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A Review of Climate Change Impacts on Mangrove Ecosystems

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Abstract

Mangrove forests, like other ecosystems, are subject to various disturbances that vary in their intrinsic nature (e.g., geological, physical, chemical, biological) in time and space. Mangroves and other coastal ecosystems offer significant opportunities for climate change adaptation and mitigation, including livelihood support, food security and storm/flood protection. Inter-related and spatially variable climate change factors including sea level rise, increased storminess, altered precipitation regime and increasing temperature are impacting mangroves at regional scales. Based on the most recent Intergovernmental Panel on Climate Change (IPCC) forecasts, mangrove forests along arid coasts, in subsiding river deltas, and on many islands are predicted to decline in area, structural complexity, and/or in functionality, but mangroves will continue to expand poleward. It is highly likely that they will survive into the foreseeable future as sea level, global temperatures, and atmospheric CO_2 concentrations continue to rise. The ultimate disturbance, climate change, may lead to a maximum global loss of 10-15% of mangrove forest, but must be considered of secondary importance compared with current average annual rates of 1-2% deforestation. Mangroves will survive into the future but there have already been, and will continue to be, more negative than positive impacts due to climate change. Mangroves are expanding their latitudinal range as global temperatures continue to rise. Mangrove forests will either experience little change or some positive impact in areas where precipitation is forecast to increase. The greatest current threat to mangrove survival, however, is deforestation and such continuing losses must be considered in tandem with the impact of climate change.

Keywords

Climate Change, Ecological Impacts, Mangroves

1. Introduction

Mangroves perform valued regional and site-specific functions [1]. Reduced mangrove area and health will increase the threat to human safety and shoreline development from coastal hazards such as erosion, flooding, storm waves and surges, and tsunami, as most recently observed following the 2004 Indian Ocean tsunami [2]. Mangrove loss will also reduce coastal water quality, reduce biodiversity, eliminate fish and crustacean nursery habitat, adversely affect adjacent coastal habitats, and eliminate a major resource for human communities that rely on mangroves for numerous products and services [1-3]. Mangrove destruction can also release large quantities of stored carbon and exacerbate global warming and other climate change trends [4]. The value of Malaysian mangroves just for storm protection and flood control has been estimated at USD 300,000 km-1 of coastline, which is based on the cost of replacing the mangroves with rock walls [5]. The mangroves of Morton Bay, Australia, were valued in 1988 at USD 4850 ha-1 based only on the catch of marketable fish [5].

Accurate predictions of changes to coastal ecosystem area and health, including in response to projected relative sea-level rise and other climate change outcomes, enable site planning with sufficient lead time to minimize and offset anticipated losses [6]. We review the state of understanding of the effects of projected climate change on mangrove ecosystems, including the state of knowledge for assessing mangrove resistance to relative sea-level rise.

2. Climate Change Consequences

2.1. Storms

During the 21st century the Intergovernmental Panel on Climate Change projects that there is likely to be an increase in tropical cyclone peak wind intensities and increase in tropical cyclone mean and peak precipitation intensities in some areas as a result of global climate change [7]. Storm surge heights are also predicted to increase if the frequency of strong winds and low pressures increase. This may occur if storms become more frequent or severe as a result of climate change [7]. The increased intensity and frequency of storms has the potential to increase damage to mangroves through defoliation and tree mortality. In addition to causing tree mortality, stress, and sulfide soil toxicity, storms can alter mangrove sediment elevation through soil erosion, soil deposition, peat collapse, and soil compression [8-9]. Areas suffering mass tree mortality with little survival of saplings and trees might experience permanent ecosystem conversion, as recovery through seedling recruitment might not occur due to the change in sediment elevation and concomitant change in hydrology [10]. Other natural hazards, such as tsunami, which will not be affected by climate change, can also cause severe damage to mangroves and other coastal ecosystems (e.g., the 26 December 2004 Indian Ocean tsunami [2].

2.2. Precipitation

Globally, rainfall is predicted to increase by about 25% by 2050 in response to climate change. However, the regional distribution of rainfall will be uneven [11-13]. Increased precipitation is very likely in high-latitudes, and decreased precipitation is likely in most subtropical regions, especially at the pole ward margins of the subtropics [7]. In the most recent assessment, the Intergovernmental Panel on Climate Change reported significant increases in precipitation in eastern parts of North and South America, northern Europe and northern and central Asia, with drying in the Sahel, the Mediterranean, southern Africa and parts of southern Asia [7]. Long-term trends had not been observed for other regions.

Changes in precipitation patterns are expected to affect mangrove growth and spatial distribution [14, 15]. Based primarily on links observed between mangrove habitat condition and rainfall trends [14, 16], decreased rainfall and increased evaporation will increase salinity, decreasing net primary productivity, growth and seedling survival, altering competition between mangrove species, decreasing the diversity of mangrove zones, causing a notable reduction in mangrove area due to the conversion of upper tidal zones to hyper saline flats. Areas with decreased precipitation will have a smaller water input to groundwater and less freshwater surface water input to mangroves, increasing salinity. As soil salinity increases, mangrove trees will have increased tissue salt levels and concomitant decreased water availability, which reduces productivity [14]. Increased salinity will increase the availability of sulfate in seawater, which would increase anaerobic decomposition of peat, increasing the mangrove's vulnerability to any rise in relative sea-level [17]. Reduced precipitation can result in mangrove encroachment into salt marsh and freshwater wetlands [18].

Increased rainfall will result in increased growth rates and biodiversity, increased diversity of mangrove zones, and an increase in mangrove area, with the colonization of previously unvegetated areas of the landward fringe within the tidal wetland zone [14, 16]. For instance, mangroves tend to be taller and more diverse on high rainfall shorelines relative to low rainfall shorelines, as observed in most global locations, including Australia [16]. Areas with higher rainfall have higher mangrove diversity and productivity probably due to higher supply of fluvial sediment and nutrients, as well as reduced exposure to sulfate and reduced salinity [14, 15]. Mangroves will likely increase peat production with increased freshwater inputs and concomitant reduced salinity due to decreased sulfate exposure [17]. These predicted responses are based on assessments from only a few areas and are currently untested in longitudinal studies at any single location. Further research is needed to confirm these hypotheses and to assess the broader significance of rainfall variability on mangroves.

2.3. Sea Level Rise

Global sea-level rise is one of the more certain outcomes of global warming, it is already likely taking place (12–22 cm occurred during the 20th century), and several climate models project an accelerated rate of rise over coming decades [7, 20, 21]. The range of projections for global sea-level rise from 1980 to 1999 to the end of the 21st century (2090–2099) is 0.18–0.59 m [7]. Recent findings on global acceleration in sea-level rise indicate that upper projections are likely to occur [20]. 'Relative sea-level change', the change in sea-level relative to the local land as measured at a tide gauge, is a combination of the change in eustatic (globally averaged) sea-level and regional and local factors. The former is the change in sea level relative to a fixed Earth coordinate system, which, over human time scales, is due primarily to thermal expansion of seawater and the transfer of ice from glaciers, ice sheets and ice caps to water in the oceans [21]. The latter is the result of vertical motion of the land from tectonic movement, the glacio- or hydro-isostatic response of the Earth's crust to changes in the weight of overlying ice or water, coastal subsidence such as due to extraction of subsurface groundwater or oil, geographical variation in thermal expansion, and for shorter time scales over years and shorter, meteorological and oceanographic factors [21]. The rate of change of relative sea-level as measured at a tide gauge may differ substantially from the relative sea-level rate of change occurring in coastal wetlands due to changing elevation of the wetland sediment surface. There are several interconnected surface and subsurface processes that influence the elevation of mangroves' sediment surface. Mangroves of low relief islands in carbonate settings that lack rivers were thought to be the most sensitive to sea-level rise, owing to their sediment-deficit environments [22-23]. However, recent studies have shown that subsurface controls on mangrove sediment elevation can offset high or low sedimentation rates [8], such that sedimentation rates alone provide a poor indicator of vulnerability to rising sea-level. The surface elevation table-marker horizon (SET-MH) method [8,24] and stakes inserted through the organic peat layer to reach consolidated substrate [25] have been used to measure trends in wetland sediment elevation and determine how sea-level relative to the wetland sediment surface is changing.

There have been observations of disparate trends in sediment elevation within an individual mangrove [24]. This highlights the importance of designing sampling methods to observe trends in change in surface elevation to adequately characterize a mangrove site. Furthermore, there can be large and significant differences between trends in mangrove sediment accretion and sediment elevation [27]: Subsurface processes, in some cases in the deepest soil horizon, have been found to be primary controlling factors of elevation change [8]. Therefore, sediment elevation monitoring needs to account for subsurface processes through the entire soil profile. The understanding of how surface and subsurface processes control mangrove sediment surface elevation, and feedback mechanisms resulting from changes in relative sea-level, is poor. There are likely several feedback mechanisms, where processes that control the mangrove sediment elevation interact with changes in sea-level. Relatively short-term observations, over periods of a few years, documented positive correlations between relative sea-level rise and mangrove sediment accretion [8], which contributes to mangroves keeping pace with regional relative sea-level rise.

The rate of inorganic sediment accretion may decrease exponentially as the sediment elevation increases due to decreased tidal inundation frequency and duration [8, 22]. It is unclear how strong the feedback mechanism is, which is likely site-specific depending on the geomorphic setting and resulting sedimentation processes. Observations over decades and longer and from numerous sites from a range of settings experiencing rise, lowering and stability in relative sea-level, may improve the understanding of this and other feedback mechanisms. If sediment accretion does increase with increased hydro period (duration, frequency and depth of inundation), because increased sedimentation can increase mangrove plant growth through direct effects on elevation as well as increased nutrient delivery, this might further increase sediment accretion through organic matter deposition as well as enhanced sediment retention with the reduced rate of flow of floodwaters that would occur with higher tree productivity and root accumulation [24].

2.4. Extreme High Water Events

The frequency of extreme high water events of a given height relative to fixed benchmarks is projected to increase over coming decades as a result of the same atmospheric and oceanic factors that are causing global sea-level to rise, and possibly also as a result of other influences on extremes such as variations in regional climate, like phases of the El Nino Southern Oscillation and North Atlantic Oscillation, through change in storminess and resulting storm surges [27]. For example, an analysis of 99th percentiles of hourly sea-level at 141 globally distributed stations for recent decades showed that there has been an increase in extreme high sea-level worldwide since 1975 [28]. In many cases, the secular changes in extremes were found to be similar to those in mean sea-level. Increased frequency and levels of extreme high water events could affect the position and health of coastal ecosystems and pose a hazard to coastal development and human safety. Increased levels and frequency of extreme high water events may affect the position and health of mangroves in some of the same ways that storms have been observed to effect mangroves, including through altered sediment elevation and sulfide soil toxicity, however, the state of knowledge of ecosystem effects from changes in extreme waters is poor.

2.5. Atmospheric CO_2 Concentration

The atmospheric concentration of CO_2 has increased 35% from a pre-industrial value, from 280 parts per million by volume (ppmv) in 1880 to 379 ppmv in 2005 [7]. In recent decades, CO_2 emissions have continued to increase: CO_2 emissions increased from an average of 6.4±0.4 GtC yr-1 in the 1990s to 7.2±0.3 GtC yr-1 in the period 2000–2005. A direct effect of elevated atmospheric CO_2 levels may be increased productivity of some mangrove species [14, 29]. Mangrove metabolic responses to increased atmospheric CO_2 levels are likely to be increased growth rates [30] and more efficient regulation of water loss [31]. For some mangrove species, the response to elevated CO_2 may be sufficient to induce substantial change of vegetation along natural salinity and aridity gradients. Ball et al. (1997) showed that doubled CO_2 had little effect on mangrove growth rates in hypersaline areas, and this may combine with reduced rainfall to create some stress [29]. The conclusion is that whatever growth enhancement may occur at salinities near the limits of tolerance of a species, it is unlikely to have a significant effect on ecological patterns [29]. However, not all species may respond similarly, and other environmental factors, including temperature, salinity, nutrient levels and the hydrologic regime, may influence how a mangrove wetland responds to increased atmospheric CO_2 levels [14]. The effect of enhanced CO_2 on mangroves is poorly understood and there is a paucity of research in this area.

2.6. Temperature

Between 1906 and 2005, the global average surface temperature has increased by 0.74°C (±0.18°C) [7]. The linear warming trend of the last fifty years (0.13°C per decade) is nearly twice that for the last 100 years. This rise in globally averaged temperatures since the mid 20th century is considered to be very likely due to the observed increase in anthropogenic greenhouse gas atmospheric concentrations [7]. The range in projections for the rise in global averaged surface temperatures from 1980 to 1999 to the end of the 21st century (2090–2099) is 1.1–6.4°C [7]. Mangroves reach a latitudinal limit at the 16°C isotherm for air temperature of the coldest month, and the margins of incidence of ground frost, where water temperatures do not exceed 24°C [15]. The optimum mangrove leaf temperature for photosynthesis is believed to be between 28 and 32°C, while photosynthesis ceases when leaf temperatures reach 38–40°C [32]. The frequency, duration and intensity of extreme cold events have been hypothesized to explain the current latitudinal limits of mangrove distribution [17]. However, the incidence of extreme cold events is not likely to be a factor limiting mangrove expansion to higher latitudes in response to increased surface temperature. The Intergovernmental Panel on Climate Change projects reduced extreme cold events [7], in correlation with projected changes in average surface temperatures. For instance, Vavrus et al. (2006) predicted a 50–100% decline in the frequency of extreme cold air events in Northern Hemisphere winter in most areas, while Meehl et al. (2004) projected decreases in frost days in the extra tropics, where the pattern of decreases will be determined by changes in atmospheric circulation [33, 34].

2.7. Ocean Circulation Patterns

Key oceanic water masses are changing, however, the Intergovernmental Panel on Climate Change reports that at present, there is no clear evidence for ocean circulation change [35]. However, there have been observations of long-term trends in changes in global and basin-scale ocean heat content and salinity, which are linked to changes in ocean circulation [35]. Changes to ocean surface circulation patterns may affect mangrove propagule dispersal and the genetic structure of mangrove populations, with concomitant effects on mangrove community structure [36]. Increasing gene flow between currently separated populations and increasing mangrove species diversity could increase mangrove resistance and resilience.

2.8. Adjacent Ecosystem Responses

Coral reefs, seagrass beds, estuaries, beaches, and coastal upland ecosystems may experience reduced area and health from climate change outcomes, including increased temperature, timing of seasonal temperature changes, and ocean acidification [37]. Mangroves are functionally linked to neighboring coastal ecosystems, including seagrass beds, coral reefs, and upland habitat, although the functional links are not fully understood [38]. Degradation of adjacent coastal ecosystems from climate change and other sources of stress may reduce mangrove health. For instance, mangroves of low islands and atolls, which receive a proportion of sediment supply from productive coral reefs, may suffer lower sedimentation rates and increased susceptibility to relative sea-level rise if coral reefs become less productive due to relative sea-level rise or other climate change outcomes.

2.9. Human Responses

Anthropogenic responses to climate change have the potential to exacerbate the adverse effects of climate change on mangrove ecosystems. For instance, we can expect an increase in the construction of seawalls and other coastal erosion control structures adjacent to mangrove landward margins as the threat to development from rising sea-levels and concomitant coastal erosion becomes increasingly apparent. Seawalls and other erosion control structures cause erosion and scouring of the mangrove immediately fronting and down current from the structure [39] Or, for example, areas experiencing reduced precipitation and rising temperature may have increased groundwater extraction to meet the demand for drinking water and irrigation. Increased groundwater extraction will increase sea-level rise rates relative to mangrove surfaces [40], increasing mangrove vulnerability. Increased rainfall could lead to increased construction of storm water drainage canals to reduce flooding of coastal upland areas, diverting surface water from mangroves and other coastal systems, reducing mangrove productivity.

3. Conclusions

To date, relative sea-level rise has likely been a smaller threat to mangroves than non-climate related anthropogenic stressors, which have likely accounted for most of the global average annual rate of mangrove loss, estimated to be 1–2%, with losses during the last quarter century ranging between 35 and 86% [41]. However, relative sea-level rise may constitute a substantial proportion of predicted future losses: Studies of mangrove vulnerability to change in relative sea-level, primarily from the western Pacific and Wider Caribbean regions, have documented that the majority of mangrove sites have not been keeping pace with current rates of relative sea-level rise [24]. Longer term studies are needed to determine if these are long-term trends or cyclical short-term patterns, and whether this is a global or regional phenomenon. Extrapolating from results in American Samoa on mangrove resilience to relative sea-level rise, a 0.2% average annual reduction in mangrove area for the Pacific Islands region is predicted over the next century based on relative sea-level trends and physiographic settings [25]. Based on this limited information, relative sea-level rise could be a substantial cause of future reductions in regional mangrove area, contributing about 10–20% of total estimated losses.

Mangrove forests occupy an inter-tidal habitat, and are extensively developed on accretionary shorelines, where sediment supply, in combination with subsurface processes that affect sediment elevation, determines their ability to keep up with sea-level rise. Rising sea-level will have the greatest impact on mangroves experiencing net lowering in sediment elevation, that are in a physiographic setting that provides limited area for landward migration due to obstacles or steep gradients. Direct climate change impacts on mangrove ecosystems are likely to be less significant than the effects of associated sea level rise. Rise in temperature and the direct effects of increased CO_2 levels are likely to increase mangrove productivity, change the timing of flowering and fruiting, and expand the ranges of mangrove species into higher latitudes. Changes in precipitation and subsequent changes in aridity may affect the distribution of mangroves. However, outcomes of global climate change besides sea-level rise are less certain, and the responses of mangrove ecosystems to changes in these parameters are not well understood. The understanding of the synergistic effects of multiple climate change and other anthropogenic and natural stressors on mangroves is also poor. For example, a mangrove that is experiencing an elevation deficit to rising sea-level may be located in an area experiencing decreased precipitation, where groundwater extraction for drinking water is predicted to increase. The combined effect of just these three stresses on the mangrove could result in an sediment surface, and at the same time decreased productivity, resulting in highly compromised resistance and resilience to stresses from climate change and other sources. Models have not been developed to predict the effects of multiple stresses such as described in this hypothetical example. There is an urgent need to test the hypotheses that have been advanced on the likely effects of global climate change on mangroves as there are many uncertainties and the effects are likely to be felt over a very long time scale.

Reduced mangrove area and health and landward mangrove migration will increase the threat to human safety and shoreline development from coastal hazards such as erosion, flooding, and storm waves and surges. Predicted mangrove losses will also reduce coastal water quality, reduce biodiversity, eliminate fish nursery habitat, adversely affect adjacent coastal habitats [38], and eliminate a major resource for human communities that traditionally rely on mangroves for numerous products and services [1, 42]. There is a need to better plan our responses to climate change impacts on mangroves, especially in its identification through regional monitoring networks, and coastal planning that facilitates mangrove migration with sea-level rise and incorporates understanding of the consequence of shoreline changes. The resistance and resilience of mangroves to sea-level rise and other climate change impacts can be improved by better "no regrets" management of other stressors on mangrove area and health, strategic planning of protected areas including mangroves and functionally linked ecosystems, rehabilitation of degraded mangroves, and outreach and education directed at communities residing adjacent to mangroves.

References

[1] Walters BB, Ronnback P, Kovacs JM, Crona B, Hussain SA, Badola R, Primavera JH, Barbier E, Dahdouh-Guebas F. Ethnobiology, socio-economics and management of mangrove forests: A review. Aquat. Bot. 2008; 89: 220-236.

[2] Dahdouh-Guebas F, Hettiarachchi S, Lo Seen D, Batelaan O, Sooriyarachchi S, Jayatissa LP, Koedam N. Transitions in ancient inland freshwater resource management in Sri Lanka affect biota and human populations in and around coastal lagoons. Curr. Biol. 2005; 15: 579-586.

[3] Nagelkerken I, Blaber SJM., Bouillon S, Green P, Haywood M, Kirton LG, Meynecke JO, Pawlik J, Penrose HM, Sasekumar A, Somerfield PJ. The habitat function of mangroves for terrestrial and marine fauna: A review. Aquat. Bot. 2008; 89: 155-185.

[4] Kristensen E, Bouillon S, Dittmar T, Marchand C. Organic carbon dynamics in mangrove ecosystems: A review. Aquat. Bot. 2008; 89: 201-219.

[5] Ramsar Secretariat. Wetland Values and Functions: Climate Change Mitigation. Gland, Switzerland. 2001.

[6] Gilman E, Ellison J, Jungblat V, VanLavieren H, Wilson L, Areki F, Brighouse G, Bungitak J, Dus E, Henry M, Sauni JI, Kilman M, Matthews E, Teariki-Ruatu N, Tukia S, Yuknavage K. Adapting to Pacific Island mangrove responses to sea level rise and other climate change effects. Climate Res. 2006; 32: 161–176.

[7] Solomon S, Qin D, Manning M, Alley RB, Berntsen T, Bindoff NL, Whetton P, Wood RA, Wratt D. Technical summary. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., Miller, H. L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 2007.

[8] Cahoon DR, Hensel P. High-resolution global assessment of mangrove responses to sea-level rise: a review. In: Gilman, E. (Ed.), Proceedings of the Symposium on Mangrove Responses to Relative Sea Level Rise and Other Climate Change Effects, 13 July 2006, Catchments to Coast, Society of Wetland Scientists 27th International Conference, 9–14 July 2006, Cairns Convention Centre, Cairns, Australia. Western Pacific Regional Fishery Management Council, Honolulu, HI, USA, ISBN: 1-934061-03-4 pp. 9–17.

[9] Piou C, Feller IC, Berger U, Chi F. Zonation patterns of Belizean offshore mangrove forests 41 years after a catastrophic hurricane. Biotropica 2006; 38: 365-372.

[10] Cahoon DR, Hensel P, Rybczyk J, McKee K, Proffitt CE, Perez B. Mass tree mortality leads to mangrove peat collapse at Bay Islands, Honduras after Hurricane Mitch. J. Ecol. 2003; 91: 1093-1105.

[11] Carpenter S, Walker B, Anderies JM, Abel N. From metaphor to measurement: resilience of what to what? Ecosystems 2001; 4: 765-781.

[12] Nystrom M, Folke C. Spatial resilience of coral reefs. Ecosystems 2001; 4: 406-417.

[13] Houghton J, Ding Y, Griggs D, Noguer M, van der Linden P, Dai X, Maskell K, Johnson C. (Eds.). Climate Change 2001: The Scientific Basis (Published for the Intergovernmental Panel on Climate Change). Cambridge University Press, Cambridge, United Kingdom, and New York, 2001.

[14] Field C. Impacts of expected climate change on mangroves. Hydrobiologia 1995; 295: 75-81.

[15] Ellison J. How South Pacific mangroves may respond to predicted climate change and sea level rise. In: Gillespie, A., Burns, W. (Eds.), Climate Change in the South Pacific: Impacts and Responses in Australia, New Zealand, and Small Islands States. Kluwer Academic Publishers, Dordrecht, Netherlands, (Chapter 15), 2000; pp. 289–301.

[16] Duke NC, Ball MC, Ellison JC. Factors influencing biodiversity and distributional gradients in mangroves. Global Ecol. Biogeogr. 1998; 7; 27-47.

[17] Snedaker S. Mangroves and climate change in the Florida and Caribbean region: scenarios and hypotheses. Hydrobiologia 1995; 295: 43-49.

[18] Rogers K, Saintilan N, Heijnis H. Mangrove encroachment of salt marsh in Western Port Bay, Victoria: the role of sedimentation, subsidence, and sea level rise. Estuaries 2005; 28: 551-559.

[19] Saintilan N, Wilton K. Changes in the distribution of mangroves and saltmarshes in Jervis Bay, Australia. Wetl. Ecol. Manage. 2001; 9: 409-420.

[20] Church J, White N. A 20th century acceleration in global sea-level rise. Geophys. Res. Lett. 2006; 33: L01602.

[21] Church J, Gregory J, Huybrechts P, Kuhn M, Lambeck K, Nhuan M, Qin D, Woodworth P. Changes in sea level. In: Houghton, J., Ding, Y., Griggs, D., Noguer, M., van der Linden, P., Dai, X., Maskell, K., Johnson, C. (Eds.), Climate Change 2001: The Scientific Basis (Published for the Intergovernmental Panel on Climate Change). Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA, (Chapter 11), pp. 639–693.

[22] Woodroffe C. Coasts: Form, Process and Evolution. Cambridge University Press, Cambridge, UK 2002.

[23] Woodroffe CD. Response of tide-dominated mangrove shorelines in northern Australia to anticipated sea-level rise. Earth Surf. Proc. Land. 1995; 20: 65-85.

[24] McKee KL, Cahoon DR, Feller I. Caribbean mangroves adjust to rising sea level through biotic controls on change in soil elevation. Global Ecol. Biogeogr. 2007; 16: 545-556.

[25] Gilman E, Ellison J, Coleman R. Assessment of mangrove response to projected relative sea-level rise and recent historical reconstruction of shoreline position. Environ. Monit. Assess. 2007; 124: 112-134.

[26] Cahoon DR, Day JW, Reed DJ. The influence of surface and shallow subsurface soil processes on wetland elevation, a synthesis. Curr. Topics Wetland Biogeochem. 1999; 3: 72-88.

[27] Church J, Hunter J, McInnes K, White N. Sea-level rise and the frequency of extreme events around the Australian coastline. In: Coast to Coast ’04-Conference Proceedings Australia’s National Coastal Conference, Hobart, 19–23 April 2004, pp. 1–8.

[28] Woodworth PL, Blackman DL. Evidence for systematic changes in extreme high waters since the mid-1970s. J. Climate 2004; 17: 1190-1197.

[29] Ball MC, Cochrane MJ, Rawason HM. Growth and water use of the mangroves Rhizophora apiculata and R. stylosa in response to salinity and humidity under ambient and elevated concentration of atmospheric CO_2. Plant Cell Environ. 1997; 20: 1158-1166.

[30] Farnsworth EJ, Ellison AM, Gong WK. Elevated CO_2 alters anatomy, physiology, growth and reproduction of red mangrove (Rhizophora mangle L.). Oecologia 1996; 108: 599-609.

[31] UNEP. Assessment and monitoring of climate change impacts on mangrove ecosystems. UNEP Regional Seas Reports and Studies No. 154. Regional Seas Programme, Nairobi, Kenya, 1994.

[32] Andrews TJ, Clough BF, Muller GJ. Photosynthetic gas exchange properties and carbon isotope ratios of some mangroves in North Queensland. In: Teas, H. J. (Ed.), Physiology and Management of Mangroves, Tasks for Vegetation Science, vol. 9. Dr. W. Junk, The Hague, 1984; pp. 15-23.

[33] Vavrus SJ, Walsh JE, Chapman WL, Portis D. The behavior of extreme cold air outbreaks under greenhouse warming. Int. J. Climatol. 2006; 26: 1133-1147.

[34] Meehl GA, Tebaldi C, Nychka D. Changes in frost days in simulations of twenty-first century climate. Clim. Dynam. 2004; 23: 495-511.

[35] Gregory JM, Dixon KW, Stouffer RJ, Weaver AJ, Driesschaert E, Eby M. A model intercomparison of changes in the Atlantic thermohaline circulation in response to increasing atmospheric CO_2 concentration. Geophys. Res. Lett. 2005; 32: L12703.

[36] Lovelock CE, Ellison JC. Vulnerability of mangroves and tidal wetlands of the Great Barrier Reef to climate change. In: Johnson, J. E., Marshall, P. A. (Eds.), Climate Change and the Great Barrier Reef: A Vulnerability Assessment. Great Barrier Reef Marine Park Authority and Australian Greenhouse Office, Australia, 2007; pp. 237–269.

[37] Kleypas JA, Feely RA, Fabry VJ, Langdon C, Sabine CL, Robbins LL. Impacts of ocean acidification on coral reefs and other marine calcifiers: a guide for future research. Workshop Report. National Science Foundation, National Oceanic and Atmospheric Administration, 2006.

[38] Mumby P, Edwards A, Arlas-Gonzalez J, Lindeman K, Blackwell P, Gall A, Gorczynska M, Harbone A, Pescod C, Renken H, Wabnitz C, Llewellyn G. Mangroves enhance the biomass of coral reef fish communities in the Caribbean. Nature 2004; 427: 533-536.

[39] Fletcher CH, Mullane RA, Richmond B. Beach loss along armored shorelines of Oahu, Hawaiian Islands. J. Coast. Res. 1997; 13: 209-215.

[40] Krauss KW, Allen JA, Cahoon DR. Differential rates of vertical accretion and elevation change among aerial root types in Micronesian mangrove forests. Estuar. Coast. Shelf Sci. 2003; 56: 251-259.

[41] Duke NC, Meynecke JO, Dittmann S, Ellison AM, Anger K, Berger U, Cannicci S, Diele K, Ewel KC, Field CD, Koedam N, Lee SY, Marchand C, Nordhaus I, Dahdouh-Guebas F. A world without mangroves? Science 2007; 317: 41-42.

[42] Ewel KC, Twilley RR, Ong JE. Different kinds of mangrove forests provide different goods and services. Global Ecol. Biogeogr. 1998; 7: 83-94.