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The State of the World's Mangrove Forests: Past, Present, and Future

Daniel A. Friess,[1,2] Kerrylee Rogers,[3] Catherine E. Lovelock,[4] Ken W. Krauss,[5] Stuart E. Hamilton,[6] Shing Yip Lee,[2,7] Richard Lucas,[8] Jurgenne Primavera,[2,9] Anusha Rajkaran,[10] and Suhua Shi[11]

[1]Department of Geography, National University of Singapore, Singapore 117570; email: dan.friess@nus.edu.sg

[2]Mangrove Specialist Group, International Union for Conservation of Nature (IUCN)

[3]School of Earth and Environmental Science, University of Wollongong, Wollongong, New South Wales 2522, Australia

[4]School of Biological Sciences, The University of Queensland, Brisbane St. Lucia, Queensland 4072, Australia

[5]Wetland and Aquatic Research Center, United States Geological Survey, Lafayette, Louisiana 70506, USA

[6]Department of Geography and Geosciences, Salisbury University, Salisbury, Maryland 21801, USA

[7]Simon F.S. Li Marine Science Laboratory, Chinese University of Hong Kong, Shatin, Hong Kong

[8]Department of Geography and Earth Sciences, Aberystwyth University, Aberystwyth SY23 3DB, United Kingdom

[9]Zoological Society of London, Iloilo City 5000, Philippines

[10]Department of Biodiversity and Conservation Biology, University of the Western Cape, Bellville 7535, South Africa

[11]School of Life Sciences, Sun Yat-Sen University, Guangzhou 510275, China

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Abstract

Intertidal mangrove forests are a dynamic ecosystem experiencing rapid changes in extent and habitat quality over geological history, today and into the future. Climate and sea level have drastically altered mangrove distribution since their appearance in the geological record ∼75 million years ago (Mya), through to the Holocene. In contrast, contemporary mangrove dynamics are driven primarily by anthropogenic threats, including pollution, overextraction, and conversion to aquaculture and agriculture. Deforestation rates have declined in the past decade, but the future of mangroves is uncertain; new deforestation frontiers are opening, particularly in Southeast Asia and West Africa, despite international conservation policies and ambitious global targets for rehabilitation. In addition, geological and climatic processes such as sea-level rise that were important over geological history will continue to influence global mangrove distribution in the future. Recommendations are given to reframe mangrove conservation, with a view to improving the state of mangroves in the future.

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1. INTRODUCTION

Intertidal mangrove forests occur along tropical, subtropical, and some temperate coasts, often overlapping with high and increasing densities of human populations. As such, they provide important ecosystem services such as fish, timber, fuelwood, coastal protection, pollution control, and cultural values for hundreds of millions of people (1). Most recently, the role of mangroves in carbon sequestration has been strongly promoted (2), with mangroves now firmly on the international climate mitigation and adaptation agenda.

Being located in a zone of increasing human population densities and conflicting coastal management priorities means that mangroves are also highly threatened across large parts of their range. Proximate drivers such as aquaculture, agriculture, and urban development have caused large-scale mangrove deforestation (3, 4), and mangroves are further degraded by resource overextraction and pollution (5). At broader scales, mangroves are impacted by long-term processes such as relative sea-level rise (rSLR) and fluctuations in sea level linked to climate oscillations (6, 7), with important implications for the vulnerability of the coastal populations who rely on mangrove resources.

Relative sea-level rise (rSLR): net sea-level rise resulting from rising sea-level and land-level changes

Effective management of mangroves needs robust knowledge of their true status. Several studies have provided a picture of the state of the world's mangrove forests. One of the earliest reports was published by the Working Group on Mangrove Ecosystems of the IUCN, titled *Global Status of Mangrove Ecosystems* (8). This report summarized the major threats to mangroves and management options available for their conservation. The *World Mangrove Atlas*, published in 1997 (9) and revised in 2010, was one of the first to estimate their global extent, and was followed by seminal and highly cited reviews that brought attention to rates of historical mangrove loss (10) and considered subsequent impacts on ecosystem processes and structure (11). Duke et al. (12) highlighted concern from the academic community in 2007 that the world would be globally deprived of the functions provided by mangroves within the next 100 years, given estimated rates of deforestation at that time.

International organizations have also contributed to discussions around the state of the world's mangroves, as reported in the *Status and Trends in Mangrove Area Extent Worldwide* (13) and *The World's Mangroves 1980–2005* (14). These documents compiled various national estimates of mangrove extent and extrapolated deforestation rates, and they have had huge policy impact. In 2014, the United Nations Environment Programme's Call to Action also highlighted mangrove loss and the need for conservation (15). However, more recent attempts to understand the state of the world's mangroves have updated current (and in many instances reducing) rates of deforestation and emphasize the future impacts of climate change (16).

Previous reports on the state of the world's mangroves have generally focused on contemporary and near future mangrove dynamics that strongly emphasize deforestation. However, mangrove forests are dynamic and their extent and condition can change rapidly, as deforestation drivers change in type and speed, and degradation drivers may dominate. Deforestation also takes place within a broader temporal context influenced by natural geological processes, which influences mangrove extent and condition now and in the future. For this reason, a holistic view of mangrove dynamics is required, examining their past, present, and potential future status, and the relative contribution of anthropogenic drivers while accounting for geological and climatic drivers. This review provides an up-to-date overview of the present state of the world's mangrove forests, focusing on mangroves as an ecosystem unit, rather than individual floral and faunal components of the ecosystem. Contemporary anthropogenic impacts are placed in the context of larger-scale and longer-term geological and climatic processes that have shaped mangroves for millions of years and will continue to do so in a future where mangroves will experience accelerating rSLR.

2. THE PAST STATE OF THE WORLD'S MANGROVES

2.1. The Appearance of Mangroves in Geological History

Past geological processes and barriers influence contemporary mangrove distribution (17). To understand the state of mangroves in geological history, it is important to understand how and where species evolved. A range of mangrove plant families diverged independently from their terrestrial ancestors during the late Cretaceous-Paleocene epoch, with the most ancient confirmed fossils belonging to the mangrove palm *Nypa*, aged at 75 million years (18). Genomic and fossil evidence suggest that *Nypa* diverged from other palms 72.1–83.6 million years ago (Mya) (19), and the fern *Acrostichum* diverged during the late Cretaceous ∼66.0–88.1 Mya (20). *Pelliceria* spp. and the extinct *Brevitricolpites* also date from the late Cretaceous (21). The common mangrove genus *Rhizophora* originated during a narrow window of 47.8–54.6 Mya (22), coinciding with the Paleocene–Eocene Thermal Maximum. Mangrove ancestors were presumably submerged by sea-level rise during that warm period and became adapted to intertidal conditions. Mangrove vegetation lineages increased steadily over the Tertiary Period (23). For example, *Xylocarpus* probably diverged from its terrestrial relatives ~19.4 Mya (24), and *Acanthus* diverged ~16.8 Mya (25).

Transgression: landward movement of the shoreline due to a rise in relative sea level

Isostatic adjustment: response of the lithosphere to unloading of previous ice sheets

Progradation: the seaward movement of the shoreline through land formation or a drop in relative sea level

The total area of mangroves across geological history is unknown, although changes in distribution through geological time have been hypothesized (17, 21, 26, 27). Fossil evidence of major mangrove taxa has been reported to originate around the ancient Tethys Sea, and populations may have become divided as this sea closed following continental drift. Continental drift later helped some mangrove taxa extend in range; it has been suggested that *Rhizophora* expanded eastward as the India plate drifted, and Australia detached from Antarctica and moved northward (27). Transport by drifting continental plates may explain why some mangrove genera have similar global distributions despite large variations in individual dispersal capability (17). Mangrove distribution probably became more extensive during the warm Eocene epoch (21); for example, *Avicennia* pollen was present in Siberia (at latitudes above 72°N) during the early–middle Eocene (28). Mangrove distribution would have reduced when global temperatures declined during the Oligocene and Miocene, with their area decreasing as mangroves retreated from cooling climates such as those found in Europe.

2.2. Global Mangrove Dynamics in the Holocene

Mangrove distribution during the Holocene (~11,700 years ago to present) was controlled by a combination of climate and rSLR. Similar to today, mangroves were constrained primarily to tropical and subtropical latitudes by climatic controls. Although the full areal extent of mangroves during the Holocene is not known, within these latitudes, sea level and its interaction with underlying geomorphology had a profound effect on mangrove distribution.

At the peak of the Last Glacial Maximum, sea levels were ~130–120 m lower than present; this lowstand and the present-day highstand represent approximate end points on global Quaternary eustatic sea-level cycles (29). The early Holocene was marked by marine transgression in some regions, with the timing and magnitude of mangrove transgressive phases being globally variable due to varying rates of sediment supply and accumulation and differing land slopes. Transgression occurred until eustatic sea level stabilized by the mid-Holocene.

Regional differences in isostatic adjustment had a pronounced effect on mangrove response to eustatic sea-level rise in areas closer to ice sheets during the Last Glacial Maximum, such as Florida and the Caribbean (**Figure 1**). Woodroffe & Davies (30) have classified the varying responses of mangroves to sea-level change over the Holocene and indicate that these responses are dependent on the interplay between surface change processes for vertical adjustment (e.g., sediment and organic matter accumulation; see Section 4.6) and rSLR, the latter in particular varying spatially (**Figure 1**). Mangroves were drowned where high rates of rSLR surpassed rates of positive vertical adjustment, as occurred during the early Holocene. Mangroves that caught up with rSLR increased their vertical position relative to the tidal frame through lateral movement along substrates, evident from transgressive mangrove facies during the mid- to late Holocene. Mangroves that kept up with rSLR accumulated organic and mineral material in situ under moderate rates of rSLR, such as the accumulation of deep mangrove peats exceeding tide range in Florida and the Caribbean. Prograded mangroves developed when rSLR rates were low and sediment supply was high, enabling the formation of new seaward substrates that facilitated lateral mangrove progradation. Emergent mangroves occurred when substrates were uplifted by tectonic processes, although such examples are rare.

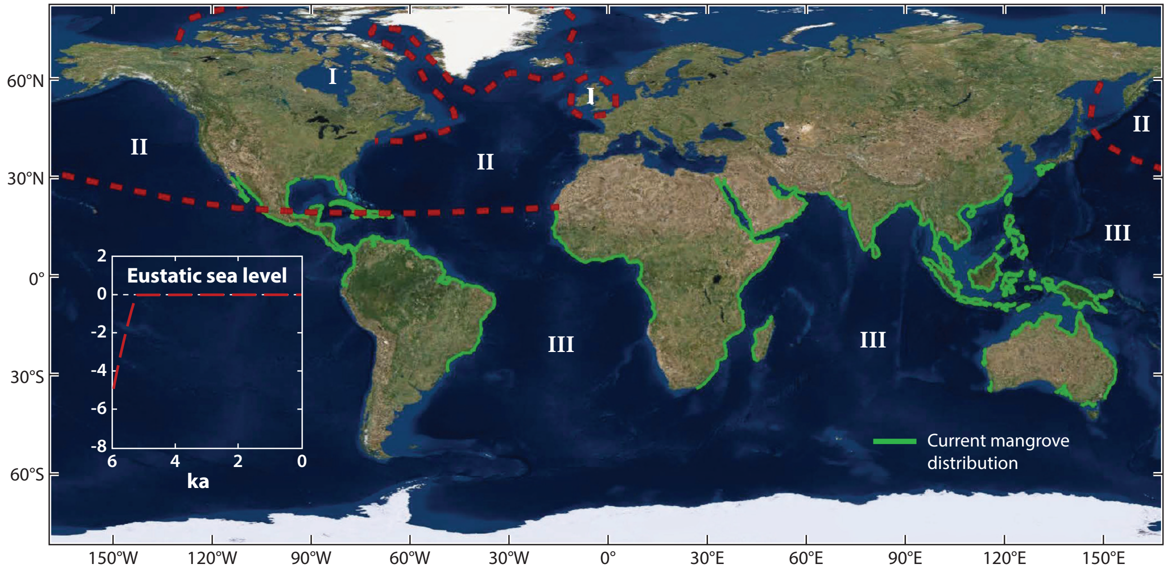

Figure 1

Zones indicating global variation in relative sea-level rise over the Holocene [zones adapted from Clark et al. (31)]. Zone I indicates areas where shorelines have been undergoing significant isostatic adjustment and ongoing shoreline uplift. Zone II indicates areas where shorelines do not exhibit a late Holocene sea-level highstand and have a protracted period of mid- to late Holocene relative sea-level rise. Zone III indicates areas where most shorelines exhibit a sea-level highstand and a longer period of relative sea-level stability. The inset global eustatic sea-level curve indicates a global pattern of early Holocene marine transgression and stabilization in sea volume. Current mangrove distribution is shown in green (32), indicating that most mangrove shorelines occur in zones where a sea-level highstand was evident in the mid- to late Holocene.

Various examples of the phases identified by Woodroffe & Davies (30) have been found in sites worldwide. Following the Last Glacial Maximum, sea-level rise accelerated sharply and rSLR was dominated by eustatic processes rather than surface processes of vertical adjustment. Accordingly, evidence of early-Holocene mangrove shorelines is now below present sea level. Mangroves along the present-day Sunda Shelf (Southeast Asia) were drowned here approximately 14,500 years ago. Located ∼200 km from the modern Mekong Delta and at water depths of ∼70–100 m, mangrove material was deposited at a time when sea level rose as much as 16 m in 300 years (33, 34). When sea levels stabilized 7,000–8,000 years ago, the mouth of the Mekong River was in the Cambodian lowlands (35) and sediment accumulation became the dominant control on mangrove distribution. The widespread occurrence of mangrove pollen in sediments in the upper few meters of deltaic stratigraphic sequences, with transitions from *Sonneratia* to *Rhizophora* to *Bruguiera* to swamp-like conditions as the delta expanded into the South China Sea, suggests lateral mangrove progradation once sea level stabilized (36, 37).

In Australia, sea-level rise was too great for mangrove development in many locations during the early Holocene. As the relationship between land elevation and sea level became increasingly dominated by surface processes of sediment accumulation, estuaries infilled and mangrove distribution changed (38–40). Woodroffe et al. (41) described three phases of response to sea-level change for the Alligator River. A transgressive catch-up phase (∼8,000 years ago) was dominated by landward mangrove transgression as sea-level rise drowned coastal river valleys. The big swamp phase (∼7,000–5,300 years ago) was associated with deceleration in the rate of eustatic sea-level rise and thus a proportionally greater influence of sediment accumulation that facilitated estuarine infill, creating an expansive intertidal zone that enabled mangroves to keep up with sea level. Finally, the sinuous/cuspate phase (<5,300 years ago) followed, whereby mangrove-dominated floodplains became grass/sedge-dominated, and mangroves retreated to estuarine shorelines as the floodplain became increasingly disconnected from tidal inundation, perhaps similar to mangrove progradation.

Mangrove response to Holocene rSLR in the west Atlantic Ocean region (Florida, Caribbean), where a protracted period of sea-level rise over the mid- to late Holocene occurred due to isostatic adjustment, differs somewhat from that of mangroves of the Indo-West Pacific region and shorelines of the southern Indian Ocean (42–45). In the west Atlantic region, the early Holocene was marked by rates of rSLR that were too high for broad mangrove development (~7,500 ka). Evident from interbedded peats and marls in Florida, the transgressive phase where mangroves were catching up occurred during the mid-Holocene and appears to have been longer in duration than elsewhere (~7,500–3,500 ka) (44). Ongoing rSLR has meant that transgressive phases dominate the mangrove stratigraphy in the region (45). Despite the dominance of transgressive phases, further deceleration in rates of rSLR in the late Holocene facilitated mangroves keeping up with sea level in some regions that were partly driven by biogenic processes of organic matter accumulation where mineral sediment supply was low (43) and mangrove progradation where sediment supply was high (46).

2.3. (Pre)historical Use of Mangroves

In addition to mangrove dynamics resulting from sea-level changes, the mid- to late Holocene began to see evidence of low-level human use of mangrove resources. Charcoal from *Rhizophora* spp. has been associated with shell middens from ~6,500 years ago (47). Nomadic communities in the Middle East settled around this time, choosing areas close to mangroves as their subsistence economies were reliant on wood and shellfish. Communities in this area became sedentary due to broader regional climate changes; as interior areas in the Middle East became progressively more arid, communities settled along the coast because mangrove resources were less affected by climatic fluctuations (48).

Coastal communities throughout history continued to use mangrove resources, and their trade became widespread over the past few centuries. Trade routes for mangrove timber have been established between East Africa and the Middle East for centuries. Such resource use may have led to mangrove degradation in heavily utilized areas, and may have had some impact on areal extent in selected locations.

A shift from subsistence to industrial use of mangrove resources, with more observable impacts on areal extent, is linked to colonial management from the eighteenth to the early twentieth centuries. In the Americas, Spanish colonial administrators in the 1750s regulated harvesting because high demand for mangrove wood for ship building led to overharvesting (49). Mangrove timber reserves were also established by German colonial administrators in East Africa in the nineteenth century to compete with the timber trade in Europe (50). Southeast Asia has a long history of mangrove exploitation and management, with forest reserves established by colonial administrators in the nineteenth and early twentieth centuries for timber and charcoal production.

By the nineteenth century, mangroves were being cleared for agriculture, such as for coconut plantations along the Caribbean coast of Colombia for export to the United States (51). Evidence suggests that mangroves in many parts of the tropics were beginning to experience substantial deforestation and degradation during this time. In some locations, this may have been somewhat balanced by increases in mangrove cover in locations where sediment delivery to the coast was enhanced due to clearing in catchments for agriculture, which facilitated mangrove progradation as they colonized newly available habitat (such as in New Zealand).

Table 1 Various mangrove deforestation rates according to different time periods and methods

Average annual deforestation rate	Time period	Method	Reference
2.00–8.00%	None given	None given	150
2.10%	Various	Literature review of data from 46 countries (representing ~60% of the world's mangrove area) upscaled globally	10
1.10–1.90%	1980–2000	Literature review of studies from differing time periods for individual countries, normalized by regression analysis and upscaled globally	13
1.00%	None given	None given	83
0.66–1.04%	1980–2005	Literature review of studies from differing time periods for individual countries, normalized by regression analysis and upscaled globally	14
0.16–0.39%	2000–2012	Robust global-scale remote sensing	32

3. THE PRESENT STATE OF THE WORLD'S MANGROVES

3.1. Mangrove Deforestation in the Twentieth Century

Preindustrial mangrove use likely did not impact the extent and habitat quality of mangrove forests to a substantial degree, but the influence of humans on mangrove resources increased in the past few centuries and peaked in the twentieth century. By the 1970s, researchers became aware of the large-scale impacts of humans on mangrove extent with increasing access to continuous satellite Earth observation. By the 1980s, large-scale land use change was the predominant cause of mangrove loss. Deforestation rates were potentially so high that it was suggested as much as 35% of the world's mangrove area had been lost in the 1980s and 1990s (10). Deforestation rates often cited in the literature range from 1 to 8% per year (**Table 1**), though their accuracy is uncertain due to lack of consistent and systematic remote sensing methods for global mangrove mapping at that time.

3.1.1. Aquaculture. Onshore aquaculture for fish and shellfish production was the leading cause of mangrove deforestation during the second half of the twentieth century (**Table 2**), particularly since the aquaculture boom in the mid-1970s and early 1980s (52). An analysis of eight countries across South America and Asia indicated that 52% of all mangroves were deforested since 1970, with 28% converted to commercial aquaculture ponds (53). In the Philippines, ~50% of the 279,000 ha of mangroves deforested between 1951 and 1988 were converted to aquaculture ponds (54). Aquaculture also degrades neighboring mangroves due to altered hydrology, pollution, and eutrophication, as discharged effluent is heavily polluted (55).

3.1.2. Agriculture. Mangroves have been deforested to produce agricultural products such as coconuts and rice, particularly in Africa, Asia, and Latin America. Rice production was responsible for 48% of all mangrove loss in southern China (>210 km^2) between the 1950s and 2010 (62) and 35% of all mangrove loss in Madagascar between 1975 and 2005 (63). The Ayeyarwady Delta in Myanmar lost 44% (~940 km^2) of its mangrove forest between 1989 and 2000, almost entirely due to rice paddies, in response to national policies to ensure food security (64).

3.1.3. Urban development. Shallow-sloping intertidal areas have often seen land cover conversion for infrastructure and urban development. Urban development may not be the largest driver of mangrove loss at regional scales (e.g., 3, 56), but can be the dominant driver in particular locations, such as the southeast coast of Brazil during the late twentieth century (65), Puerto Rico in the 1960s (66), and Douala, Cameroon, in the 1970s–2000s (67). Large areas of mangroves and associated mudflats have also been lost to urban development in China. Singapore's mangrove

Table 2 Subnational and national estimates of late twentieth-century mangrove loss due to aquaculture for various countries across the tropics

Country	Region(s)	Time period	Mangroves lost to aquaculture	Annualized rates of loss	Reference
Bangladesh	Bay of Bengal	1977–2005	11%	0.4%	56
Bangladesh	Five estuaries	1972–2010	7%	0.2%	53
Brazil	Northeast Pernambuco	1973–2005	9.6%	0.3%	57
Brazil	Nine estuaries	1987–2009	13%	0.6%	53
China	Six estuaries	1973–2007	40%	1.1%	53
Ecuador	National, excluding Guayas	1970–2006	30%	0.8%	58
Ecuador	Random sample	1966–2006	40%	1.0%	53
India	Godavari estuary	1992–2004	30%–40%	2.5–3.3%	59
India	Six estuaries	1972–2009	4%	0.1%	53
Indonesia	Andaman Sea	1977–2005	63%	2.3%	56
Indonesia	Nine estuaries	1972–2010	48%	1.3%	53
Peru	North	1962–2007	17%	0.4%	60
Thailand	Andaman Sea	1977–2005	41%	1.5%	56
Thailand	Six estuaries	1973–2006	19%	0.6%	53
Vietnam	Ca Mau	1968–2003	30%	0.9%	61
Vietnam	Nine estuaries	1975–2009	53%	1.6%	53

extent has declined by 91% (75 to 6.44 ha) since the 1950s (68) due to industrial development and the damming of mangrove-fringed estuaries to create freshwater reservoirs. A further 33% of the nation's remaining mangrove forests are expected to be lost between 2011 and 2030, as current policy favors ongoing seaward expansion of urban land use to support economic and population growth (68).

3.1.4. Forest products. The overextraction of provisioning ecosystem services such as timber and fuelwood can lead to large-scale land cover changes. Mangroves are used for fuelwood and charcoal due to the high calorific value of their wood. Fuelwood and charcoal production has caused mangrove deforestation in Latin America (49), West and East Africa (63, 69), and parts of Southeast Asia such as Myanmar (70), although their use for subsistence versus industry differs geographically. The scale of deforestation can be large; for example, 16% of Madagascar's mangrove loss between 1975 and 2005 was due to logging (63).

Across Latin America, mangrove forests have long been exploited for tannins. This became a large commercial enterprise (particularly in Colombia, Costa Rica, Ecuador, and Panama) in the late 1940s, reaching its peak by 1970 (49). A rich history of mangrove harvesting for timber and fuelwood is also found among Pacific islands (71), with harvesting likely being light and historically sustainable on islands with large proportional mangrove areas.

Tannins: organic substances extracted from mangrove bark and used in the leather industry

3.1.5. Other proximate drivers of deforestation. Several other proximate drivers of mangrove deforestation exist beyond those described above (8, 15). Threats include mangrove conversion to salt ponds in Africa and South Asia, which are constructed within hypersaline mangrove areas and create salt deposits through evaporation. Oil and gas production causes mangrove loss during drilling and infrastructure development. Large oil deposits are found under mangroves in many countries of West Africa and South America, and in the Mahakam Delta and West Papua in

Indonesia (8). Mangroves in these locations experience extensive oil spills from ship sources and piping infrastructure within or close to the mangrove. This has been a particular issue in the Niger Delta in Nigeria, with an estimated 100,000 tonnes of oil per decade impacting mangroves (72).

3.2. Mangrove Deforestation in the Early Twenty-First Century

Our knowledge of mangrove area dynamics at local to global scales has increased significantly since 2000 due to advances in remote sensing and data access, which facilitates mapping at increasing spatial resolutions and temporal frequencies. The *World Atlas of Mangroves* estimated the global area of mangroves during 2000–2001 to be 152,361 km^2 (73), based on maps from a range of sources and supplemented by remote sensing. A similar literature review approach modeled global mangrove extent at 157,400 km^2 in 2000 (14). However, substantial biases exist in estimating national and global mangrove extent by upscaling literature reviews of selected studies with differing methodologies (74). Thus, the first full remote sensing estimate of global mangrove area estimated global mangrove extent to be 137,760 km^2 during 2000–2001 (75), with a later study estimating extent at 137,600 km^2 for the year 2010 (76). Importantly, these remote sensing estimates are ~15,000–20,000 km^2 lower than literature and survey-based estimates of the same period. Big data approaches building on existing global data sets have calculated global mangrove area to be on the order of 83,495 km^2 to 173,067 km^2 for the year 2000 (32), depending on the method and definition of mangroves used (e.g., thresholds for tree height and canopy cover).

In addition to estimating global area, repeated remote sensing data and big data approaches have allowed more rigorous estimates of deforestation rates in the early twenty-first century as compared to previous estimates in the twentieth century (**Table 2**). Hamilton & Casey (32) estimated annual mangrove forest loss averaging 0.26–0.66% globally between 2000 and 2012. The spatial distribution of twenty-first century mangrove loss is far from even (**Table 3**), with rates in Southeast Asia consistently twice the global rate. Of the countries with substantial mangrove holdings, Myanmar experienced the highest rates of loss at 0.5–0.7% per year from 2000–2012 (3, 32), more than four times the global mangrove average.

Early twenty-first century global mangrove loss rates are almost an order of magnitude lower than those reported for the twentieth century (Section 3.1). Declining rates of loss may be attributed to reduced cover (reduced availability of mangrove to convert), although mangroves in

Table 3 Top 10 countries with the highest average annual deforestation rates between the years 2000 and 2012 (32)[a]

Country	Average annual deforestation rate (%)
Myanmar	0.70
Malaysia	0.41
India	0.27
Indonesia	0.26
United States	0.22
Thailand	0.20
Cuba	0.14
Philippines	0.11
Mexico	0.08
Brazil	0.05
Global average	0.16

[a]Only countries with >1% of the world's mangrove cover are included.

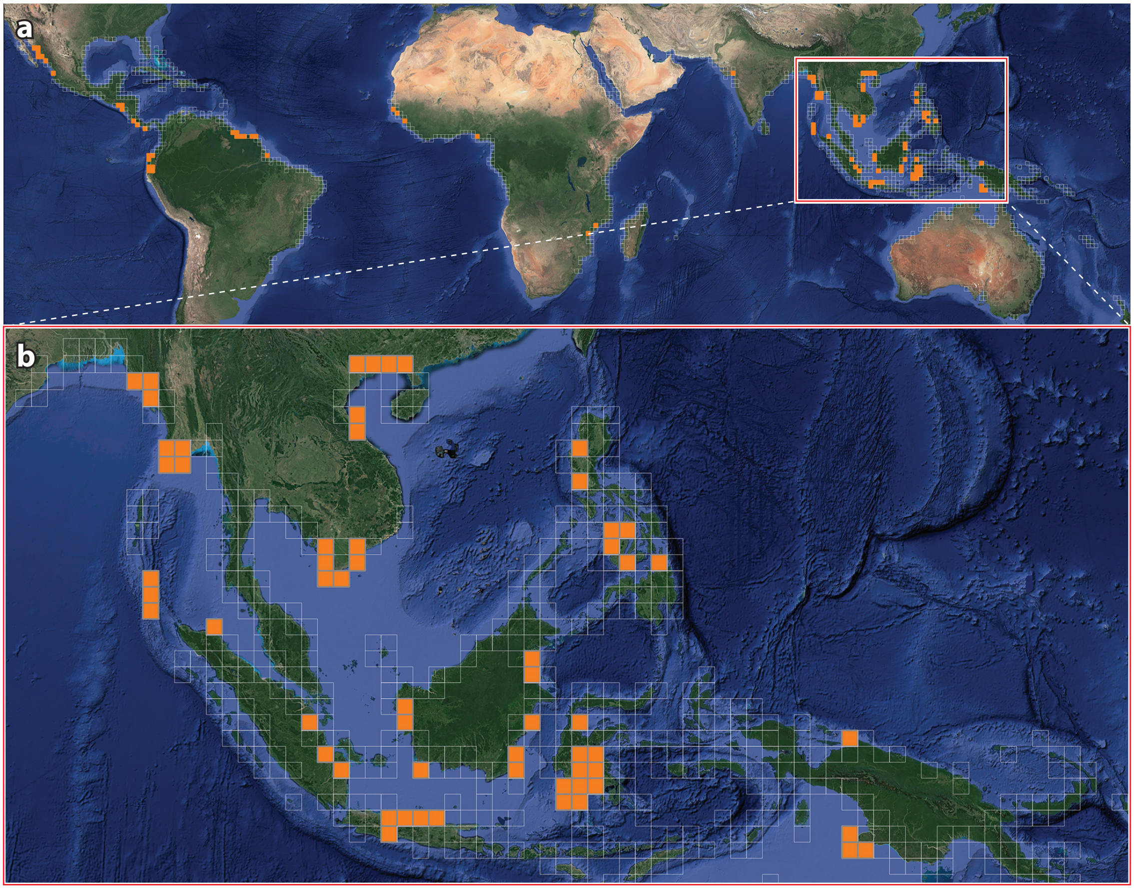

Figure 2

1° × 1° tiles where mangroves (*gray*) and hotspots of substantial change (losses and/or gains) in mangrove extent were observed (*orange*) between 1996 and 2010 (4). Panel *a* is a global overview; panel *b* (enlargement of *inset*) highlights areas of substantial change in Southeast Asia, a key deforestation hotspot. Figure adapted from Thomas et al. (4).

many parts of the world are now better protected than they were in the 1970s to 1990s due to various national and international conservation policy instruments (77–79; see also Section 4.2). Data quality may also partially explain a reduction in global mangrove loss rate between the twentieth and twenty-first centuries. Pre-2000 estimates of global mangrove loss were not derived by methodologically consistent remote sensing analyses, so the high rates of twentieth century loss might be questionable.

Although mangrove loss was not so rapid during the first part of the twenty-first century, mangroves continue to be lost to human activities. The spatial distribution of mangrove loss between 1996 and 2010 has been shown at a 1 decimal degree spatial scale (**Figure 2**), with 12–38% of tiles containing evidence of mangrove loss (4). At least 50% of tiles in Southeast Asia show mangrove loss, with several other hotspots in South America. Commodity production is still the main driver of mangrove loss globally, especially in Southeast Asia. Aquaculture still dominates, accounting for 30% of mangrove loss in Southeast Asia between 2000 and 2012. Mangroves were also converted for other commodities such as rice (22%, mainly in Myanmar) and oil palm (16%) over the same period (3).

Although rates of mangrove loss are now lower than during the twentieth century, there is still considerable progress that can be made to fully protect mangrove resources. A lower global mangrove deforestation trend masks substantial regional and national losses (16), particularly in Southeast Asia. A focus on mangrove extent also hides the importance of mangrove degradation and associated reductions in habitat quality.

3.3. The Scale of Mangrove Degradation

The state of the world's mangroves is often communicated through metrics of areal extent and deforestation, but simplistic area measurements alone are weak indicators of global mangrove conditions, as they do not consider degradation within remaining mangroves. Losses of fauna, ecosystem functionality, and ecosystem services are less reported, especially over large scales. Degradation and a reduction in such indicators due to existing (e.g., pollution on urbanized coasts, seawall or road construction altering the hydrologic regime) and future (e.g., sea-level rise) threats have important implications for mangrove conservation. However, degradation (and its relationship with ecosystem service provision) is more challenging to measure than areal extent. Changes in hydroperiod as a result of diking or pollution from major urban centers may not inflict immediate tree mortality, but they cause gradual decline in growth and productivity. This has important ramifications for mangrove faunal and microbial assemblages, and biogeochemical pathways including carbon sequestration and emissions (80, 81).

Degradation can also be caused by well-meaning but ill-informed conservation initiatives, and the use of area metrics as the currency for mangrove status can pose significant threats. For example, it may encourage the replacement of native mangroves with fast-growing exotic species, which could lead to the replacement of biodiverse forests with monospecific plantations that lack both structural and ecological complexity. Such actions may achieve short-term virtual increases in mangrove area, but may result in long-term latent degradation and decrease in ecosystem service production (82).

4. THE FUTURE STATE OF THE WORLD'S MANGROVES

In 2007, it was suggested that due to land cover change the world could be deprived of the ecosystem functions provided by mangroves by the end of this century (12). It is therefore encouraging that the opening decade of this century has seen a marked reduction in global mangrove deforestation rates, even if rates of degradation are largely unknown. However, will this reduction in mangrove deforestation rate continue into the future, and where are the future hotspots of mangrove loss? Mangrove conservation is high on the international policy agenda, and the Global Mangrove Alliance (a collective of international NGOs) aims to eliminate deforestation and increase global mangrove area by 20% over current extent by 2030 through conservation and rehabilitation (83). However, such ambitious targets are set against a backdrop of increasing human pressure along the coast alongside the longer-term threat of sea-level rise and short-term sea-level fluctuations.

4.1. Future Anticipated Land Use Changes

Land use change is still expected to be the major cause of mangrove loss in the short- and medium-term future. This will be driven in part by continuing urbanization; coastal populations are expected to increase by 35–102% between 2000 and 2030, reaching as much as 1.3 billion people (84). Urban and peri-urban areas are estimated to expand by a further 1.2 million km^2 by 2030 to accommodate such population increases (85), and it is expected that a substantial proportion of this expansion will occur in the coastal tropics. This will lead to direct habitat loss through land cover conversion to urban development, and degradation because of increased resource use and urban pollution (5).

Increasing populations provide future challenges for economic and food security. Aquaculture production will increase to help close the gap between future global population increases and demand for protein (86). However, this will have adverse environmental impacts; according to Edwards (87, p. 2), "there is no panacea for environmentally sustainable aquaculture on the horizon to meet the increasing demand for aquatic food." Aquaculture has intensified over recent decades through the use of pellet feed and hormones to increase production, and such a trend is likely to continue, with concomitant concerns over local pollution. However, intensification will reach limits of economic sustainability, requiring further areal expansion over land and sea (88, 89). Future expansion of aquaculture area into terrestrial crop areas is expected, although conflicts with other agricultural production (52, 87) mean that remaining natural coastal areas are also at risk. In Indonesia, aquaculture production is expected to grow by 7% per year between 2012 and 2030, and government targets are set even higher, with an additional 26 million hectares of land suggested to be made available for aquaculture expansion (90). A proportion of this identified suitable land will include low-lying mangrove areas.

Clearance to create space for oil palm plantations has recently been identified as a threat to mangroves (3). While salinized mangrove areas are not ideal for palm oil production, some level of production can still be achieved in saline soils (91). Oil palm is of particular concern in Southeast Asia and West Africa now and in the future, with several countries setting ambitious palm oil production targets to maximize economic and food security. It is unclear whether production increases can be satisfied by increasing yields in current plantations, so an expansion of oil palm area is expected in the future. Because large areas of major palm oil-producing countries such as Malaysia and Indonesia have already been converted to oil palm, such expansion may instead open new deforestation frontiers, such as Papua, Indonesia (3). Here, the Merauke Integrated Food and Energy Estate has been proposed, requiring the conversion of 1.2 million hectares of forested area (including mangroves) to cash crop and biofuel plantations (92). Deforestation frontiers linked to oil palm may also open up in other countries such as Myanmar. Myanmar currently has one of the highest national mangrove deforestation rates in the world, although the largest losses have occurred in Rakhine State and the Ayeyarwady Delta. Net mangrove extent has remained relatively stable over the past 30 years in the south of the country, although substantial losses and gains in mangrove area have occurred (93), and mangroves here have become increasingly degraded (94). Mangrove degradation is anticipated to accelerate and net mangrove area in the south to decline substantially in the future. The Myanmar government has set targets to become self-sufficient in palm oil, and this can only occur in the south of the country due to climatic constraints in other parts of Myanmar. Furthermore, Myanmar is undergoing a period of economic liberalization, encouraging more agricultural development in the country (64, 95). Identifying future deforestation frontiers and implementing adequate environmental safeguards are necessary to limit future mangrove degradation, accompanied by efforts focusing on planning for more sustainable utilization of mangrove-lined coasts.

4.2. Current and Future Mangrove Conservation Measures

Future land use challenges may be tempered by the increasing international policy focus on mangroves. Mangroves are implicitly or explicitly included under several international conservation policy mechanisms, including the Ramsar Convention on Wetlands and the Convention on Biological Diversity. The latter has been strengthened with the recent introduction of the Aichi Targets, which aim to improve the global status of biodiversity by 2020. Target 11 is particularly applicable to mangroves, requiring countries to designate at least 10% of their coastal and marine areas as protected areas. Approximately 36% of the world's mangroves are legally protected (78), and this should increase further under Aichi Target 11. However, a focus on gross area may promote the creation of very large marine protected areas (VLMPAs). By virtue of their size, VLMPAs are generally located in offshore areas, where space is available, tenure arrangements are less complicated, and the numbers of stakeholders involved are lower. This may discourage the further protection of mangroves as their coastal location, often fringing and disjunct distributions, and their location along coasts with multiple land uses and stakeholders make it more complicated to create large protected areas. An increase in mangrove protected area extent also requires concomitant increases in funding and enforcement (79).

Blue carbon: carbon sequestered and stored by coastal vegetated ecosystems, mostly in their anoxic soils

Payments for ecosystem services (PES): system in which ecosystem service "buyers" pay a "seller" to conserve an ecosystem service or stop land management practices that degrade ecosystem services

Mangroves are relevant to the achievement of the United Nations Sustainable Development Goals (SDGs), which set several targets to improve environmental and development parameters by 2030. Mangroves apply in particular to Goal 14, Life Below Water, which encourages the sustainable use of coastal and marine resources. Mangroves can also contribute to other SDGs, including Goal 2, Zero Hunger, through provisioning ecosystem services such as fisheries, and Goal 13, Climate Action, through carbon sequestration and storage.

The ability of mangroves to sequester and store carbon has brought them to the attention of international climate change policy makers. Mangroves and other blue carbon ecosystems (96) have become the focus of various international initiatives, such as the International Blue Carbon Initiative and the International Partnership for Blue Carbon. Wetland emissions have been incorporated into guidelines for national emissions reporting (97) and under the recent Paris Agreement of the United Nations Framework Convention on Climate Change, which sets ambitious targets for climate change mitigation and adaptation over the coming decades through Nationally Determined Contributions (NDCs). These climate change policy mechanisms provide growing incentives for mangrove conservation, as mangrove deforestation may be responsible for CO_2 emissions of up to 317 million tonnes year^{-1} (98), including emissions from the top meter of the soil (99). Mangrove conservation can thus make a substantial contribution to the NDCs of several mangrove-holding countries, especially those with extensive coastlines (2, 100).

The carbon sequestration and storage potential of mangroves makes them suitable for emerging payments for ecosystem services (PES) mechanisms. This can include REDD+ (Reducing Emissions from Deforestation and Degradation), where land owners are paid to protect carbon through "avoided deforestation." PES have attracted much attention in terrestrial forest conservation, and efforts are underway to also incorporate mangroves, since they can store 3–5 times more carbon per hectare than terrestrial forests (101). The community-led Mikoko Pamoja project in Gazi Bay, Kenya, is probably the most well-known mangrove PES project to date. This project conserves and restores 117 ha of mangroves previously used for wood products, with resulting carbon credits sold on the voluntary carbon market (102).

Despite keen interest and some small-scale pilot studies, progress in mangrove PES remains at a largely embryonic stage and PES has not yet been implemented at large scales. Mangrove PES face many challenges (103) such as data uncertainties, a lack of research into PES implementation, high opportunity costs in the coastal zone, and inadequate legislative frameworks. PES schemes may also be perceived as "green grabbing" (104), as the purchasing of carbon credits by business conglomerates can disempower local communities. More work is required to overcome these important economic, social, and political challenges.

4.3. Can Global Mangrove Area Be Increased Through Rehabilitation?

Planting has been the major strategy for rehabilitation to replace mangroves lost to deforestation. Efforts to do this have been significant in the past decade and will expand further with recent and future global initiatives. Mangrove rehabilitation became a priority for donors and international organizations after the 2004 Southeast Asian tsunami, including the establishment of the Mangroves for the Future program from the International Union for the Conservation of Nature (IUCN) and United Nations Development Programme in 11 countries across South and Southeast Asia. The IUCN also promotes the Bonn Challenge, where world leaders came together to commit to restoring 350 million hectares of forest lands (potentially including mangroves) by 2030. Within this international policy context, the Global Mangrove Alliance was recently established by the world's principal conservation organizations to work toward the ambitious targets of increasing global mangrove area (83).

Success of large-scale mangrove rehabilitation is low (105–107), so substantially increasing global mangrove area through rehabilitation will be challenging. A large-scale study of mangrove rehabilitation found that the median survival of planted seedlings was only 51%, with subsequent survivorship to adult stages ranging from 0 to 100% (108). Plantings in the Philippines have averaged 10–20% success (105), and 40% of plantings in Sri Lanka completely died (107).

Survivorship is often low due to planting in locations where physical parameters such as inundation are beyond the physiological thresholds of the planted species. Oversimplified planting protocols favor the planting of a limited group of species (often *Rhizophora* spp.). The planting of propagules often occurs seaward of the existing coastline where access may be unimpeded and land tenure is less contentious, although these areas are located at elevations less favorable for long-term mangrove survival (102). Tidal inundation, linked to surface elevation and relative position in the tidal frame, is a key determinant of mangrove establishment and distribution (106), and planting at lower elevations reduces the inundation-free period when buoyant propagules can take root without being dislodged by tidal and wave action (110).

Compared to suboptimal planting on low elevation mudflats, regeneration of the large areas of abandoned aquaculture ponds in the mid- to upper-intertidal zone through hydrological restoration (109) has achieved greater success at returning large areas of mangroves to locations where they have been previously deforested. If conducted properly, hydrological rehabilitation in ponds can have higher success rates than seafront plantings (e.g., 111), and thus can provide greater ecosystem service provision (112). Importantly, hundreds of thousands of hectares of ponds potentially exist for rehabilitation, so efforts to reach large-scale rehabilitation targets could be more achievable here.

Although rehabilitation in more landward locations such as abandoned ponds is preferable, planting still occurs in suboptimal seaward sites due to socioeconomic, political, and legal issues. Most coastal landscapes in the tropics have complex and unclear land tenure arrangements, so it is challenging to access abandoned ponds and identify stakeholders who are able to commit their ponds to rehabilitation. Governance and institutional issues also hamper rehabilitation, with poor coordination among government agencies at different scales (107, 113). Government agencies often have conflicting mandates that limit pond rehabilitation, such as mandates for mangrove rehabilitation versus aquaculture production (79, 114). Government agencies must also gain the commitment of the local communities who often manage these lands (105, 113).

Notwithstanding the myriad issues of area-based rehabilitation metrics (Section 3.3), achieving rehabilitation at the scale required to reach targets set by the Bonn Challenge, the Global Mangrove Alliance, and national governments will be a challenge. Complex tenure arrangements in coastal landscapes pose one of the biggest challenges and must be resolved through community consultations before rehabilitation begins. Tools exist to help identify landscapes with greater rehabilitation potential, such as the Restoration Opportunities Assessment Methodology (ROAM) approach. ROAM prioritizes potential rehabilitation sites based on a comprehensive suite of socioeconomic and biophysical criteria (115). Once sites are identified, local communities are often best placed to conduct and monitor rehabilitation (116).

Accommodation space: the vertical space within which sediments can be accumulated

4.4. Natural Increases in Mangrove Area

In addition to human-assisted rehabilitation, a proportion of targets to replace deforested mangroves can be met by natural increases in mangrove area. Mangroves can naturally colonize deforested and degraded areas if environmental conditions are below key biophysical thresholds. More than 15% of mangroves deforested in Southeast Asia between 2000 and 2012 reverted back to mangroves during this period (3), in part through natural colonization. Mangroves can also colonize new mudflat areas once key biophysical thresholds are below the tolerance of pioneer plant species. Prograding mudflats are generally found near large rivers and deltas, and examples of episodic mangrove colonization include the Sundarbans (on the delta of the Ganges-Brahmaputra) in South Asia (117), the northeast coast of South America (118), and New Zealand (119).

Mangroves are naturally increasing their area at their latitudinal limits in locations where dispersal barriers are not present. Expansion into subtropical and temperate saltmarsh habitats occurs in the United States (Atlantic coast), Peru, Mexico (Pacific coast), China, Australia, and South Africa. Although increases in mangrove area at their range limit are unlikely to drastically increase global mangrove area, they can make substantial contributions to mangrove extent in these locations. Mangrove expansion also has important impacts on fauna, ecological interactions, and soil and carbon dynamics (120–122).

At large scales, poleward mangrove movement has been attributed to increases in temperature, decreases in low temperature and freeze events, and changes in water availability (123, 124). Mangrove species commonly linked with large-scale poleward expansion are *Avicennia germinans* (United States), *Avicennia schaueriana* (Peru), *Rhizophora stylosa* (Australia), and *Bruguiera gymnorhiza* (South Africa).

At smaller scales, mangrove expansion is influenced by diaspore availability, dispersal barriers, and disturbance. Plant-plant facilitation (e.g., trapping of mangrove propagules by some salt marsh species) may also encourage mangrove establishment (125). Successful establishment of *A. germinans* in *Spartina alterniflora* habitats in the United States (126) and *Avicennia marina* in *S. maritima* habitats in South Africa (127) is facilitated by similar niche requirements and morphology of coexisting saltmarsh grass species, until mangroves outcompete the saltmarsh through shading.

4.5. Future Sea-Level Rise Increasing Mangrove Area

The schema of mangrove response to sea-level changes in the Holocene suggested by Woodroffe & Davies (30; see also Section 2.2) can be used to hypothesize how mangroves may respond to accelerated sea-level rise in the future. Mangrove settings that catch up, keep up, or prograde with sea-level rise create accommodation space (128), giving opportunities for mangrove expansion. Mangroves will be able to remain stable or expand in areas seaward in locations where sediment supply exceeds local rates of sea-level rise.

Transgression may be possible where the landward margin of mangroves is unimpeded by artificial or natural barriers, such as in north Australia, east Indonesia, Papua New Guinea, West Africa, and parts of southwest Florida, where coastal plains are largely not developed or urbanized. Transgression may be a key mechanism to reduce the proportion of wetlands ultimately threatened by sea-level rise (129). However, mangroves are backed by seawalls and coastal infrastructure along many coastlines, so their migration will require large-scale changes in coastal land planning (130).

4.6. Future Sea-Level Rise Reducing Mangrove Area and Health

Surface elevation change: vertical adjustment of the mangrove surface as the result of multiple surface and subsurface processes

Although rSLR may promote some mangrove expansion in the future, it is a serious threat to mangroves over the next century and beyond in locations where accommodation space is limited. rSLR will increase average hydroperiods in the intertidal zone, which may push mangroves beyond their species-specific thresholds of tolerance. The geological record indicates that mangroves can adjust to sea-level rise (see Section 2.2) and that the response variably depends upon rates of rSLR and sediment supply (131). However, the geologic record is limited in informing the future, because landscapes have a different geomorphology now compared to the early Holocene; humans have influenced sediment dynamics in recent centuries and built barriers that prevent mangrove transgression. Rivers are a key source of sediment that allows minerogenic mangroves to adjust to rising sea levels, though a major increase in river dam projects over the next 15 years (132) will severely curtail sediment inputs into tropical coastal zones.

Although data are limited, an analysis of 27 sites across the Indo-Pacific suggests that the majority are currently not keeping pace with rates of rSLR (6). Extrapolating this to hypothesize mangrove distribution in 2100 is limited by constraints shared by a variety of models, but loss projections for tidal wetlands range from less optimistic losses of 46–59% with moderate sea-level rise projections (133) to more optimistic outlooks of 0–30% (129). A large mangrove extent is potentially vulnerable to being submerged; regional and global models suggest that mangroves in Sri Lanka, Java and Sulawesi (Indonesia), the Gulf of Thailand, the Philippines, the Caribbean, and the west coast of Mexico are particularly at risk (6, 129). These areas show a reduction in vertical accommodation space as rates of sea-level rise exceed rates of surface elevation change.

Mangroves are not always passive biological features in the coastal zone; rather, in many settings they are able to influence their fate directly in response to sea-level rise by modifying their surface elevations and reducing the rate of overall rSLR they experience. Thus, models that rely only on accretion or incorporate no surface elevation change processes may substantially over- or underestimate actual mangrove vulnerability to sea-level rise. Mangroves modify their surface elevations through several minerogenic and biogenic processes (130) (**Figure 3**), so they may in some instances be able to maintain their relative position in the tidal frame.

Minerogenic processes contribute to surface elevation change, such as sediment deposition and subsequent accretion. Mangrove vegetation can actively facilitate sediment deposition by baffling tidal flows and influencing the retention of recently deposited sediments through rapid fine root ingrowth into surface layers, netting the majority of sediments delivered by single tidal floods (135). Mangrove root and seedling density influences vertical accretion (136, 137), and the spatial complexity of root structures influences sediment particle size (138). However, in settings with higher sediment availability, rates of sediment accretion have been shown to be less dependent on vegetation (119).

Several biogenic inputs also contribute to surface elevation change. Mangrove trees deposit leaf litter and woody debris on the soil surface in volumes (1–28 Mg ha^{-1}) that can contribute to elevation change if organic matter is buried quickly and export is limited (134). In some settings, roots play an important role in soil volume expansion (139). This is particularly the case in peat-forming mangroves in low-sediment settings, but root volume expansion may supplement soil surface elevation gain even in high-sediment settings (140). Benthic microbial mats in mangroves can also add up to 2.7 mm year^{-1} of surface elevation adjustment toward offsetting sea-level rise (43).

Soil surface elevation can also drop with disturbances, which results in local increases in rates of rSLR. Surface elevation losses can be acute as a result of peat collapse following short-term disturbances (141) or can manifest over longer time periods, as a result of either land use changes and anthropogenic impact (e.g., hydrologic modifications or the extraction of groundwater, oil,

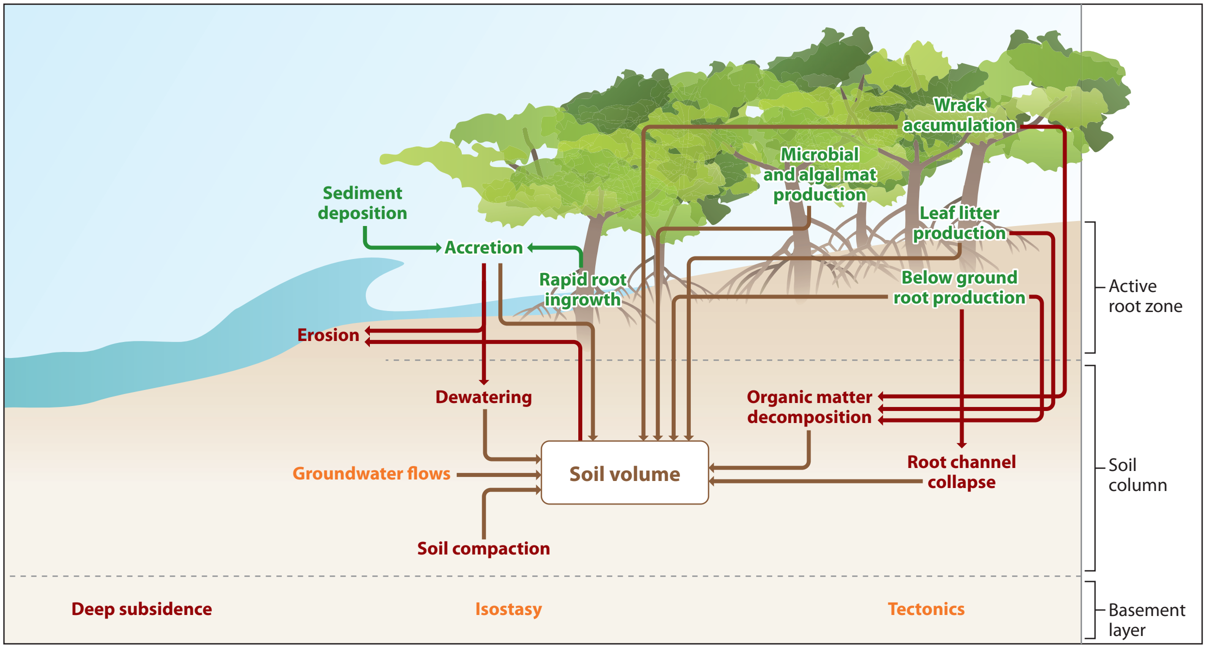

Figure 3

Summary of the major surface elevation change processes that occur in the mangrove system. Green labels denote processes that increase surface elevation; red labels denote processes that decrease surface elevation; and orange labels denote processes that may both increase and decrease surface elevation.

and gas) or land movement (e.g., tectonics, isostasy). In highly organic soils, decomposition is an important component of elevation loss. Rates of decomposition are reduced in conditions with low soil oxygen, but as a trade-off with greater ecophysiological stress to the trees. As roots die, reduced root turnover and root channel collapse lead to progressive losses of surface elevation, as evidenced by elevation losses surrounding experimental cutting of individual mangrove trees (142).

Data availability constrains our knowledge of how mangrove surfaces will respond by the end of this century. Much of our contemporary understanding of mangrove responses to sea-level rise stems from the use of radioisotope analysis of soil cores or the establishment of surface elevation tables (SETs). The latter technique is able to measure and infer many of the surface elevation processes described above (143), but contemporary SET records are still quite short in duration (3–15 years), which constrains their insights on timescales relevant to sea-level rise. The spatial distribution of both soil cores and SET benchmarks is also limited, which is problematic because surface elevation change processes differ geographically and across geomorphic settings. SET deployment has focused on the United States, Caribbean, and Australia (143), although networks are expanding in Southeast Asia and South Africa. Increased geographic distribution of surface elevation monitoring and increasing record length by combining SETs and radioisotope dating may give us a better picture of contemporary mangrove dynamics in the face of rSLR.

4.7. Changing Climatic Conditions and Oscillations

Climate change is altering the frequency and intensity of climatic cycles (e.g., El Niño Southern Oscillation, Pacific Decadal Oscillation), with far-reaching effects on sea level, climate (temperature, rainfall, intense storms), wind fields, and wave energy. Mangroves are highly sensitive to all these factors and are likely to be influenced by altered climate cycles and associated increasing climatic variability.

Altered patterns of rainfall may have some influence on mangrove diversity, distribution, and productivity now and in the future (144, 145). Mangroves use rainfall to support their metabolism either through uptake through roots or directly by the canopy (146, 147). The recent extensive dieback of mangroves in northern Australia, attributed to an extremely low sea-level event and extended drought associated with El Niño (7, 148) as well as earlier reports of dieback due to storms, drought, and other extreme climatic events (149), underscores the importance of extreme climatic events on mangroves. Although only 0.2% of global mangrove area has been reported to have suffered mortality due to such events (149), this could increase in the future. Subtropical and tropical regions with low to moderate rainfall and high climatic variability are particularly at risk of changing climatic oscillations.

5. PRIORITIES TO SECURE THE FUTURE OF THE WORLD'S MANGROVE FORESTS

Mangroves are receiving increased attention in academic and policy-making spheres. Our knowledge of the natural and anthropogenic drivers of mangrove dynamics, and how to best protect and rehabilitate them, is constantly improving. However, this review has shown that substantial knowledge and implementation gaps remain. Following the order of the previous sections in this review, a number of research and conservation priorities are suggested:

- The importance of mangroves must be better quantified: Mangrove deforestation has occurred in part because the true value of mangroves has not been fully understood. Now, conservation and rehabilitation are increasingly driven by the acknowledgment that mangroves provide important ecosystem services to coastal populations. The full range of ecosystem services provided by mangroves must be accounted for, in order to integrate them with other socioeconomic values in the coastal zone.
- More robust information is needed on mangrove extent and rates of loss: Many researchers and policy makers still claim that mangroves are being lost at 1–3% per year, when the true rate of loss may be almost an order of magnitude lower (16, 32). Older statistics are based on literature reviews and calculations of low rigor, but repeatable remote sensing methods are now available to monitor global-scale mangrove dynamics (32, 75, 76). The continued promotion of global remote sensing data collection and sharing will ensure that conservation targets are established using robust evidence of mangrove area change (74).
- An increased focus is needed on mangrove degradation: A focus on mangrove deforestation takes focus away from degradation as a key indicator of mangrove health. Ambitious targets to reduce mangrove deforestation or increase global mangrove area will mean little if the world's remaining mangroves suffer severe degradation from local and regional stressors. It is possible to quantify degradation at small scales, although there is an urgent need to quantify the distribution of mangrove degradation at larger scales through remote sensing techniques, so rehabilitation activities can be proactively deployed before mortality ensues.
- Rehabilitation should be based on tangible outcomes, not targets: Several countries and global organizations have advocated ambitious area targets for mangrove rehabilitation. Although these efforts are laudable, they can have serious perverse impacts, such as encouraging planting in areas such as mudflats that have large open spaces but are suboptimal for mangrove growth (105). Landward areas such as abandoned ponds are more suitable, but more complex to achieve at scale. Rehabilitation targets should be reframed to focus

on success criteria linked to rehabilitation outputs (e.g., percentage survival, vegetation densities similar to natural forests) instead of inputs (e.g., area planted, number of seedlings planted). Focusing on rehabilitation effectiveness rather than rehabilitation effort will ensure that lessons are learned from past failures and rehabilitation practices are improved, so that limited resources are used in a cost-effective manner.

- Mangrove protection is more efficient than rehabilitation: Rehabilitation is not a quick fix, and restoring area and ecosystem service provision is challenging and expensive to undertake at scale. Protecting existing mangroves is more cost-effective and has better ecological outcomes compared to rehabilitating lost habitat. Deforestation rates have decreased, but can be reduced further, especially in countries (such as Myanmar) that still experience rapid mangrove loss.
- More accurate projections of mangrove resilience to sea-level rise are required: There is now a strong understanding of the processes contributing to surface elevation change (128, 134), but it is still challenging to measure and monitor them appropriately in order to project the vulnerability of mangroves to future sea-level rise. Several techniques exist to measure such processes but they need to be used correctly; for example, measurements of sediment accretion alone should not be compared to sea-level rise projections, as they are not a suitable proxy of net surface elevation change. More importantly, a combination of approaches, such as accretion marker horizons, rod surface elevation tables, and isotope analysis from soil cores, are required, if the various processes and timescales that control mangrove vulnerability to sea-level rise are to be better quantified.
- Research networks and collaboration: The mangrove research field is at an inflection point; it is rapidly expanding, attracting researchers from different fields, and beginning to have real management and policy impact at national and international levels. This needs to continue by building networks of researchers, promoting voices from traditionally underresearched parts of the tropics, and strengthening links among researchers, local communities, practitioners, and policy makers so that research has a chance to be translated into positive actions. Positive outcomes for mangrove conservation and restoration are likely to be most successful when these activities are representative of all stakeholders involved in mangrove management and conservation. Mangroves are also geographically diverse across the tropics, and knowledge must reflect this diversity.

6. CONCLUSIONS

Hundreds of millions of people rely on the ecosystem services provided by mangroves, and research continues to improve our understanding of mangrove processes and how they contribute to sustainable coastal zones. Such knowledge is timely, because mangroves have experienced severe loss and degradation due to human influences, particularly land use change, overexploitation, and pollution. Although deforestation rates may no longer be as high as their peak in the 1970s and 1980s (10), mangroves continue to be lost throughout their range (32).

Importantly, anthropogenic mangrove loss sits within a longer-term envelope of changing geological and climatic conditions. Throughout geologic history until the past century, geological conditions related to climate and sea level were the primary drivers of mangrove distribution and change. Anthropogenic land use change has overwhelmed these geologic signatures over the past 150 years, but in the future geological and climatic processes are likely to increase their influence on mangroves and the human communities who rely on them, as rates of sea-level rise continue to accelerate. Thus, in the future mangroves will need to be managed and facilitated to adapt to both human and geological drivers of change.

Researchers, managers, and policy makers now have several tools to better understand the state of the world's mangroves, and to aid monitoring, conservation, and rehabilitation. However, understanding the true state of the world's mangroves, and the multiple human and geological drivers that affect mangrove dynamics, requires research and management to go further. Over the next decade, a more interdisciplinary approach to mangrove management and conservation is required, that encompasses knowledge of geological and climatic processes alongside an understanding of plant evolution, land use change, agricultural economics, socioecological systems, local and traditional knowledge, governance, and conservation science.

SUMMARY POINTS

1. Mangroves are an ecosystem of global importance, providing ecosystem services to hundreds of millions of people.
2. Mangrove distribution has changed dramatically over geological history, following dominant climatic and sea-level trends.
3. Rates of mangrove deforestation have decreased globally, although some countries (Myanmar, Malaysia) are still experiencing high rates of loss, and this may increase in the future as countries continue to follow ambitious development plans.
4. The degradation of remaining mangrove areas is a major concern but receives less attention than deforestation.
5. Future mangrove loss may be offset by increasing national and international conservation initiatives that incorporate mangroves, such as the Sustainable Development Goals, Blue Carbon, and Payments for Ecosystem Services.
6. Mangrove rehabilitation, if conducted properly, has the potential to recover some previous mangrove losses.
7. Increasing conservation gains have to be measured against a dynamic and uncertain climate. rSLR may drown mangroves, and increasing uncertainty in large-scale climatic oscillations may also impact mangrove forests.

FUTURE ISSUES

1. The future is potentially bright for mangroves; contemporary rates of mangrove deforestation are lower than in the late twentieth century, and there is increased awareness of the importance of mangroves in academia, management, and policy circles.
2. However, some proximate drivers of mangrove deforestation may increase in the future as many tropical nations utilize mangrove areas for economic security. In particular, we expect oil palm to increase in importance as a proximate driver of mangrove deforestation in Southeast Asia and West Africa.
3. Mangrove rehabilitation efforts will increase in scale, though a reliance on overambitious area targets in the future may encourage species-poor plantations in place of natural or assisted rehabilitation of mangrove patches that produce a diverse range of ecosystem functions.

4. Eustatic sea-level rise is projected to increase in rate substantially over the next century. Importantly, the distribution of sea-level rise will be spatially variable across the tropics, affecting some regions and their mangroves more than others.
5. River damming will increase sharply along many major rivers across the tropics over the next 15 years. This will substantially reduce fluvial sediment sources to the coast and limit a key mechanism by which mangroves can adjust to sea-level rise.
6. The future climate in the tropics will become more uncertain and climate oscillations may become more extreme. This may make mangroves more susceptible to changes in physical conditions that can sometimes lead to mass diebacks, as seen recently in northern Australia.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. government.

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