

Impacts of climate change on mangrove ecosystems: a region by region overview

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Abstract. 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. This review highlights extreme regional variation in climate change threats and impacts, and how these factors impact the structure of mangrove communities, their biodiversity and geomorphological setting. All these factors interplay to determine spatially variable resiliency to climate change impacts, and because mangroves are varied in type and geographical location, these systems are good models for understanding such interactions at different scales. Sea level rise is likely to influence mangroves in all regions although local impacts are likely to be more varied. Changes in the frequency and intensity of storminess are likely to have a greater impact on N and Central America, Asia, Australia, and East Africa than West Africa and S. America. This review also highlights the numerous geographical knowledge gaps of climate change impacts, with some regions particularly understudied (e.g., Africa and the Middle East). While there has been a recent drive to address these knowledge gaps especially in South America and Asia, further research is required to allow researchers to tease apart the processes that influence both vulnerability and resilience to climate change. A more globally representative view of mangroves would allow us to better understand the importance of mangrove type and landscape setting in determining system resiliency to future climate change.

Key words: coastal wetlands; cyclone; resiliency; sea level rise; Special Feature: Wetlands and Global Climate and Land-Use Change; storms; surface elevation change; vulnerability.

Citation: Ward, R. D., D. A. Friess, R. H. Day, and R. A. MacKenzie. 2016. Impacts of climate change on mangrove ecosystems: a region by region overview. *Ecosystem Health and Sustainability* 2(4):e01211. doi:10.1002/ehs.2.1211

Introduction

Climate change is likely to have a substantial impact on mangrove ecosystems (Ellison 2015), through processes including sea level rise (SLR), changing ocean currents, increased storminess, increased temperature, changes in precipitation and increased CO₂ (Fig. 1) (McKee et al. 2012). These factors are inter-related and spatially variable on inter-regional scales (climate, geomorphology, biodiversity, forest structure, tidal range, climate change impacts).

The aim of this review was to present the impacts of a range of climate change factors on mangroves at a regional scale, and then to synthesize these trends at a global

scale. We first describe the various climate change impacts expected to affect the mangrove ecosystem, particularly sea level rise, storminess, precipitation, and temperature. We then assess the relative vulnerability (sensitivity, exposure, and adaptive capacity, Glick and Stein 2010) of mangrove regions to these climate change impacts. A regional approach is required because while mangroves are a pan-tropical ecosystem type, they vary substantially across space in terms of their biodiversity, ecological structure, physiology, hydrodynamic and geomorphological settings, and tolerance to environmental factors such as temperature and salinity (e.g., Saenger 2002, Spalding et al. 2010). Furthermore, the impacts of climate change are likely to be geographically variable at both a regional and local scale, which suggests that the literature should be reviewed using a region by region approach.

An understanding of mangrove vulnerability and resiliency to climate change requires us to move beyond an

Manuscript received 6 October 2015; revised 15 January 2016; accepted 24 January 2015; published 21 April 2016.

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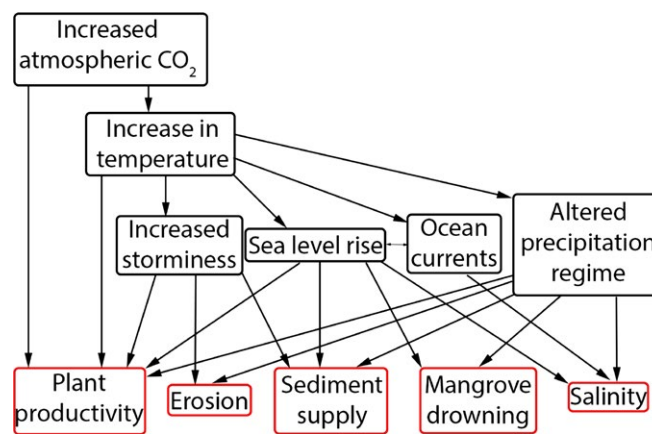


Fig. 1. Conceptual framework principal impacting factors of climate change and how they are likely to negatively influence mangrove communities.

assessment of regional variation in climate change processes to incorporate biological and ecological system variability. Using such an approach we can ask questions such as: will the increased species diversity of South East Asia's mangroves make them more resilient to sea level rise through increased autochthonous material production, and more resilient to increased storminess due to species-specific regeneration potential? Is there likely to be an increased impact from tropical storms on the coasts of South America and West Africa and if so, what long-term impact will this storminess have on mangroves? What impacts will large increases in both temperature and precipitation have on mangroves in the Middle East? The regional area, compositional, and geomorphological variability in mangroves makes them a good model ecosystem with which to study these questions over inter-regional and global scales.

Impacts of Climate Change on Mangrove Ecosystems

Sea level rise

Processes contributing to mangrove vulnerability to sea level rise

Sea level rise is a major potential climate change threat to mangrove ecosystems, because mangroves are sensitive to changes in inundation duration and frequency as well as salinity levels that exceed a species-specific physiological threshold of tolerance (Ball 1988, Friess et al. 2012). Increases in flooding duration can lead to plant death at the seaward mangrove margins (He et al. 2007) as well as shifts in species composition (Gilman et al. 2008), ultimately leading to a reduction in productivity (Castañeda-Moya et al. 2013) and ecosystem services. Coastal flooding is expected to increase in the future because global sea levels have risen by 3.2 mm/yr over recent decades (Church and White

2011) and are likely to rise by between 0.28 and 0.98 m by 2100 (IPCC 2013). Regional factors also strongly influence local sea level, and resultant SLR rates are highly variable, from 1.9 mm/yr in the Caribbean to 7.5 mm/yr in parts of Indonesia (Nerem et al. 2010), and up to 9 mm/yr in the lower Mississippi River Delta (NOAA 2015).

Tidal range is likely to significantly influence the level of impact of SLR on mangroves. Mangroves located in micro-tidal areas are generally at greater risk from SLR than those situated in macro-tidal environments due to their lower elevation capital (Lovelock et al. 2015a). A recent global meta-analysis has also shown how the geomorphic setting can affect vulnerability to sea level rise, with back basin mangroves less vulnerable than fringing mangrove types due to species and sediment deposition differences (Sasmito et al. *in press*). The same meta-analysis also showed how vulnerability to sea level rise is affected by management regime, with naturally and anthropogenically disturbed mangroves suffering peat and surface elevation collapse, and positive management interventions causing positive surface elevation gains compared to sea level rise.

Factors contributing to mangrove resilience to sea level rise

Mangroves have considerable resilience to fluctuations in sea level (Woodroffe and Grindrod 1991) due to their ability to actively modify their environment through surface elevation change processes, and their ability to migrate inland over successive generations (Krauss et al. 2014). Positive surface elevation change is influenced via the inputs of autochthonous and allochthonous organic matter as well as the trapping and retention of inorganic sediments and subsurface compaction (Krauss et al. 2014). Thus, adaptation to global SLR is likely to be driven not only by local rates of SLR, but by available sediment, autochthonous peat production, land uplift/subsidence and localized

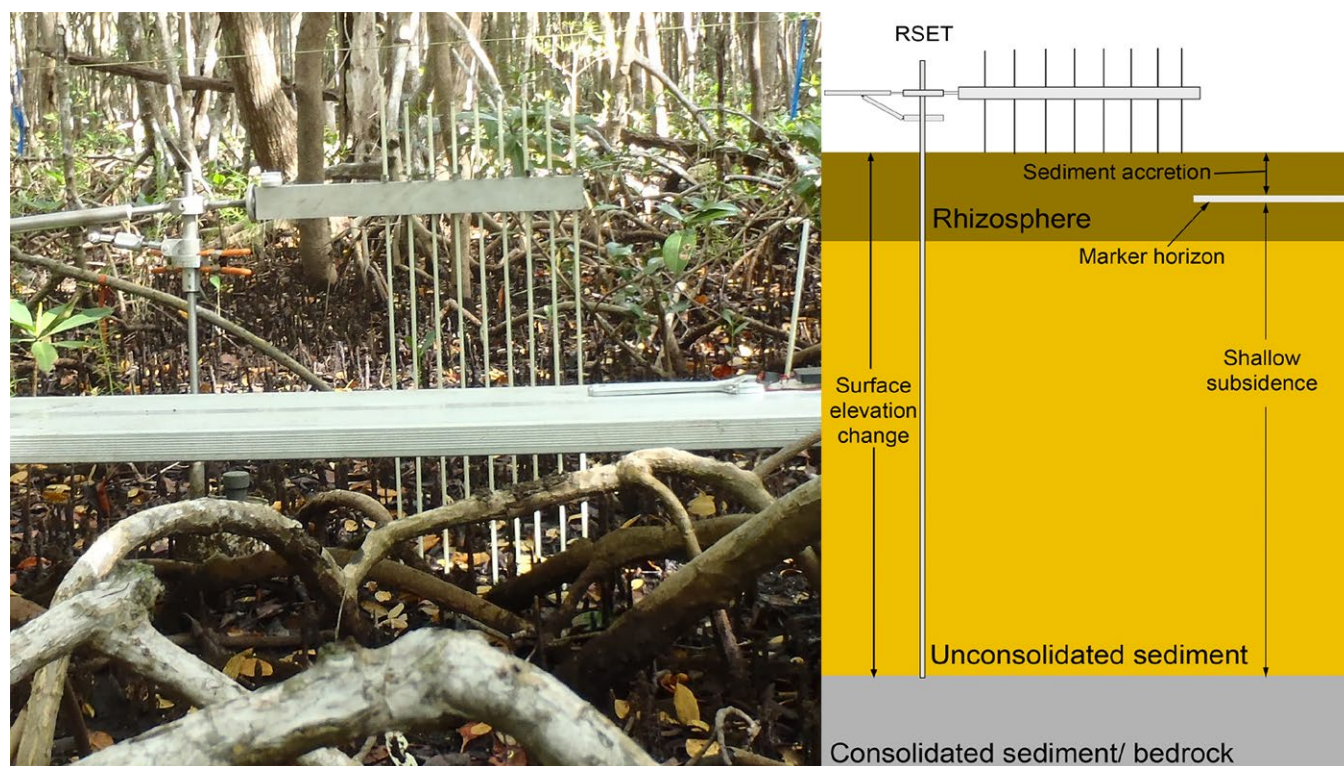


Fig. 2. Rod Surface Elevation Table (RSET) within mangroves measuring short-term (annual) sediment accretion taking into account subsidence. Figure redrawn from Webb et al. (2013), Photo courtesy of RHD.

sediment auto-compaction (Krauss et al. 2014). Mangrove forests promote sediment trapping and retention through a variety of mechanisms including: (1) slowing water velocities through aerial roots thus promoting deposition of sediments (Furukawa and Wolanski 1996); (2) microbial filamentous algal mats trapping and binding sediment; and (3) accumulation of litter and woody debris (Krauss et al. 2005). These mechanisms can lead to vertical accretion rates between 0.7 and 20.8 mm/yr, though mechanisms are highly site-specific (McKee et al. 2007, Krauss et al. 2010).

Measuring mangrove resilience to sea level rise

The measurement of sediment accretion is essential for determining changes related to sea level rise (Ward et al. 2014). Historical sediment accretion, here defined as addition of organic/inorganic material to the surface, is often estimated by using radionuclides as marker horizons (^{137}Cs) or to measure the levels of accumulation (i.e., ^{210}Pb activity) along the soil profile (Appleby and Oldfield 1992). These methods provide an important insight into historical sediment accretion relative to a specific layer in the soil. However, in order to incorporate shallow subsidence processes together with current sediment accretion (to calculate net surface elevation change), the Rod Surface Elevation Table (RSET) method (Cahoon et al. 2002) has been extensively utilized (Fig. 2). The RSET consists of a steel

rod driven to refusal (e.g., bed rock), which acts as a stable datum over which expansion or contraction of the entire soil column is measured. In many coastal areas, there has been large-scale development along mangrove margins (both urban and agricultural), limiting the ability of mangroves to migrate landward. Thus, it is important to identify how surface elevation within mangroves is changing and both of these methods provide millimeter accuracy data essential for predicting the impacts of SLR within coastal wetlands (Ward et al. 2015).

Storminess

Storms can significantly influence mangrove productivity and health and globally extreme weather events have been predicted to increase in frequency and severity (IPCC 2013). Bender et al. (2010) have suggested a potential doubling in the frequency of Atlantic hurricanes as a direct result of anthropogenic climate change increased frequency of extreme La Niña events (Cai et al. 2015). However, there is considerable spatial variability in storm formation and strength (Fig. 3).

Intense storm events can also have both destructive and constructive impacts on mangrove ecosystems. The intensity of storms in a particular coastal zone is likely to be influenced by mangrove position in relation to storm track, storm characteristics (e.g., wind velocity, storm

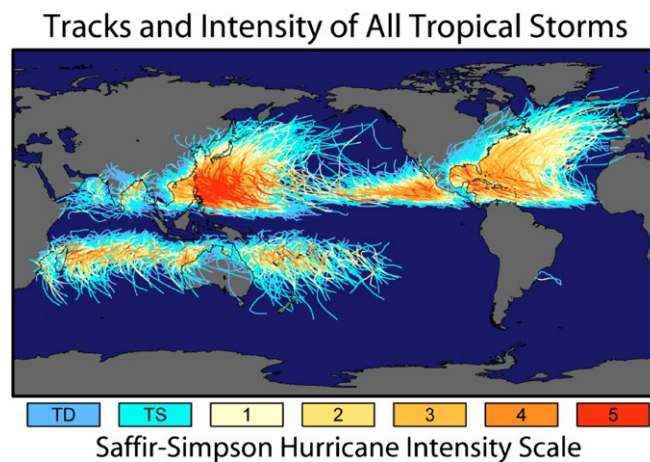


Fig. 3. Global distribution of tropical cyclone tracks between 1851 and 2006. TD refers to Tropical Depression (≤ 17 m/s), TS Tropical Storm (18–32 m/s), Category One (33–42 m/s), Category Two (43–49 m/s), Category Three (50–58 m/s), Category Four (59–69), and Category Five (≥ 70 m/s). Tropical cyclones do not form close to the equator and there is only one recorded tropical cyclone recorded along the Atlantic and Pacific coasts of South America. Source: NASA (2006).

intensity radius of maximum wind) and degree of exposure (Krauss et al. 2005, Piou et al. 2006, Zhang et al. 2008) as well as occurrence of storm in relation to high tide, particularly in meso- and macro-tidal areas (Gedan et al. 2011).

Particular mangrove species show physiological traits that increase resiliency to the damage caused by storms; these traits include large nutrient reserves, rapid nutrient turnover rates, and plant traits such as tolerance to inundation and salinity, and in some species (e.g., *Avicennia* spp.) re-sprouting from epicormic shoots (Alongi 2008, Aung et al. 2013). However, hurricanes and cyclones can substantially impact mangroves through wave activity at the seaward margins uprooting trees and wind damage breaking branches and defoliating the canopy (Smith et al. 1994, Doyle et al. 1995). In extreme cases, this can lead to complete removal, or large-scale loss of the mangrove forest and resultant peat collapse and rapid decrease in soil elevation (Cahoon et al. 2003, Paling et al. 2008). Extreme storm events can also have medium to long-term successional impacts on mangroves by providing a rapid input of allochthonous sediment, which can increase soil elevation (Smith et al. 2009, Smoak et al. 2013). Whelan et al. (2009) reported sediment deposition of up to 56 mm from Hurricane Wilma in Florida. Rapid sediment input events that can occur during intense storms are potentially important to maintain soil elevation in the face of SLR. In addition to long-term maintenance in soil elevation, intense storms can also provide nutrient pulses, particularly important for arid zone mangroves (Castañeda-Moya et al. 2010), stimulating both productivity and mangrove growth (Lovelock et al. 2011).

Precipitation

The IPCC (2013) predict that there will be extreme changes in rainfall around the world, with substantial

regional variation. Variable precipitation will be further complicated by changes in temperature, influencing both evaporation and transpiration rates. Changing rainfall patterns are likely to influence the distribution, extent, and growth rates of mangrove forests (Gilman et al. 2008) particularly in mangroves at the edge of their tolerances. For example, extreme changes in precipitation may alter seasonal average salinity in some mangrove systems, although this will be variable between fringe, estuarine, and interior mangroves. Decreases in precipitation and increases in evaporation lead to increases in soil salinity and resultant decreases in seedling survival, productivity, growth rates, and resultant mangrove loss and conversion to hypersaline mudflats (apicum) in the upper tidal zone (Field 1995, Duke et al. 1998), potentially over decadal timeframes (Eslami-Andargoli et al. 2009). Periods of increased precipitation were also linked to a subsequent increase in mangrove area as a result of the landward migration of mangroves into the salt marsh zone where salt marshes occur at the landward boundary of the mangrove (Eslami-Andargoli et al. 2009). Krauss et al. (2006) suggest that in mangroves with little variation in soil moisture (i.e., Micronesia) responses to increases in precipitation could be species-specific, with *Sonneratia alba* showing high growth rates in response to increases in precipitation, whereas no response was observed for *Bruguiera gymnorrhiza*. Increased precipitation can also result in decreased pore water salinity and sulfate concentration, which can increase mangrove productivity (Gilman et al. 2007). Precipitation increases are also likely to increase riverine discharge, which in estuarine mangroves will increase allochthonous sediment inputs, mangrove surface elevation, and resilience to SLR (Ranasinghe et al. 2013).

Table 1. Mangrove areal coverage, plant species diversity and expected climate change impacts in mangrove regions by 2100. Precipitation change: – indicates a decrease and + an increase. *Source:* IPCC (2013, 2014).

Region	Mangrove area (ha)†	Percentage of global mangrove	No. species	Rates of SLR mm/yr	Temp increase	Precipitation change	Tropical cyclone increase
Africa	2 770 609.1	20.1	14	1.1–3.8	Very likely	Very likely (+ East & South) (– West)	No signals of change
Asia	5 776 173.4	41.9	55	2.0–5.4	Very likely	Very likely (+)	Likely
Australia and New Zealand	1 009 713.4	7.3	36 (1 NZ)	2.0–3.8	Very likely	Very likely (+)	Likely
Central America and the Caribbean	1 787 705.1	13.0	11	1–2.5	Very likely	Very likely decrease in wet season	Likely
Middle East	33 770.9	0.3	2	2.2–3.3	Very likely	Likely	No signals of change
North America	252 284.7	1.8	4	3.0–5.1	Very likely	Very likely (–)	Likely
Pacific	623 755.1	4.5	35	1.4–2.0	Very likely	Very likely (+)	Likely
South America	1 522 620	11.1	11	2–3.5	Very likely	Very likely (+ West & South east) otherwise no change	Likely

Sources: †Giri et al. (2011a).

Temperature

Global temperatures are predicted to increase by up to 4.8° C by 2081–2100 relative to 1986–2005 (IPCC, 2013, RCP8.5). This temperature increase is likely to influence mangrove species composition, phenology, productivity, and ultimately the latitudinal range of their distribution. At present, many mangroves are latitudinally confined by minimum air temperature of the coldest month of 16° C (Saenger 2002) with peak leaf photosynthesis at 28–32° C (Ball and Sobrado 2002) as well as by low sea temperature, which can limit the flotation time of propagules (Duke et al. 1998) although in some regions most notably North America, short-term freezing events have a greater influence on latitudinal distribution (Cook-Patton et al. 2015). Temperature influences the ability of mangroves to assimilate CO₂ as a result of the limitations to biochemical reactions (Ball et al. 1988) and freeze plant tissue leading to vascular embolism, dehydration, or cellular rupture (Krauss et al. 2008). Mangroves expand into salt marsh communities at higher latitudes in both the northern and southern hemispheres as a result of increasing temperatures and a reduction in frost events, although plant death has been noted during harsh winters at extreme latitudes (Cavanaugh et al. 2013, Saintilan et al. 2014). Where temperatures exceed that of peak photosynthesis productivity decreases and when leaf temperatures exceed 38–40° C, photosynthesis ceases (Clough et al. 1982). Furthermore, high temperatures increase evaporation rates, which can result in salinity increases; the synergistic impacts of salinity and aridity can influence species diversity, size, and productivity

of mangrove forests (Smith and Duke 1987, Ball and Sobrado 2002).

Regional Situation

There are substantial regional variations in mangrove area, biodiversity, and potential magnitudes and impacts of climate change. The greatest areal coverage of mangroves and biodiversity occurs in Asia (41.9%) followed by Africa (20.1%), Central America and the Caribbean (13.0%), South America (11.1%), Australia and New Zealand (7.3%), Pacific Islands (4.5%), North America (1.8%), and the Middle East (0.3%) (Table 1) (Giri et al. 2011a), but there is a great regional variation in mangrove ecology.

Australia and New Zealand

Regional setting

With its extensive coastline spanning from the tropics in the Northern Territory to the southern latitudinal limits of mangroves in Victoria, Australia has the second largest mangrove distribution globally, accounting for 7.1% (977 975 ha) of the world's mangroves (Giri et al. 2011a, Fig. 4). In contrast, New Zealand has a small mangrove resource of only 31 738 ha (Giri et al. 2011a, Fig. 4), and New Zealand is at the southern latitudinal limit of global mangrove extent. Due to their wide latitudinal range, mangroves in Australia are hugely diverse in terms of species composition and structure. This region is likely to be impacted by both rises in sea level, and in some areas changes in precipitation, although a well-developed managed

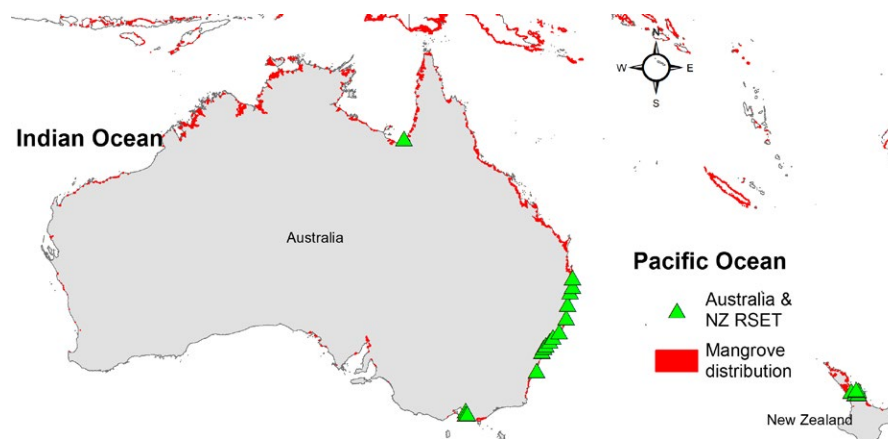


Fig. 4. Distribution of mangroves and the location of mangrove RSETs in Australia and New Zealand (NZ). Data derived from Giri et al. (2011a).

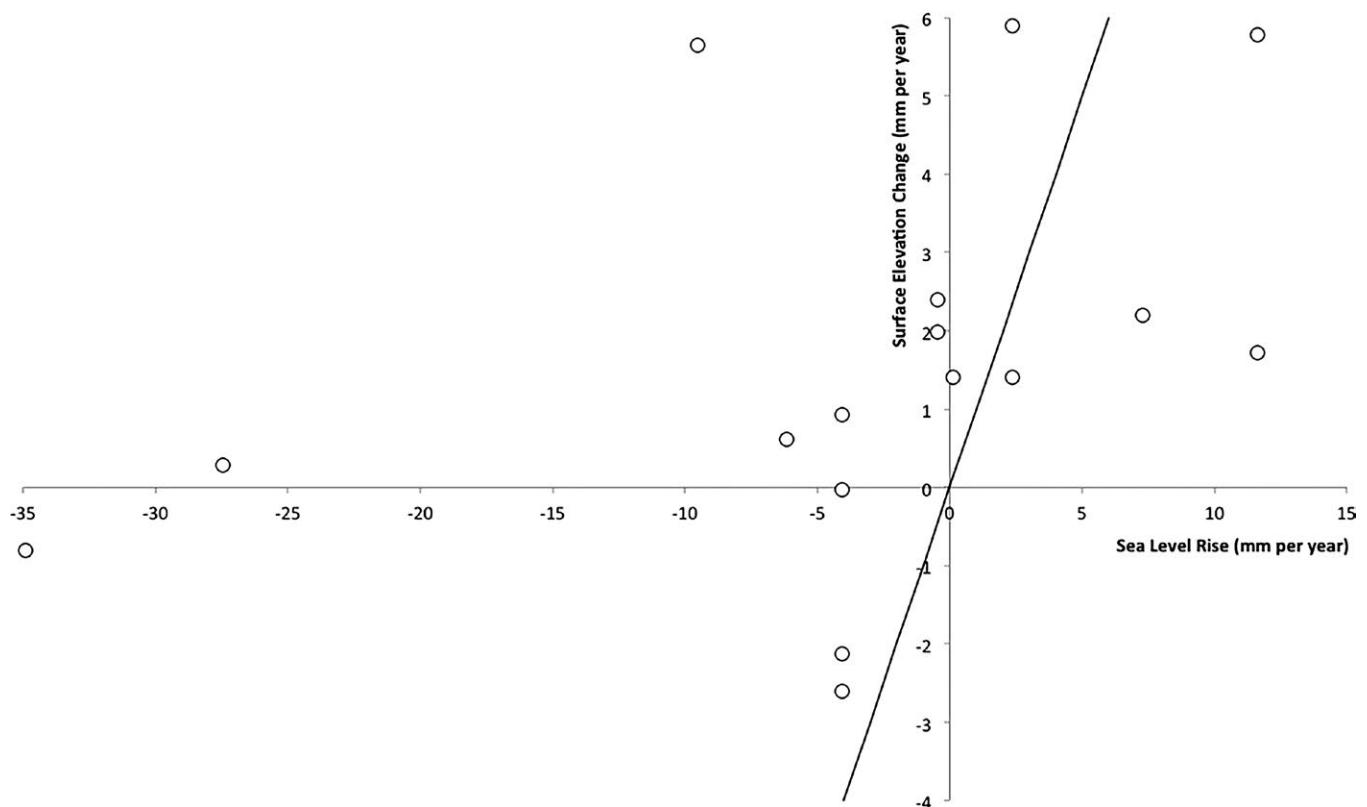


Fig. 5. A comparison of surface elevation change rates and SLR (recorded over the same time period) for various sites in East and South Australia. Black line = 1:1 line. Sites to the left of the line show a rate of elevation change greater than local SLR. Sites to the right of the line show a rate of elevation change lower than local SLR. Sources: Lovelock et al. (2011, 2015a,b), Rogers et al. (2006, 2013, 2014b).

retreat policy is likely to provide some measure of protection for mangroves.

Sea level rise

A considerable amount of research has been conducted on the vulnerability and response of mangroves to SLR in Australia, using a variety of approaches. Since

2000, several studies throughout Australia, and in the Firth of Thames, New Zealand, have used the RSET method to measure surface elevation change dynamics in response to SLR. Sites vary in their vulnerability to SLR (Fig. 5), and in many instances, surface elevation increases are greater in mangroves compared to adjoining salt marshes, due to the greater ability of mangroves to produce below-ground root material

and to trap sediments with above-ground mangrove root structures (i.e., pneumatophores and prop roots, Saintilan 2009). Mangroves in north west Australia are considered to be some of the least vulnerable in the region due to the large macrotidal setting and sediment supply (Lovelock et al. 2015a).

Observed surface elevation change rates have formed the basis for SLR vulnerability modeling using several approaches, which can project future habitat distribution, and its impact on threatened species under various SLR scenarios (Traill et al. 2011). SLR vulnerability models project that mangroves may be lost if they cannot migrate landwards (primarily due to obstruction by urban development), though mangrove loss may not be as great as concomitant intertidal ecosystems such as salt marshes.

Rogers et al. (2013) found differing sedimentary responses of mangroves, salt marshes and their ecotones, with mangroves exhibiting the highest surface elevation change, followed by salt marshes and finally the mangrove-salt marsh ecotone within south east Australia. Annual incremental plant community modeling showed no net loss of coastal wetland under moderate rates of SLR (3.65 mm/yr) with a suggestion that some salt marsh will be replaced by mangroves following historical trends for the area (Rogers et al. 2013).

Traill et al. (2011) also suggest that mangroves will replace salt marshes where their distribution overlaps in Australia as inundation increases with SLR, with some estuaries at the latitudinal transition of salt marshes and mangroves suggested to be completely dominated by mangroves by the end of the century under some SLR scenarios (Oliver et al. 2012). Coastal wetlands may transition from salt marsh to mangrove-dominated for a number of reasons: (1) mangroves are generally found at lower elevations compared to salt marshes in Australia, so can tolerate projected increased inundation; (2) mangroves exhibit greater rates of surface elevation change compared to salt marshes, so can better keep pace with SLR; and (3) other facilitative interactions between both ecosystems (Friess et al. 2012) increase the success rates of mangrove seedling establishment into salt marsh areas. Other studies, such as in Darwin Harbour in northern Australia (Crane et al. 2015), have modeled the impact of SLR on mangrove forests without including surface elevation change data. While studies that assume static mangrove elevation through time may substantially over- or underestimate overall mangrove vulnerability to SLR, they are still useful to understand how increasing inundation can influence vegetation species dominance and spatial patterning.

While surface elevation change can lead to ecosystem replacement, mangroves can also migrate laterally over time to higher elevations further landward, if anthropogenic or topographical barriers do not exist. Landward migration was modeled in the Hunter Estuary, New South Wales, with saline wetlands (mangroves and salt marshes) increasing in areal extent by 20–56% (depend-

ing on sea level rise scenario) if development barriers such as flood gates were removed (Rogers et al. 2014a). Australia is one of the few countries to have begun planning for the landward migration of mangroves. A framework for managed retreat of coastal ecosystems has been proposed for Queensland in SE Australia by Abel et al. (2011). A key component of this framework is to undertake strategic land-use planning with the strong inclusion of stakeholders living along the coast; gaining their acceptance and willingness to retreat is key, especially along heavily developed shorelines.

Precipitation

While inundation is a key driver, precipitation also plays a role in determining salt marsh-mangrove transitions in Australia. Increased precipitation in the second half of the 20th century may have facilitated mangrove invasion into salt marsh areas during that period by increasing freshwater fluvial input into the coastal zone, and reducing soil salinity in saline, high-intertidal locations (Saintilan and Williams 1999). Thus, on small scales, increases in precipitation may outweigh the impact of local SLR in promoting mangrove expansion into salt marsh areas (Saintilan and Wilton 2001). Such conclusions have been supported by experimental studies in Moreton Bay, Queensland. In a study between 1972 and 2004, a significant positive relationship was found between the proportion of days with precipitation ≥ 10 mm and annual rates of landward expansion of mangroves into salt marsh. Thus, drier years after 1990 due to repeated El Niño events have resulted in a lower rate of landward mangrove expansion compared to the wetter 1970s–1980s period (Eslami-Andargoli et al. 2009).

Temperature

The world's southernmost mangroves are found in Victoria, Australia, and mangroves have been expanding into areas previously dominated by salt marsh since at least the 1950s, due to increases in temperature, interacting with other factors such as sedimentation and SLR (Saintilan et al. 2014). However, temperature may not be the only factor determining the southern latitudinal limit of mangroves. A study on the growth and phenology of *Rhizophora stylosa* in New South Wales suggests that this species has not yet reached its thermal boundary (Wilson and Saintilan 2012), so may be additionally limited by dispersal opportunity or a suitable geomorphological setting available for colonization.

Future research foci and synergistic impacts for Australia and New Zealand

Mangroves cover a wide latitudinal range in Australia and New Zealand, so it is difficult to summarize the potential synergistic effects of climate change

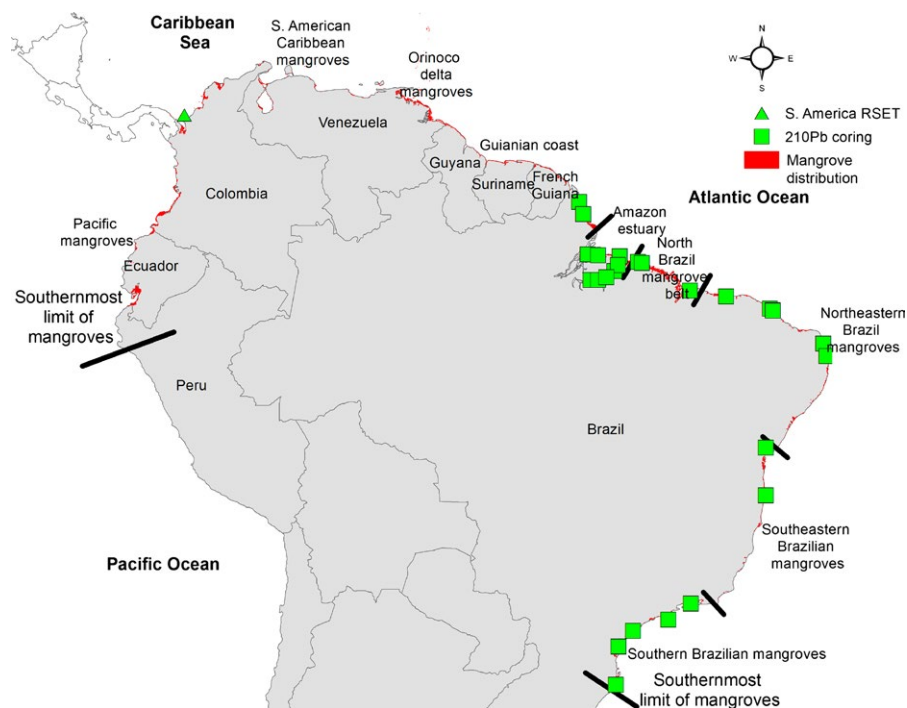


Fig. 6. Latitudinal limits, ecoregions, and location of mangroves in South America. Recent expansion (1 site in 2005, all others between 2013 and 2015) of historical (~100 yr) sediment accretion data from ^{210}Pb coring. Data derived from Giri et al. (2011a).

stressors for the entire region. This region could shed light on such synergistic effects when studied at the latitudinal boundary of mangrove extent in south Australia and north New Zealand. Many interactions could exist at this boundary, especially concerning temperature, which allows mangroves to theoretically expand southwards and sea level rise, which could create new geomorphological settings for mangroves to establish. Increasing CO_2 concentrations in the atmosphere may also interact with climate change impacts by promoting greater below-ground plant productivity, thus increasing surface elevation gains and resilience to sea level rise (*sensu* Langley et al. 2009). However, the effect of CO_2 increase and potential surface elevation gain will not be as great in minerogenic mangroves in Australia and New Zealand. CO_2 may not show positive synergistic interactions on mangrove growth with increasing temperatures, as would be expected with other plant types. Mangrove growth may be suppressed at the latitudinal boundary where they encroach salt marsh, because mangrove seedlings are outcompeted by rapidly growing salt marsh vegetation under elevated CO_2 conditions (McKee and Rooth 2008).

Compared to other parts of the world, climate change impacts on mangroves are relatively well studied in Australia and New Zealand, especially for research concerning sea level rise and temperature impacts. With an impressive baseline to build upon, future research could allow this region to be a model system to study the synergistic interactions between climate

change impacts, and the impacts of El Niño on mangrove ecosystems.

South America

Regional setting

Mangroves occur in all South American countries with maritime borders except Argentina, Uruguay, and Chile (Fig. 6), covering a variety of climatic regimes including tropical rain forest, tropical monsoon and tropical dry, semiarid, warm temperate, and maritime temperate. The climate in northern South America is strongly influenced by the inter-tropical convergence zone (ITCZ) resulting in seasonally high precipitation (Garreaud et al. 2008). On the Pacific coast, the cold Humboldt current has a cooling and drying influence on the climate of Chile, Peru, and Ecuador limiting the southern boundary of mangroves (Saintilan et al. 2014). On the Atlantic coast, in the north east of Brazil, the climate is semiarid and precipitation is influenced by the location of the ITCZ, which results in a short rainy season during the boreal spring at its southernmost extent (Da Silva 2004). Inter-annual climate variability is strongly driven by El Niño–Southern Oscillation (ENSO) leading to below normal rainfall and a decrease in extreme precipitation events in most of tropical South America during El Niño years (Grimm and Tedeschi 2009), although conversely, along the Peruvian, Ecuadorian and south eastern Brazilian coastline, precipitation is considerably greater (Grimm and Natori 2006).

South America contains one of the largest tracts of continuous mangrove forest (north Brazil mangrove belt 742 360 ha, Fig. 6). South American mangroves are typified by low mangrove diversity comprised of: *Rhizophora mangle*, *R. racemosa*, *R. harisonii*, *Avicennia germinans*, *A. tomentosa*, *A. officinalis*, *A. bicolor*, *A. schaueriana*, *Laguncularia racemosa*, *Pelliciera rhizophorae* and/or *Conocarpus erectus* (Duke 1992).

Sea level rise

Rates of SLR for South America are greatest around the Amazon estuary (~3.5 mm/yr) (UN CEPAL 2011) although due to the macro-tidal regime, limited coastal development and large fluvial sediment input is unlikely to result in substantial areal loss of mangrove. Rates for the Caribbean and Atlantic coasts of South America (with the exception of the Amazon estuary) reflect global mean SLR rates, as do those in Peru in the Pacific. Ecuador and the Pacific coast of Colombia are predicted to undergo lower local SLR (~2 mm/yr) (Mitrovica et al. 2001a, UN CEPAL 2011). Predictions of SLR do not take into account land uplift/subsidence, which varies along the South American Coast. The tropical Pacific coast, south east Brazil and the majority of the north east of Brazil are undergoing land subsidence of ~0.6 mm/yr and rates in the Amazon estuary of ~0.9 mm/yr (Peltier 1999). Conversely, the states of Maranhão, Alagoas, Sergipe, and north Bahia in Brazil (north eastern Brazil, Fig. 4) and the state of Delta Amacuro in Venezuela are undergoing land uplift ~1.8 mm/yr. The Caribbean coast of South America is predominantly static and neither undergoing uplift nor subsidence (Mitrovica et al. 2001b).

Few studies have investigated sediment accretion in South American mangroves (Sanders et al. 2008, 2010) although a recent expansion of radionuclide monitoring in Brazil (Fig. 6) suggests that in many sites sediment accretion is currently keeping pace with SLR (accretion rates between 2.2 and 10.2 mm/yr).

In sites where sediment accretion is unlikely to keep pace with SLR, a landward migration is likely to occur leading to losses at the leading edge. However, the ability of sites to migrate is dependent on development in areas surrounding mangroves. Sites in the semiarid north east of Brazil are typically located in estuaries and have often substantial legal and illegal housing developments in the areas surrounding the mangroves providing a barrier to landward mangrove migration (Da Silva Bezerra et al. 2014). A similar situation occurs in many other regions of South America (Godoy and de Lacerda 2015), however, in north Brazil, due to the macro-tidal range, low surrounding topography, strong and well implemented protection legislation, limited coastal development, and scale of the mangroves that occur there it is unlikely that SLR will have a significant impact on mangrove area (Ruben et al. 2002).

Precipitation

Maintenance of surface elevation for the subsiding, predominantly minerogenic mangroves of South America requires an external sediment source. In estuarine mangroves, allochthonous sediments are typically derived from either fluvial or marine sources (Cahoon et al. 2006), although in the north east of Brazil, a substantial amount of sediment is derived from eolian sources. The availability of fluvial sediment depends on precipitation, dams/weir presence, and fluvial sediment entrainment. Current predictions suggest that there will be an increase in seasonal differences in precipitation with an overall slight increase in annual precipitation in northern South America (Kitoh et al. 2011). These precipitation patterns are likely to lead to increased fluvial sediment in the Orinoco, Amazon, and Parnaíba estuaries as well as estuarine mangroves located on the Caribbean coast (Anthony et al. 2013). In these large estuarine systems, high freshwater inputs could potentially lead to mangrove loss and replacement by riparian flood forest vegetation such as *varzea* or *restinga* (França et al. 2012). Pacific South American deltaic mangroves are currently maintained by steep slopes in the catchment, high precipitation and high sediment loads (Restrepo and Lopez 2008). Therefore, precipitation is likely to increase in these areas, thereby maintaining current high sediment loads and surface elevation in the face of SLR (Kitoh et al. 2011). In the south east and north east of Brazil, both total wet season precipitation and annual precipitation are predicted to decrease by 2100 suggesting that at least in estuarine mangroves there could be a decrease in available suspended sediment (Grimm 2011, Jones and Carvalho 2013).

Storminess

Catastrophic erosional storms are rare along South American coasts (Fig. 3) (Pilkey 2006). In mangroves where the main sediment supply is from marine sources, storms can provide an important input to maintain surface elevation (Pereira et al. 2011). Storms may be especially likely to maintain sediment input in protected bays or estuaries where there is limited fluvial sediment input and low wave energy. Within the south east of Brazil, Sanders et al. (2008) have suggested that in sites with limited fluvial or marine derived sediment input, autochthonous production from accumulated organic matter can potentially occur at rates equivalent to eustatic SLR, thus maintaining surface elevation without an allochthonous sediment supply.

Temperature

The current southernmost limit of mangroves on the Pacific coast of South America are monospecific stands of *A. germinans* in the Virrila (5°50' S) and Piura

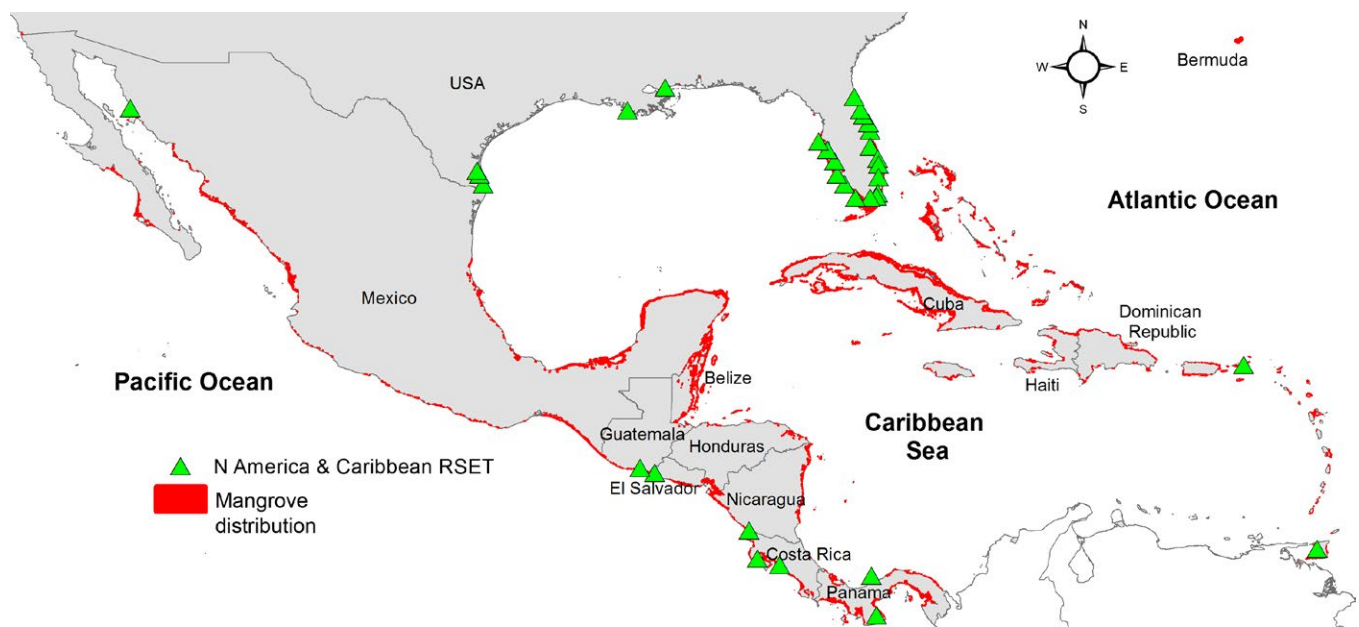


Fig. 7. Distribution of mangroves and the location of mangrove RSETs in North America and the Caribbean. Data derived from Giri et al. (2011a).

estuaries ($5^{\circ}30' S$) in Peru. There has been substantial increase in the extent of these stands between 1987 and 2014 although no reported increase in latitudinal extent, most likely due to the cold Peruvian current and a lack of suitable conditions for mangrove propagation and growth along this arid coastline (Saintilan et al. 2014). On the Atlantic coast of South America, the southernmost limit of mangroves occurs in the Lagoa de Santo Antônio in Santa Catarina, Brazil ($28^{\circ}28.5' S$) and *L. racemosa* and *A. schaueriana* dominate. The southernmost limit of mangroves in Brazil has not changed over the last 36 yr and *L. racemosa* is most likely at its southernmost extent limited by temperature (Soares et al. 2012). However, mean annual air temperatures are likely to increase by $3\text{--}5^{\circ} C$ as a result of climate change by 2100 thus increasing the latitudinal extent of mangroves in southern Brazil. Note that the southward flowing current, there provides a transport mechanism for propagules to colonize sheltered estuarine systems, which would increase the ability of mangroves to expand their distribution with climate change (Soares et al. 2012).

Future research foci and synergistic impacts for South America

Predicted increases in precipitation in much of South America combined with low storm incidence and low rates of sea level rise, in part as a result of land uplift, are likely to limit the impacts of climate change on mangroves in South America. These factors combined with increased temperatures at the latitudinal extremes of mangrove distribution, a predicted increase in the strength and frequency of El Niño, and a

resultant decrease in the cooling influence of the Humboldt Current in western South America could provide an increase in the distribution of mangroves within South America. However, in semiarid regions of South America where mangroves typically occur in estuaries, and irrigation and damming is more prevalent, predicted decreases in precipitation are likely to have a substantial impact on mangroves. In South America there is currently an increasing research focus on the impacts of SLR, sediment availability, and temperature principally in Brazil.

North America, Central America, and the Caribbean

Regional setting

Climate change may have some very significant impacts on mangroves of North and Central America and the Caribbean due to a high incidence of tropical storms, areas of high relative SLR, and steep gradients of precipitation and temperature. Mangroves are found in 34 countries and territories in this region (Fig. 7) with 60% of the coverage located in Mexico (741 917 ha) and Cuba (421 538 ha) (Giri et al. 2011a). Mangroves naturally occur on the Pacific Coast from a northern extent in Baja California, Mexico and southward contiguous with South American mangroves. On the Atlantic Coast, mangroves occur in all countries with a maritime border in Central America and the Caribbean, up the coast of Mexico to a northern extent along the subtropical Gulf of Mexico coast of the USA and the Atlantic coast of Florida, USA. Rather far removed is the island territory of Bermuda in the Atlantic where the

northernmost mangroves in the world exist (32°20' N) due to the warming influence of the Gulf Stream (Giri et al. 2011a). North and Central America and the Caribbean are typified by the same low diversity as in South America, with a single species, *A. germinans*, dominating in the northern Gulf of Mexico, three more species *R. mangle*, *L. racemosa*, and *C. erectus*, present in almost all other areas, and five other species *R. racemosa*, *R. harisonii*, *A. bicolor*, *A. schaueriana*, and *Pelliciera rhizophorae*, occurring sporadically in Central America and the Caribbean (FAO 2007). Exotic species have been introduced into North America and have naturalized in the state of California (*Avicennia marina*, Moran 1980, Scott et al. 2011) and Florida (*Bruguiera gymnorhiza* and *Luernitzera racemosa*, Fourqurean et al. 2010).

Sea level rise

High subsidence in the Mississippi River Delta region results in one of the highest rates of relative SLR in the world at greater than 9 mm/yr along the coast of Louisiana (NOAA 2015), about three times higher than the current global average. All coastal wetlands in the Louisiana deltaic areas are vulnerable to loss and/or relocation landward due to SLR, especially given the micro-tidal environment with a mean tide range <0.5 m (Day et al. 2007). Elsewhere in the region, rates of ~1–3 mm/yr (NOAA 2015) are closer to the eustatic SLR rate. Mangroves in the Caribbean region appear to be keeping pace with or expanding under current SLR conditions predominantly driven by both subsurface and surface peat accumulation, although this is locally variable (McKee et al. 2007). The threat of accelerated SLR in the future may hinder this ability of mangroves to maintain elevation with respect to sea level. SLR is expected to result in landward mangrove forest migration and tidal freshwater forested wetland displacement within these regions (Doyle et al. 2010, Krauss et al. 2011). Extensive areas of nonmangrove coastal wetlands, as well as a low upland topographic profile, provide ample opportunity for mangrove migration, however, high coastal human populations present barriers due to existing and expanding urban centers.

Precipitation

Central America is one of the regions where climate change models consistently predict increases in temperature and decreases in precipitation during the wet season (Giorgi 2006, Neelin et al. 2006, Rauscher et al. 2008, Maurer et al. 2009). Furthermore, increases in the frequency of extreme El Niño events as a result of climate change (Cai et al. 2015) are likely to lead to increases in severe droughts in the south Pacific and northern Caribbean and Pacific coasts (Maurer et al. 2009). Decreased rainfall will potentially limit sediment supply in estuarine mangroves and autochthonous litter production through increased water stress

and thus the ability of mangroves in this region to keep up with SLR (Cahoon 2014). Conversely, during El Niño years along the southern Caribbean coast of Central America an increase in rainfall occurs and it has been predicted that this will increase in both intensity and frequency (Cai et al. 2015), potentially increasing catchment runoff and consequently sediment supply in estuarine mangroves in this area (Mitsch et al. 2010).

There is a steep gradient of mean annual precipitation along the coast of the Gulf of Mexico from >1500 mm/yr in Louisiana, Mississippi, and Alabama, USA to <700 mm/yr in south Texas and Tamaulipas, Mexico (Maurer et al. 2002). Along this gradient, Osland et al. (2014) identified regional ecological thresholds and nonlinear relationships between measures of freshwater availability and the relative abundance of pioneer plant species in tidal wetlands. The threshold differentiating between vegetated and unvegetated wetlands was identified as 765 mm/yr for mean annual precipitation. Species thresholds for moisture availability have implications for the ability of succulent, graminoid, or woody (e.g., mangrove) wetland species to thrive in place of unvegetated flats (salt pans, salinas). The border area between the USA and Mexico in the Gulf of Mexico is projected to be the most sensitive to change with increasing future rainfall patterns. Conversely, a lack of rain may occasionally facilitate mangrove expansion in coastal Louisiana, where widespread marsh dieback was attributed to a drought which did not affect adjacent mangroves (McKee et al. 2004).

Storminess

Hurricanes are common in the Atlantic and Pacific along all the mangrove-lined coasts of North America, Central America, and the Caribbean (Fig. 3), with several events causing substantial damage to mangroves, for example, Hurricanes Andrew (1992) and Wilma (2005) in Florida (Doyle et al. 1995, Swiadek 1997, Baldwin et al. 2001, Smith et al. 2009), Hurricane Mitch (1998) on the Caribbean coast of Honduras (Cahoon et al. 2003), Hurricanes Pauline and Rick (1997) and Carlotta (2012) on the Pacific Coast of Mexico (Taylor et al. 2013). The characteristics of damage and recovery are species-specific, depend on the magnitude of winds, storm surge height, sediment deposition and/or erosion. *Avicennia germinans* is able to resprout following storm damage (Doyle et al. 1995). Low tidal ranges in this area make the mangrove coasts particularly vulnerable to storms, especially in the event of an increase in the frequency and intensity of hurricanes.

Temperature

Winter temperature minima are a major factor determining the distribution of mangroves in North America. In coastal areas of the southeastern United States,

climate exerts a strong selective pressure for freeze tolerance by interspersing long periods of mild winters with episodic severe killing freezes. Within the Gulf of Mexico, *A. germinans* has a differential tolerance to frost damage (McMillan and Sherrod 1986) and individuals from northern populations in Louisiana exhibit greater frost tolerance than southern populations in Florida. *A. germinans* can survive temperatures as low as -6.5°C in lab experiments (Pickens and Hester 2011). Giri et al. (2011b) used Landsat imagery to show the contraction and expansion of *A. germinans* in Louisiana between 1984 and 2010, which was strongly correlated with the occurrence of winter freeze events. Recently, the northernmost record of *R. mangle* was documented as a new occurrence on the Atlantic coast of Florida (Zomlefer et al. 2006). Modeling winter temperatures for the southeastern United States, Osland et al. (2013) identified 30-yr minimum temperature thresholds for mangrove forest presence and dominance as -8.9°C and -7.0°C , respectively. Furthermore, salt marshes in Louisiana, Texas, and parts of Florida are most vulnerable to being replaced by mangroves with as little as a 2.0°C to 4.0°C increase in mean annual minimum temperature (Osland et al. 2013).

Future research foci and synergistic impacts for North and Central America and the Caribbean

Various aspects of the four climate change components, sea level rise, storminess, precipitation, and temperature, combine to create synergistic effects of increased vulnerability within North and Central America and the Caribbean. Accelerated SLR resulting in higher water levels within mangroves would increase the deleterious effects of waves and storm surges due to tropical storms, which have a high and possibly increasing incidence throughout the area. Drought along the coast of Texas, United States, could make mangroves more vulnerable to SLR and storms. In the Northern Gulf of Mexico, SLR-induced landward migration and warm winter temperatures would both result in mangrove migration to the north, increasing exposure to the sporadic killing freezes common in the area. In a hypothetical “perfect storm” scenario, after years of warm winters resulting in poleward expansion, mangroves negatively affected by a late winter freeze might be totally devastated by an early season hurricane, particularly in Louisiana and Florida, United States. The scientific community in this region, especially the United States and Mexico, has been conducting research on the impacts of SLR for decades, but has only recently considered the macroclimatic drivers of precipitation and temperature as factors within coastal wetland vulnerability assessments to climate change (Osland et al. 2016). Emphasis needs to be placed on investigating the thresholds for regime shifts from marsh to mangrove or salt flat along the

gradients that exist along the Pacific coast of Mexico and the northern Gulf of Mexico.

Africa

Regional setting

Africa accounted for over 20% of the world’s mangrove extent in 2001 (Giri et al. 2011a) with the southernmost mangroves occurring in Angola and South Africa and the northernmost occurring in Mauritania and Egypt on the west and east coasts, respectively (Fig. 8). The geomorphological setting of Africa’s mangroves varies markedly, though is predominantly controlled by strong hydrodynamics, due to the large fetch of the Atlantic and Indian Oceans (Fig. 8). Thus, mangroves are fragmented along the coast, found in a variety of sheltered hydrodynamic settings, on deltas, estuaries, back-barrier locations, and atolls (Fig. 9).

Sea level rise

The extent of mangroves in West Africa has changed dramatically throughout geological history in response to SLR changes between glacial and interglacial periods (Dupont et al. 2000). However, the varied geomorphological settings within which Africa’s mangroves are situated make it difficult to make broad statements of present-day SLR vulnerability, which is compounded by a lack of empirical data on the present vulnerability of Africa’s mangroves to SLR (Webb et al. 2013, Yang et al. 2014). Sparse data suggest that a number of mangroves in Africa are minerogenic (Balke and Friess 2016), though fluvial sediment supply is substantially lower in Africa compared to Asia, the Americas and Oceania (Milliman and Meade 1983), and a number of rivers are seasonal. A link between low accretion rates, SLR and mangrove loss has been made for mangroves in Cameroon, where a long-term sediment deficit (determined by radiocarbon dating of soil cores) coincided with a period of mangrove retreat in the Cameroon Estuary, Cameroon (Ellison and Zouh 2012).

Only isolated sites in East Africa have measured present-day surface elevation change directly. These sites have been experiments to study particular processes that affect surface elevation change, such as the impact of tree harvesting and girdling on surface elevation (Lang’at et al. 2014). While the focus of these studies has not been on the SLR vulnerability of mangroves directly, the results can still be used for such purposes. Natural stands in Gazi Bay, Kenya have increased in surface elevation by an average of 4.2 mm/yr in the top 80 cm of the soil column, noting that lower layers of the soil column were not examined (Lang’at et al. 2014), which is higher than the contemporary SLR of 1.1 mm/yr along the coast of Kenya (Kebede et al. 2010).

A paucity of regionally-specific information on surface elevation change hampers assessments of sea level rise



Fig. 8. Distribution of mangroves and the location of mangrove RSETs in Africa. Data derived from Giri et al. (2011a).

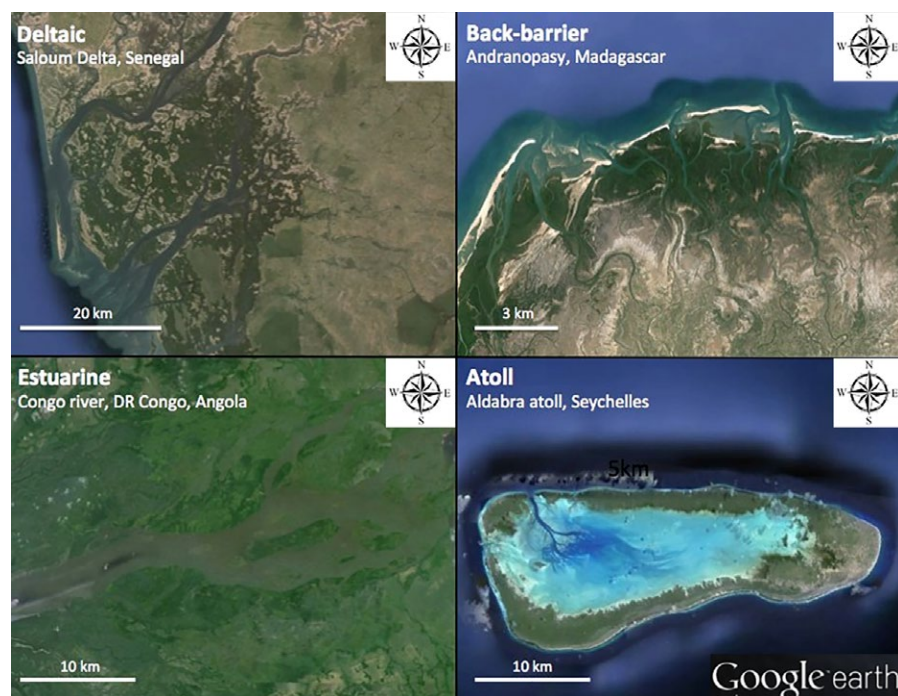


Fig. 9. The various geomorphological settings in which mangroves in Africa can be found. Source: Google Earth (2015); each panel downloaded September 2015.

vulnerability, which must be based on accurate, location-specific rates of surface elevation change. The future distribution of mangroves forced by SLR has been analyzed for particular small estuaries in South Africa such as the Mngazana, which was projected to lose almost 50% of

its mangrove by the end of the century under a relative rate of SLR of 3.7 mm/yr (Yang et al. 2014). However, due to a lack of data on surface elevation change in Africa, estimates of surface elevation change for this minerogenic estuarine site were based on data from biogenic

atoll mangroves in the Caribbean, so may not reflect true surface elevation response of mangroves at this location. Losses in estuaries such as the Mngazana may be partially offset by landward migration to higher elevations upstream, as keeping in mind that many coastlines in Africa may not be actively blocked by development. However, migration is not a long-term solution for survival and research does not currently exist to verify this.

Temperature

Mangrove distribution on the west coast of Africa is limited to the tropics, potentially due to the aridity of the Sahara Desert in the north and the Namib Desert in the south (Fig. 8). Mangrove range through geological history has expanded and contracted as these deserts shifted over long time scales (Dupont et al. 2000). Because of the constraints imposed by these two deserts, recent latitudinal expansion in the sub-tropics due to temperature rise is thus only observed on Africa's east coast. Range expansion benefits were shown in an extensive survey of mangrove area in a study conducted in South Africa in the 1950s–1960s, which showed that mangroves were limited in the position of a 19° C air temperature isotherm (Macnae 1963). However, with increasing temperatures, mangroves have been observed to be expanding southwards from this baseline, overcoming challenges of dispersal (Saintilan et al. 2014). The growth and expansion of mangroves planted outside of their current range also suggests that new areas are suitable for mangrove establishment (Hoppe-Speer et al. 2015). Species distribution models have been used to predict species-specific expansion potential under future warming (Quisthoudt et al. 2013), with *A. marina* and *Bruguiera gymnorrhiza* predicted to expand beyond their current latitudinal limits by the end of this century, assuming suitable colonizable intertidal space is available in those regions.

Future research foci and synergistic impacts for Africa

African mangroves have been the focus of few studies related to climate change, so future research is required to create baselines similar to better studied regions such as Australia/New Zealand and the Americas. Without such baseline data on mangrove response to individual climate change stressors, we are not currently in a position to understand their response under interacting stressors.

Asia

Regional setting

Asia (including South, South east, and East Asia) accounts for 41.9% of the world's mangroves; Indonesia alone accounted for 22.6% of global mangrove extent in 2001 (Giri et al. 2011a). Mangrove vegetation species diversity differs markedly across Asia, with South east

Asia the epicenter of mangrove diversity (51 species), whereas only 11 species are found in Japan, at the northern latitudinal limit of mangroves in Asia (considerably higher than in the Pacific, Americas, Africa, and the Middle East (Spalding et al. 2010). Asia's mangroves are experiencing rapid, large-scale clearance for agricultural and aquacultural activities and face substantial policy challenges to their conservation and management (Richards and Friess 2016), issues which are likely to be exacerbated by climate change impacts in the future.

Sea level rise

Current and predicted SLR is variable across the large Asian region, as is mean tidal range. Alongi (2008) identified the east coast of India, the Andaman Islands, east Sumatra, Sulawesi, the Philippines, Vietnam, and southern China as particular hotspots vulnerable to future SLR due to a low tidal range and lower sediment input. While quantitative studies at the regional scale are lacking, some locations in Asia have been studied for local SLR vulnerability. The Sundarbans (India/Bangladesh), has lost 17 000 ha of mangrove since the 1970s, largely attributed to the effects of SLR (Rahman et al. 2011). Such loss has important implications for biodiversity, with future SLR potentially resulting in the loss of 96% of Bengal tiger habitat on the Bangladeshi side of the Sundarban mangroves (Loucks et al. 2010).

Asia's mangroves may respond differently to SLR compared to other regions, due to their high plant species diversity. Multispecies forests have been suggested to be more resilient to SLR due to interspecific facilitation (Huxham et al. 2010) and increased below-ground root production (Lang'at et al. 2014), allowing mangroves to increase their surface elevations through biogenic processes.

However, the influence of biogenic processes on surface elevation change may be outweighed by significantly changing coastal sediment conditions. Mangrove sites in Asia are predominantly minerogenic (Balke and Friess 2016), so continued sediment supply is essential for the long-term resilience of Asia's mangroves to SLR. 4740 million tons of sediment (38% of the global total) enter the Asian coastal zone every year, though 31% of this is retained by dams (Syvitski et al. 2005). Some rivers have had a significant reduction in fluvial sediment loads entering the coastal zone due to river modification and damming. The Red (Vietnam), Chao Phraya and Gulf of Thailand (Thailand), and Indus (Pakistan) rivers have experienced a 76%, 83%, and 93% reduction in annual coastal sediment yield, respectively, over a 30–40 yr period (Gupta et al. 2012), which may cause a sediment deficit in downstream coastal mangroves. Sediment and surface elevation deficits, coupled with predicted rising sea levels, are likely to have important flooding impacts on

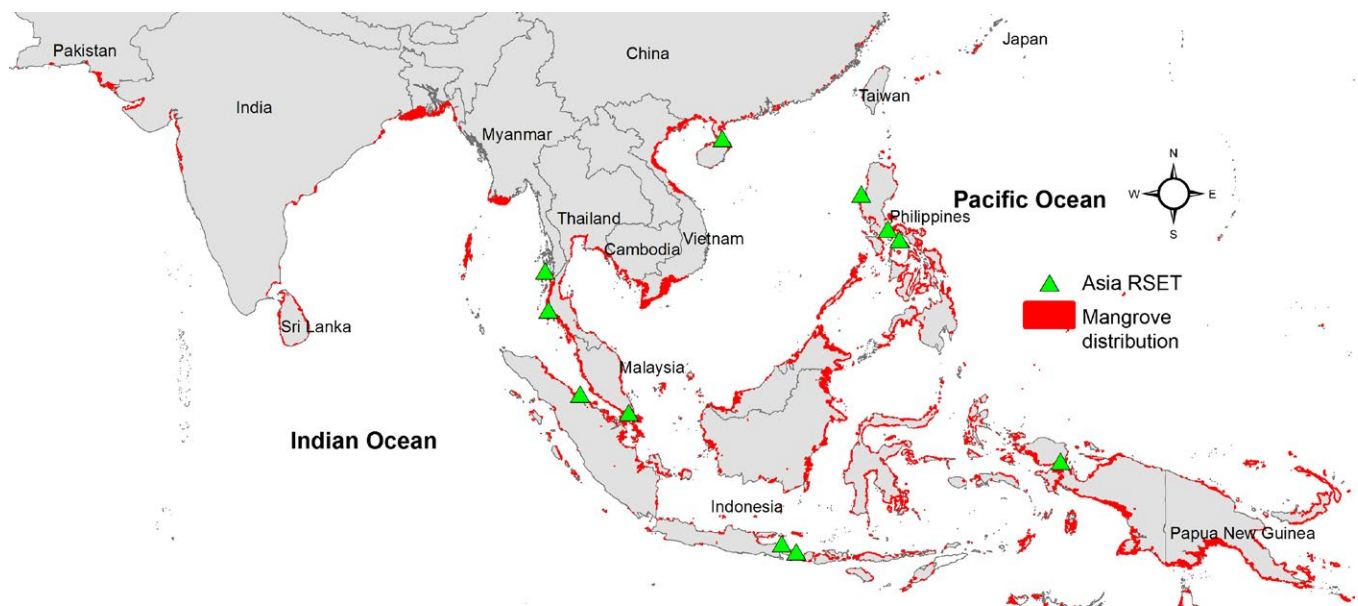


Fig. 10. Distribution of mangroves and the recent expansion of mangrove RSETs in Asia (2010–2015). Data derived from Giri et al. (2011a).

mangrove habitat, agricultural land and human settlements in socioeconomically important deltas such as the Mekong (Le et al. 2007, R. A. MacKenzie et al. *unpublished manuscript*). Such cases show how direct anthropogenic factors can interact with sea level rise to substantially increase the vulnerability of mangroves to submergence.

A particular issue in Asia, alongside other under-researched regions such as Africa and the Middle East, is a lack of region-specific information on surface elevation change rates, and subsequent mangrove vulnerability to SLR. Measurements of surface elevation change are heavily biased toward North/Central America and Australia (Webb et al. 2013), where species composition and geomorphological settings, and hence vulnerability and response to SLR, can vary markedly. Recent regional collaborative efforts, involving the University of Queensland (Australia), National University of Singapore (Singapore), US Forest Service (USA), Department of Marine Affairs and Fisheries (Indonesia), Center for International Forestry Research (Indonesia), Ateneo de Manila University (Philippines), Universiti Kembangan Malaysia (Malaysia), Vietnam National University (Vietnam), Xiamen University (China), and others have aimed to close this gap by promoting a rapid expansion of the RSET methodology throughout the region (Fig. 10). This network of RSETs has begun to project the vulnerability of the region's mangroves to sea level rise, with a mean elevation deficit of 6 mm/yr across the study sites. Therefore, mangroves in the region could be submerged beyond the physiological tolerance of mangroves within the next 100–300 yr, with sediment deprived micro-tidal sites around the Gulf of Thailand, south east Sumatra (Indonesia) and north Java (Indonesia), submerged by 2070 (Lovelock et al. 2015a).

Storminess

Storms and cyclones are likely to increase in strength in Asia's cyclone belt (Fig. 3) over the 21st century (IPCC 2014), so mangroves there are likely to be increasingly disturbed by such high-magnitude, low-frequency events. However, Asia's high species richness may increase its resiliency to cyclone impacts. Recovery to Cyclone Nargis, which struck the Ayeyarwady delta in Myanmar in 2008, was species-specific. Rhizophoraceae-dominated areas showed mortality of >90% due to their geomorphological position and inability to resprout, whereas mixed and non-Rhizophoraceae-dominated area showed a mortality rate of <20%, with rapid canopy closure within 4 yr of the event, due to a greater resprouting ability of mangrove genera other than *Rhizophora* (Aung et al. 2013). On a landscape-scale, cyclone disturbance on the delta was of a much lower magnitude compared to large-scale agricultural change (Webb et al. 2014). Anecdotal evidence suggests that a similar pattern has emerged in response to the November 2013 Typhoon Haiyan in the Philippines, with areas dominated by *Avicenniaceae* more resilient to disturbance.

Temperature changes

Asia's mangroves cover the wide latitudinal range of mangrove distribution. IPCC (2014) projects that it is *very likely* that the whole of Asia will warm from <2° C to 6° C by 2100 (Table 1), with greater temperature increases experienced at higher latitudes, so we may expect a range expansion of mangroves into salt marsh habitat at the northern range limit in Asia, similar to that observed in North America and Africa.

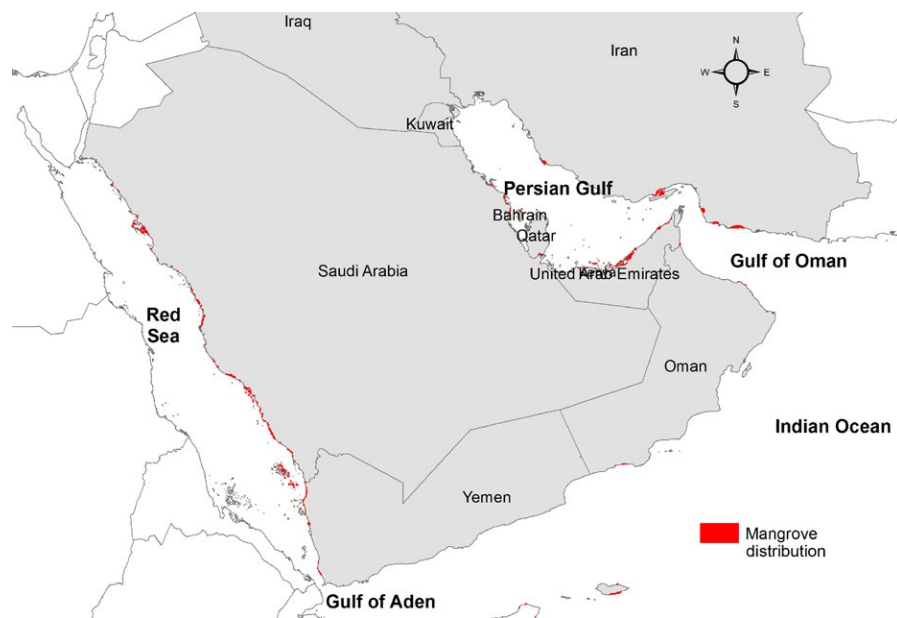


Fig. 11. Distribution of mangroves in the Middle East. Data derived from Giri et al. (2011a).

The Asian latitudinal limit of mangroves has been extended northwards by the planting of *Kandelia obovata* in Kagoshima Prefecture, Japan, and Zheihang, China (Saintilan et al. 2014), suggesting that climatic conditions are suitable north of the current natural latitudinal limit. However, it should be mentioned that competitive exclusion of mangroves by invasive *Spartina alterniflora* occurs in meso- and poly-haline sites, which may also limit their distribution (Zhang et al. 2012).

Future research foci and synergistic impacts for Asia

Research on mangroves and climate change interactions has increased in Asia in the last decade, with a rapidly expanding network of RSETs allowing a greater understanding of Asian mangrove resilience to sea level rise. It is at present unclear what synergistic impacts will affect Asian mangroves, though their predominantly minerogenic nature suggests that surface elevation processes would be affected more by anthropogenic disturbances such as river damming (Lovelock et al. 2015a), outweighing potential synergistic interactions of surface elevation gains and carbon dioxide (Langley et al. 2009). Research on other climate change impacts such as temperature and precipitation will contribute to a better understanding of synergistic interactions of climate change stressors in Asia.

Middle East

Regional setting

Within the Middle East mangroves are found in very few locations, typically small estuaries, with the majority of forests occurring in Saudi Arabia (20 000 ha

predominantly on the Red Sea and Gulf of Aden coasts) and Iran (19 000 ha predominantly in the Gulf of Oman) (FAO 2007) (Fig. 11). Some of the most northerly mangrove forests occur within the Middle East. The mangroves within this region are typically composed of *A. marina* only, although *Rhizophora mucronata* is also found in mangroves in Saudi Arabia (rarely), Iran, and Yemen, and has been introduced to other sites in the Persian Gulf.

Sea level rise

In comparison to other regions of the world, there have been far fewer studies on the impacts of climate change on mangroves within the Middle East. A recent study by Alothman et al. (2014) estimated recent relative SLR to be 2.2 mm/yr in the Persian Gulf taking into account subsidence rates of 0.7 mm/yr. Within the Gulf of Aden and the Red Sea local SLR has been estimated to be 3.3 mm/yr (Woodworth et al. 2009). In this region the high rate of SLR, coupled with the constrained location within estuaries, and rapid development (Nadim et al. 2008) will limit landward migration of mangroves as a result of climate change. Blankespoor et al. (2014) have suggested that up to 96% of coastal wetlands including mangroves are likely to be lost from the region as a result of sea level rise. Although the paucity of data concerning surface elevation change in Middle Eastern mangroves means that a detailed understanding of their future is lacking.

Temperature and precipitation

Temperatures in the Middle East are predicted to increase by up to 7° C by the end of the century

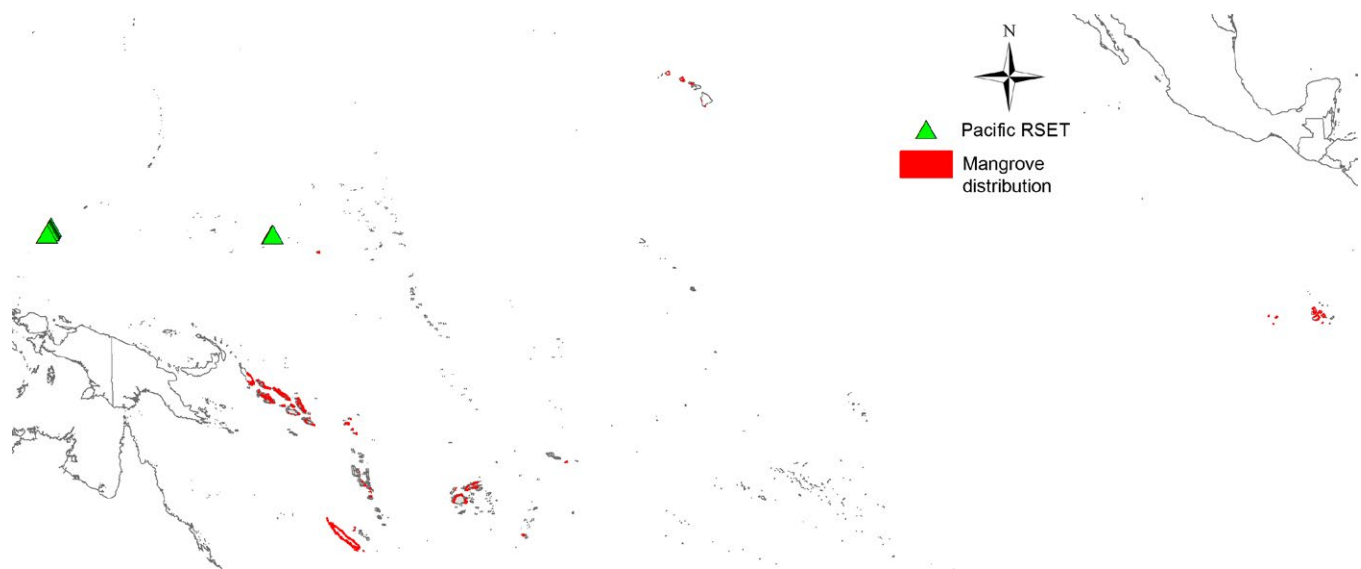


Fig. 12. Distribution of mangroves and the location of mangrove RSETs in the Pacific. Data derived from Giri et al. (2011a).

(Lelieveld et al. 2012). This very high temperature increase has the potential to limit mangrove growth rates due to moisture limitation by locally higher evaporation rates increasing salinity and temperatures exceeding the maximum tolerance (average air and soil temperatures 35° C and 30° C, respectively, and episodic maxima of 40° C, Clough 2013). At the same time, precipitation has been predicted to decrease in the Levant and Red Sea areas (Kostopoulou et al. 2014) although there may be small increases in precipitation (up to 10 more wet d/yr) within the Persian Gulf (Lelieveld et al. 2012). Decreases in precipitation are likely to increase salinity in already hyper-saline mangrove forests as well as limit fluvial sediment supply, important for maintaining surface elevation (Clough 2013, Ranasinghe et al. 2013, Kostopoulou et al. 2014).

Future research foci and synergistic impacts for the Middle East

Typically for arid regions, mangroves within the Middle East are limited to estuaries. Sea level rise rates in the Middle East are either at or below the global average, however, tied with decreases in precipitation, high freshwater abstraction rates from rivers, and increased temperatures and thus evaporation rates and related salt-stress, mangroves in the Middle East are likely to be at substantial risk from climatic change. However, due to the limited available data for this region concerning mangrove species responses to temperature and salinity, sediment accumulation rates related to SLR and fluvially derived terrestrial sediment it is difficult to predict the impacts of climate change on the mangroves located there.

Pacific Islands

Regional setting

Mangrove forests are found on islands throughout the western Pacific, with the largest expanse of mangroves occurring along the coasts of Papua New Guinea. Nearly 70% of Pacific Island mangroves can be found there (Ellison 2000), supporting 35 different species (Gilman et al. 2008). Diversity then declines east of Papua New Guinea to American Samoa (Woodroffe 1987, Ellison 1991, Gilman et al. 2008), where the remote isolated nature of the more eastern islands limits the long distance dispersal of propagules (Ellison 1991) (Fig. 12). The geomorphic setting also changes from west to east, with larger land masses (e.g., Papua New Guinea, New Caledonia) in the west typically supporting extensive deltaic/estuarine mangroves and smaller high islands and atolls in the east typically supporting mangroves in embayments, harbors, lagoons, and reef flats as well as inland mangroves (Woodroffe 1987). Differences in geomorphology across the Pacific also translate to differences in response to climate change, particularly to SLR, as geomorphology influences sedimentation rates, landward migration, and freshwater nutrient and sediment inputs (Woodroffe 1987, 1993, Krauss et al. 2010).

Pacific Island mangroves represent only 3% of global mangrove extent (Gilman et al. 2007). Despite their small area, on a per hectare basis high island mangroves can be just as productive as larger, continental mangroves (Woodroffe 1987). For example, litterfall rates, a proxy for productivity, from high islands in the region range from 7.7 to 15 t·ha⁻¹·yr⁻¹ (Sasekumar and Loi 1983, Woodroffe and Moss 1984, Leach and Burgin 1985) compared to values from Florida (4.4–8.1 t·ha⁻¹·yr⁻¹; Twilley et al.

1986), Australia (3.8–19.6; Duke et al. 1981) or the global value of $9.8 \text{ t ha}^{-1} \text{ yr}^{-1}$ derived from Alongi (2014). Furthermore, they can account for a large proportion of total island area (i.e., 12–14% on the islands of Yap, Pohnpei, or Kosrae) (MacLean et al. 1988, Falanruw 1994) and many island peoples rely on mangrove forests as their main source of fiber, fuel, or food. Products harvested from mangroves in Micronesia represented 50% of the annual household income (Naylor and Drew 1998).

High island mangroves typically occur in deltaic or estuarine conditions. High rainfall in these tropical wet regions results in high loads of freshwater, nutrients, and terrigenous sediments that sustain these ecosystems (Ellison 2000). Delivery of upland sediment loads coupled with belowground root production have resulted in mangrove forests that have been, and continue to be, positioned to survive current rates of SLR (Ellison and Stoddart 1991, Krauss et al. 2010). Low island mangroves include embayment, harbor, and inland mangroves. Unlike high island mangroves, there is not a large supply of upland sediments. Instead, low island mangrove soils are largely maintained by the accumulation of vegetative detritus and below-ground root growth and to a lesser extent coralline derived sediments (Ellison 2000, Gilman et al. 2007).

Sea level rise

Stratigraphic records from Pacific mangroves have revealed that in the past, high island mangroves have kept up with SLR rates of 4.5 mm/yr ; whereas low island mangroves have kept up with rates of 1.2 mm/yr (Ellison and Stoddart 1991). These differences in accumulation rates related to high vs. low mangrove island suggest that high island mangroves may be less vulnerable to SLR (McLeod and Salm 2006, Alongi 2008) and these high island mangroves are currently keeping pace with regional SLR ($2.0\text{--}4.0 \text{ mm/yr}$) (Church et al. 2006). However, the pattern of accumulation may depend upon mangrove zone. For example, SET measurements over a 6-yr time period on the high islands of Kosrae and Pohnpei in the Federated States of Micronesia revealed that fringe mangroves were the most vulnerable to SLR compared to riverine or interior sites (Krauss et al. 2010). The opposite pattern was observed in long-term sediment accretion rates determined from ^{210}Pb dating of mangrove sediments on the island of Babeldaob in the Republic of Palau, although this will be verified by concurrent RSET measurements (MacKenzie et al. *in press*). Low island mangroves have been identified as most vulnerable to SLR (McLeod and Salm 2006) and are threatened by current rates of SLR (Gilman et al. 2007, Alongi 2008, Krauss et al. 2003, MacKenzie et al. *in press*). This is not only due to the lack of terrestrial sediment inputs to, and small areal extent of, low island mangroves (Gilman et al. 2008), but to the fact that the

low, constant elevation of low atoll islands provides no inland refuge for landward migration. Mangrove forests can grow along the edges of interior lagoons in some Pacific atolls (e.g., the Marshall Islands) (Woodroffe 1987), but these mangroves will eventually drown as they have no landward position to migrate to under increased rates of sea level rise. Opportunities for inland migration do exist for many Pacific high islands, but this depends upon the ability of the mangrove species to colonize new habitat, the condition of that habitat, the slope of the adjacent land, and the presence of barriers (e.g., roads, seawalls, buildings) (Gilman et al. 2006). Increased development over the past few decades has resulted in barriers along Pacific Island coasts (e.g., roads, buildings, bridges) (Merlin et al. 1996, MacKenzie 2008), which will limit the ability of mangroves to migrate inland. Using the upper IPCC projections for SLR, Gilman et al. (2007) predict that the extent of Pacific Island mangroves could be reduced by 12.4%, largely due to their inability to migrate inland. While such losses of mangroves would have severe implications for many island nations as mangroves are vital components of Pacific Island subsistence economies, island institutional capacity may increase the ability of future management actions and coastal planning to aid in the ability of mangroves to migrate inland. These actions include protecting coastal areas that currently support mangroves from the construction of coastal engineering structures to prevent coastal erosion, determining adequate setbacks by assessing site-specific rates for landward migration, and in areas where development is deemed necessary, the construction of expendable or portable structures (Gilman et al. 2008). Mangrove species are also expected to shift from more salt-tolerant species to species that prefer lower salinities, although this has yet to be documented in this region (Ellison 2000).

Precipitation

SLR is expected to have the greatest impact on spatially compact Pacific Island mangroves compared to larger continental forests (McLeod and Salm 2006, Alongi 2008). However, other climate change impacts in the Pacific region could potentially influence the resilience of mangroves to SLR. For example, over the last 50 yr precipitation has generally increased north east of the Southern Pacific Convergence Zone (SPCZ) and declined to the south (Brown et al. 2013). Climate models predict future rainfall to increase in the SPCZ and ITCZ. Increased rainfall has been positively correlated with tree growth and litterfall (Krauss et al. 2007) and delivery of upland sediments to these ecosystems (Golbuu et al. 2007), although Strauch et al. (2014) demonstrated that sediment loads can actually increase with decreasing rainfall in Hawaii due to decreases in drying periods resulting in greater soil

cohesion in catchments. The accumulation of organic matter as well as the retention of upland soils can positively influence surface accretion rates in mangroves (Krauss et al. 2014). This association of organic matter accumulation and mineral soil retention suggests that increased rainfall in some areas may actually have a positive impact on Pacific Island mangroves. Increased rainfall has and is expected to continue to result in reduced ocean water salinities (Brown et al. 2013), which will likely decrease pore water salinities and sulfate concentrations resulting in increased mangrove production (Snedaker 1995, Ellison 2000, Gilman et al. 2007).

Future research foci and synergistic impacts for the Pacific Islands

General circulation models as well as various down-scaled models predict that islands in the western Pacific will experience increased amounts and potentially more intense rainfall events. The frequency of El Niño events is also expected to increase in a warmer climate (Cai et al. 2015) and as a result an increase in typhoon intensity (Zhang et al. 2015). Increased rainfall will likely positively influence high island mangroves due to increased sediment loads (Krauss et al. 2010), but it is not clear how this will impact other ecological parameters of Pacific Island mangroves (e.g., forest structure, mangrove productivity). Furthermore, while mangroves in the region currently appear to be quite resilient to typhoons (Kauffman and Cole 2010, MacKenzie and Cormier 2012), it is not clear how their response to typhoons will vary in a changing climate, under increased development pressures, or the combination of both. Additional studies are also needed to measure sediment accretion rates with both radio-nuclides and RSETs as well as studies measuring root growth and resultant surface elevation change. These data will also allow us to examine how mangroves are responding to changes in rates of SLR and how this response varies among different types of mangroves (i.e., high island vs. low island atolls, oceanic vs. deltaic). Information from these studies will not only increase our understanding of how Pacific Island mangroves are responding to climate change, it can also be used to identify mangroves that may be more resilient to the impacts of climate change and can continue to provide societal benefits to the region (Naylor and Drew 1998).

Conclusions

Mangrove communities globally are expected to be substantially influenced by climate change-related physical processes in the future. This review has highlighted the extreme regional variation in mangrove communities, their biodiversity, threats, protection, climatic influences,

and level of understanding. Sea level rise is regionally variable and is likely to have a lesser impact in areas with high sediment availability, uplifting or stable coasts, high productivity, and large tidal ranges such as the Amazon estuary and Parnaíba delta. However, where there is extensive coastal development such as Asia, South and North America, very high rates of SLR such as Indonesia and Mississippi delta or in low island mangroves such as the Pacific, mangroves are likely to be substantially threatened. This review has indicated how predicted changes to precipitation regimes and temperature are likely to influence mangroves and suggested potential future threats to regions such as South America and West Africa, which are currently not influenced by storm surges.

In areas with high precipitation such as some Pacific Islands, increased available sediment from terrestrial sources and litterfall together with increased nutrient inputs can lead to increased tree growth and an increase in surface elevation. Conversely mangroves in semiarid areas with predicted decreases in future precipitation such as the Middle East and north east Brazil are likely to suffer from increases in salt-stress and resultant decreases in productivity combined with decreases in sediment input. These predicted shifts suggest a negative outlook for future mangroves particularly with respect to sea level rise. Similarly, during periods of drought, mangroves are likely to be less resistant to the impacts of storms. Such effects are likely to be seen in drier regions, such as Texas in North America.

Influences of temperature are regionally variable with no recorded change in latitudinal distribution as a result of temperature increase in South America, whereas in North America and South Africa there has been an increase in the latitudinal distribution of mangroves. In Australia increases in temperature combined with sedimentation and SLR have resulted in expansion of mangroves into areas previously dominated by salt marsh although no latitudinal expansion.

The regional perspective of this review has drawn attention to the numerous geographical knowledge gaps of climate change impacts, with some regions particularly understudied, such as Africa and the Middle East. There has been a recent drive to address these information gaps, most notably in South America and Asia, however, we call for a concerted effort to broaden our knowledge base through national capacity building and international collaboration. There has been little research conducted on current and changing sedimentary dynamics outside of the main research centers (Central/North America, the Pacific and Australia/New Zealand, and only recently South east Asia and South America) and there are few inter-regional comparisons upon which to study large-scale processes that could influence how mangroves respond to climate change on regional scales. However, the wide variation in mangrove ecosystem characteristics within and among regions allows us to tease apart the

processes that control vulnerability and resiliency to the varied impacts of climate change.

Acknowledgments

RDW acknowledges the Rising Stars Initiative (University of Brighton), the Federal University of Para, Federal University of Parana, Federal University of Ceara, and the Federal University of São Paulo for funding and logistical support in sea level rise vulnerability analysis in South America. DAF acknowledges the Asia Pacific Network for Global Change Research (ARCP2014-14NMY(B&ES)) and the National University of Singapore (R-109-000-141-133/R-109-000-184-720/R-109-000-158-646), who have funded sea level rise vulnerability monitoring for several sites in South east Asia. RHD is supported by the U.S. Geological Survey's Ecosystems Mission Area. RAM acknowledges the USDA Forest Service Pacific South West Research Station and the U.S. Agency for International Development, who have funded sea level rise vulnerability monitoring for several sites in South east Asia and the western Pacific. We would like to thank Mike Osland of the U.S. Geological Survey and two anonymous reviewers for making helpful comments to the manuscript. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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