Available online at www.sciencedirect.com
ScienceDirect
Aquatic Botany xxx (2008) xxx–xxx
Aquatic botany
www.elsevier.com/locate/aquabot

Review

Threats to mangroves from climate change and adaptation options

Eric L. Gilman [a,*], Joanna Ellison [b], Norman C. Duke [c], Colin Field [d]

[a] IUCN, Global Marine Programme, 2718 Napuaa Place, Honolulu, HI 96822, USA
[b] University of Tasmania, School of Geography and Environmental Studies, Locked Bag 1-376, Launceston, Tasmania 7250, Australia
[c] University of Queensland, Centre for Marine Studies, Brisbane, Australia
[d] University of Technology - Sydney, 11 Darnley Street, Gordon, NSW 2072, Australia

Received 28 February 2007; received in revised form 11 December 2007; accepted 20 December 2007

Abstract

Mangrove ecosystems are threatened by climate change. We review the state of knowledge of mangrove vulnerability and responses to predicted climate change and consider adaptation options. Based on available evidence, of all the climate change outcomes, relative sea-level rise may be the greatest threat to mangroves. Most mangrove sediment surface elevations are not keeping pace with sea-level rise, although longer term studies from a larger number of regions are needed. Rising sea-level will have the greatest impact on mangroves experiencing net lowering in sediment elevation, where there is limited area for landward migration. The Pacific Islands mangroves have been demonstrated to be at high risk of substantial reductions. There is less certainty over other climate change outcomes and mangrove responses. More research is needed on assessment methods and standard indicators of change in response to effects from climate change, while regional monitoring networks are needed to observe these responses to enable educated adaptation. Adaptation measures can offset anticipated mangrove losses and improve resistance and resilience to climate change. Coastal planning can adapt to facilitate mangrove migration with sea-level rise. Management of activities within the catchment that affect long-term trends in the mangrove sediment elevation, better management of other stressors on mangroves, rehabilitation of degraded mangrove areas, and increases in systems of strategically designed protected area networks that include mangroves and functionally linked ecosystems through representation, replication and refugia, are additional adaptation options.

Keywords: Adaptation; Climate change; Mangrove; Mitigation; Sea-level rise

Contents

* Corresponding author. Tel.: +1 808 722 5424.
E-mail addresses: eric.gilman@iucn.org (E.L. Gilman), joanna.Ellison@utas.edu.au (J. Ellison), n.duke@uq.edu.au (N.C. Duke), cdf1@ozemail.com.au (C. Field).

0304-3770/$ – see front matter
doi:10.1016/j.aquabot.2007.12.009

1. Introduction

Climate change components that affect mangroves include changes in sea-level, high water events, storminess, precipitation, temperature, atmospheric CO_2 concentration, ocean circulation patterns, health of functionally linked neighboring ecosystems, as well as human responses to climate change. Of all the outcomes from changes in the atmosphere's composition and alterations to land surfaces, relative sea-level rise may be the greatest threat (Field, 1995; Lovelock and Ellison, 2007). Although, to date, it has likely been a smaller threat than anthropogenic activities such as conversion for aquaculture and filling (IUCN, 1989; Primavera, 1997; Valiela et al., 2001; Alongi, 2002; Duke et al., 2007), relative sea-level rise is a substantial cause of recent and predicted future reductions in the area and health of mangroves and other tidal wetlands (IUCN, 1989; Ellison and Stoddart, 1991; Nichols et al., 1999; Ellison, 2000; Cahoon and Hensel, 2006; McLeod and Salm, 2006; Gilman et al., 2006, 2007a,b).

Mangroves perform valued regional and site-specific functions (e.g., Lewis, 1992; Ewel et al., 1998; Walters et al., this issue). 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 (Danielsen et al., 2005; Kathiresan and Rajendran, 2005; Dahdouh-Guebas et al., 2005a,b, 2006). 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 (Ewel et al., 1998; Mumby et al., 2004; Nagelkerken et al., this issue; Walters et al., this issue). Mangrove destruction can also release large quantities of stored carbon and exacerbate global warming and other climate change trends (Ramsar Secretariat, 2001; Kristensen et al., this issue). The annual economic values of mangroves, estimated by the cost of the products and services they provide, have been estimated to be USD 200,000–900,000 ha^{-1} (Wells et al., 2006). 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 (Ramsar Secretariat, 2001). The mangroves of Moreton Bay, Australia, were valued in 1988 at USD 4850 ha^{-1} based only on the catch of marketable fish (Ramsar Secretariat, 2001). Mangroves can also be provided with an economic value based on the cost to replace the products and services that they provide, or the cost to restore or enhance mangroves that have been eliminated or degraded. The range of reported costs for mangrove restoration is USD 225–216,000 ha^{-1}, not including the cost of the land (Lewis, 2005). In Thailand, restoring mangroves is costing USD 946 ha^{-1} while the cost for protecting existing mangroves is only USD 189 ha^{-1} (Ramsar Secretariat, 2001).

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 (Titus, 1991; Mullane and Suzuki, 1997; Hansen and Biringer, 2003; Gilman et al., 2006, 2007a; Berger et al., this issue). 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 and resilience to relative sea-level rise. Resistance is used here to refer to a mangrove's ability to keep pace with rising sea-level without alteration to its functions, processes and structure (Odum, 1989; Bennett et al., 2005). Resilience refers to the capacity of a mangrove to naturally migrate landward in response to rising sea-level, such that the mangrove ecosystem absorbs and reorganizes from the effects of the stress to maintain its functions, processes and structure (Carpenter et al., 2001; Nystrom and Folke, 2001). We then identify adaptation options to avoid and minimize adverse outcomes from predicted mangrove responses to projected climate change.

2. Climate change threats

2.1. 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 (Cazenave and Nerem, 2004; Church et al., 2001, 2004a; Holgate and Woodworth, 2004; Thomas et al., 2004; Church and White, 2006; Solomon et al., 2007). 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 (Solomon et al., 2007). Recent findings on global acceleration in sea-level rise indicate that upper projections are likely to occur (Church and White, 2006).

'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 (Church et al., 2001). 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 (Church et al., 2001). 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. Additional variability might be caused by differences in local tectonic processes, coastal subsidence, sediment budgets, and meteorological and oceanographic factors between the section of coastline where the coastal wetland is situated and a tide gauge, especially when the tide gauge is distant from the wetland.

2.1.1. Mangrove vulnerability to sea-level rise

Mangrove systems do not keep pace with changing sea-level when the rate of change in elevation of the mangrove sediment surface is exceeded by the rate of change in relative sea-level. There are several interconnected surface and subsurface processes that influence the elevation of mangroves' sediment surface (Table 1). 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 (Thom, 1984; Ellison and Stoddart, 1991; Woodroffe, 1987, 1995, 2002). However, recent studies have shown that subsurface controls on mangrove sediment elevation can offset high or low sedimentation rates (Cahoon et al., 2006; Cahoon and Hensel, 2006), such that sedimentation rates alone provide a poor indicator of vulnerability to rising sea-level.

The surface elevation table-marker horizon (SET-MH) method (Boumans and Day, 1993; Cahoon and Lynch, 1997; Cahoon et al., 2002; Krauss et al., 2003; Rogers et al., 2005a,b; Cahoon and Hensel, 2006; McKee et al., 2007) and stakes inserted through the organic peat layer to reach consolidated substrate (Gilman et al., 2007b) have been used to measure trends in wetland sediment elevation and determine how sea-

Table 1
Processes known to control the elevation of mangrove sediment surfaces

Process	Influence on mangrove sediment surface elevation
Sediment accretion and erosion	Sediment accretion and erosion are determined by a mangrove's geomorphic setting, which affects the sources of sediment, sediment composition, and method of delivery (Furukawa and Wolanski, 1996; Furukawa et al., 1997; Woodroffe, 1990, 2002). Fine sediment particles are carried in suspension into mangrove systems from coastal waters during tidal inundation, form large flocs (cohesive clay and fine silt), which settle in the forest during slack high tide as the friction caused by the high mangrove vegetation density slows tidal currents. Wrack or plant litter on the soil surface can also trap mineral sediment, and contribute to vertical accretion (Cahoon et al., 2006). Water currents during ebb tides are too low to re-entrain the sediment. Thus, the mangrove structure causes sediment accumulation (Furukawa and Wolanski, 1996). Storms and extreme high water events can alter the mangrove sediment elevation through soil erosion and deposition (Cahoon et al., 2003, 2006). Sedimentation varies by mangrove species and their root type (Furukawa and Wolanski, 1996; Krauss et al., 2003).
Biotic contributions	Biotic contributions to soil elevation vary from low (allochthonous mineral soils) to very high (autochthonous peat soils), where surface processes include the accumulation of decaying organic matter such as leaf litter, and the formation of living benthic microbial, algal or root mats (Woodroffe, 1992, 2002; Cahoon et al., 2006). The accumulation of leaf litter is controlled by aboveground production, consumption by detrivores, microbial decomposition and tidal flushing (Middleton and McKee, 2001; Cahoon et al., 2006).
Belowground primary production	When belowground root growth exceeds root decomposition, soil organic matter accumulates, causing a net increase in soil volume and contributes to a rise in sediment elevation. Root growth, or the lack thereof, has been shown to be a substantial control on mangrove soil elevation at some sites (Cahoon et al., 2003, 2006; Cahoon and Hensel, 2006; McKee et al., 2007). In particular, mangroves in carbonate settings, such as on low oceanic islands remote from continental sources of sediment, have autochthonous soil, composed primarily of mangrove roots, where belowground primary productivity and organic matter accumulation are primary controls on sediment elevation (Cahoon et al., 2006; McKee et al., 2007).
Autocompaction	Autocompaction, the lowering of the sediment surface and reduction in sediment volume, is caused by the oxidation (decomposition) and compression of organic material, and inorganic processes, including rearrangement of the mineral architecture, silica solution, clay dehydration and other diagenetic processes (Pizzuto and Schwendt, 1997; Cahoon et al., 1999; Allen, 2000; Woodroffe, 2002; Cahoon and Hensel, 2006). Autocompaction is understood to decrease asymptotically with the age of the mangrove (Woodroffe, 2002). Mangroves suffering mass tree mortality, caused by storms or other acute sources of stress, at sites with substrate composed primarily of peat or organic mud, are susceptible to substantial lowering in elevation of their sediment surface through peat collapse and soil compression (e.g., Cahoon et al., 2003).
Fluctuations in water table levels and pore water storage	Hydrology directly affects wetland elevation through processes of compression and dilation storage (Cahoon et al., 2006). The more water that is incorporated into the sediment below the water table, referred to as 'dilation storage' or 'shrink–swell', the more the sediment dilates, increasing sediment volume, increasing the elevation of the wetland sediment surface (Cahoon et al., 2006). The amount of dilation storage and degree of change in elevation of the sediment surface varies with soil type. Changes in groundwater inputs, such as from long-term changes in precipitation levels resulting from climate change, would result in a long-term change in mangrove elevation. Short-term cyclical influences include variability in precipitation and tidal range. Research conducted to date has demonstrated the short-term effects of groundwater recharge on mangrove elevation (Rogers et al., 2005a; Whelan et al., 2005). Research is lacking to demonstrate effects of long-term trends in changes in groundwater inputs.

level relative to the wetland sediment surface is changing. There have been observations of disparate trends in sediment elevation within an individual mangrove (Krauss et al., 2003; Rogers et al., 2005b; McKee et al., 2007). 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 (Krauss et al., 2003; Rogers et al., 2005a; Whelan et al., 2005; Cahoon et al., 2006): Subsurface processes, in some cases in the deepest soil horizon, have been found to be primary controlling factors of elevation change (Whelan et al., 2005; Cahoon and Hensel, 2006). 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 (Cahoon and Hensel, 2006), 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 (Allen, 1990, 1992; French, 1991, 1993; Saad et al., 1999; Woodroffe, 2002; Cahoon and Hensel, 2006). 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 hydroperiod (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 (Cahoon et al., 1999; McKee et al., 2007). This would be a negative feedback loop, as the increased sedimentation, and concomitant rise in elevation of the mangrove sediment surface, resulting from increased hydroperiod, would decrease the hydroperiod. Furthermore, increased hydroperiod may increase the mangrove substrate pore water storage (Cahoon et al., 1999), contributing to a rise in elevation of the sediment surface, reducing the hydroperiod.

The understanding of mangroves as opportunistic colonizers with distribution controlled through ecological responses to environmental factors (Tomlinson, 1986; Naidoo, 1985, 1990; Duke, 1992; Wakushima et al., 1994a,b; Duke et al., 1998; Cannicci et al., this issue) highlights the importance of the geomorphic setting in determining where mangrove ecosystems establish, their structure and functional processes (Woodroffe, 2002). An understanding of a mangrove's geomorphic setting, including sedimentation processes (sediment supply and type), hydrology, and energy regime, is likewise important in understanding resistance and responses to changes in sea-level, as these affect both surface and subsurface controls on elevation of the mangrove sediment surface. However, there has been no significant correlation observed between trends in mangrove sediment elevation and relative sea-level, tidal range, or soil bulk density, nor have correlations been observed between geomorphic class and trends in mangrove sediment elevation (Cahoon and Hensel, 2006). Until predictive sediment elevation models are developed for mangrove ecosystems, site-specific monitoring is necessary to assess vulnerability and responses to projected changes in sea-level.

2.1.2. Mangrove responses to changes in relative sea-level

When changing sea-level is the predominant factor controlling mangrove position, there are three general mangrove responses to sea-level trends:

- Stable site-specific relative sea-level: when sea-level is not changing relative to the mangrove surface, mangrove position is generally stable;
- Site-specific relative sea-level falling: when sea-level is falling relative to the mangrove surface, mangrove margins migrate seaward and possibly laterally if these areas adjacent to the mangrove develop conditions suitable for mangrove establishment; and
- Site-specific relative sea-level rising: if sea-level is rising relative to the elevation of the mangrove sediment surface, the mangrove's seaward and landward margins retreat landward as the mangrove species maintain their preferred hydroperiod. The mangrove may also expand laterally into areas of higher elevation. Environmental conditions for recruitment and establishment of mangroves in new areas that become available with relative sea-level rise include suitable hydrology and sediment composition, competition with non-mangrove plant species and availability of waterborne seedlings (Krauss et al., this issue). The seaward mangrove margin migrates landward from mangrove tree dieback due to stresses caused by a rising sea-level such as erosion resulting in weakened root structures and falling of trees, increased salinity, and too high a duration, frequency, and depth of inundation (Naidoo, 1983; Ellison, 1993, 2000, 2006; Lewis, 2005). Mangroves migrate landward via seedling recruitment and vegetative reproduction as new habitat becomes available landward through erosion, inundation, and concomitant change in salinity (Semeniuk, 1994). Depending on the ability of individual mangrove species to colonize newly available habitat at a rate that keeps pace with the rate of relative sea-level rise (Field, 1995; Duke et al., 1998; Lovelock and Ellison, 2007; Di Nitto et al., in press), slope of adjacent land and presence of obstacles to landward migration of the landward mangrove boundary (e.g.,

seawalls, roads), some mangroves will gradually be reduced in area, may revert to a narrow fringe, survival of individual trees or experience local extirpation.

Numerous factors other than change in relative sea-level can affect mangrove margin position, as well as structure and health. To predict mangrove responses to relative sea-level rise, it is necessary to determine if the change in sea-level is the predominant control over mangrove position and health, or if other stressors are predominant controls. Observation of a significant positive correlation between a change in relative sea-level and change in position of mangrove margins has been used to support the inference that change in site-specific relative sea-level is the predominant influence in determining the mangrove margin positions (Saintilan and Wilton, 2001; Wilton, 2002; Gilman et al., 2007a).

When sea-level rising relative to the elevation of the mangrove sediment surface is the predominant factor controlling mangrove position, mangrove responses over decades will generally follow trends shown by paleoenvironmental reconstructions of mangroves to past sea-level fluctuations (Woodroffe et al., 1985; Ellison and Stoddart, 1991; Woodroffe, 1995; Shaw and Ceman, 1999; Ellison, 1993, 2000; Berdin et al., 2003; Dahdouh-Guebas, this issue; Ellison, this issue). Mangrove resistance and resilience to relative sea-level rise over human time scales are a result of four main factors: (i) the rate of change in sea-level relative to the mangrove sediment surface determines mangrove vulnerability (Cahoon and Hensel, 2006; Cahoon et al., 2006; Gilman et al., 2007b). (ii) Mangrove species composition affects mangrove responses: because different mangrove vegetation zones have different rates of change in sediment elevation (Krauss et al., 2003; Rogers et al., 2005b; McKee et al., 2007), some zones are more resistant and resilient to rising sea-level. Also, because mangrove species have differences in time required to colonize new habitat that becomes available with relative sea-level rise, the species that colonize more quickly may outcompete slower colonizers and become more dominant (Lovelock and Ellison, 2007). (iii) The physiographic setting, including the slope of land upslope from the mangrove relative to that of the land the mangrove currently occupies, and presence of obstacles to landward migration, affects mangrove resistance (Gilman et al., 2007a). Finally, (iv) cumulative effects of all stressors influence mangrove resistance and resilience. Mangroves are not expected to respond in accordance with Bruun rule (a predictive model of beach erosion) assumptions because mangroves have different sediment budget processes than beaches, and because predictive models of coastal erosion produce inaccurate results for small-scale, site-specific estimates (Bruun, 1988; List et al., 1997; Komar, 1998; Pilkey and Cooper, 2004).

2.2. 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 (Woodworth and Blackman, 2004; Church et al., 2001, 2004b). 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 (Woodworth and Blackman, 2004). 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.

2.3. 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 (Houghton et al., 2001; Solomon et al., 2007). 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 (Church et al., 2001; Houghton et al., 2001; Solomon et al., 2007).

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 (Smith et al., 1994; Woodroffe and Grime, 1999; Baldwin et al., 2001; Sherman et al., 2001; Woodroffe, 2002; Cahoon et al., 2003, 2006; Cahoon and Hensel, 2006; Piou et al., 2006). 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 (Cahoon et al., 2003). 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 [Danielsen et al., 2005; Kathiresan and Rajendran, 2005; Dahdouh-Guebas et al., 2005a,b, 2006]).

2.4. 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 (Houghton et al., 2001).

Increased precipitation is very likely in high-latitudes, and decreased precipitation is likely in most subtropical regions, especially at the poleward margins of the subtropics (Solomon et al., 2007). 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 (Solomon et al., 2007). Long-term trends had not been observed for other regions.

Changes in precipitation patterns are expected to affect mangrove growth and spatial distribution (Field, 1995; Ellison, 2000). Based primarily on links observed between mangrove habitat condition and rainfall trends (Field, 1995; Duke et al., 1998), 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 hypersaline 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 (Field, 1995). 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 (Snedaker, 1993, 1995). Reduced precipitation can result in mangrove encroachment into salt marsh and freshwater wetlands (Saintilan and Wilton, 2001; Rogers et al., 2005a).

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 (Field, 1995; Duke et al., 1998). 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 (Duke et al., 1998). 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 (McKee, 1993; Field, 1995; Ellison, 2000). Mangroves will likely increase peat production with increased freshwater inputs and concomitant reduced salinity due to decreased sulfate exposure (Snedaker, 1993, 1995).

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.

2.5. Temperature

Between 1906 and 2005, the global average surface temperature has increased by 0.74 °C (±0.18 °C) (Solomon et al., 2007). 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 (Solomon et al., 2007). 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 (Solomon et al., 2007).

Increased surface temperature is expected to affect mangroves by (Field, 1995; Ellison, 2000):

(i) changing species composition;
(ii) changing phenological patterns (e.g., timing of flowering and fruiting);
(iii) increasing mangrove productivity where temperature does not exceed an upper threshold; and
(iv) expanding mangrove ranges to higher latitudes where range is limited by temperature, but is not limited by other factors, including a supply of propagules and suitable physiographic conditions.

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 (Ellison, 2000). 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 (Clough et al., 1982; Andrews et al., 1984).

The frequency, duration and intensity of extreme cold events have been hypothesized to explain the current latitudinal limits of mangrove distribution (Woodroffe and Grindrod, 1991; Snedaker, 1995). 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 (Solomon et al., 2007), 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 extratropics, where the pattern of decreases will be determined by changes in atmospheric circulation.

2.6. 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 (Solomon et al., 2007). In recent decades, CO_2 emissions have continued to increase: CO_2 emissions increased from an average of 6.4 ± 0.4 GtC a^{-1} in the 1990s to 7.2 ± 0.3 GtC a^{-1} in the period 2000–2005.

A direct effect of elevated atmospheric CO_2 levels may be increased productivity of some mangrove species (Field, 1995; Ball et al., 1997; Komiyama et al., this issue). Mangrove metabolic responses to increased atmospheric CO_2 levels are likely to be increased growth rates (Farnsworth et al., 1996) and more efficient regulation of water loss (UNEP, 1994). 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. The greatest effect may be under low salinity conditions. Elevated CO_2 conditions may enhance the growth of mangroves when carbon gain is limited by evaporative demand at the leaves but not when it is limited by salinity at the roots. There is no evidence that elevated CO_2 will increase the range of salinities in which mangrove species can grow. 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 (Ball et al., 1997). 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 (Field, 1995). The effect of enhanced CO_2 on mangroves is poorly understood and there is a paucity of research in this area.

Table 2
Adaptation options to augment mangrove resistance and resilience to climate change

Adaptation option	Description
"No regrets" reduction of stresses	Eliminate non-climate stresses on mangroves (e.g., filling, conversion for aquaculture, pollution) in order to augment overall ecosystem health, in part, to reduce mangrove vulnerability to and increase resilience to stresses from climate change. These "no regrets" mitigation actions are justified and beneficial even in the absence of adverse effects on mangroves from climate change (Adger et al., 2007; Julius and West, 2007).
Manage activities in catchment that affect mangrove sediment elevation	In order to attempt to augment mangrove resistance to sea-level rise relative to the mangrove sediment surface, activities within the mangrove catchment can be managed to minimize long-term reductions in mangrove sediment elevation, or enhance sediment elevation. For instance, limiting development of impervious surfaces within the mangrove catchment and managing rates and locations of groundwater extraction can reduce alteration to natural groundwater recharge to the mangrove systems, which might be an important control on mangrove elevation. Also, avoiding and limiting human activities that reduce mangrove soil organic matter accumulation, such as the diversion of sediment inputs to mangrove systems, nutrient and pollutant inputs into mangroves, and mangrove timber harvesting can contribute to maintaining relatively natural controls on trends in sediment elevation. Depending on the tree species and nutrient added, nutrient enrichment can affect mangrove productivity, changing root production and organic material inputs, changing the rate of change in sediment elevation (Feller et al., 2003; McKee et al., 2002, 2007). Enhancement of mangrove sediment accretion rates, such as through the beneficial use of dredge spoils, could augment mangrove sediment elevation (Lewis, 1990), but would need to avoid excessive or sudden sediment deposition (Ellison, 1998).
Managed retreat	Site planning for some sections of shoreline containing mangroves, such as areas that are not highly developed, may facilitate long-term retreat with relative sea-level rise (Dixon and Sherman, 1990; Mullane and Suzuki, 1997; Gilman, 2002). "Managed retreat" involves implementing land-use planning mechanisms before the effects of rising sea-level become apparent, which can be planned carefully with sufficient lead time to enable economically viable, socially acceptable and environmentally sound management measures. Coastal development could remain in use until the eroding coastline becomes a safety hazard or begins to prevent landward migration of mangroves, at which time the development can be abandoned or moved inland. Adoption of legal tools, such as rolling easements, can help make eventual abandonment more acceptable (Titus, 1991). Zoning rules for building setbacks and permissible types of new development can be used to reserve zones behind current mangroves for future mangrove habitat. Managers can determine adequate setbacks by assessing site-specific rates for landward migration of the mangrove landward margin. Construction codes can plan for mangrove landward migration based on a desired lifetime for coastal development (Mullane and Suzuki, 1997). Any new construction of minor coastal development structures, such as sidewalks and boardwalks, could be required to be expendable with a lifetime based on the assessed sites' erosion rate and selected setback. Rules could prohibit construction of coastal engineering structures, which obstruct natural inland migration of mangroves. This managed coastal retreat will allow mangroves to migrate and retain their natural functional processes.
Fortification	While mangroves provide natural coastal protection that is expensive to replace with artificial structures (Mimura and Nunn, 1998; Walters et al., this issue), for some sections of highly developed coastline adjacent to mangroves, site planning may justify use of hard engineering technology (e.g., groins, seawalls, revetments, bulkheads) and other shoreline erosion control measures (e.g., surge breakers, dune fencing, detached breakwaters) to halt erosion. As a result, mangrove ecosystem services will gradually be reduced: The structure will prevent the mangroves' natural landward migration and the mangrove fronting the structure, as well as immediately downstream in the direction of longshore sediment transport from the structure, will eventually be converted to deepwater habitat (Tait and Griggs, 1990; Fletcher et al., 1997; Mullane and Suzuki, 1997; Mimura and Nunn, 1998).

Table 2 (*Continued*)

Adaptation option	Description
Representation, replication and refugia through a system of protected area networks	Protected areas can be established and managed to implement mangrove representation, replication and refugia. Ensuring representation of all mangrove community types when establishing a network of protected areas and replication of identical communities to spread risk can increase chances for mangrove ecosystems surviving climate change and other stresses (Julius and West, 2007). Ensuring that a portfolio of each different community type is represented is a strategy for optimizing climate change resilience as this representation increases the change that at least one of these communities with disparate physical and biological parameters will survive climate change stressors and provide a source for re-colonizing. Replication, through the protection of multiple areas of each mangrove community type, by protecting multiple examples of each vegetation zone and geomorphic setting can help avoid the loss of a single community type (Roberts et al., 2003; Salm et al., 2006; Wells, 2006). Protected area selection can include mangrove areas that act as climate change refugia, communities that are likely to be more resistant to climate change stresses (Palumbi et al., 1997; Bellwood and Hughes, 2001; Salm et al., 2006). For instance, mature mangrove communities will be more resistant and resilient to stresses, including those from climate change, than recently established forests. Protecting refugia areas that resist and/or recover quickly from disturbance in general, or that are predicted to be able to keep pace with projected relative sea-level rise can serve as a source of recruits to re-colonize areas that are lost or damaged. Protected area site selection should account for predicted ecosystem responses to climate change (Barber et al., 2004). For instance, planners need to account for the likely movements of habitat boundaries and species ranges over time under different sea-level and climate change scenarios, as well as consider an areas' resistance and resilience to projected sea-level and climate changes and contributions to adaptation strategies. Site-specific analysis of resistance and resilience to climate change when selecting areas to include in new protected areas should include, for example, how discrete coastal habitats might be blocked from natural landward migration, and how severe are threats not related to climate change in affecting the site's health. A system of networks of protected areas can be designed to protect connectivity between coastal ecosystems, including mangroves (Crowder et al., 2000; Stewart et al., 2003; Roberts et al., 2001, 2003). Protecting a series of mature, healthy mangrove sites along a coastline could increase the likelihood of there being a source of waterborne seedlings to re-colonize sites that are degraded. Protected area designs should include all coastal ecosystems to maintain functional links (Mumby et al., 2004).
Mangrove rehabilitation	Mangrove enhancement (removing stresses that caused their decline) can augment resistance and resilience to climate change, while mangrove restoration (ecological restoration, restoring areas where mangrove habitat previously existed) (Kusler and Kentula, 1990; Lewis, 2005; Lewis et al., 2006; Bosire et al., this issue) can offset anticipated losses from climate change.
Regional monitoring network	Given uncertainties about future climate change and responses of mangroves and other coastal ecosystems, there is a need to monitor and study changes systematically. Establishing mangrove baselines and monitoring gradual changes through regional networks using standardized techniques will enable the separation of site-based influences from global changes to provide a better understanding of mangrove responses to sea-level and global climate change, and alternatives for mitigating adverse effects (CARICOMP, 1998; Ellison, 2000). For instance, coordinated observations of regional phenomena such as a mass mortality event of mangrove trees, or trend in reduced recruitment levels of mangrove seedlings, might be linked to observations of changes in regional climate such as reduced precipitation. The monitoring system, while designed to distinguish climate change effects on mangroves, would also therefore show local effects, providing coastal managers with information to abate these sources of degradation (a "no-regrets" adaptation approach).
Outreach and education	Outreach and education activities can augment community support for adaptation actions. The value of wetlands conservation is often underestimated, especially in less developed countries with high population growth and substantial development pressure, where short-term economic gains that result from activities that adversely affect wetlands are often preferred over the less-tangible long-term benefits that accrue from sustainably using wetlands. Education and outreach programs are an investment to bring about changes in behavior and attitudes by having a better informed community of the value of mangroves and other ecosystems. This increase in public knowledge of the importance of mangroves provides the local community with information to make informed decisions about the use of their mangrove resources, and results in grassroots support and increased political will for measures to conserve and sustainably manage mangroves.

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 (Bindoff et al., 2007). 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 (Gregory et al., 2005; Bindoff et al., 2007).

Changes to ocean surface circulation patterns may affect mangrove propagule dispersal and the genetic structure of mangrove populations, with concomitant effects on mangrove

Please cite this article in press as: Gilman, E.L., et al., Threats to mangroves from climate change and adaptation options, Aquat. Bot. (2008), doi:10.1016/j.aquabot.2007.12.009

community structure (Duke et al., 1998; Benzie, 1999; Lovelock and Ellison, 2007). 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 (Harvell et al., 2002; Kleypas et al., 2006; Mydlarz et al., 2006). Mangroves are functionally linked to neighboring coastal ecosystems, including seagrass beds, coral reefs, and upland habitat, although the functional links are not fully understood (Mumby et al., 2004). 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 (Table 2) (Tait and Griggs, 1990; Fletcher et al., 1997; Mullane and Suzuki, 1997). 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 (Krauss et al., 2003), increasing mangrove vulnerability. Increased rainfall could lead to increased construction of stormwater drainage canals to reduce flooding of coastal upland areas, diverting surface water from mangroves and other coastal systems, reducing mangrove productivity.

3. Adaptation options

To reduce the risk of adverse outcomes from predicted mangrove responses to projected climate change, adaptation activities can be taken in an attempt to increase the resistance and resilience of ecosystems to climate change stressors (Scheffer et al., 2001; Turner et al., 2003; Tompkins and Adger, 2004; Julius and West, 2007). Alternative options for adaptation for climate-sensitive ecosystems, including mangroves, are summarized in Table 2.

Mangrove ecosystems were able to persist through the quaternary despite substantial disruptions from large sea-level fluctuations, demonstrating that mangroves are highly resilient to change over historic time scales (Woodroffe, 1987, 1992). However, over coming decades, mangrove vulnerability and responses to climate change will be highly influenced by anthropogenic disturbances, including direct sources of degradation such as clearing and filling, and human responses to climate change that adversely affect mangroves. Measures can be taken to avoid and minimize these anthropogenic sources of stress (Table 2), which reduce mangrove resistance and resilience to climate change.

Management authorities are encouraged to assess coastal ecosystem vulnerability to climate change and institute appropriate adaptation measures to provide adequate lead time to avoid and minimize social disruption and cost, minimize losses of coastal ecosystem services, and maximize available options. The selection of adaptation strategies is likely to be made as part a broader coastal site-planning process, where mitigation actions are typically undertaken to address both climate and non-climate threats (Gilman, 2002; Adger et al., 2007). This analysis requires balancing multiple and often conflicting objectives of allowing managers and stakeholders to sustain the provision of ecological, economic, and cultural values; address priority threats to natural ecosystem functioning; maintain ecological processes and biodiversity; achieve sustainable development; and fulfill institutional, policy, and legal needs (Gilman, 2002).

4. 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% (Valiela et al., 2001; FAO, 2003; Duke et al., 2007). 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 (Cahoon et al., 2006; Cahoon and Hensel, 2006; Gilman et al., 2007b; McKee et al., 2007). 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 (Gilman et al., 2006). 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 accelerated rate of rise in sea-level relative to the mangrove 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 (Mumby et al., 2004), and eliminate a major resource for human communities that traditionally rely on mangroves for numerous products and services (Ewel et al., 1998; Walters et al., this issue). 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.

Acknowledgements

We are grateful for assistance in the preparation of this article provided by Professor Richard Coleman, University of Tasmania, Dr. Roy R. ‘‘Robin’’ Lewis III, Lewis Environmental Services, Inc., and Ms. Serena Fortuna, Food and Agriculture Organization of the United Nations. Comments provided by Editor of the Special Issue Professor Dahdouh-Guebas, Editor-in-Chief Professor Jan Vermaat, the managing editor, and four anonymous peer reviewers, greatly improved the article.

References

Adger, W.N., Agrawala, S., Mirza, M.M.Q., Conde, C., O'Brien, K., Pulhin, J., Pulwarty, R., Smit, B., Takahashi, K., 2007. Assessment of adaptation practices, options, constraints and capacity. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 717–743.

Allen, J.R., 2000. Morphodynamics of Holocene salt marshes: a review sketch from the Atlantic and Southern North Sea coasts of Europe. Quat. Sci. Rev. 19, 1155–1231.

Allen, J.R., 1992. Tidally induced marshes in the Severn Estuary, southwest Britain. In: Allen, J.R., Pye, K. (Eds.), Saltmarshes: Morphodynamics, Conservation and Engineering Significance. Cambridge University Press, Cambridge, pp. 123–147.

Allen, J.R., 1990. Constraints on measurement of sea level movements from salt-marsh accretion rates. J. Geol. Soc. Lond. 147, 5–7.

Alongi, D.M., 2002. Present state and future of the world's mangrove forests. Environ. Conserv. 29, 331–349.

Andrews, T.J., Clough, B.F., Muller, G.J., 1984. 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, pp. 15–23.

Baldwin, A., Egnotovich, M., Ford, M., Platt, W., 2001. Regeneration in fringe mangrove forests damaged by Hurricane Andrew. Plant Ecol. 157, 149–162.

Ball, .M.C., Cochrane, .M.J., Rawason, H.M., 1997. 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. 20, 1158–1166.

Barber, C.V., Miller, K., Boness, M. (Eds.), 2004. Securing Protected Areas in the Face of Global Change: Issues and Strategies. IUCN, Gland, Switzerland.

Bellwood, D.R., Hughes, T., 2001. Regional-scale assembly rules and biodiversity of coral reefs. Science 292, 1532–1534.

Bennett, E.M., Cumming, G.S., Peterson, G.D., 2005. A systems model approach to determining resilience surrogates for case studies. Ecosystems 8, 945–957.

Benzie, J.A.H., 1999. Genetic structure of coral reef organisms, ghosts of dispersal past. Am. Zool. 39, 131–145.

Berdin, R., Siringan, F., Maeda, Y., 2003. Holocene relative sea-level changes and mangrove response in Southwest Bohol, Philippines. J. Coast. Res. 19, 304–313.

Berger, et al. Advances and limitations of individual-based models to analyze and predict dynamics of mangrove forests: a review. Aquat. Bot., doi:10.1016/j.aquabot.2007.12.015, this issue.

Bindoff, N.L., Willebrand, J., Artale, V., Cazenave, A., Gregory, J., Gulev, S., Hanawa, K., Le Quéré, C., Levitus, S., Nojiri, Y., Shum, C., Talley, L., Unnikrishnan, A., 2007. Observations: oceanic climate change and sea level. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., Tignor, M., Miller, H. (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.

Bosire, J., Dahdouh-Guebas, F., Walton, M., Crona, B.I., Lewis III, R.R., Field, C., Kairo, J.G., Koedam, N. Functionality of restored mangroves: a review. Aquat. Bot., this issue.

Boumans, R.M.J., Day Jr., J.W., 1993. High precision measurements of sediment elevation in shallow coastal areas using a sediment-erosion table. Estuaries 16, 375–380.

Bruun, P., 1988. The Bruun Rule of Erosion by sea-level rise: a discussion of large-scale two and three-dimensional usages. J. Coast. Res. 4, 627–648.

Cahoon, D.R., Hensel, P., 2006. 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.

Cahoon, D.R., Hensel, P.F., Spencer, T., Reed, D.J., McKee, K.L., Saintilan, N., 2006. Coastal wetland vulnerability to relative sea-level rise: wetland elevation trends and process controls. In: Verhoeven, J.T.A., Beltman, B., Bobbink, R., Whigham, D. (Eds.), Wetlands and Natural Resource Management. Ecological Studies, vol. 190. Springer-Verlag, Berlin/Heidelberg, pp. 271–292.

Cahoon, D.R., Hensel, P., Rybczyk, J., McKee, K., Proffitt, C.E., Perez, B., 2003. Mass tree mortality leads to mangrove peat collapse at Bay Islands, Honduras after Hurricane Mitch. J. Ecol. 91, 1093–1105.

Cahoon, D.R., Lynch, J.C., Hensel, P., Boumans, R., Perez, B.C., Segura, B., Day Jr., J.W., 2002. A device for high precision measurement of wetland sediment elevation: I. Recent improvements to the sedimentation-erosion table. J. Sediment. Res. 72, 730–733.

Cahoon, D.R., Day, J.W., Reed, D.J., 1999. The influence of surface and shallow subsurface soil processes on wetland elevation, a synthesis. Curr. Topics Wetland Biogeochem. 3, 72–88.

Cahoon, D.R., Lynch, J.C., 1997. Vertical accretion and shallow subsidence in a mangrove forest of southwestern Florida, USA. Mangroves Salt Marshes 1, 173–186.

Cannicci, et al. Faunistic impact on vegetation structure and ecosystem function in mangrove forests. Aquat. Bot., this issue.

CARICOMP, 1998. Caribbean Coastal Marine Productivity (CARICOMP): a Cooperative Research and Monitoring Network of Marine Laboratories, Parks, and Reserves. CARICOMP Methods Manual Level 1. Manual of Methods for Mapping and Monitoring of Physical and Biological Parameters in the Coastal Zone of the Caribbean. CARICOMP Data Management Center, Centre for Marine Sciences, University of the West Indies, Mona, Kingston, Jamaica.

Carpenter, S., Walker, B., Anderies, J.M., Abel, N., 2001. From metaphor to measurement: resilience of what to what? Ecosystems 4, 765–781.

Cazenave, A., Nerem, R., 2004. Present-day sea level change: observations and causes. Rev. Geophys. 42, 1–20.

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

Church, J., White, N., Coleman, R., Lambeck, K., Mitrovica, J., 2004a. Estimates of the regional distribution of sea-level rise over the 1950 to 2000 period. J. Climate 17, 2609–2625.

Church, J., Hunter, J., McInnes, K., White, N., 2004b. 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.

Church, J., Gregory, J., Huybrechts, P., Kuhn, M., Lambeck, K., Nhuan, M., Qin, D., Woodworth, P., 2001. 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.

Clough, B.F., Andrews, T.J., Cowan, I.R., 1982. Physiological processes in mangroves. In: Clough, B.F. (Ed.), Mangrove Ecosystems in Australia: Structure, Function and Management. Australian National University Press, Canberra, pp. 193–210.

Crowder, L.B., Lyman, S., Figueira, W., Priddy, J., 2000. Source-sink population dynamics and the problem of siting marine reserves. Bull. Mar. Sci. 66, 799–820.

Dahdouh-Guebas, F., Jayatissa, L.P., Di Nitto, D., Bosire, J.O., LoSeen, D., Koedam, N., 2005a. How effective were mangroves as a defence against the recent tsunami? Curr. Biol. 15, R443–R447.

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

Dahdouh-Guebas, F., Koedam, N., Danielsen, F., Sørensen, M.K., Olwig, M.F., Selvam, V., Parish, F., Burgess, N.D., Topp-Jørgensen, E., Hiraishi, T., Karunagaran, V.M., Rasmussen, M.S., Hansen, L.B., Quarto, A., Suryadiputra, N., 2006. Coastal vegetation and the Asian tsunami. Science 311, 37–38.

Danielsen, F., Soerensen, M., Olwig, M., Selvam, V., Parish, F., Burgess, N., Hiraishi, T., Karunagaran, V., Rasmussen, M., Hansen, L., Quarto, A., Nyoman, S., 2005. The Asian tsunami: a protective role for coastal vegetation. Science 310, 643.

Dahdouh-Guebas, F. Long-term retrospection on mangrove development using transdisciplinary approaches: a review. Aquat. Bot., this issue.

Di Nitto, D., Dahdouh-Guebas, F., Kairo, J.G., Decleir H., Koedam, N. Sea level rise effects on mangrove propagule establishment: experimental study using digital terrain modeling. Mar. Ecol. Prog. Ser., in press.

Dixon, J.A., Sherman, P.B., 1990. Economics of Protected Areas. A New Look at Benefits and Costs. Island Press, Washington, DC, USA.

Duke, N.C., Meynecke, J.O., Dittmann, S., Ellison, A.M., Anger, K., Berger, U., Cannicci, S., Diele, K., Ewel, K.C., Field, C.D., Koedam, N., Lee, S.Y., Marchand, C., Nordhaus, I., Dahdouh-Guebas, F., 2007. A world without mangroves? Science 317, 41–42.

Duke, N.C., Ball, M.C., Ellison, J.C., 1998. Factors influencing biodiversity and distributional gradients in mangroves. Global Ecol. Biogeogr. 7, 27–47.

Duke, N.C., 1992. Mangrove floristics and biogeography. In: Robertson, A.I., Alongi, D.M. (Eds.), Tropical Mangrove Ecosystems. American Geophysical Union, Washington, DC, USA, pp. 63–100.

Ellison, J.C. Long-term retrospection on mangrove development using sediment cores and pollen analysis: a review. Aquat. Bot., this issue.

Ellison, J., 2006. Mangrove paleoenvironmental response to climate change. In: Gilman, E. (Ed.), Proceedings of the Symposium on Mangrove Responses to Relative Sea-Level Rise and Other Climate Change Effects, Society of Wetland Scientists 2006 Conference, 9–14 July 2006, Cairns, Australia. Western Pacific Regional Fishery Management Council and United Nations Environment Programme Regional Seas Programme, Honolulu, USA and Nairobi, Kenya, ISBN: 1-934061-03-4 pp. 1–8.

Ellison, J., 2000. 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), pp. 289–301.

Ellison, J.C., 1998. Impacts of sediment burial on mangroves. Mar. Pollut. Bull. 37, 8–12.

Ellison, J., 1993. Mangrove retreat with rising sea level, Bermuda. Estuar. Coast. Shelf Sci. 37, 75–87.

Ellison, J., Stoddart, D., 1991. Mangrove ecosystem collapse during predicted sea level rise: Holocene analogues and implications. J. Coast. Res. 7, 151–165.

Ewel, K.C., Twilley, R.R., Ong, J.E., 1998. Different kinds of mangrove forests provide different goods and services. Global Ecol. Biogeogr. 7, 83–94.

FAO, 2003. Status and Trends in Mangrove Area Extent Worldwide. Food and Agriculture Organization of the United Nations, Forest Resources Division, Paris.

Farnsworth, E.J., Ellison, A.M., Gong, W.K., 1996. Elevated CO_2 alters anatomy, physiology, growth and reproduction of red mangrove (*Rhizophora mangle* L.). Oecologia 108, 599–609.

Feller, I.C., McKee, K.L., Whigham, D.F., O'Neill, J.P., 2003. Nitrogen vs. phosphorus limitation across an ecotonal gradient in a mangrove forest. Biogeochemistry 62, 145–175.

Field, C., 1995. Impacts of expected climate change on mangroves. Hydrobiologia 295, 75–81.

Fletcher, C.H., Mullane, R.A., Richmond, B., 1997. Beach loss along armored shorelines of Oahu, Hawaiian Islands. J. Coast. Res. 13, 209–215.

French, J.R., 1993. Numerical simulation of vertical marsh growth and adjustment to accelerated sea-level rise, North Norfolk, UK. Earth Surf. Proc. Land 18, 63–81.

French, J.R., 1991. Eustatic and neotectonic controls on salt marsh sedimentation. In: Kraus, N.C., Gingerich, K.J., Kriebel, D.L. (Eds.), Coastal Sediments '91. American Society of Civil Engineers, New York, pp. 1223–1236.

Furukawa, K., Wolanski, E., Mueller, H., 1997. Currents and sediment transport in mangrove forests. Estuar. Coast. Shelf Sci. 44, 301–310.

Furukawa, K., Wolanski, E., 1996. Sedimentation in mangrove forests. Mangroves Salt Marshes 1, 3–10.

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

Gilman, E., Ellison, J., Sauni Jr., I., Tuaumu, S., 2007b. Trends in surface elevations of American Samoa mangroves. Wetl. Ecol. Manag. 15, 391–404.

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

Gilman, E.L., 2002. Guidelines for coastal and marine site-planning and examples of planning and management intervention tools. Ocean Coast. Manag. 45, 377–404.

Gregory, J.M., Dixon, K.W., Stouffer, R.J., Weaver, A.J., Driesschaert, E., Eby, M., 2005. A model intercomparison of changes in the Atlantic thermohaline circulation in response to increasing atmospheric CO_2 concentration. Geophys. Res. Lett. 32, L12703.

Hansen, L.J., Biringer, J., 2003. Building resistance and resilience to climate change. In: Hansen, L.J., Biringer, J.L., Hoffmann, J.R. (Eds.), Buying Time: A User's Manual for Building Resistance and Resilience to Climate Change in Natural Systems. WWF Climate Change Program, Berlin, Germany, pp. 9–14.

Harvell, C.D., Mitchell, C.E., Ward, J.R., Altizer, S., Dobson, A.P., Ostfeld, R.S., Samuel, M.D., 2002. Climate warming and disease risks for terrestrial and marine biota. Science 296, 2158–2162.

Holgate, S.J., Woodworth, P.L., 2004. Evidence for enhanced coastal sea level rise during the 1990s. Geophys. Res. Lett. 31, L07305.

Houghton, J., Ding, Y., Griggs, D., Noguer, M., van der Linden, P., Dai, X., Maskell, K., Johnson, C. (Eds.), 2001. 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.

IUCN, 1989. The impact of climatic change and sea level rise on ecosystems. Report for the Commonwealth Secretariat, London.

Julius, S.H., West, J.M. (Eds.), 2007. Draft. Preliminary Review of Adaptation Options for Climate-Sensitive Ecosystems and Resources. Synthesis and Assessment Product 4.4. U.S. Climate Change Science Program. U.S. Environmental Protection Agency, Washington, DC, USA.

Kathiresan, K., Rajendran, N., 2005. Coastal mangrove forests mitigated tsunami. Estuar. Coast. Shelf Sci. 65, 601–606.

Kleypas, J.A., Feely, R.A., Fabry, V.J., Langdon, C., Sabine, C.L., Robbins, L.L., 2006. 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, and the U.S. Geological Survey, Washington, DC

Komar, P., 1998. Beach Processes and Sedimentation, second ed. Prentice Hall, Upper Saddle River, NJ, USA.

Komiyama, A., Ong, J.E., Poungparn, S. Allometry, biomass and productivity of mangrove forests: a review. Aquat. Bot., doi:10.1016/j.aquabot.2007.12.006, this issue.

Krauss, K.W., et al. Environmental drivers in mangrove establishment and early development: a review. Aquat. Bot., doi:10.1016/j.aquabot.2007.12.014, this issue.

Krauss, K.W., Allen, J.A., Cahoon, D.R., 2003. Differential rates of vertical accretion and elevation change among aerial root types in Micronesian mangrove forests. Estuar. Coast. Shelf Sci. 56, 251–259.

Kristensen, et al. Organic carbon dynamics in mangrove ecosystems: a review. Aquat. Bot., doi:10.1016/j.aquabot.2007.12.005, this issue.

Kusler, J.A., Kentula, M.E. (Eds.), 1990. Wetland Creation and Restoration: The Status of the Science. Island Press, Washington, DC, USA.

Lewis III, R.R., Erftemeijer, P., Hodgson, A., 2006. A novel approach to growing mangroves on the coastal mud flats of Eritrea with the potential for relieving regional poverty and hunger: comment. Wetlands 26, 637–638.

Lewis III, R.R., 2005. Ecological engineering for successful management and restoration of mangrove forests. Ecol. Eng. 24, 403–418.

Lewis III, R.R., 1992. Scientific perspectives on on-site/off-site, in-kind/out-of-kind mitigation. In: Kusler, J.A., Lassonde, C. (Eds.), Effective Mitigation: Mitigation Banks and Joint Projects in the Context of Wetland Management Plans. Proceedings of the National Wetland Symposium, 24–27 June 1992, Palm Beach Gardens, FL, USA, pp. 101–106.

Lewis III, R.R., 1990. Creation and restoration of coastal plain wetlands in Florida. In: Kusler, J.A., Kentula, M.E. (Eds.), Wetland Creation and Restoration: The Status of the Science. Island Press, Washington, DC, USA, pp. 73–101.

List, J., Sallenger Jr., A., Hansen, M., Jaffe, B., 1997. Accelerated relative sea-level rise and rapid coastal erosion: testing a causal relationship for the Louisiana barrier islands. Mar. Geol. 140, 347–365.

Lovelock, C.E., Ellison, J.C., 2007. 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, pp. 237–269.

McKee, K., 1993. Soil physiochemical patterns and mangrove species distribution-reciprocal effects? J. Ecol. 81, 477–487.

McKee, K.L., Cahoon, D.R., Feller, I., 2007. Caribbean mangroves adjust to rising sea level through biotic controls on change in soil elevation. Global Ecol. Biogeogr. 16, 545–556.

McKee, K.L., Feller, I.C., Popp, M., Wanek, W., 2002. Mangrove isotopoic (delta 15N and delta 13C) fractionaries across a nitrogen vs. phosphorous limitation gradient. Ecology 83, 1065–1075.

McLeod, E., Salm, R., 2006. Managing Mangroves for Resilience to Climate Change. IUCN, Gland, Switzerland.

Meehl, G.A., Tebaldi, C., Nychka, D., 2004. Changes in frost days in simulations of twenty-first century climate. Clim. Dynam. 23, 495–511.

Middleton, B.A., McKee, K.L., 2001. Degradation of mangrove tissues and implications for peat formation in Belizean island forests. J. Ecol. 89, 818–828.

Mimura, N., Nunn, P., 1998. Trends of beach erosion and shoreline protection in rural Fiji. J. Coast. Res. 14, 37–46.

Mullane, R., Suzuki, D., 1997. Beach Management Plan for Maui. University of Hawaii Sea Grant Extension Service and County of Maui Planning Department, Maui, HI, USA.

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., 2004. Mangroves enhance the biomass of coral reef fish communities in the Caribbean. Nature 427, 533–536.

Mydlarz, L.D., Jones, L.E., Harvell, C.D., 2006. Innate immunity, environmental drivers, and disease ecology of marine and freshwater invertebrates. Annu. Rev. Ecol. Syst. 37, 251–288.

Nagelkerken, et al. The habitat function of mangroves for terrestrial and marine fauna: a review. Aquat. Bot., doi:10.1016/j.aquabot.2007.12.007, this issue.

Naidoo, G., 1990. Effects of nitrate, ammonium and salinity on growth of the mangrove *Bruguiera gymnorrhiza* (L.) Lam. Aquat. Bot. 38, 209–219.

Naidoo, G., 1985. Effects of waterlogging and salinity on plant–water relations and on the accumulation of solutes in three mangrove species. Aquat. Bot. 22, 133–143.

Naidoo, G., 1983. Effects of flooding on leaf water potential and stomatal resistance in *Bruguiera gymnorrhiza*. New Phytol. 93, 369–373.

Please cite this article in press as: Gilman, E.L., et al., Threats to mangroves from climate change and adaptation options, Aquat. Bot. (2008), doi:10.1016/j.aquabot.2007.12.009

Nichols, R., Hoozemans, F., Marchand, M., 1999. Increasing flood risk and wetland losses due to sea-level rise: regional and global analyses. Global Environ. Change 9, S69–S87.

Nystrom, M., Folke, C., 2001. Spatial resilience of coral reefs. Ecosystems 4, 406–417.

Odum, E.P., 1989. Ecology and Our Endangered Life-Support Systems. Sinauer Associates Inc., Sunderland, USA.

Palumbi, S.R., Grabowsky, G., Duda, T., Geyer, L., Tachino, N., 1997. Speciation and population genetic structure in tropical Pacific sea urchins. Evolution 51, 1506–1517.

Pilkey, O.H., Cooper, J.A., 2004. Society and sea level rise. Science 303, 1781–1782.

Piou, C., Feller, I.C., Berger, U., Chi, F., 2006. Zonation patterns of Belizean offshore mangrove forests 41 years after a catastrophic hurricane. Biotropica 38, 365–372.

Pizzuto, J.E., Schwendt, A.E., 1997. Mathematical modeling of autocompaction of a Holocene transgressive valley-fill deposit, Wolfe Glade, Delaware. Geology 25, 57–60.

Primavera, J., 1997. Socio-economic impacts of shrimp culture. Aquacult. Resour. 28, 815–827.

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

Roberts, C.M., Branch, G., Bustamante, R.H., Castilla, J.C., Dugan, J., Halpern, B.S., Lafferty, K.D., Leslie, H., Lubchenco, J., McArdle, D., Ruckelshaus, M., Warner, R.R., 2003. Application of ecological criteria in selecting marine reserves and developing reserve networks. Ecol. Appl. 13, S215–S228.

Roberts, C., Halpern, B., Palumbi, S., Warner, R., 2001. Designing marine reserve networks: why small, isolated protected areas are not enough. Conserv. Biol. Pract. 2, 10–17.

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

Rogers, K., Saintilan, N., Cahoon, D.R., 2005b. Surface elevation dynamics in a regenerating mangrove forest at Homebush Bay, Australia. Wetl. Ecol. Manage. 13, 587–598.

Saad, S., Husain, M.L., Asano, T., 1999. Sediment accretion of a tropical estuarine mangrove: Kemarnan, Terengganu, Malaysia. Tropics 8, 257–266.

Saintilan, N., Wilton, K., 2001. Changes in the distribution of mangroves and saltmarshes in Jervis Bay, Australia. Wetl. Ecol. Manage. 9, 409–420.

Salm, R.V., Done, T., McLeod, E., 2006. Marine protected area planning in a changing climate. In: Phinney, J.T., Hoegh-Guldberg, O., Kleypas, J., Skirving, W., Strong, A. (Eds.), Coral Reefs and Climate Change: Science and Management. American Geophysical Union, Washington, DC, pp. 207–221.

Scheffer, M., Carpenter, S., Foley, J., Folke, C., Walker, B., 2001. Catastrophic shifts in ecosystems. Nature 413, 591–596.

Semeniuk, V., 1994. Predicting the effect of sea-level rise on mangroves in northwestern Australia. J. Coast. Res. 10, 1050–1076.

Shaw, J., Ceman, J., 1999. Salt-marsh aggradation in response to late-Holocene sea-level rise at Amherst Point, Nova Scotia, Canada. n 9, 439–451.

Sherman, R.E., Fahey, T.J., Martinez, P., 2001. Hurricane impacts on a mangrove forest in the Dominican Republic, damage patterns and early recovery. Biotropica 33, 393–408.

Smith III, T.J., Robblee, M.B., Wanless, H.R., Doyle, T.W., 1994. Mangroves, hurricanes and lightning strikes. BioScience 44, 256–262.

Snedaker, S., 1995. Mangroves and climate change in the Florida and Caribbean region: scenarios and hypotheses. Hydrobiologia 295, 43–49.

Snedaker, S., 1993. Impact on mangroves. In: Maul, G.A. (Ed.), Climate Change in the Intra-American Seas: Implications of Future Climate Change on the Ecosystems and Socio-economic Structure of the Marine and Coastal Regimes of the Caribbean Sea, Gulf of Mexico, Bahamas and N. E. Coast of South America. Edward Arnold, London, pp. 282–305.

Solomon, S., Qin, D., Manning, M., Alley, R.B., Berntsen, T., Bindoff, N.L., Chen, Z., Chidthaisong, A., Gregory, J.M., Hegerl, G.C., Heimann, M., Hewitson, B., Hoskins, B.J., Joos, F., Jouzel, J., Kattsov, V., Lohmann, U., Matsuno, T., Molina, M., Nicholls, N., Overpeck, J., Raga, G., Ramaswamy, V., Ren, J., Rusticucci, M., Somerville, R., Stocker, T.F., Whetton, P., Wood, R.A., Wratt, D., 2007. 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.

Stewart, R.R., Noyce, T., Possingham, H.P., 2003. Opportunity cost of ad hoc marine reserve 5 design decisions: an example from South Australia. Mar. Ecol. Prog. Ser. 253, 25–38.

Tait, J.F., Griggs, G., 1990. Beach response to the presence of a seawall. Shore Beach 58, 11–28.

Thom, B.G., 1984. Coastal landforms and geomorphic processes. In: Snedaker, S.C., Snedaker, J.G. (Eds.), The Mangrove Ecosystem: Research Methods. UNESCO, Paris, pp. 3–15.

Thomas, R., Rignot, E., Casassa, G., Kanagaratnam, P., Acuna, C., Akins, T., Brecher, H., Frederick, E., Gogineni, P., Krabill, W., Manizade, S., Ramamoorthy, H., Rivera, A., Russell, R., Sonntag, J., Swift, R., Yungel, J., Zwally, J., 2004. Accelerated sea-level rise from West Antarctica. Science 306, 255–258.

Titus, J.G., 1991. Greenhouse effect and coastal wetland policy: how Americans could abandon an area the size of Massachusetts at minimum cost. Environ. Manage. 15, 39–58.

Tomlinson, P.B., 1986. The Botany of Mangroves. Cambridge University Press, Cambridge, UK.

Tompkins, E.L., Adger, N.W., 2004. Does adaptive management of natural resources enhance resilience to climate change? Ecol. Soc. 19, 10.

Turner, B.L., Kasperson, R., Matsone, P., McCarthy, J., Corell, R., Christensene, L., Eckley, N., Kasperson, J., Luerse, A., Martello, M., Polsky, C., Pulsipher, A., Schiller, A., 2003. A framework for vulnerability analysis in sustainability science. PNAS Early Edition 100, 8074–8079.

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

Valiela, I., Bowen, J., York, J., 2001. Mangrove forests: one of the world's threatened major tropical environments. Bioscience 51, 807–815.

Vavrus, S.J., Walsh, J.E., Chapman, W.L., Portis, D., 2006. The behavior of extreme cold air outbreaks under greenhouse warming. Int. J. Climatol. 26, 1133–1147.

Wells, S., Ravilous, C., Corcoran, E., 2006. In the Front Line: Shoreline Protection and Other Ecosystem Services from Mangroves and Coral Reefs. United Nations Environment Programme World Conservation Monitoring Centre, Cambridge, UK.

Wakushima, S., Kuraishi, S., Sakurai, N., Supappibul, K., Siripatanadilok, S., 1994a. Stable soil pH of Thai mangroves in dry and rainy seasons and its relation to zonal distribution of mangroves. J. Plant Res. 107, 47–52.

Wakushima, S., Kuraishi, S., Sakurai, N., 1994b. Soil salinity and pH in Japanese mangrove forests and growth of cultivated mangrove plants in different soil conditions. J. Plant Res. 107, 39–46.

Walters, et al. Ethnobiology, socio-economics and adaptive management of mangroves: a review. Aquat. Bot., this issue.

Wells, S., 2006. Establishing National and Regional Systems of MPAs—A Review of Progress With Lessons Learned. UNEP World Conservation Monitoring Centre, UNEP Regional Seas Programme, ICRAN, IUCN/WCPA – Marine.

Whelan, K.R.T., Smith III, T.J., Cahoon, D.R., Lynch, J.C., Anderson, G.H., 2005. Groundwater control of mangrove surface elevation: shrink–swell of mangrove soils varies with depth. Estuaries 28, 833–843.

Wilton, K., 2002. Coastal wetland habitat dynamics in selected New South Wales estuaries, vol. 1. Ph.D. Thesis. Australian Catholic University, Fitzroy, Australia.

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

Woodroffe, C.D., 1995. Response of tide-dominated mangrove shorelines in northern Australia to anticipated sea-level rise. Earth Surf. Proc. Land. 20, 65–85.

Woodroffe, C.D., 1992. Mangrove sediments and geomorphology. In: Alongi, D., Robertson, A. (Eds.), Tropical Mangrove Ecosystems. Coastal and Estuarine Studies. American Geophysical Union, Washington, DC, pp. 7–41.

Woodroffe, C.D., 1990. The impact of sea-level rise on mangrove shorelines. Prog. Phys. Geogr. 14, 483–520.

Woodroffe, C.D., 1987. Pacific island mangroves: distributions and environmental settings. Pacific Sci. 41, 166–185.

Woodroffe, C.D., Grime, D., 1999. Storm impact and evolution of a mangrove-fringed chenier plain, Shoal Bay, Darwin, Australia. Mar. Geol. 159, 303–321.

Woodroffe, C.D., Thom, B.G., Chappell, J., 1985. Development of widespread mangrove swamps in mid-Holocene times in northern Australia. Nature 317, 711–713.

Woodroffe, C.D., Grindrod, J., 1991. Mangrove biogeography: the role of quaternary environmental and sea-level change. J. Biogeogr. 18, 479–492.

Woodworth, P.L., Blackman, D.L., 2004. Evidence for systematic changes in extreme high waters since the mid-1970s. J. Climate 17, 1190–1197.

Please cite this article in press as: Gilman, E.L., et al., Threats to mangroves from climate change and adaptation options, Aquat. Bot. (2008), doi:10.1016/j.aquabot.2007.12.009