Chapter 8
Climate Change and Mangroves

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Abstract Climate change impacts on mangroves have received considerable attention due to rising temperatures, sea level and greenhouse gas concentrations, changes in ocean circulation and precipitation patterns, and increasing extreme weather events. Mangrove responses depend on whether critical thresholds are reached. High temperatures and low precipitation lead to extreme warming events, driving increasing mangrove mortality. Sea-level rise (SLR) will be the prime driver of future mangrove change with a critical threshold of ~6 mm a^{-1}. Predicted rates are expected to exceed this threshold at intermediate (10 Gt CO_2 a^{-1}) to very high (~124 Gt CO_2 a^{-1}) emission scenarios. The Gulf of Mexico, northern Caribbean, East Asia, the Philippines, and eastern India are vulnerable due to increasing cyclones and storms, and Africa, Mexico, Pakistan, western India, and NW Australia are vulnerable due to high temperatures and increased aridity. Losses are expected on most oceanic islands, East Asia, Indonesia, Vietnam, India, Australia, and in river deltas due to low tidal ranges, subsidence, and lack of accommodation space. Mangroves may expand where rainfall will increase such as in Central America, SE Brazil, N and W South America, Malaysia, and Thailand. High rates of mangrove carbon sequestration may be a viable mitigation strategy, although mangrove carbon stocks and sequestration rates equate to only 1.6–2.6% of all other ecosystems. Only ~10% of mangrove carbon projects may be financially sustainable but would contribute ~30 $MtCO_{2eq}$ a^{-1} and yield an investment return of ~US \$3.7 billion a^{-1}, sufficient to meet many national climate mitigation goals.

Keywords Blue carbon · Climate change · Climate mitigation · Mangroves · Sea-level rise

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8.1   Introduction

Living at the intertidal edge between land and sea in the low latitudes, mangroves are subjected constantly to changes in environmental forces making them susceptible to climate change. The intertidal zone is highly dynamic physically, chemically, and geologically, with wide changes in wave action, tides, temperature, salinity, anoxia, and rainfall; it is mainly these forces that shape mangrove forests over time and space (Alongi 2009; Twilley and Day 2013).

Mangroves are thus highly adapted to a harsh, physically demanding environment, exhibiting a high degree of ecological stability and persistence in the face of environmental inconstancy. As such, they have a variety of ecosystem properties that serve to either facilitate and augment recovery from, or resilience to, disturbance including some that are unique, such as simple architecture, highly efficient but complex biotic controls, multiple morphological and physiological adaptations, especially to cope with salt and anoxia, and high ability to retain labile carbon, nutrients, and other elements (Alongi 2009; Twilley and Day 2013).

Much of the evidence for the high adaptability of mangroves to natural and human-induced disturbances comes from patterns of recovering forest stands that are reminiscent of pioneer-phase forests, as forest structure and composition develop from a complex interplay of physiological tolerances and competitive interactions that lead to a mosaic of 'arrested or interrupted' succession sequences, in response to changes in shoreline evolution and physiochemical gradients (Fromard et al. 1998; Alongi 2008). Some mangroves, however, either do not survive or are heavily impacted depending on the extent, severity, and duration of the disturbance.

Anthropogenic disturbance impacts on mangroves, including climate change, have received much attention of late due mainly to signs of increasingly severe changes in climate, such as rising temperatures and sea-level, changes in ocean circulation, rising atmospheric and marine greenhouse (GHG) concentrations, changes in precipitation patterns, and increasing frequency and severity of extreme weather events, such as drought and cyclones. Despite continued deforestation, mangroves still play important roles in the coastal zone in low latitudes where population growth is rapid, and poverty is endemic. Mangrove ecosystems are important both ecologically and economically, offering many ecosystem services such as ameliorating coastal erosion and the impacts of tsunamis and cyclones, and providing nursery and fishing grounds and breeding sites for many semiterrestrial, estuarine, and marine organisms, and serve as a reliable source of wood, food, and traditional medicines. They also play crucial biogeochemical and geochemical roles in the tropical coastal ocean.

This chapter will critically assess the impacts of climate change on mangrove forests and their associated waterways. The primary focus will be on sea-level rise, considering their intertidal nature, as well as rising levels of GHGs, temperatures, extreme weather events, and changes in rainfall patterns. Predictions will be offered based on analysis of the latest assessment of the Intergovernmental Panel on Climate Change (IPCC 2021). Finally, possible mitigation of climate change impacts will be

discussed in light of recent work on carbon sequestration ('blue carbon') in these unique ecosystems.

8.2 Impacts of Climate Change

To realistically gauge future impacts, it is highly instructive to examine past and current episodes of climatic disturbances on mangroves. Such evidence offers insights into how mangroves respond to global environmental change.

8.2.1 Rising Temperatures, Increased Storms, Extreme Weather Events, and Precipitation Changes

During 2011–2020, the increase in global surface temperature (GST) since 1850–1900 was 1.09 (range: 0.95–1.20) °C with a further likely 1.5 °C increase during 2021–2040 and a very likely crossing of the 2 °C threshold during 2040–2060 period. Over the 2081–2100 period, average GST is very likely to be higher by 1.0–1.8 °C in the low CO_2 emission scenario and by 3.3–5.7 °C in the high emission scenario (IPCC 2021). By the year 2300, GST will be in the range of 0.9–9.6 °C higher depending in the rate of CO_2 emissions. Similarly, global mean sea surface temperatures (SST) have increased 0.88 °C (range: 0.68–1.01 °C) since 1900 and are projected to increase by 0.86 °C (0.43–1.47 °C) and by 2.89 °C (2.01–4.07 °C) by 2100 under low and high rates of CO_2 emissions, respectively (IPCC 2021). The tropical ocean has been warming faster than other regions since 1950 with fastest warming in parts of the Indian Ocean, western boundary currents, and the western Pacific Ocean due to a combination of local atmosphere-ocean coupling, the Indonesian Throughflow, and trends in the Walker circulation (IPCC 2021).

Mangroves show complex, but mostly positive, responses to increasing air and coastal ocean temperatures up to a critical threshold. Warmer temperatures affect mangroves by (1) altering species composition, (2) changing phenological patterns such as the timing of flowering and fruiting, (3) increasing plant productivity and canopy respiration where temperature does not exceed an upper threshold, and (4) expanding species ranges to higher latitudes where range is temperature-limited but not limited by other factors (Gilman et al. 2008; Jennerjahn et al. 2018). Rises in temperature may also result in (1) decreased survival in arid and increasingly arid zones, (2) increased water vapour deficit, (3) increased secondary production, and (4) shifts in species dominance and biodiversity (Alongi 2002, 2015). Rates of leaf photosynthesis peak for most species at or below 30 °C and leaf CO_2 assimilation rates of many species decline as temperatures increase from 33 °C to 35 °C (Alongi 2015).

Variations in air temperatures over long stretches of time have greatly influenced mangrove development. In Qinzhou Bay in tropical China, mangrove forests alternately flourished and deteriorated during warm and cold intervals, respectively, over the past ~3000 cal yr BP (calibrated years before the present) (Zhang et al. 2021). Mangroves expanded their development during the warm ~2220–1750 cal yr BP and ~1370–600 cal yr BP periods but deteriorated during the cold ~3000–2200 cal yr BP, ~1750–1350 cal yr BP, and the warming ~600 to 0 cal yr BP periods. Changes in relative sea-level, seawater temperature, salinity, and hydrodynamic conditions did not appear to have an impact on mangrove forest changes, but climate change, especially variation in air temperature, was the primary driver controlling mangrove development. Contrary to expectation, warming during the past 600 years has resulted in a decline in forest development, suggesting that the rise in air temperature during the Anthropocene has been too rapid to accommodate a positive mangrove response.

Latitudinal expansion of mangroves at the expense of salt marsh is underway (Cavanaugh et al. 2015; Whitt et al. 2020), encroaching in the Gulf of Mexico, Florida, New Zealand, Australia, southern China, and southern Africa, with air temperature and rainfall best explaining range expansion. This expansion and rising temperatures may impact the structure and function of mangrove flora and fauna by altering species' survivability, physiology, behaviour, and competitive abilities (da Silva Vianna et al. 2020).

While mangrove expansion appears to be driven primarily by increasing temperatures and reduced frequency of extreme cold events, changes in precipitation patterns and increasing frequency of storms cannot be ruled out as co-factors. Increased temperatures have affected the frequency and intensity of extreme weather events, such as droughts, storms, and cyclones. Direct impacts include increased erosion or smothering by sediment deposition and disturbance from intense wave action. Temperature anomalies, defined as extreme temperature events more than three standard deviations from the long-term mean (1951–1980), have shifted more than one standard deviation towards higher values, leading to more extreme warming events (Hansen et al. 2012).

The increased occurrence of such events is having a dramatic impact on mangroves, particularly more frequent episodes of mass mortality (Lovelock et al. 2017; Sippo et al. 2018, 2020; Duke et al. 2021; de Gomes et al. 2021; Zhu et al. 2021). The exemplar of such occurrences is the massive dieback of mangroves in the Gulf of Carpentaria, Australia (Duke et al. 2021), where 6–10% of the mangrove vegetation died back along 1000 km of shoreline during the summer of 2015–2016. The onset of the dieback was coincident with unprecedented high temperatures, low rainfall, and the lack of a normal monsoon. An unusually lengthy severe drought coupled with a temporary drop in sea-level associated with the 2015–2016 El Niño (Abhik et al. 2021) contributed to the mass mortality. Dieback conditions have severe consequences for ecosystem functioning as evidenced by a shift from a decline in oceanic carbon and alkalinity export (Sippo et al. 2020), loss of ecosystem carbon stock (de Gomes et al. 2021), and a weakening of GHG cycling with a lowering of both sink/source cycles in dry years (Zhu et al. 2021).

Recent large-scale mortality associated with extreme climatic events in Australia has accounted for 22% of all reported forest loss over the past six decades, suggesting the increasing importance of such extreme events (Sippo et al. 2018). In Mangrove Bay, Western Australia, there have been two dieback events over a 16-year period with the most recent one coincident with the dieback in the Gulf of Carpentaria; both dieback episodes on opposite sides of the continent coincided with periods of low sea-level due to intensification of ENSO leading to increased soil salinities and subsequent canopy loss and reduced recruitment (Lovelock et al. 2017). However, not all mangrove forests are significantly affected by extreme weather events, as found for Colombian mangroves in the Caribbean that appeared to be resilient to short ENSO-related drought events (Galeano et al. 2017). At the other extreme, some species such as *Avicennia germinans* may be resilient to extreme freeze events due to genetically based freeze tolerances (Hayes et al. 2020).

Rainfall patterns in the subtropics and tropics are changing, with weaker monsoons but more frequent and intense rainfall in parts of Africa, South Asia, and Southeast Asia (Alongi 2021). Higher rainfall ordinarily leads to more luxuriant and productive mangroves; rainfall-based thresholds have been identified for mangrove range limits in western North America, western Gulf of Mexico, western South America, Western Australia, the Middle East, north-west Africa, east-central Africa, and west-central Africa (Osland et al. 2017).

8.2.2 Sea-Level Rise (SLR)

Global mean sea level (GMSL) increased 0.2 (range: 0.15–0.25) m over the 1901–2018 period at a rate of 1.7 (range: 1.3–2.2) mm a^{-1} with an accelerated rate of 3.7 (range: 3.2–4.2) mm a^{-1} over 2006–2018, due to continued thermal expansion of the ocean and melting of glaciers and ice sheets (IPCC 2021).

Mangroves thrive at the ocean edge where they are naturally adapted to changes in sea-level over long timescales (Alongi 2002, 2015, 2021; Ward and de Lacerda 2021). The paleoenvironmental record indicates that over millennial timescales, mangroves have been exposed to different sea-level trajectories, suggesting a broad capacity to adjust to sea-level variations, as inorganic sediment supply, organic matter sequestration, and belowground root growth endow mangrove forests with considerable natural resilience in response to SLR (Woodroffe et al. 2016). Mangrove resistance and resilience to relative SLR over timescales of years to decades are the result of four main factors: (1) the rate of sea-level change relative to the mangrove soil surface, (2) species composition, (3) the physiographic setting, including the slope of the forest relative to that of the land the mangrove currently occupies, and (4) the presence of obstacles to landward migration (Gilman et al. 2008).

The ability of mangroves to adjust to rises in sea level depends on the sediment accretion rate relative to the rate of sea-level change, known as relative sea-level rise (RSLR). An analysis (Fig. 8.1) of mangrove accretion rates versus local mean SLR
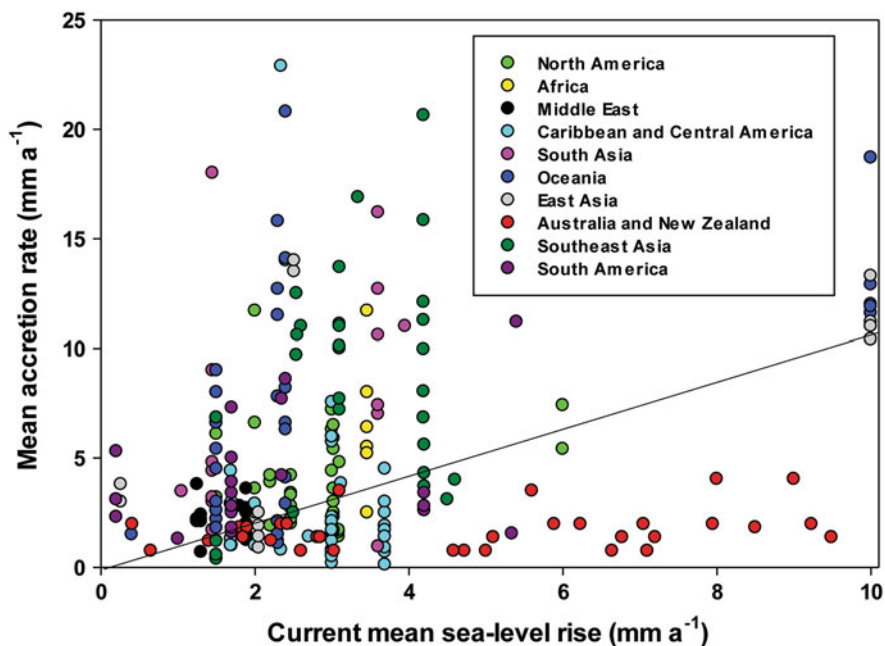
Fig. 8.1 The relationship between measured rates of mangrove soil accretion (mm a^{-1}) and current rates of mean sea-level rise (mm a^{-1}) worldwide. The sea-level rise data are from satellite altimetry or tide gauge data available from http://www.node.noaa.gov/General/sealevel.html. Mangrove sedimentation data are from references in Fig. 9.1 caption in Alongi (2021). The solid line delimits a 1:1 relationship between mean accretion rate and rate of sea-level rise (reproduced with permission from Alongi 2021)

indicates that mangroves located in the following locations (i.e. data points below the solid line in Fig. 8.1) are not keeping pace with RSLR: Australia, New Zealand, the Caribbean, Central America, on some, but not all (Esteban et al. 2019) low coral islands, and in subsiding river deltas such as the Sundarbans and in Southeast Asia. In contrast, mangroves (i.e. data points above the solid line in Fig. 8.1) located in other parts of Southeast Asia and the Pacific (e.g. New Guinea), South America, Africa, the Middle East, South Asia, and East Asia are keeping pace with current SLR as many of these forests occur in areas of rapid accretion due to highly impacted and populated catchments, especially in China, Brazil, and India.

However, the wide scatter of data points reflects how mangroves in disparate coastal settings in different parts of the world respond very differently to the same rate of SLR. This variability is also because some of the methods used to measure surface accretion (e.g. radionuclides) have considerable uncertainty; accretion rates do not reflect changes in surface elevation gain as a forest may be rapidly accumulating soil, but the local area may be subsiding, resulting in a net decrease relative to sea-level as is currently happening in many tropical river deltas (e.g. Sundarbans, Mekong). An analysis of recent trends in mangrove surface elevation changes across
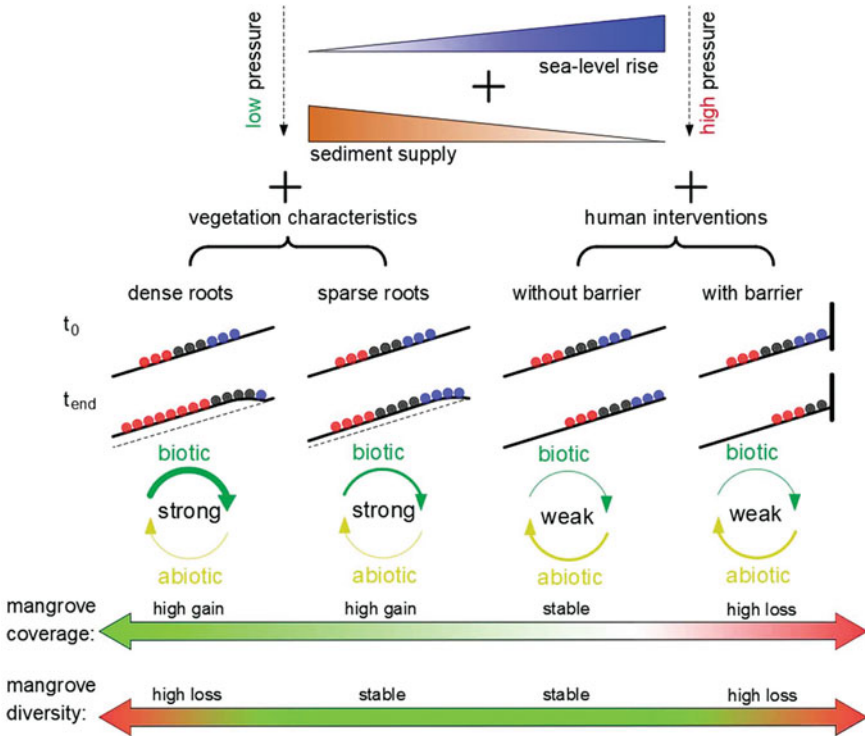
Fig. 8.2 Model results showing the complexity of mangrove response under different sea-level rise and sediment supply conditions. Under low environmental pressures, profile and vegetation distribution changes are determined by vegetation characteristics, while possible responses under high environmental pressures are mainly impacted by the presence or absence of anthropogenic barriers. The role of bio-morphodynamic feedback is indicated i.e., 'strong' versus 'weak', and arrow thickness represents the relative strengths of biotic and abiotic interactions (reproduced from Xie et al. 2020. Licensed under CC BY 4.0)

the Indo-Pacific region shows that for 69% of mangroves the current rates of SLR exceed soil surface elevation (Lovelock et al. 2015).

Mangrove responses to RSLR are complex, with clear species-specific differences in response to waterlogging and SLR (Cardona-Olarte et al. 2006; Chen and Wang 2017). For instance, the cosmopolitan species *Avicennia marina* and *Rhizophora stylosa* are highly tolerant to waterlogging, but their responses vary with immersion depth and time, salinity, and temperature (Mangora et al. 2014; Chen and Wang 2017).

A modelling study (Xie et al. 2020) has demonstrated the complexity of mangrove responses to RSLR (Fig. 8.2), illustrating the importance of the interaction between mangroves and hydrologic-sedimentary processes, both in the absence and in the presence of anthropogenic barriers impeding inland migration. Mangrove area can increase despite SLR if sediment supply is sufficient and landward

accommodation space is available (Fig. 8.2), but tidal barriers are detrimental to mangrove survival and may result in species loss. Bio-morphological feedback may cause spatial and temporal variations in sediment delivery across the forest and reduced deposition despite longer inundation (Xie et al. 2020). Such feedback may decouple accretion rate from inundation time, altering habitat conditions and causing loss of biodiversity even when forest coverage remains stable or is increasing. Further, the model indicates that vegetation-induced flow resistance linked to root density may be a major factor steering the inundation-accretion decoupling and thus species distribution. Therefore, mangroves show considerable resilience to fluctuations in relative sea-level due to their ability to actively modify their environment through surface elevation changes (Ward and de Lacerda 2021) and their ability to migrate inland over time (Krauss et al. 2014).

Positive surface elevation change is facilitated by deposition of organic matter as well as by subsurface compaction and trapping and retention of inorganic sediments (Krauss et al. 2014; McKee et al. 2021). Thus, forest survival is likely driven not only by local rates of SLR, but also by sediment availability, autochthonous peat production, land uplift/subsidence rates and localized sediment auto-compaction. Fringe mangroves are on average most susceptible to SLR, but high tree densities can facilitate surface accretion, surface elevation change, and tree survival in areas most susceptible to SLR (Kumara et al. 2010; McKee et al. 2021; Ward and de Lacerda 2021).

The effect of SLR on the landward migration of mangroves is highly site-specific: while seaward mangroves may be most susceptible to drowning and loss, there may be landward migration if there is available space. This process can be helped by oceanographic anomalies (Lopez-Medellin et al. 2011). For example, on the Pacific coast of Mexico, a significant increase in mangrove area has occurred in the lagoons of Magdalena Bay in Baja California during the past four decades, especially during the El Niño anomalies of the 1980s and 1990s, while at the same time the mangrove fringe was receding. The observed change was attributed to the combined action of the warmer waters of the El Niño events and SLR. These two processes were sufficient to flood large areas of tidal salt flats dispersing mangrove seedlings inland.

8.2.3   Rising Atmospheric CO_2

Over the past 50 years, mean atmospheric CO_2 concentrations have increased from 326 ppm to 416 ppm and are still rising (IPCC 2021). Elevated atmospheric CO_2 concentrations enhance photosynthesis, growth, and leaf chlorophyll concentrations in most mangroves, with responses being species-specific and variable, depending on salinity, temperature, nutrient availability, and water-use efficiency (Reef et al. 2016; Tamimia et al. 2019; Manea et al. 2020; Maurer et al. 2020; Jacotot et al. 2021). The response of mangroves to increasing CO_2 concentrations is, however, complex due to interactive effects of elevated CO_2 with various other drivers, such as temperature and salinity (see early references in Alongi 2002, 2015). For example,

transpiration efficiency of the species *Rhizophora mangle*, *Avicennia germinans*, *Conocarpus erectus*, and *Lumnitzera racemosa* increased with increasing CO_2 concentrations, but only at low salinity (Alongi 2015).

Most mangrove species will respond positively to increasing CO_2 levels, but some species will respond negatively or will exhibit no or little change. In greenhouse experiments, growth of *A. germinans* seedlings was enhanced only under elevated CO_2 and high nutrient conditions, but root growth doubled under low nutrient and elevated CO_2 conditions (Reef et al. 2016). Under similar experimental conditions, *A. germinans* seedlings exhibited increased salt tolerance and high photosynthetic rates under increasing, ambient, and high CO_2 levels and with a dose of the osmolyte, glycine betaine, which increases tolerance to environmental stress (Maurer et al. 2020). Other species also exhibit complex outcomes when subjected to elevated CO_2 concentrations with different amounts or rates of other physicochemical factors. For example, when subjected to ambient CO_2 and a temperature of 38 °C, *Rhizophora apiculata* seedlings responded positively to the high temperature but elevated CO_2 enhanced growth only at a lower temperature; under high temperature and elevated CO_2, the seedlings nearly died (Tamimia et al. 2019).

Thus, mangrove species show variable outcomes to elevated CO_2 when subjected to other drivers such as increasing temperatures and tidal inundation. Confounding responses have been observed in other species such as *A. marina*, *R. stylosa*, *Kandelia obovata*, and *Aegiceras corniculatum* (Jacotot et al. 2018; Yin et al. 2018; Manea et al. 2020). Net photosynthetic rates and water-use efficiency of *A. marina* and *R. stylosa* increased when grown under elevated (800 ppm) CO_2 levels and increasing tidal flooding to simulate sea-level rise (Jacotot et al. 2018), but these gains were minimal under longer flooding conditions. Such complex responses may offer a competitive advantage when mangroves encroach upon salt marshes. Growth of a model salt marsh community with *A. corniculatum* and *A. marina* under increasing CO_2 and low salinity resulted in the mangroves outcompeting the salt marsh species and with *A. marina* producing 48% more biomass under elevated CO_2 (Manea et al. 2020). In contrast, *A. corniculatum* was unaffected by higher CO_2, but had 36% greater growth than marsh plants when grown under full seawater.

Increased CO_2 can result in changes in the root microbiome (Yin et al. 2018). Over a period of 20 weeks with elevated CO_2, leaf chlorophyll levels in *K. obovata* increased as did microbial root biomass, with a shift in composition of ammonia-oxidizing archaea. There was also a shift in carbon utilization from sugars, amino acids, and carboxylic acids under ambient conditions to use of additional substrates in the following order: amino acids > carbohydrates > polymers > carboxylic acids > amines > phenolic acids, indicating a change in carbon metabolism.

8.2.4 Coastal Acidification

Open ocean pH has declined since preindustrial times by about 0.1 unit due to uptake of atmospheric carbon released from fossil fuel combustion, cement production, and land-use change (IPCC 2021). The subsequent hydrolysis of increasing CO_2 in seawater increases the hydrogen ion concentration thereby reducing pH and altering seawater carbonate chemistry. In tropical and subtropical coastal waters, however, pH is lower than in the open ocean and much more variable.

Nearly all tropical estuarine and nearshore waters, including mangrove tidal creeks and waterways, naturally exhibit very wide variations (see Table 4 in Alongi 2020a) in pH (range: 4.4–9.5), salinity (range: 0–47.4 psu), and carbonate chemical parameters, especially pCO_2 (range: 4–32,763 µatm). Tropical estuarine and coastal waters are in fact a strong source of CO_2 emissions to the atmosphere due to pCO_2 and $[CO_3^{2-}]$ oversaturation. Oversaturation and highly variable pH are the net result of high rates of mostly microbial respiration, eutrophication, and fluvial discharge, including export of alkalinity, organic matter, and CO_2, deposition of anthropogenic acids and bases, intense weathering, land-use change, acid sulphate soil discharge, and acidic groundwater (Duarte et al. 2013). Regulation of estuarine and coastal pH is therefore more complex than in the open ocean.

Mangroves are likely to be very resilient to coastal acidification considering the highly variable physiochemistry of tidal waters (Alongi 2020a) and the ordinarily low pH of mangrove soil (range: 4–7) as interstitial water is usually acidic due to root excretion of organic acids such as polyphenolic acids (tannins) and microbial decomposition of organic matter (Alongi 2009). Subsurface transport of groundwater derived from acidic soil waters also plays a major role in maintaining acidic conditions (Sippo et al. 2016).

Some mangrove ecosystems are apparent buffers of acidification in the tropical coastal zone due to net export of alkalinity (Sippo et al. 2016; Maher et al. 2018; Call et al. 2019; Reithmaier et al. 2020; Cabral et al. 2021; Saderne et al. 2021). In six Australian mangrove creeks, alkalinity fluxes ranged from an import of 1.2 mmol m^{-2} d^{-1} to an export of 117 mmol m^{-2} d^{-1} with a mean export of DIC (Sippo et al. 2016). Upscaling globally, mangrove alkalinity exports equate to 4.2 Tmol a^{-1}, equivalent to about 14% of global river or continental shelf benthic alkalinity fluxes. Export of large amounts of DIC and alkalinity increases coastal ocean pH, partly counteracting coastal acidification, so mangroves may thus be one of the largest sources of alkalinity to the tropical coastal ocean, helping to buffer acidification.

The ability of mangroves to buffer acidification, however, likely depends on geomorphological setting. For instance, in a semi-enclosed lagoon surrounded by a 25-m-wide fringe of *R. mangle* in southwestern Puerto Rico (García-Troche et al. 2021), biweekly sampling over 2 years measured pCO_2 and DIC/TA ratios ranging from 497 to 845 µatm (mean = 674) and 0.882–0.904 (mean = 0.896). These values imply heterotrophy was the main driver for persistent acidification, which was

maximal during the wet season, indicating that mangrove lagoons with limited water exchange and high carbon input will not ameliorate acidification.

8.2.5   Increasing Hypoxia

The expansion of oxygen minimum layers and dead zones illustrates the global decline in dissolved oxygen (DO) concentrations in the ocean since the mid-twentieth century, and the subsequent change in geographic and vertical ranges of marine organisms in the last 20 years (IPCC 2021). DO concentrations are declining fastest in the tropical latitudes where higher temperatures decrease the saturation capacity of DO in seawater while simultaneously increasing rates of microbial respiration that consumes and depletes DO. Deoxygenation is driven by increasing SSTs and eutrophication and is likely widespread in tropical ecosystems such as coral reefs, seagrass beds, and mangrove forests (Altieri et al. 2019).

Mangroves are naturally subject to hypoxia for intermittent spatial and temporal periods with the main drivers being: (1) physical features, such as ponds and channels, that reduce O_2 replenishment by increasing stratification and reducing tidal flushing, all enhanced by tides, seasonality, and extreme weather, (2) their complexity and high organic matter production result in the trapping of organic material which fuels decomposition and subsequent O_2 depletion, and (3) naturally rapid rates of O_2 consumption can lead to a decline in DO which can be exacerbated by the dampening of water flow by the forest (Altieri et al. 2021).

Mangroves have several mechanisms to cope with and mediate low DO levels and can to a considerable extent, counteract hypoxia. They possess structural and physiological attributes such as aboveground roots that supply oxygen to the remainder of the tree and can utilize oxygen stored in their tissues, create oxygenated microhabitats, absorb oxygen from the atmosphere and/or redistribute oxygen internally to counter low-oxygen conditions (Altieri et al. 2021). In addition, several trophic groups have high tolerances to hypoxia, including fish, molluscs, and a variety of benthic and planktonic invertebrates. Some of these tolerances are facilitated by mutualistic relationships with other organisms, including the trees. Diel cycling of DO occurs naturally in tidal mangrove waters, with a wide range of values (range: <1 to >8 mg l^{-1}; Altieri et al. 2021) mimicking the wide range of other physicochemical parameters such as pH, salinity, and pCO$_2$. This variability is the net result of tidal changes in temperature, high respiration rates, eutrophication, fluvial discharge, tidal exchange of alkalinity, organic matter and CO_2, deposition of anthropogenic acids and bases, intense weathering, land-use change, acid sulphate soil discharge, and acidic groundwater (Alongi 2020a).

8.3   Predictions

The latest IPCC assessment (IPCC 2021) makes the following climate change predictions:

- Compared with 1850–1900, mean global air temperature over the 2021–2040 period is very likely to increase a further 1.5 °C with the 2 °C warming level very likely to be crossed during the 2041–2060 period. Average global air temperature over the 2081–2100 period is very likely to be higher by 1.0–1.8 °C in the low CO_2 emissions scenario ('SSP1-1.9') and by 3.3–5.7 °C in the high emission scenario ('SSP5-8.5'). Global air temperatures are likely to range from 0.9 °C to 9.6 °C higher by 2300 depending on the emissions scenario.
- Marine heatwaves will likely increase by two to nine times in 2081–2100 than currently under 'SSP1-1.9' and 3–15 times more frequently under 'SSP5-8.5' with the largest changes in the tropical ocean. The amount of ocean warming since 1971 will likely at least double by 2100 under a low emissions scenario and will increase four to eight times under a scenario of high CO_2 emissions and will likely continue to increase until at least 2300, even for the low emissions scenario.
- SSTs are projected to increase 0.86 (range: 0.43–1.47) °C and by 2.89 (range: 2.01–4.07) °C by 2100 under low and high CO_2 emission scenarios, respectively.
- High salinity regions will become saltier, and low salinity areas will become less salty, with large-scale patterns growing in amplitude over this century.
- Ocean currents will change in the twenty-first century in response to changes in wind stress. The Indonesian Throughflow and all four eastern boundary upwelling systems are projected to weaken in low latitudes.
- Precipitation will very likely increase over the tropical ocean and likely increase in large parts of the monsoon regions but will likely decrease in the subtropics. ENSO-associated rainfall variability will increase significantly by 2050–2100. Frequency and intensity of rainfall will continue to increase across Asia.
- Ocean pH will likely decrease -0.38 ± 0.005 under a high emissions scenario by 2081–2100, with increased temporal and spatial variability in the coastal ocean. pH will be lower in tropical coastal waters due to increased eutrophication and respiration due to higher temperatures.
- More severe hypoxia or anoxia is predicted in highly populated coastal areas.
- South and Southeast Asian monsoonal circulations will weaken with a decreasing trend of monsoon frequency over the Bay of Bengal resulting in increasing breaks or dry spells.
- The East Asian monsoon will get stronger due to SST changes in the Pacific with increased rainfall.
- The West African monsoon will continue to recover from the very dry period (1970s to 1990s) with more extreme events with an increase in rainfall in east and central Africa and a decrease in west Africa with a delayed wet season.
- Increase in frequency and intensity of extreme weather events such as cyclones and drought.

- Onset of the South American monsoon season will continue to be delayed.
- Rainfall extremes during the Australasian and maritime monsoons have increased since the 1970s with prediction of increased rainfall over Indonesia.
- River floods are projected to increase in humid west Africa, especially in the deltas of the Niger, Volta, and Gambia Rivers.
- There is medium confidence that rainfall will decrease in Central America and in small islands in the western Indian Ocean, western Tropical Pacific, and Caribbean.

Logically, under a high CO_2 emissions scenario, mangroves in future will not fare as well as under a low emissions scenario, although any predictions must be tempered with caution due to the considerable uncertainties in many of the models used. However, mangroves will almost certainly decline under the following conditions: (1) at air and sea surface temperatures at or above the forecasted increase of >3.3 °C and 2.89 °C, respectively, which are above critical thresholds, (2) under greater and more frequent marine heatwaves whereby dieback events would increase, (3) changes in ocean currents such as a decrease in the Indonesian Throughflow may result in a weakening of mangrove propagule dispersal lessening the chance of mangrove survival and recruitment in more favourable habitats, (4) increased rainfall will facilitate mangrove growth and vice versa in areas of predicted drought/dryness/increased salinity, (5) more frequent and intense hypoxia will affect some mangrove-associated biota such as nekton, plankton, and benthos, and (6) in areas where monsoons are expected to weaken mangroves will likely decline in area, biodiversity, and change in species composition and dominance, and vice versa in areas of stronger monsoons. Increased cyclones can offer some benefits (increased rainfall) but stronger cyclones (higher winds) will result in greater damage. Of course, as found from experimental studies, results are likely to be complex once interactive effects are considered such as the confounding effects on mangrove growth of higher CO_2 concentrations, higher temperatures, and lower salinity (Alongi 2002).

Negative responses by mangroves will lead to other effects, as the loss of forest area will lead to decreases in ecosystem services, including cultural functions (Jennerjahn et al. 2018). Any shift in community composition will likely lead to changes in provisioning services such as fisheries outputs, including aquaculture, fuelwood, building materials, and traditional medicines. Regulating ecosystem services will likely also change. For instance, coastal protection from cyclones, tsunamis, waves, and floods will inevitably decline due to loss of mangroves related to rapid RSLR, reduced freshwater inflow, and increasing intensity of storms. Water quality maintenance will probably decline/increase and decrease/increase with increased freshwater flow and altered tidal hydrology. Increased/reduced allochthonous sediment input related to increased/decreased freshwater input may increase/decrease protection of the coastline, beach erosion, land stabilization, and climate regulation; nutrient cycling, biodiversity and nursery functions will also be altered.

Table 8.1 Predicted rates of sea-level rise (mm a^{-1}) under (a) five CO_2 emission scenarios[a] and (b) five different temperature rise scenarios during the 2040–2060 and 2080–2100 periods (IPCC 2021). Values are forecasted medians, and ranges are in parentheses. Green values indicate probable mangrove survival, yellow values indicate possible survival and red values indicate probable mangrove drowning.

Rate of sea-level rise (mm a^{-1})	(a) CO_2 emissions scenarios[a]				
	Very low	Low	Intermediate	High	Very high
2040–2060	4.2 (2.9–6.1)	4.9 (3.6–6.9)	5.9 (4.5–8.0)	6.5 (5.1–8.7)	7.3 (5.7–9.8)
2080–2100	4.3 (2.5–6.6)	5.3 (3.3–8.1)	7.8 (5.3–11.5)	10.4 (7.5–14.9)	12.2 (8.8–17.7)
Rate of sea-level rise (mm a^{-1})	(b) Global surface air temperature scenarios				
	1.5 °C	2.0 °C	3.0 °C	4.0 °C	5.0 °C
2040–2060	4.1 (3.0–5.8)	5.1 (3.8–7.1)	6.0 (4.7–8.2)	6.5 (5.1–8.6)	7.3 (5.8–9.8)
2080–2100	4.3 (2.6–6.5)	5.5 (3.5–8.3)	7.9 (5.4–11.6)	9.9 (7.2–14.2)	11.8 (8.6–17.0)

[a] Current CO_2 emissions are 40 Gt CO_2 a^{-1} compared with the very low (−15 Gt CO_2 a^{-1}), low (−10 Gt CO_2 a^{-1}), intermediate (10 Gt CO_2 a^{-1}), high (≈82 Gt CO_2 a^{-1}), and very high (≈124 Gt CO_2 a^{-1}) model emissions scenarios

Arguably, sea-level rise is likely to be the prime driver of mangrove response in future. Although palaeorecords indicate that mangroves are resilient to increasing sea-level over historical timescales (Ellison 2000; Alongi 2015), current and predicted rates of SLR are rapid in comparison, likely too rapid to facilitate mangrove adjustment and encroachment landwards. Mangroves expanded between 9800 and 7500 years ago at a rate driven mainly by the rate of relative SLR, but it was highly likely (90% probability) that they were unable to sustain accretion when relative SLR exceeded 6.1 mm a^{-1} (Saintilan et al. 2020). This finding agrees with the data in Fig. 8.1 that rates of SLR greater than 6 mm a^{-1} represent a critical threshold for submergence. Mangrove forests are likely 'losers' with respect to RSLR in regions where there is substantial subsidence, such as in river deltas and on islands, such as the Sundarbans and the Solomons, respectively (Albert et al. 2018), a low tidal range, changes in precipitation, and/or declining ecological conditions (Cinco-Castro and Herrera-Silveira 2020). The reality is that, as they have in the past, mangroves will respond in complex ways to future SLR. If the rate of SLR is slow enough (≤ ~6 mm a^{-1}), some forests will likely survive although there will probably be significant changes in forest structure and species

Table 8.2 Predicted mangrove responses to forecasted climate change by 2100 based on IPCC (2021) climatological criteria and ecological criteria (Alongi 2008, 2015, 2021; Lovelock et al. 2015; Jennerjahn et al. 2018; Saintilan et al. 2020)

Region	Prediction
Southern United States	Increase in damage/destruction from increasingly frequent and stronger hurricanes. Latitudinal expansion continues.
Africa	Continued poleward expansion in S. Africa. High risk of losses due to deforestation/degradation as most mangroves highly fragmented. Losses from high heat and aridity in NW and SE Africa.
Middle East	Losses due to increasing aridity, especially in Red Sea. Landward expansion/migration unlikely.
Caribbean/Central America	Increasing ENSO rainfall likely to increase sediment delivery along S. Caribbean coast of Central America. Decline in Mexican mangroves (both coasts) due to increasing aridity.
South America	SE Brazilian mangroves likely to increase due to increased temperatures. N. South American mangroves unlikely to be impacted due to increased rainfall and sediment supply. Pacific coast mangroves likely to continue increasing in size but no poleward expansion due to cold currents and arid conditions.
South Asia	Arid-zone mangroves likely to decline in Indus delta due to low rainfall, subsidence, and low sediment delivery. E. India vulnerable to low tidal range, subsidence, and increased cyclone activity.
Southeast Asia	Philippines, Indonesia, and Vietnam vulnerable to SLR due to low tidal range. River delta mangroves likely to decline with SLR, subsidence, and decreased sediment supply.
East Asia	S. China mangroves vulnerable to SLR due to lack of upland space for migration and increased typhoon activity.
Pacific Islands	Islands of Oceania highly vulnerable to SLR due to lack of upland space for landward migration.
Australia/New Zealand	Mangroves in NW Australia likely to decline due to increasing aridity. SE Queensland and SE Australia mangroves not keeping pace with SLR. New Zealand mangroves likely to expand on north island as temperatures increase.

composition, morphology, and anatomy, including changes in fibre wall thickness, bark anatomy, changes in vascular vessel densities, formation of hypertrophied lenticels and adventitious roots, and increased aerenchyma development (Alongi 2015). At higher rates of SLR ($\geq \sim 6$ mm a^{-1}), mangroves will only survive if there is sufficient land space higher up on shore to accommodate forest establishment (Table 8.1).

Regional vulnerability will depend on other drivers in addition to SLR including temperature, aridity, salinity, storm and cyclone frequency and intensity, and coastal setting. For instance, mangroves situated in river- and tide-dominated settings would best be able to cope with climate change as allochthonous materials from land and sea will enable sediment accretion to keep pace with rising seas; these areas would include macrotidal estuaries and wet tropical coastal regions (Jennerjahn et al. 2018; McKee et al. 2021).

Based on these criteria, several studies (Alongi 2008, 2015, 2021; Lovelock et al. 2015; Jennerjahn et al. 2018; Saintilan et al. 2020) have identified regions most vulnerable to climate change (Table 8.2). Increasing frequency and intensity of hurricanes, cyclones, and typhoons will negatively impact the Gulf of Mexico, northern Caribbean, East Asia, The Philippines, and eastern India whereas high temperatures and increased aridity will cause losses in northwest and southeast Africa, Mexico, Pakistan, western India, the Middle East, and northwest Australia (Table 8.2). Due to a combination of low tidal ranges, subsidence, and lack of accommodation space, mangrove losses will occur on most Pacific Ocean, Indian Ocean and Caribbean Sea Islands, East Asia, east coast of Sumatra, north coast of Java, Sulawesi, southern Vietnam, eastern India, northeast and southeast Australia, and in many river deltas, such as in the Sundarbans, Mekong, Ayeyarwaddy, and Niger Rivers. A few areas are especially vulnerable and are currently experiencing mangrove drowning, including low coral islands in the Indo-West Pacific and the Caribbean. A major co-factor facilitating mangrove loss is erosion, agriculture/aquaculture and degradation and deforestation coupled with a high degree of fragmentation, such as in Africa and Asia (Bryan-Brown et al. 2020).

Some forest expansion and little or no responses by mangroves are forecast in regions where rainfall will increase, such as along the south Caribbean and Pacific coasts of Central America (e.g. Costa Rica), in southeast Brazil, along the western and northern coasts of South America, west coast of Peninsular Malaysia, and the southwest coast of Thailand. Latitudinal expansion will continue along the Gulf of Mexico coast of the United States, both coasts of Florida, SE and E Australia, New Zealand, southern Africa.

8.4   Climate Change Mitigation

8.4.1   Significance of Mangrove Blue Carbon

"Blue carbon," defined as the carbon sequestered and stored by coastal ocean ecosystems, including mangroves (Fig. 8.3), has been increasingly used conceptually to document the carbon management potential of these ecosystems to protect and, if necessary, to restore them to maintain and expand their ability as critical carbon sinks to assist in reducing GHG emissions (Alongi 2018). When these coastal habitats are destroyed, their carbon is released back into the atmosphere, thus reversing the effect of fostering carbon sequestration in REDD+ (Reducing Emissions from Deforestation and Forest Degradation) and other rehabilitation projects (IOC 2011; Sifleet et al. 2011; Herr et al. 2012).

There are three components of carbon sequestration in mangroves: (1) the annual sequestration rate, that is, the annual flux of organic carbon (C_{ORG}) transferred to anaerobic soils and sediments where it cannot undergo oxidation to CO_2 to be returned to the atmosphere, (2) the amount of carbon stored in above- and belowground biomass, and (3) the total ecosystem C stock stored belowground as a result
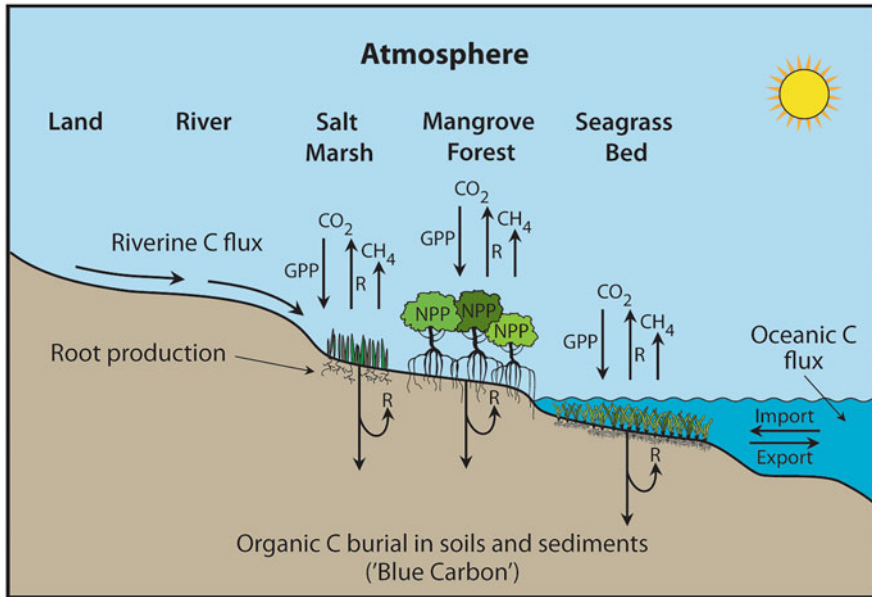
Fig 8.3 Conceptual model of blue carbon in coastal ecosystems. *GPP* gross primary production, *NPP* net primary production, *R* respiration, *CO₂* carbon dioxide, *CH₄* methane (reproduced with permission from Alongi 2018)

of prior sequestration, that is, historical sequestration over a given habitat's lifetime. There has been impressive growth in mangrove blue carbon papers reflecting the need of NGOs and various agencies for more data, as well as a lot of enthusiasm for the idea that blue carbon storage and sequestration are of great significance in reducing carbon emissions to ameliorate the effects of climate change.

The destruction of mangrove forests, especially if the soil horizon is removed or disturbed, can result in significant carbon losses (Pendleton et al. 2012; Huxham et al. 2018), especially if converted to aquaculture ponds, cattle pastures, and infrastructure upon deforestation, to the extent that more than 50% of mangrove carbon has been lost and returned to the atmosphere. Immediate removal of biomass and soil results in extremely high losses (see Table 2, Alongi 2020b) with CO_{2eq} emissions averaging 1802.2 Mg ha^{-1} a^{-1} and ranging from 407.0 to 2781.5 Mg ha^{-1} a^{-1} as estimated for mangroves in Brazil, Mexico, the Philippines, Honduras, Dominican Republic, Indonesia, and Costa Rica. Most emissions are derived from loss of soils to a depth of 1 m, so if soils deeper than 1 m are dredged, the estimated CO_2 eq flux to the atmosphere will be much greater. Assuming total deforestation of mangroves (biomass + soils to 1 m depth) and using the mean CO_{2eq} emission of 1802.2 $MgCO_{2eq}$ ha^{-1} a^{-1} and multiplying by an annual average deforestation rate of 0.16% (Hamilton and Casey 2016; Hamilton and Friess 2018) and the low and high estimates of global mangrove area of 83,495 km^2 (Hamilton and Casey 2016) and 137,760 km^2 (Giri et al. 2011), we estimate annual losses of

Table 8.3 Estimated global mean C stocks, C sequestration rates and CO_2 emissions due to losses from mangrove forests, salt marshes, seagrass meadows, coral reefs, the tropical coastal ocean, and terrestrial ecosystems. Table is derived from Table 3 in Alongi (2020b)

Ecosystem	Global mean C stock (Pg C_{org})	Global C sequestration (Tg C_{org} a^{-1})	Current conversion rate (% a^{-1})	Carbon emissions (Pg CO_{2eq} a^{-1})
Mangrove	6.17–9.99	14.98–24.27	0.16	0.088–0.14[a] (0.036–0.058)
Salt Marsh	1.74	11.66	1.32	0.084
Seagrass	2.61	35.31	1.5	0.144
Coral Reef	0.03	3.0	0.43	0.0005
Tropical coastal ocean	36.0	3.9	0.93	0.5
Tropical forest	553.0	1100.0	0.53	10.8
Temperate forest	292.1	300.0	0.70	7.5
Boreal forest	395.0	246.6	0.80	11.6
Tropical grass-land/savanna	455.4	315.0	0.70	11.7
Temperate grassland	226.4	210.0	0.55	4.6
Desert and xeric shrub land	119.7	432.3	0.3	1.3
Montane grasslands/ forests	90.3	ND	0.49	1.6
Mediterranean forest	87.4	212.8	ND	ND
Tundra	1486.0	528.0	ND	ND
Boreal peatlands	427.0	191.7	ND	0.26
Tropical peatlands	119.2	31.8	ND	1.48

[a] Estimated assuming total forest biomass and soil losses to a depth of 1 m and low and high area estimates as discussed in text. CO_2 emissions based on global sequestration rate are in parentheses

between 24.08 and 39.7 $TgCO_{2eq}$ a^{-1} or 0.0024 and 0.0039 $PgCO_{2eq}$ a^{-1}, respectively.

Are mangrove blue C stocks and C sequestration rates globally significant? The global mean C stock for mangroves is the largest of any ecosystem in the global tropical ocean (Table 8.3). Although mean mangrove C stocks per unit area are the largest among the world's ecosystems (except tundra and peatlands), global mangrove C stocks equate to only 1.6–2.6% of individual terrestrial ecosystem global C stocks (Table 8.3). Regarding C sequestration among coastal environments, seagrass meadows sequester slightly more than one-third to twice the amount mangroves store. Mangroves sequester ~50–76% of tropical peatlands globally but only 4%

compared to other terrestrial ecosystems (range: 1.3–8%). CO_2 emissions due to deforestation and other destructive land-use practices result in large returns of CO_2 to the atmosphere, for a total of ~51.7 Pg CO_{2eq} a^{-1} (Table 3 in Alongi 2020b). Assuming that all mangroves are destroyed at a rate of 0.16% a^{-1}, total CO_2 emissions can range from 0.088 to 0.142 Pg CO_{2eq} a^{-1} depending on total mangrove area. This range equates to 0.17–0.27% of total estimated global carbon emissions.

While there is no doubt that mangroves store and sequester large amounts of carbon relative to their small global area, they play only a minor global role in storing C_{org} and in mitigating CO_2 emissions. Mangrove CO_2 emissions are, however, significant throughout the tropical coastal ocean, accounting for about 18–28% of CO_2 emissions from the tropics (seagrasses account for 29% and coral reefs 0.1% of tropical coastal ocean emissions; the remaining 52.9% is accounted for by nearshore coastal waters and subtidal benthos). It must be noted that these C stock and C rate estimates are crude and can only point to relative differences, as there are significant data limitations. Taillardat et al. (2018) similarly estimated that mangroves buffer only 0.42% of the global fossil fuel emissions (as of 2014) due primarily to their limited spatial extent in the coastal zone.

Climate change mitigation is, however, likely to be more significant and effective at the national scale especially in countries losing mangroves rapidly, such as in Indonesia and Myanmar (Taillardat et al. 2018). An estimate of national mangrove sequestration potential showed that they can contribute significantly to mitigation of CO_2 emissions if deforestation rates remain low (Taillardat et al. 2018). For example, mangroves in countries such as Nigeria, Colombia, Bangladesh, Ecuador, and Cuba accounted for >1% of national CO_2 emissions. In countries with high deforestation rates such as Malaysia and Myanmar, the carbon storage potential of remaining mangroves was less than the carbon emissions generated by deforestation. In some countries, mangrove mitigation potential is a significant percentage of national losses, such as Papua New Guinea (34.9%), Gabon (11.3%), Panama (8.3%), Mozambique (8.3%), and Cameroon (8.4%), underscoring the importance of mangrove mitigation at the national and regional scale.

National-scale mitigation raises the issue of the viability of mangrove blue carbon financing (Alongi 2018; Zeng et al. 2021) as the protection or restoration of blue carbon is steadily gaining credence as a key natural climate solution with a recent spike in public and private sector interests and investments for nature-based carbon financing mechanisms. The success or failure of a blue carbon project depends on multiple factors, including increased involvement from key stakeholders and constraints by knowledge gaps in both management, science, and carbon markets. An extensive analysis of the potential and limits of mangrove projects for climate change mitigation (Zeng et al. 2021) modelled the magnitude of certifiable carbon from mangrove blue carbon projects and its mitigation potential as well as the relative profitability of these projects to produce a global map of mangrove blue carbon return on investment. The analyses indicated a limited global potential with only ~20% of the world's mangrove forests qualifying for blue carbon funding and only ~10% financially sustainable for over 30 years. However, this small percentage would contribute up to 29.8 $MtCO_{2eq}$ a^{-1} and yield a return on investment of ~US

$3.7 billion a^{-1}. These results point to a disproportionately large potential of blue carbon finance that can be leveraged to meet national climate mitigation goals, especially coupled to other conservation goals to protection mangrove carbon stocks and biodiversity (Zeng et al. 2021).

8.4.2   Future CO_2 Emissions

A predictive model of mangrove carbon emissions (Adame et al. 2021) has recently projected emissions and soil carbon sequestration potential under 'business as usual' rates of mangrove loss. Emissions could reach up to 2391 Tg CO_{2eq} by 2100 and would increase up to 3392 Tg CO_{2eq} if soil carbon sequestration is included. About 90% of these emissions are predicted to come from Southeast and South Asia (west Coral Triangle, Sunda Shelf, and Bay of Bengal), followed by the Caribbean (tropical Northwest Atlantic) and Andaman coast (west Myanmar) and north Brazil shelf (Fig. 8.4).

The west Coral Triangle, the Sunda Shelf, and the Bay of Bengal had the highest predicted emissions (712 Tg CO_{2eq}, 452 Tg CO_{2eq}, and 369 Tg CO_{2eq}, respectively) due to losses to agriculture/aquaculture at 985 Tg CO_{2eq}, contributing to 73% of emissions (Fig. 8.4). Erosion was an important driver of loss in these provinces,
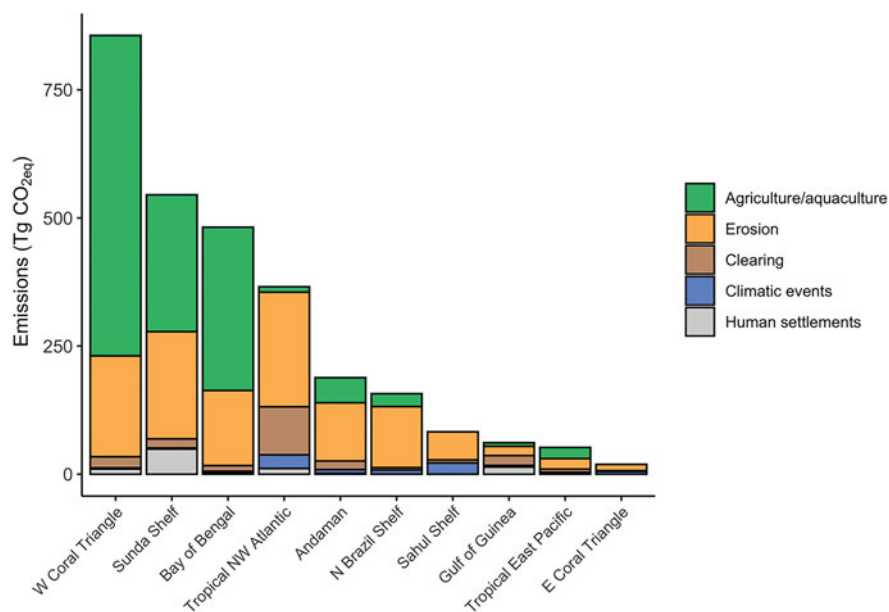

Fig. 8.4 Cumulative CO_{2eq} emissions (Tg) over the 2010–2100 period attributed to the proximate drivers of mangrove loss for the marine provinces ranked in the top ten for future CO_2 emissions (reproduced from Adame et al. 2021. Licensed under CC BY 4.0)

accounting for 23%, 38%, and 30% of their emissions, respectively. Erosion was similarly a large driver of mangrove loss in the Andaman (west Myanmar, Bangladesh, and east India) province, accounting for 98 Tg CO_{2eq} or 60% of its total emissions. Another hotspot for mangrove carbon emissions was predicted for the tropical northwest Atlantic which had large emissions due to erosion (191 Tg CO_{2eq}), clearing (80 Tg CO_{2eq}), and extreme climate events (23 Tg CO_{2eq}) with total emissions projected to reach 312 Tg CO_{2eq} by 2100 (Fig. 8.4). Lower CO_2 emission hotspots were predicted to occur on the north Brazil shelf, the Sahul shelf, Gulf of Guinea, tropical east Pacific, and east Coral Triangle (Fig. 8.4). Thus, most mangrove carbon losses by the end of the century will be the result of natural and anthropogenic factors, especially cultivation, erosion, and clearing, rather than as a direct result of climate change. This may provide humanity with a window of opportunity to address the forces currently resulting in mangrove decline.

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