore disturbed forests. Unfortunately, the success has frequently been limited due to the lack of a conceptual framework guiding such efforts, particularly given the absence of clear objectives and performance measures to gauge the success of such management strategies (Field 1999, Kairo et al. 2001, Twilley & Rivera-Monroy 2005, Samson & Rollon 2008). Understanding if nutrient and carbon cycling could be rehabilitated in perturbed mangrove forests on a long term basis requires a clear definition of terms. Field (1999) proposed that rehabilitation of an ecosystem is the act of *"partially or, more rarely, fully replacing structural or functional characteristics of an ecosystem that have been diminished or lost, or the substitution of alternative qualities or characteristics than those originally present with proviso that they have more social, economic or ecological value than existed in the disturbed or degraded state"*. In contrast, restoration of an ecosystem *is "the act of bringing an ecosystem back into, as nearly as possible, its original condition"*. In this conceptual framework, restoration is seen as a special case of rehabilitation. Field (1999) stressed *"land use managers are concerned primarily with rehabilitation and are not much concerned with ecological restoration. This is because they require the flexibility to respond to immediate pressures and are wary of being obsessed with recapturing the past"*. Because this definition has not been clearly included in mangrove management plans, it is not surprising that despite the recognized ecological role of mangrove forest there are no long-term studies assessing whether the functional properties (including carbon sequestration and primary productivity) have been restored through management in regions where restoration/rehabilitation projects have been implemented (e.g., Twilley et al. 1998, Samson & Rollon 2008). Recent reviews indicate that newly created mangrove ecosystems may or may not resemble the structure and function of undisturbed mangrove ecosystems and that objectives should be clearly established before any major small or landscape level rehabilitation is implemented (Kairo et al. 2001, Lewis 2005, Twilley & Rivera-Monroy 2005).

To our knowledge, there is no published information describing projects specifically aiming to enhance carbon sequestration through restoration or rehabilitation. However, a good indicator of potential magnitude of this sink is information reported for mangrove plantations or sites undergoing rehabilitation. Aboveground biomass estimates in replanted mangroves stand have varied from 5.1 Mg ha^{-1} in a 80 year plantation (Putz & Chan 1986) to 12 Mg ha^{-1} in a 12 year-old stand (Kairo et al. 2008), with part of the variation attributed to the age of plantations, management systems, species and climatic conditions (Bosire et al. 2008). Species variation in root biomass allocation was observed in a 12-year old replanted mangroves where *S. alba* allocated higher biomass to the root components (75.5 ± 2.0 Mg ha^{-1}) followed by *A. marina* (43.7 ± 1.7 Mg ha^{-1}) and *R. mucronata* 24.9 ± 11.4 Mg ha^{-1} (Tamooh et al. 2008). From the few data available, it would appear that productivity of replanted sites is in the same range as expected for natural forests, e.g. litter production in 7-year old *R. mucronata* plantation in Vietnam ranged between 7.1 and 10.4 Mg DW ha^{-1} yr^{-1}, and 8.9 to 14.2 Mg DW ha^{-1} yr^{-1} for *R. apiculata* monocultures (Nga et al. 2005). Overall, young mangrove forest can store from 2.4 to 5.8 Mg C ha^{-1} in aboveground biomass while C in root biomass ranges from 21 to 36 Mg C ha^{-1}. These values are first- order approximations based on average carbon content of plant material (48%). The study of McKee & Faulkner (2000) also suggested that productivity of restored mangrove stands (both above- and belowground) were similar to those of natural stands, and any variability more likely to be related to environmental conditions rather than to the natural or replanted status. Thus, site selection and a critical assessment of environmental conditions appears a critical factor to ensure that the natural productivity of replanted mangrove stands is ensured.

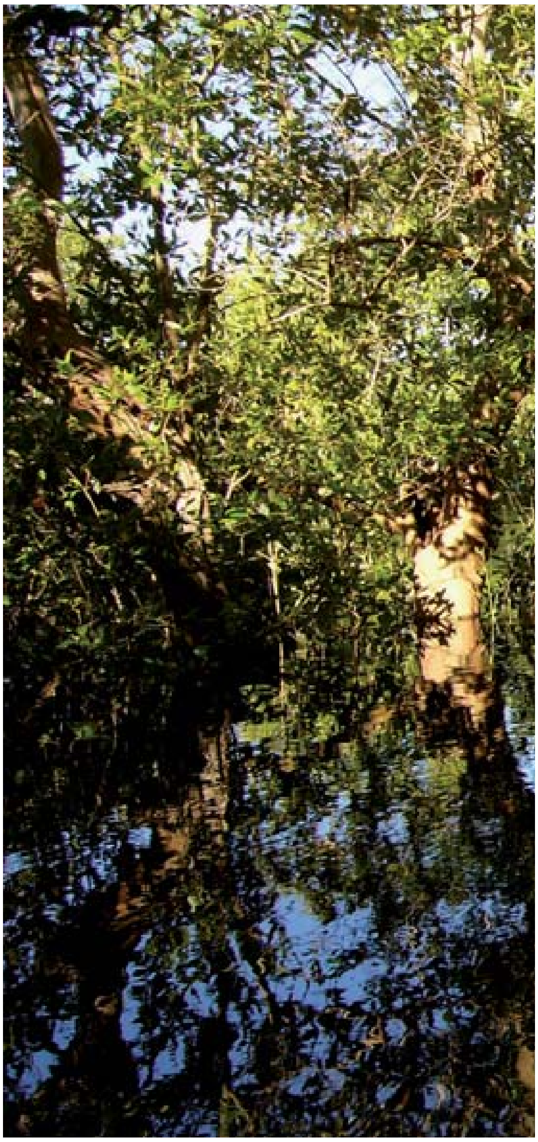
Threats to mangrove ecosystems

Mangrove forests are estimated to have occupied 75% of the tropical coasts worldwide (Chapman 1976), but anthropogenic pressures have reduced the global range of these forests to less than 50% of the original total cover (Spalding et al.1997, Valiela et al. 2001). These losses have largely been attributed to anthropogenic pressures such as over-harvesting for timber and fuel-wood production, reclamation for aquaculture and saltpond construction (Spalding et al., 1997, Farnsworth & Ellison (1997), mining, pollution and damming of rivers that alter water salinity levels. Oil spills have impacted mangroves dramatically in the Caribbean (Ellison & Farnsworth 1996), but little documentation exists for other parts of the world (Burns et al. 1994). Similarly, information (if any) about carbon losses associated to clear-falling are difficult to obtain since this activity is illegal in most countries; actual records of total biomass extracted to use mangrove area for other purposes (e.g., roads, urban development) is also rare making it difficult to determine this component in global estimates of carbon sequestration. Field (1999) underlined how, historically, information about mangrove use and rehabilitation projects usually remains in the grey literature in government agencies where it is difficult to obtain it for evaluation of management strategies and develop research priorities. Perhaps the major cause of mangrove decline has been conversion of the area to aquaculture. In the Indo-Western Pacific region alone, 1.2 million hectares of mangroves had been converted to aquaculture ponds by 1991 (Primavera 1995). These numbers, given their large magnitude, make it evident that conservation, rehabilitation and replantation efforts are critically needed to ensure the sustainability of these unique habitats for the future (Duke et al. 2008). There are, however, also positive signs emerging: (i) the latest FAO assessments suggests that although the rate of mangrove loss is still high, it has decreased significantly and was estimated at an annual relative loss of ~0.7% the period 2000-2005, (ii) replantation or rehabilitation initiatives are increasing, (iii) an increasing number of coastal mangrove wetlands have been designated as Ramsar sites during the past decade.

Management recommendations to enhance the potential of mangroves as a carbon sink

The data presented above make it clear that rehabilitation/restoration or plantation of mangrove forests are not only to be encouraged based on ecological or socio-economical considerations, but also have the potential of providing an efficient sink of CO_2, both on short and longer time-scales (i.e. biomass production during forest establishment and growth, accretion of carbon in mangrove sediments). The magnitude of this carbon sink, however, can be expected to be highly variable, and depends both on factors related to the primary production side (i.e. productivity will depend in part on the species or species assembly, latitude, and site conditions such as nutrient status, hydrology etc.) and on factors influencing the degree of longer-term sequestration of biomass in sediments, such as the rate of sediment deposition and exchange of carbon with adjacent systems. Indeed, there is a diversity of geomorphological settings where mangrove forest growth and develop, and that can be subdivided into a continuum of landforms based on the relative processes of river input, tides, and waves (Woodroffe, 2002). There is some indication that these diverse geomorphological habitats, each with different vegetation types, results in specific mangrove structural and productivity characteristics. This correlation between coastal landform and ecological function has particularly been documented relative to the net primary productivity (NPP) and detritus exchange across a variety of mangrove locations (Twilley & Rivera-Monroy, 2009). Thus, given the paucity of documented case studies, proposing specific guidelines for mangrove management/ rehabilitation in the face of their carbon sink potential would be premature. Particularly since mangrove rehabilitation efforts have had mixed success (Field et al. 1998, Kairo et al. 2001 and references therein) and inadequate planting strategies can lead to large-scale failures (Samson & Rollon 2008). These ecological and management aspects need to be considered for all mangrove rehabilitation or restoration initiatives where adequate selection of the right combination of both species and sites is critical in enabling a successful establishment of mangroves.

One proposed strategy to improve our capability to estimate and forecast mangrove carbon and nutrient cycling patterns with limited, but robust information, is the use of simulation models. This approach, in association with field studies, shows some promises to develop tools for improving and enhancing management plans for mangrove protection, rehabilitation and restoration; including optimal scenarios for carbon allocation and CO_2 uptake, not only due to landscape-level natural variations, but also under the influence of human disturbances (e.g climate change). Current available models have been useful in synthesizing current knowledge about mangrove forest dynamics (see Berger et al 2008 and references therein). The modeling approach is suitable for simultaneously evaluating the effects of environmental changes and disturbances on ecological processes such as tree recruitment, establishment, growth, productivity, and mortality (Berger et al. 2008). Such estimates on the sustainability of mangrove resources may contribute not only to evaluating impacts of mangrove degradation to socio-economic systems but also help assessing the role of mangrove forest in the global carbon cycle.



A mature Avicennia marina *stand during high tide (i.e. flooded) conditions, Gazi Bay (Kenya) © Steven Bouillon, K.U.Leuven*

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