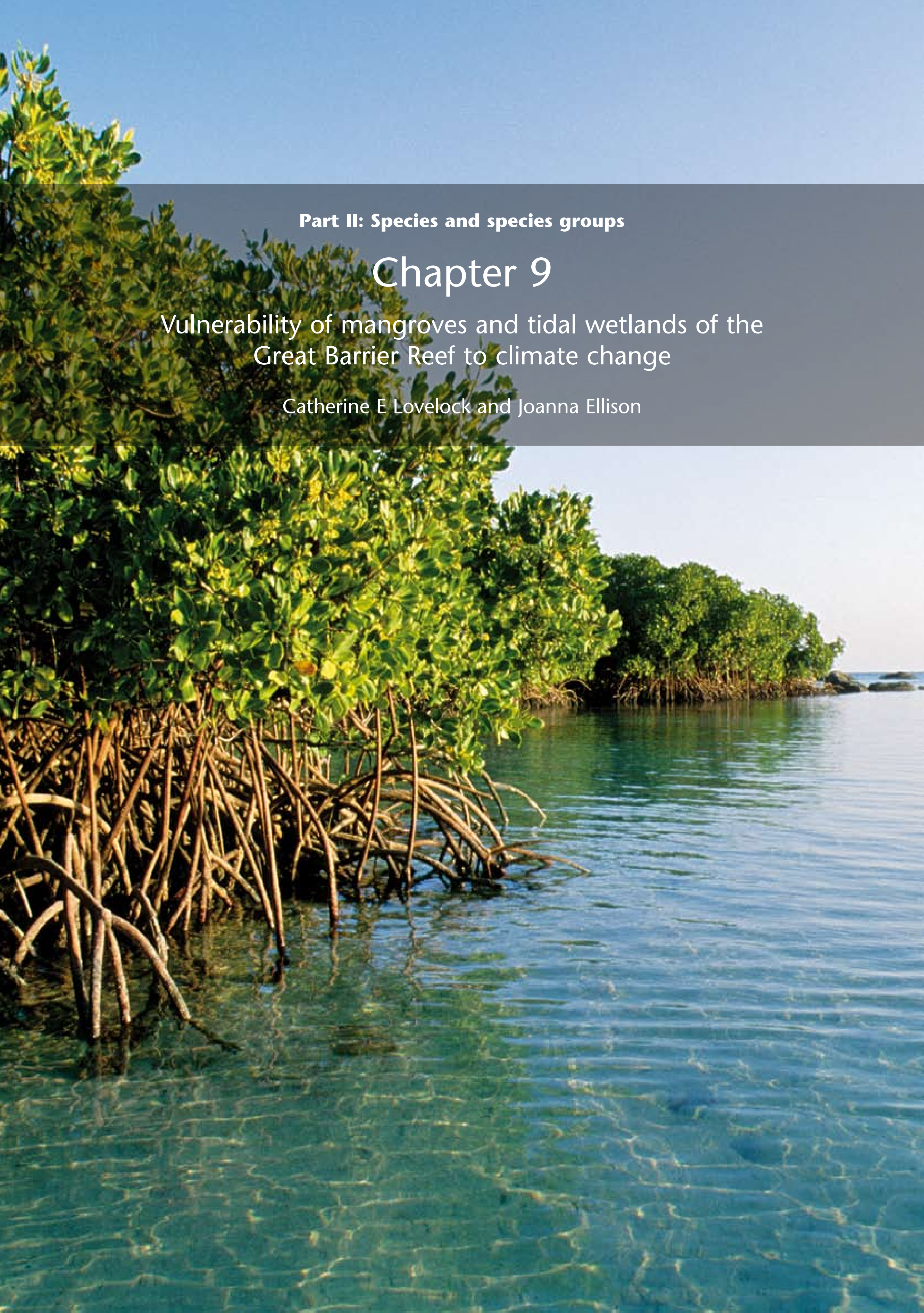
Part II: Species and species groups

Chapter 9

Vulnerability of mangroves and tidal wetlands of the Great Barrier Reef to climate change

Catherine E Lovelock and Joanna Ellison



9.1 Introduction

Climate change will have an enormous influence on the intertidal wetlands of the Great Barrier Reef (GBR). Increases in atmospheric carbon dioxide (CO_2) concentrations and associated increases in air and sea temperatures, rising sea level, changes in oceanic circulation, rainfall patterns and frequency and intensity of storms are highly likely to affect the physiology, ecology and ultimately the stability of wetland habitats (Table 9.1). The intertidal position of mangroves, salt marshes and salt flats makes them particularly vulnerable to changes in sea level, although other climate change factors will also exert a strong influence on wetland communities (Table 9.1). Past rises in sea level have led to increases in the area of mangroves in northern Australia[186]. However, past climate change has occurred with limited human modification of the coast compared to current levels of development. Human activities have resulted in loss of wetlands, disruption to connectivity, enhanced availability of nutrients, changed sediment dynamics and the creation of structures that will prevent landward migration of wetlands with sea level rise (eg roads, berms, bunds and sea walls). Many of these human impacts will reduce the resilience of intertidal wetlands to climate change. To conserve the intertidal wetlands of the GBR and the ecosystem services they provide, we will need to manage the coastal zone in a way that enhances the resilience of mangroves, salt marshes and salt flats during climate change.

Table 9.1 *Predicted effects of climate change factors on mangroves and key references*

Climate change	Processes affected	Likely impact	References
Altered ocean circulation patterns	- Dispersal - Gene flow	- Changes in community structure	Duke et al.[73], Benzie[25]
Increased air and sea temperature	- Respiration - Photosynthesis - Productivity	- Reduced productivity at low latitudes and increased winter productivity at high latitudes	Clough and Sim[55], Cheeseman et al.[49], Cheeseman[48], Cheeseman et al.[50]
Enhanced CO_2	- Photosynthesis - Respiration - Biomass allocation - Productivity	- Increased productivity, but dependent on other limiting factors (salinity, humidity, nutrients)	Ball et al.[20]
UVB radiation	- Morphology - Photosynthesis - Productivity	- Few major effects	Lovelock et al.[113], Day and Neale[66]
Rising sea level	- Forest cover - Productivity - Recruitment	- Forest loss seaward - Migration landward, but dependent on sediment inputs and other factors (Table 9.3) and human modifications to the landscape - loss of salt marsh and salt flats	Ellison and Stoddart[84], Woodroffe[188], Morris et al.[126], Semeniuk[158], Cahoon et al.[42], Rogers et al.[152]

Climate change	Processes affected	Likely impact	References
Extreme storms	- Forest growth - Recruitment reduced - Reduced sediment retention - Subsidence	- Reduced forest cover	Woodroffe and Grime[189], Baldwin et al.[16], Cahoon et al.[42]
Increased waves and wind	- Sedimentation - Recruitment	- Changes in forest coverage, depending on whether coasts are accreting or eroding (interaction with sediment stabilisation from seagrass loss)	Semeniuk[158]
Reduced rainfall	- Reduction in sediment supply - Reduced ground water - Salinisation	- Loss of surface elevation relative to sea level - Mangrove retreat to landward - Mangrove invasion of salt marsh and freshwater wetlands - Reduced photosynthesis - Reduced productivity - Species turnover - Reduced diversity - Forest losses	Rogers et al.[151, 152], Whelan et al.[182], Smith and Duke[168]
Reduced humidity	- Photosynthesis - Productivity	- Reduced productivity - Species turnover - Loss of diversity	Ball et al.[20], Clough and Sim[55], Cheeseman et al.[49], Cheeseman[48]
Enhanced rainfall	- Increased sedimen-tation - Enhanced ground-water - Less saline habitats - Productivity	- Maintain elevation relative to sea level - Maintenance of surface elevation - Increased diversity - Increased productivity - Increased recruitment	Rogers et al.[152], Whelan et al.[182], Krauss et al.[109], Smith and Duke[168]

Conservation of mangrove and salt marsh habitats is critical for sustained coastal productivity because of the high value of the ecosystem services they provide[56,85,98] (Tables 9.2 and 9.3). Mangroves occupy approximately 1,000,000 hectares of the intertidal zone of rivers, embayments and islands of Australia, with the majority of areas occurring in Queensland, Northern Territory and Western Australia[97,170]. The GBR has approximately 20 percent of Australia's mangrove resources (207,000 hectares). Salt marshes and salt flats occupy an approximately equivalent area as mangrove forests within the GBR[a]. Changes in the extent and function of mangrove forests, salt marshes and salt flats

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with global climate change could potentially have large affects on the coasts and nearshore waters of the GBR lagoon. For example, a loss of mangrove forests could reduce banana prawn landings or result in the liberation of a proportion of the huge pool of carbon stored in stabilised wetland sediments to coastal waters and the atmosphere (Table 9.3).

Table 9.2 *Outline of some of the major ecosystem services provided by mangroves, salt marshes and other wetlands within the GBR and the processes potentially impacted by climate change*

Ecological Services	Impact
Habitat	Fisheries and diversity
Nursery for fauna	Fisheries and diversity
Sediment trapping	Water quality
Carbon storage in sediments and biomass	Atmospheric carbon cycling
Nutrient cycling	Water quality and coastal waters productivity
Hydrological damping	Water quality, protection from storms, erosion and tsunamis

The ecosystem services provided by mangroves, salt marshes and salt flats include biofiltration, carbon and nutrient retention and cycling, physical protection of coasts during storms and other large scale disturbances, and habitat for fauna, algae and microbial communities, many of which are confined to wetland habitats (Tables 9.2 and 9.3). Loss and degradation of mangroves and other tidal wetlands have occurred because of clearing, modification for human uses and through pollution of coastal waters[2,181,3,5,142]. This has resulted in an estimated global reduction in mangrove cover of 35 percent since the early 1980s, with a reported 14 percent loss in cover in Australia from 1983 to 1990[181,5]. Although there is legislative protection of intertidal wetlands in Queensland, human modifications within the coastal zone will reduce the resilience of ecosystems, making them more vulnerable to environmental pressures like climate change[82,45].

In this chapter, we first give a brief account of intertidal wetlands within the GBR and then provide a qualitative assessment of the exposure, sensitivity and vulnerability of mangroves, salt marshes and salt flats to climate change. We provide a generalised account of ecosystem services (Table 9.3), and give an outline of models and methods that are currently used in assessing vulnerability of wetlands to climate change. We conclude this chapter with a list of issues for environmental managers and significant gaps in our knowledge that need to be filled in order to better understand changes in the extent, community composition and functioning of mangrove habitats that are occurring with climate change; and place the impacts of these changes within the context of continued sustainability of the GBR.

Table 9.3 *Summary of magnitude of some of the ecosystem services provided by mangroves*[b]

Ecosystem service	Stocks	Rate of ecosystem service or productivity	References and assumptions
Fisheries			
Seaward fringe	Fish 20 to 290 kg per ha	Prawns 450 to 1000 kg per ha per year	Robertson and Blaber[146], Blaber[27]
High intertidal	Fish 6 kg per ha		Mazumder et al.[124], salt marsh, reported as 0.56 fish m^{-2} (assuming 1 fish = 1 gram)
Sediment trapping			
Seaward fringe		50 to 600 Mg per ha per year	Furukawa et al.[96], Saenger[155], Alongi et al.[13]
High intertidal		4 Mg per ha per year	Furukawa et al.[96] – 5 g m^{-2} $tide^{-1}$, assume tidal inundation 20 percent of each year
Nutrient and carbon retention and cycling			
Carbon storage	385 Mg C per ha	3000 to 3500 kg per ha per year	Chmura et al.[52] (reported as 0.0055 grams C per cm^{-3} – assume soils are 1 metre deep and average bulk density of 0.7 grams per cm^{-3} DM Alongi, unpublished data.
Nitrogen storage	20 Mg N per ha	140 to 170 kg per ha per year	Lovelock unpublished data derived from ratio of C:N of 20 in sediment organic matter
Carbon export		TOC: 2640 kg C per ha per year DOC: 500-1500 kg per ha per year	DM Alongi, unpublished data. Dittmar et al.[67], Twilley[179], Ayukai et al.[15]
Nitrogen export		Total 35 kg per ha per year DON 25 kg per ha per year PON 18 kg per ha per year	Alongi et al.[7]

b The value of fisheries habitat and sediment trapping is considered for seaward fringing mangroves (low intertidal) and high intertidal. Key: C = carbon; N = nitrogen; TOC = total organic carbon; DOC = dissolved organic carbon; DON = dissolved organic nitrogen; PON = particulate organic nitrogen, ha = hectare , Mg = mega gram or 1 000 000 g

9.1.1 Mangroves, salt marshes and salt flats

Mangroves, salt marshes and salt flats have communities of plants with special physiological and morphological adaptations that allow them to grow in the intertidal zone of the marine environment[46,114]. Mangroves are mainly comprised of woody tree species, salt marshes are comprised of short herbaceous and woody species and salt flats are encrusted by films of cyanobacteria and other desiccation tolerant microorganisms. The positions of these communities in the intertidal zone make them particularly sensitive to sea level rise and other factors that influence hydrology of the intertidal zone. Accurate elevation surveys at a range of sites (Bermuda, West Papua, Hinchinbrook Island and the Darwin Harbour) have shown that the position of mangroves relative to mean sea level is variable, but often occurs below mean sea level[29,184,79,81]. Mangroves can occur up to 0.4 metres below mean sea level at the seaward edge of the mangrove and above the mean high tide at the landward edge of the mangrove[79,81]. Salt marsh communities occupy a position landward of mangroves or higher in the intertidal zone, often intergrading with terrestrial vegetation on the landward edge[1]. Salt flats also occur landward or higher in the intertidal than mangroves and are best developed in areas with high evaporation and low rainfall. These environmental conditions are unfavourable for the development of extensive salt marsh and mangroves[93] but instead favour the development of cyanobacteria dominated crusts or mats. The position of mangroves, salt marshes and salt flats relative to each other and to sea level gives rise to the high vulnerability of these habitats to sea level rise and highlights the potential for disruption and relocation of vegetation zones and the structure of the vegetation with climate change.

The patterns in diversity of plant species within salt marshes and mangroves and of microorganisms on salt flats are correlated with factors that will be influenced by climate change[72,1,153]. For example, within the GBR, mangroves increase in diversity from south to north[177,72] while salt marsh species diversity increases from north to south[62]. Mangrove tree species diversity is also influenced by rainfall, with higher diversity of mangrove tree species in moist compared to arid estuaries[168]. Additionally, intertidal microbial mat community diversity declines with longer periods of desiccation higher in the intertidal[153].

Mangrove forest structure is characterised by zones of tree species, in patterns that often run perpendicular to the shore, and by strong gradients in tree height[115]. Tree height declines from tall forests fringing open water or rivers (up to 50 metres) to shorter forests (less than 1 metre) and salt marsh and salt flats on the landward margins. The variation in forest structure, habitat type and productivity across the intertidal region is related to the underlying geomorphology[187,184,158] that reflects the strong spatial patterns in inundation frequency, sediment and nutrient inputs, salinity and biological processes (eg bioturbation and predation)[167,156,18]. Many of these processes are influenced by climate change (Table 9.1) and are also affected by human activities.

Consideration of how vegetation structure will be altered by climate change is important because vegetation structure influences ecosystem function[187,184,158,180]. Variation in tree height of mangrove forests is correlated with primary productivity[156]. Additionally, different species of mangroves have different morphological and biochemical properties that influence ecosystem processes. For example, tissue of *Avicennia* spp. is richer in nitrogen than that of *Rhizophora* spp., resulting in differences in rates of primary consumption and decomposition[178,144,145,166,174,59,28]. Faunal communities are also influenced by forest structure[4,6] and have flow-on effects on ecosystem function. For example, crabs that bury and shred leaf litter and make burrows influence carbon and nutrient cycling and the hydrological properties of mangroves[143,140].

Although most mangrove forests within the GBR are within estuaries and embayments, there are many mangrove-dominated islands offshore. Steers[172] first described these low wooded islands as reef top associations of windward shingle ridges that provide protection for leeward sand cays and intermediate mangrove swamps on patch reefs. In the northern GBR, 34 low wooded islands have been found to occur over 4 degrees of latitude extending north from Low Isles (16° 23′ S, 145° 34′ E)[176]. More recently, Neil[130] classified Green Island in Moreton Bay (27° 25′ S) as a low wooded island, with differences from the northern islands only due to the lower temperatures and higher wave energy conditions of southern latitudes. While mangroves of low wooded islands are smaller in extent than mainland mangroves, mangroves of low wooded islands have close connections with the reefs and seagrass beds, providing fish breeding habitat and mangrove based food webs within reef-dominated settings. They also provide essential nesting sites for migratory birds (eg Imperial Pied Pigeon). Mean elevation of mangrove/lagoon margins on the low wooded islands was found to be 0.36 metres below mean sea level (Ellison, unpublished data). Their low position in the intertidal zone and limited sediment supply to the islands may make them highly vulnerable to sea level rise.

In arid areas of the GBR, landward mangrove forests are often replaced with extensive high intertidal cyanobacterial encrusted salt flats and salt marshes that are dominated by succulent salt marsh species[168]. Sedge-like salt marshes also occur on the landward edge of mangroves, and are well developed where fresh water inputs are high[1,35]. Australian tropical salt marsh communities are characterised by low stature but highly productive species that support a wide range of fauna[1]. Salt marsh and salt flat habitats are among the most vulnerable to climate change. They are often highly disturbed by human activities[3]. Urban, industrial and agricultural developments within or on the landward edge of salt marshes will prevent their migration upslope in response to rising sea level. Additionally they are being squeezed by mangrove encroachment on the seaward edge[3,152]. Grazing, weeds and vehicle traffic add to the pressures on salt marshes further reducing the resilience of salt marshes to global climate change[3].

9.1.2 The role of mangroves in the Great Barrier Reef

9.1.2.1 Physical structure

Mangrove tree species have aerial roots of varying architectures (eg stilts, pnuematophores, knees and buttresses) that have a significant impact on the function of mangrove-dominated estuaries. Lower stems and root structures, including pneumatophores cause friction within wetlands, slowing water velocities and resulting in deposition of sediments[96,185]. Through the process of trapping sediments and particulate organic matter[96,9,13] water quality in adjacent habitats (seagrass and coral reefs) is enhanced[185].

The role of mangrove roots in preventing coastal erosion is critical[95,121,122,119,123]. They also may have some role in protection from storm surges and tsunamis[60,63,58]. Roots also bind sediments preventing resuspension[190,109]. They provide sites for associated flora (eg macroalgae), that adhere to above ground roots[149], further increasing the friction to tidal flow. The fauna associated with aboveground roots graze on algal and microbial material and benefit from protection from predation[139,111,147,6,163].

9.1.2.2 Carbon and nutrient storage and cycling

One of the key ecosystem services of mangroves, salt marshes and salt flats is the retention of carbon and nutrients within aboveground biomass and sediments. In mangroves, approximately half the nutrient and carbon stocks can be in the sediments[11]. Mangroves have higher soil carbon contents than salt marsh soils, and both exceed carbon contents of most terrestrial soils making them particularly important in regional and global carbon and nutrient budgets[179,52,10,12].

Growth of mangroves within the GBR is limited by nutrient availability[31]. (Lovelock and Feller, unpublished data). Nitrogen fixation in mangroves can occur at high rates (eg Woitchik et al.[183]) but imported nitrogen is required to meet the demand of primary production of the forests[30,10]. Very little nitrogen is lost from undisturbed mangroves via denitrification or in tidal exchange[7] due in part to the high efficiency of internal cycling within tree tissues[90,91] and sediments[13]. Development within the catchments of the GBR and nutrient enrichment of coastal waters can alter nutrient cycling in mangroves, resulting in leakage through enhanced denitrification[13] and reductions in the efficiency of tree internal nutrient cycling[91,92]. How carbon and nutrient cycling processes are influenced by factors associated with global climate change is not known, but increases in temperature and changes in rainfall may have significant effects on microbial processes and nutrient retention in forest biomass.

Although there is evidence for net uptake of carbon and nutrients by mangrove ecosystems, there is exchange among mangroves and adjacent regions with mangroves providing important carbon and nutrient subsidies to coastal waters[8,33,67]. Export of detrital particulate matter and dissolved nitrogen and carbon from mangroves and intertidal wetlands can be substantial[179,8,67] (Table 9.3), but seasonally variable[32,15], indicating that changes in rainfall patterns could affect outwelling of materials from mangroves. Salt flats in the high intertidal zone fix and sequester carbon and nitrogen within cyanobacterial crust communities[134,30,107]. Phosphorus is also sequestered in salt flats due to evaporation of seawater, rain and fresh water inputs[141]. These materials accumulated on salt flats can also be released in seasonal pulses with fresh water flow or during high tides[141].

9.1.2.3 Fauna and dependencies

Mangrove forests and associated salt flats and salt marsh support a diverse and abundant fauna. While invertebrates and fish are highly diverse groups that are abundant in mangrove habitats, many species of reptiles (including turtles, crocodiles and lizards), birds and mammals also use mangroves as habitat[145,6,154,108]. Many species of mobile fauna access mangrove and associated habitats seasonally when the tide permits, while others are resident. The mangrove – salt marsh/salt flat habitat can be viewed as a complex connected mosaic of habitats that are intermittently accessible to mobile fauna with affinities to reefs and other subtidal habitats[118,159]. These mobile fauna also have a role in the transfer of materials between habitats through grazing, predation, and excretion[137,160]. The contribution of animals to material exchange between mangroves and other adjacent habitats could be similar to or exceed the exchange of particulate and dissolved material with tidal flow[137].

Some of the most conspicuous fauna in mangrove forests, due to their burrows, are crabs and mud lobsters. Crabs perform critical ecological functions, influencing forest structure by consuming propagule[s167], aiding in processing of leaf litter, oxygenating the sediments, and contributing to surface friction and thus to slowing water movement that facilitates fluxes of nutrient and other materials between mangrove sediments and tidal waters[141]. Crabs are consumed by large predatory fish[160] but also produce copious larvae, which are an important food source for many juvenile fish

utilising mangroves[143]. Mangroves also support a wide diversity of other invertebrates, for example[153] species of macrobenthic species were recorded from Missionary Bay[6].

Crab species, and other fauna partition the intertidal zone, with species having a preferences for differing inundation regimes. High intertidal salt marshes, which in some areas may be most vulnerable to sea level rise, have at least 13 species of crabs[6,124]. Although there are many studies of fish use of fringing mangroves[87], there is little knowledge of transient use of high intertidal salt marsh and salt flat areas. In a recent study of fish abundance in high intertidal salt marsh habitat, the abundance of fish was greater in the salt marsh than in the mangroves when adjusted for water volume, suggesting the high intertidal may provide important resources for fish[124]. Moreover, some invertebrate species appeared to be confined to feeding in the salt marsh – mangrove ecotone[100] adding further impetus for conservation of these areas with climate change.

Arboreal residents in mangroves are also highly diverse and abundant. These include spiders, ants, beetles and other insects, bats and birds. Some are specialists on mangrove flora (eg leaf miners, wood borers, seed and insect feeders) and many have important effects on forest growth, structure and recruitment[133,145,89,88].

9.1.2.4 Fisheries

Mangroves are nurseries for fish and crustaceans. This is one of the key attributes of mangroves that contribute to their high economic value[146,23,22]. Along the Queensland coast, as in other locations, mangrove cover is positively correlated with fisheries landings[27,118]. In the study of Manson et al.[118] the relationship between mangrove area and perimeter (edge) was significant for banana prawns, mud crabs and barramundi, which are known to spend part of their life cycles in mangroves, but were also significant for other species not directly associated with mangrove habitats (eg tiger prawns, blue swimmer crabs and blue threadfin). These results indicate that mangroves provide resource subsidies to connected habitats that lead to increased fish stocks. Investigation of fish diets using stable isotope techniques also indicated that mangrove resources make a significant contribution to fish diets in species that are not resident in mangroves[125]. The single offshore commercially important species included in Manson et al's[119] analysis, coral trout, did not show a significant association with the area of mangrove habitat. However, in other regions in the world mangroves are known to support ecologically and economically important fish species[127,108,21,128,129,51].

Connectivity of mangroves with other adjacent habitats has been observed to increase productivity. For example, close proximity of mangroves and seagrass enhanced productivity of many species[129,164,159]. Although there are few studies of faunal dependence on high intertidal habitats, it is likely that for some species access and connectivity to the high intertidal area is important for enhanced total productivity[124] (see chapter 19).

9.1.3 Critical factors for mangrove survival

9.1.3.1 Physiological limits to tree growth

Although mangrove trees are adapted to being inundated with salt water, there are physiological limits to their capacity to withstand inundation. Mangroves are sensitive to increases in the frequency and duration of flooding that will occur with sea rise[116,83]. As the frequency and duration of inundation increases, growth of trees will decline and forests may retreat landward. The underlying

coastal topography or bathymetry (the extent and slope of coastal plains) influences the frequency and duration of inundation and thus modifies exposure to sea level rise, with truncated, steeply sloping coastlines having the greatest exposure. Tidal range and sediment dynamics, in conjunction with other climatic and biological variables, will also influence the impact of sea level rise on mangrove growth and survival (see section 9.2.5).

Both mangroves and salt marsh plants have their roots in the marine environment, but for most of the time have their leaves in the air, taking up gaseous CO_2 via their stomata during photosynthetic carbon gain. Stomata are sensitive to CO_2 concentrations, temperature, humidity and salinity of soils, and thus mangrove and salt marsh productivity is likely to be affected by enhanced CO_2, ultraviolet B (UVB) radiation, air and sea temperature and altered patterns of rainfall[19 20,55] (Table 9.1). Additionally, mangrove species have differing tolerances to environmental conditions[54,17,112]. Thus some species are likely to be more sensitive to climate change than others, ultimately resulting in changes in species composition of the tree community and concomitant alterations in ecosystem function and associated faunal communities. The paleontological data indicate that the Rhizophoraceae had greater dominance during periods of past sea level rise than they have presently[47,57,99,102]. This may suggest that the area of mangrove dominated by Rhizophoraceae could expand in the future, possibly at the expense of other species.

Species of mangroves from the family Rhizophoraceae are also particularly sensitive to physical damage inflicted by wind or hail. These species cannot be coppiced, having no epicormic buds from which to resprout after canopy damage[177,16]. Species from the Rhizophoraceae dominate forests of northern Australia and elsewhere in the tropics. Thus, *Rhizophora* forests may be particularly adversely affected by enhanced cyclonic frequency or intensity and other disturbances that damage aerial parts of trees.

9.1.3.3 Limits to faunal distributions

Many fauna associated with mangroves are mobile, either having larvae that are distributed within the water column, or populations that can migrate to more suitable habitat with changes in forest structure and productivity. Fauna that are confined to habitats that are at risk from sea level rise (eg high intertidal salt marsh) will be more susceptible to climate change than those using habitats that can migrate spatially, but may not be greatly reduced in area (eg seaward mangrove fringes). Mangrove losses that may occur with increased frequency and intensity of storms are likely to reduce diversity and abundance of fauna, as has been seen with other disturbances[118]. Changes in the availability or spatial arrangement of interconnected habitats (seagrass – mangroves – high intertidal), due to sea level rise, storms damage or human activity could also have a negative impact on fauna and food webs (chapter 19).

9.2 Vulnerability of mangroves to climate change

9.2.1 Changes in ocean circulation

Since mangroves have water-dispersed propagules, dispersal may be influenced by changes in oceanic circulation patterns. There are few data assessing the connectivity of populations of mangroves for the region, but a study of genetic variation in the common mangrove species *Avicennia marina* indicated

separate populations that do not currently interbreed[73,25]. Although most mangrove propagules and other debris are contained within estuaries, because of hydrological properties of estuaries[185], changes in oceanic circulation (Steinberg chapter 3) may influence dispersal and thus the genetic structure of mangrove populations. Enhanced gene flow among separated populations may increase the adaptive capacity of mangrove species. Introductions of northern mangrove species to more southern localities may also be possible (eg studies on drift seeds by Hacker[101], Smith et al.[165]) and could increase the diversity and productivity of southern mangrove communities, but range-shifts and introductions of northern mangrove species to southern locations have not yet been documented.

9.2.2 Changes in temperature

Plant and soil biochemical processes will be affected by increases in water and air temperatures. Two key processes that determine productivity; photosynthetic carbon gain and respiration, are highly sensitive to temperature. Photosynthesis in mangroves in much of the tropics is limited by high midday leaf temperatures which drive high vapour pressure deficits between leaves and air, resulting in stomatal closure[55,48,50]. In contrast, photosynthesis is limited by low temperature at southern latitudes[173]. Increases in temperature combined with declines in humidity and rainfall could reduce productivity in some northern sites by accentuating midday depressions in photosynthesis. Conversely increasing primary production would be expected at southern latitudes through increases in the length of the growing season. The effects of temperature on primary production are likely to be strongly influenced by other climate change and environmental factors that influence stomatal aperture and photosynthetic rates (eg rainfall, humidity and nutrient availability).

Respiration (CO_2 efflux) from plants and microbial communities in sediments approximately doubles with every 10ºC increase in temperature. The predicted 2ºC increase in temperature (Lough chapter 2) could therefore increase plant and soil respiration by approximately 20 percent, resulting in reduced net carbon gain, increased methane emissions and decreases in soil carbon storage[64]. As mangroves and salt marshes have large carbon and nutrient stores in soils and plant biomass[148,179,52] (Table 9.3) increases in temperature and associated increases in respiration may have negative effects on carbon balance. These effects on carbon balance may not be matched by increases in production, which in some cases, particularly in northern regions, may be reduced (eg Clark[53] for terrestrial forest ecosystems). There are significant gaps in our knowledge of how increases in temperature will influence the balance between plant productivity, respiration and microbial activity in mangroves and associated wetlands of the GBR.

9.2.3 Changes in atmospheric chemistry

Carbon dioxide is the substrate for photosynthesis and influences respiration. Due to the sensitivity of these key physiological processes to elevated CO_2, primary production in plant communities are highly sensitive to atmospheric CO_2 concentrations[68,86,20,70]. Concentrations of CO_2 in the atmosphere have already increased from 350 to 370 parts per million in the last 20 years and are predicted to approximately double by 2080, with potentially profound effects on physiological and ecological processes in all plant communities.

There are few studies of the impacts of elevated CO_2 on mangroves. Only two studies, Farnsworth et al.[86] and Ball et al.[20] directly address this issue. In other higher plants, photosynthesis and growth is often enhanced at doubled atmospheric CO_2 concentrations, however the level of enhancement is dependent on other interacting environmental factors[69,138]. Growth enhancements are also attributed to declines in respiration under enhanced CO_2 concentrations that are in the order of approximately 20 percent[70]. In mangroves, elevated CO_2 conditions (twice ambient) had little effect on growth rates when growth was limited by salinity, but increased growth by up to 40 percent when growth was limited by humidity[20]. Faster growing, less salt tolerant species were more responsive to elevated CO_2 conditions, having enhanced growth rates compared to slower growing more salt tolerant species. This may suggest that upstream productivity and expansion of mangroves into fresh and brackish wetlands could occur at an accelerating pace.

Another common plant adaptation to elevated CO_2 concentrations is decreased nitrogen invested in leaves and a concomitant increase in the carbon:nitrogen ratio of plant tissues. Changes in the stoichiometry of carbon and nutrients in plant tissue will have flow on effects to consumers[175] and on decomposition processes[28]. Elevated CO_2 concentrations are therefore likely to impact food webs, carbon and nutrient cycling and the quality of exports from mangroves.

The available data suggest that under future elevated CO_2 primary production is likely to be enhanced, although not uniformly over the range of mangrove environments within the GBR. Increases in CO_2 concentrations may partially reduce the negative effects of reduced humidity and rainfall expected where temperatures increase in northern regions. Increasing levels of CO_2 may also change patterns of species dominance and accelerate mangrove encroachment into adjacent brackish and freshwater wetlands.

9.2.4 Changes in UV

Ultraviolet B (UVB) radiation is damaging to proteins and nucleotides and thus enhanced levels can lead to damage in plant tissues. Mangroves have a suite of pigments that absorb UVB radiation within their leaves likely due to their evolution in tropical latitudes where UVB radiation levels are high[113]. Impacts of enhanced UVB radiation are most likely to affect plants in temperate regions. Anticipated effects include small reductions in photosynthetic rates and altered morphology[44]. Although, UVB radiation is predicted to have a large effect on subtidal primary producers, effect on intertidal plants is not expected to be large[66].

9.2.5 Sea level rise

9.2.5.1 Exposure and sensitivity – sea level rise

Mangroves, salt marshes and salt flats are within the intertidal zone of low energy coasts and are thus highly sensitive to rising sea level. During past sea level rise mangroves were unable to withstand rates of sea level rise that exceeded 1.4 mm per year (Bermuda[79]). However, sea level rise thresholds for mangrove loss and for changes to intertidal wetland communities will vary depending on a range of interacting factors, including geomorphological setting, tidal range, accretion (eg from sediment inputs), subsidence[79,39], tree growth rates and species composition[39,42,109]. Current rates of sea level rise

in the GBR are 2.9 mm per year (Lough chapter 2) but there is no evidence to suggest that fringing mangroves are declining. In contrast, increases in mangrove cover through recruitment into landward salt marshes have been documented in southern Australia[157,152] and encroachment of mangroves into fresh water wetlands has been observed in northern Australia[14].

Geomorphological setting and tidal regimes of mangrove habitats and associated wetlands will strongly influence responses to sea level rise[187,184,158]. Typological classifications of geomorphology[186,158,103] underlie most models of the effects of sea level rise on wetlands. For example, the classification of river delta, lagoon or estuary describes both the landform and summarises a range of landscape processes including sediment supply, wave energy and water flow rates. Thus, geomorphological classification systems combined with other modelling tools have been commonly used for the assessment of vulnerability of coastal environments to sea level rise[132,162,131].

Tidal ranges are also anticipated to have a large impact on wetland responses to sea level rise, with greater exposure expected in areas with smaller tidal ranges compared to those with larger tidal ranges[158,188] (Figure 9.1). In the GBR, mean tidal range varies widely from 1.7 to 6.2 metres (Figure 9.2). Recent models to assess the vulnerability of wetlands to sea level rise used tidal range as a key parameter, with vulnerability directly proportional to the inverse of tidal range[132] (Figure 9.3). For example, the northern GBR with its relatively low tidal range has a greater risk of wetland loss with sea level rise compared to the southern GBR that has a higher tidal range.

9.2.5.3 Impacts – sea level rise

Many of the mangrove areas of the GBR region are associated with broad, flat coastal plains that often have large areas of intertidal salt flat and high intertidal salt marsh (eg Fitsroy River[71]). In previous high sea level stands salt flats and salt marsh areas were covered in mangrove forests, in what Woodroffe[186,187] has called the 'big swamp' phase of estuary development. Sea level in the GBR region has dropped by approximately one metre in the last 6000 years resulting in mangrove forests that currently occupy the edges of coastal plains with the development of salt flats and salt marshes behind them (landward), and in areas of high rainfall, the development of extensive fresh water marshes. With sea level rise landward migration of mangroves into salt marshes, fresh water wetlands or agricultural lands (where there are no significant human barriers to prevent this) is highly probable. Landward migration is known to have occurred in the past[84,79,188], and in some areas in Australia, and globally, is already occurring (eg King Sound in northwest Western Australia[158]; Mary River, Northern Territory[14]; southern Australian salt marshes[157,152]), resulting in significant changes in diversity and ecosystem function, often necessitating changes in human utilisation of the coast[c][77,105,106,131].

Although changes are anticipated in vegetation structure and coverage of intertidal wetlands with sea level rise, understanding of the functional consequences of these changes remains mainly qualitative. The impacts of sea level rise on tidal wetland fauna, sediment trapping, nutrient and carbon fluxes are currently not known with any certainty. Using data from Table 9.3, and physical parameters available from the audit of Australian estuaries database we provide a preliminary assessment of the impacts of sea level rise on some of the ecosystem services provided by mangroves and associated wetlands

c Millenium Ecosystem Assessment 2005. www.millenniumassessment.org/en/index.aspx.

(Table 9.4). This estimation of impact is based on topographic proxies, for example, a high ratio of the area of salt marsh to mangrove is indicative of a gently sloping coastal plain, and tidal range. This is a simplification that does not account for human activities that influence wetland plant distributions (eg barriers to landward migrations and changes in sediment dynamics and nutrient enrichment).

Figure 9.1 *Variation in tidal range over the GBR*

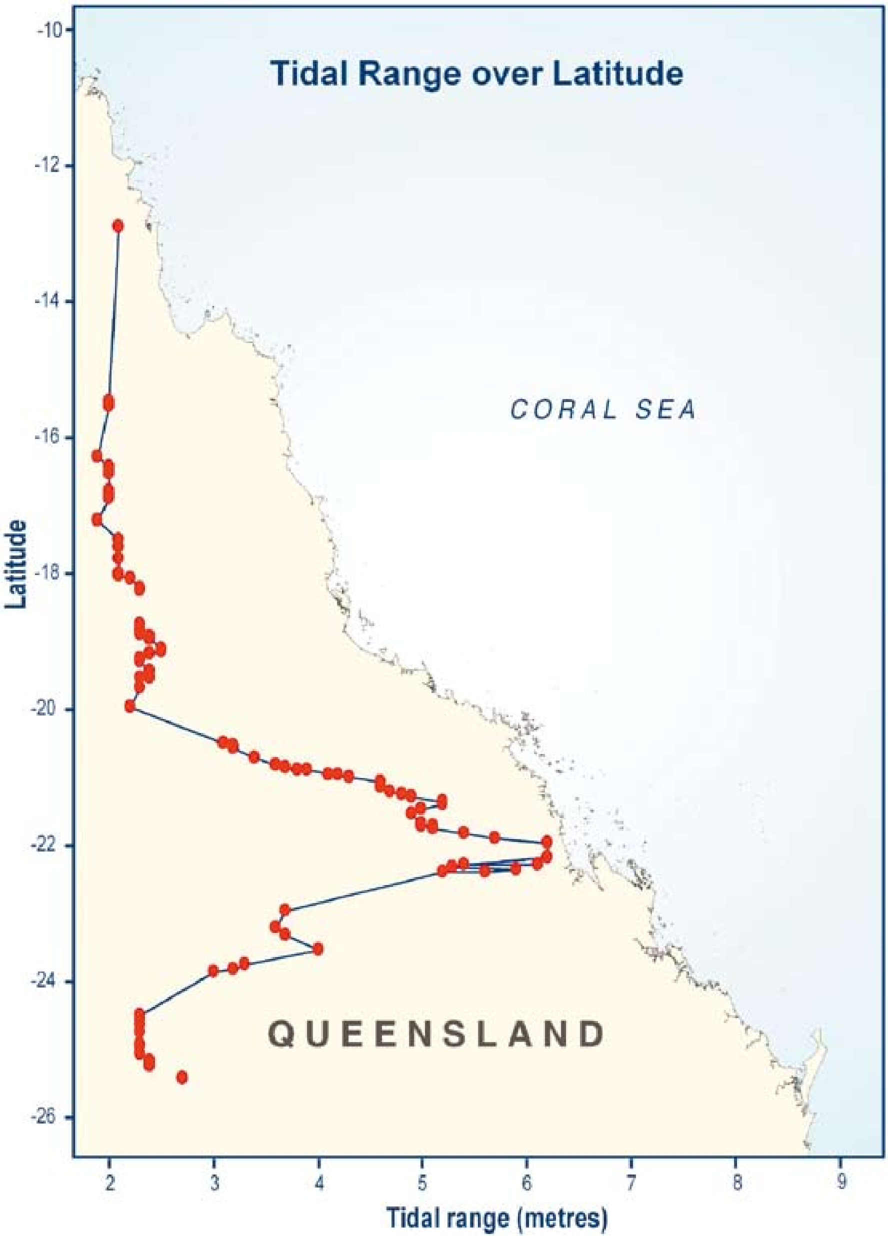


Figure 9.2 *Model indicationg the processes influencing vertical accretion in mangrove ecosystems (Adapted from Cahoon et al. 1999 by Diane Kleine)*

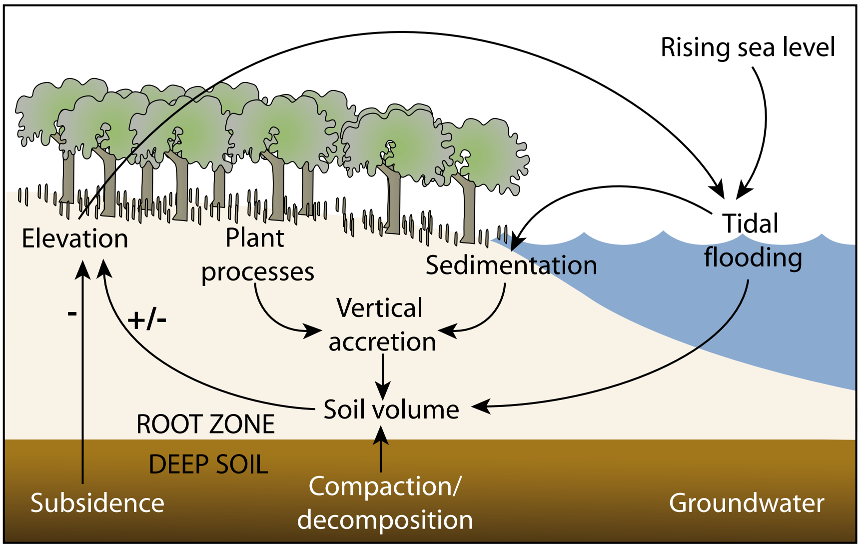


Figure 9.3 *Effects of tidal range on the proportion of mangroves affected by rising sea level. With similar bathymetry a greater proportion of mangrove forest will be lost in settings with low (microtidal) compared to high (macrotidal) tidal ranges*

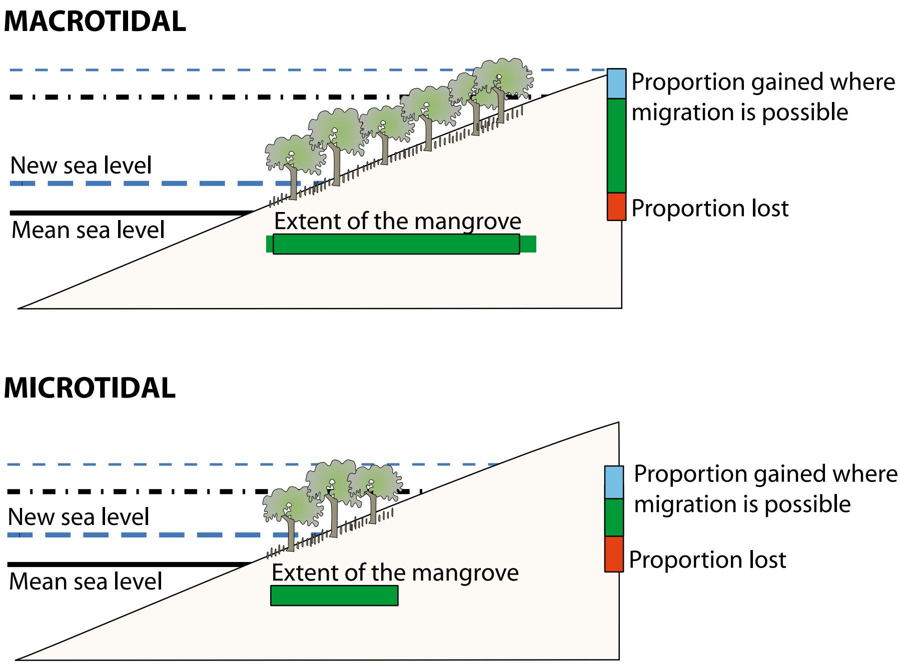


Table 9.4 *Projected changes in estuaries with sea level rise exceeding vertical accretion (no changes in rainfall, temperature or storms are considered)**

Mangrove: tidal flat+salt marsh area (km²)	Tidal range**	Exemplary estuary	Vertical migration possible	Projected change in mangrove area	Sediment trapping	Carbon and nutrient retention	Flora and Fauna
Greater than 20	Low	Johnstone	No	–	Reduced through time	Decreased as mangrove sediments eroded	Reduction in diversity of high intertidal fauna
Greater than 20	High	Pioneer	No	–	Reduced through time	Decreased as mangrove sediments eroded	Reduction in diversity of high intertidal fauna
1 to 2	Low	Burdekin	Yes – but reduced through time	+	Same or increase through time	Same – increased though time	Loss of salt marsh flora and fauna, increase in mangrove species
1 to 2	High	Sarina Inlet	Yes – but reduced through time	++	Same or increase through time	Same – increased though time	Loss of salt marsh flora and fauna, increase in mangrove species
Greater than 0.5	Low	Bohle	Yes	++	Same or increase through time	Increased though time	Loss of salt marsh flora and fauna, increase in mangrove species
Greater than 0.5	High	Fitsroy	Yes	++	Same or increase through time	Increased though time	Loss of salt marsh flora and fauna, increase in mangrove species

* The ratio of mangrove:salt marsh+salt flat vegetation was obtained from www.ozestuaries.com

** Low less than 2.5 metres, High greater than 2.5 metres

9.2.5.4 Adaptive capacity – sea level rise

Mangrove forests and other intertidal wetlands may adapt to rising sea level and remain stable if the rate of vertical accretion of the soil surface of the wetland equals or exceeds the rate of sea level rise[39,126]. This simple idea underpins many of the current models used to assess wetland stability with rising sea level (eg Nicholls et al.[132], Simas et al.[163], Nicholls[131]). Wetland soil surface elevation and its response to sea level are influenced by a suite of interacting processes and feedback mechanisms (Figure 9.3) that occur on both the surface and subsurface (Table 9.5). Elevation of the wetland soil surface is directly influenced by soil volume, which is related to several interrelated processes. Tidal floodwaters deliver sediments to wetlands, where aerial roots and pneumatophores of mangroves enhance sediment deposition, adding to soil volume[109]. In addition, soil volume is related in part to soil organic matter accumulation, which is the net result of root growth (positive soil volume) and root decomposition (negative soil volume)[37,42,43]. Groundwater drainage and storage result in shrinking and swelling of soils (negative and positive soil volume)[182], and soil compaction (reduced soil volume) also influences soil elevation. As soil elevation increases the hydroperiod, which is the frequency, depth, and duration of tidal flooding, decreases (negative feedback)[38]. When sea level rises, hydroperiod increases. So as long as soil elevation gain matches sea level rise, the wetland will maintain the same relative elevation within the tidal frame, migrating upslope if need be.

Table 9.5 *Factors affecting the soil surface elevation of wetlands and wetland stability*

Surface processes	Impact	Interacting factors
Sedimentation	Positive	Rainfall, river flows, sediment availability (catchment land use)
Subsurface processes		
Root growth	Positive (soil volume and sediment trapping and binding)	Factors that affect productivity: Nutrient enrichment, elevated CO_2, humidity, rainfall, sedimentation
Decomposition	Negative	Dependent on sediment type, species, tidal regime
Deep soil layer compaction/subsidence	Negative	Groundwater, tectonic activity
Groundwater inputs	Positive/negative	Rainfall, tidal amplitude

This model (Figure 9.3) and the instrumentation devised to test the model, the rod surface elevation table (RSET)[40,41] have been used to understand the vulnerability of wetlands to sea level rise by describing the trajectory of the elevation of coastal wetlands in response to a range of environmental conditions. In mangrove-salt marsh ecotones in southeastern Australia RSETs indicate that mangroves are invading salt marshes in the region because of subsidence of the soil surface due to reductions in groundwater inputs associated with El Niño cycles[151,152]. Subsidence increases tidal inundation, which favours the recruitment and growth of mangroves. Over the range of sites assessed by Rogers et al.,

sedimentation was a significant process in maintaining soil surface elevation in some wetlands but only accounted for 50 percent of variation in surface elevation. This result underscores the importance of other surface and subsurface processes in the maintenance of soil surface elevation and thus responses to sea level rise[151,152,43]. Using RSETs Cahoon et al.[43] observed subsidence of 37 mm per year in highly organic mangrove soils in Honduras after a severe hurricane damaged the forest, demonstrating the importance of tree growth for the maintenance of soil elevation. In both salt marshes and mangroves, nutrient enrichment has been observed to enhance vertical accretion and surface elevation through deposition of roots[126,117]. In mangroves in Micronesia, data from RSETs indicate pnuemataphore type (ie mangrove species) plays an important role in the maintenance of surface elevation through differential abilities of species to promote sedimentation and sediment binding[109].

9.2.5.5 Vulnerability and thresholds – sea level rise

Of the 97 estuaries within the GBR that have been surveyed[d], the ratio of salt marsh-salt flat to mangrove exceeds one in 30 percent of estuaries (Figure 9.4). The high proportion of salt marsh-salt flat:mangrove indicates there is a gently sloping coastal plain that is currently infrequently inundated but which may allow for a significant expansion of mangroves landward with sea level rise. Conversely, in areas of the GBR where mangrove to salt marsh ratios are high (Figure 9.5), due to steep coastal topography or to modifications by humans where barriers to landward migration of the intertidal have been created[61,110], mangrove cover is likely to be reduced with sea level rise. Reductions in intertidal wetland cover are particularly likely where there are low rates of vertical accretion and the soil surface of the wetland cannot keep up with sea level, due to some combination of low sediment availability, low root growth rates or subsurface subsidence.

The large range in tidal amplitude over the GBR also suggests that the vulnerability of mangroves to sea level rise will be variable along the coast. Following the approach of Semeniuk[158] and Woodroffe[188], mangroves and wetlands in the high tidal range areas of the GBR (latitudes greater than 20° S) should be less vulnerable to sea level rise than those in areas with low tidal ranges (latitudes less than 20° S). Geomorphological settings of highest vulnerability include low wooded islands that have a relatively low tidal range, no possibility of landward migration and limited sediment inputs. Nicholls et al.[132] defined a dimensionless relative sea level rise (RSLR* = RSLS[e]/tidal range) with a critical value ($RSRL^*_{crit}$) above which wetlands will be lost unless landward migration occurs. Data from the Caribbean, which is microtidal, suggests that $RSLR^*_{crit}$ ranges between 0.18 and 0.5. Estimates of RSLR* from the GBR, using current rates of sea level rise in the GBR (2.9 mm per year) ranges between 0.4 at sites with high tidal ranges and up to 1.6 at sites with low tidal ranges. The threshold, $RSLR^*_{crit}$ for the GBR is yet to be established, but it could be a useful tool for developing quantitative assessments of vulnerability of GBR wetlands to sea level rise.

d www.ozesturies.org

e Relative Sea Level State

Figure 9.4 *Ratio of salt marsh to mangrove area in the GBR*

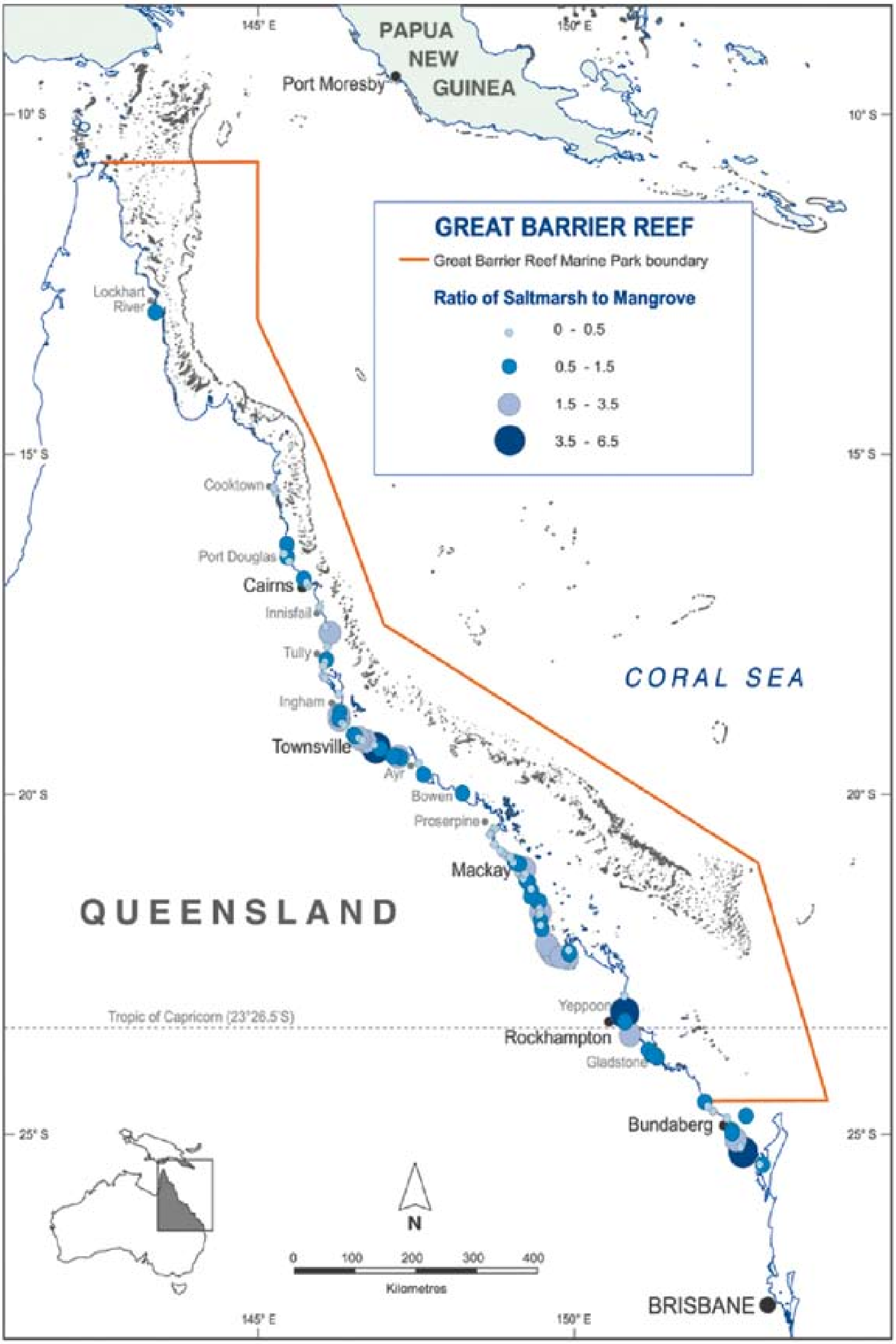
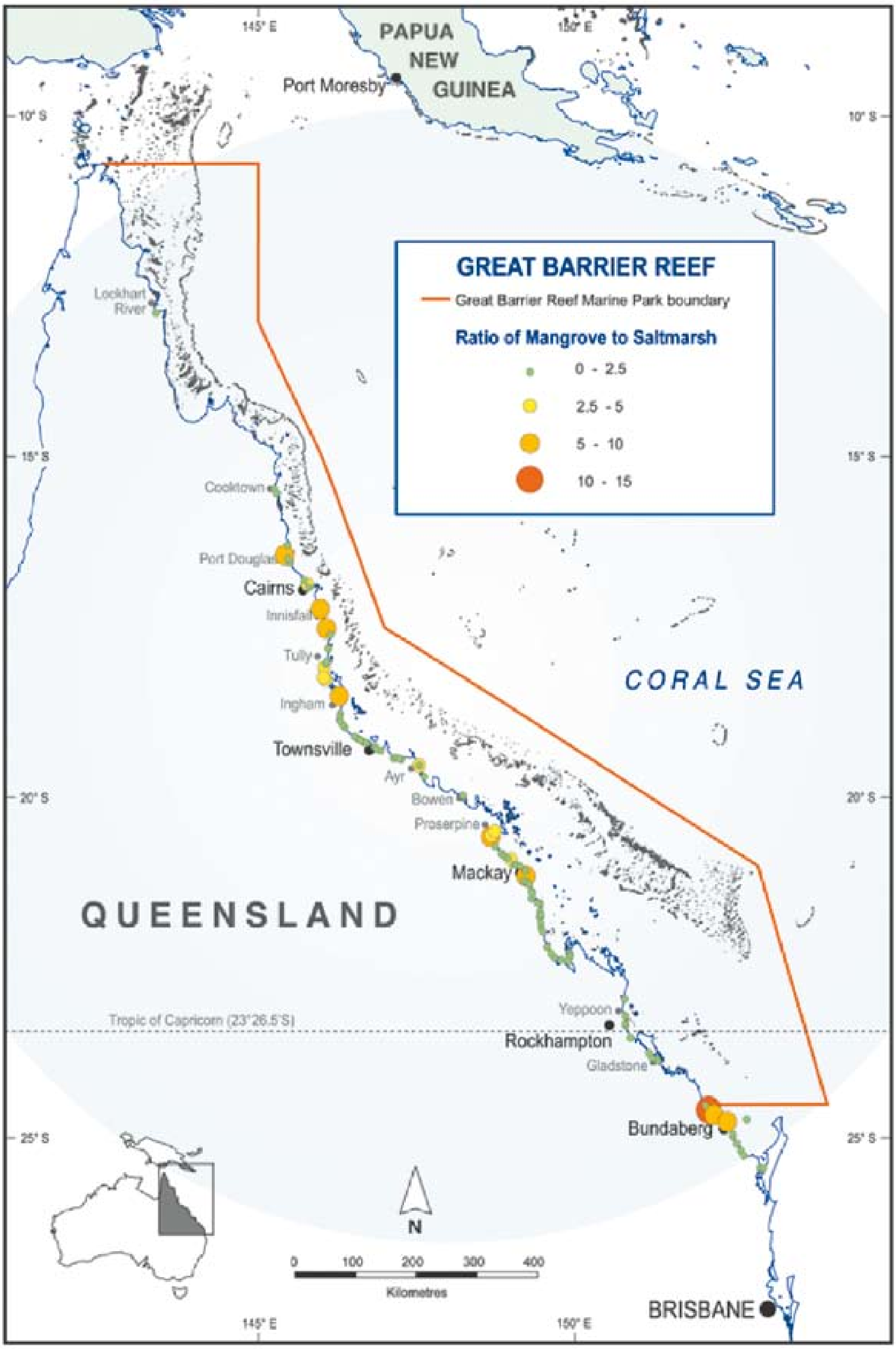


Figure 9.5 *Ratio of mangrove to salt marsh in the GBR*



9.2.6 Physical disturbance – tropical storms

Mangroves have an important role in protecting coasts from storm and tsunami damage[169,119,123,60,63]. Most tropical ports in Australia recommend small craft use mangroves as protection in the event of cyclones. For example, from the Port Douglas cyclone protection plan 'The creeks and waterways off Dicksons Inlet, within the mangrove areas, offer the best shelter/protection for small vessels'[f]. Storms can have a large impact on mangroves, with catastrophic destruction being observed in the Caribbean and Bangladesh[169,120,42], often with very slow recovery[161,136], or none at all[42]. Intense storms can strongly influence surface elevation of wetlands through erosion, deposition and subsurface processes that can subsequently influence rates of recovery[36]. Quantitative data from Australia on impacts of cyclones on mangroves, and their recovery are rare[24,189].

Data from the Caribbean indicate mangroves can recover from severe storm damage providing patches of reproductive trees remain, and hydrology and sediments are not altered to an extent where reestablishment is prevented[169,80,161]. Tree species differ in their response to cyclones, with species from the Rhisophoraceae being particularly vulnerable as they are unable to resprout[16]. The effects of cyclones on fauna associated with mangroves in Australia are not known, but loss of mangroves from human disturbances in Kenya and Malaysia resulted in declines in diversity and abundance of fauna (reviewed in Manson et al.[118]).

9.2.7 Rainfall and river flood plumes

Changes in rainfall will have a major effect on intertidal wetlands of the GBR. The predicted changes in rainfall with climate change on the GBR are complex, with increases in rainfall predicted in some regions and decreases in others. There are also predicted to be increases in the intensity of rainfall events that are likely to influence erosion and other processes in catchments of the GBR (Lough chapter 2) having flow on effects on intertidal wetlands.

Rainfall influences species composition, diversity and productivity of intertidal wetlands. Freshwater inputs to intertidal wetlands reduce salinity, increase the water content of soils and deliver sediments and nutrients creating conditions that are favourable for plant physiological function[168,18]. Rainfall also influences groundwater inputs, which can lead to the maintenance of soil surface elevation through subsurface swelling of soils[182,151]. Connectivity of habitats with flushing accumulated material from salt flats to mangroves and nearshore waters is also strongly influenced by rainfall[141] (see chapter 19).

In the GBR and other locations, sediment delivery to the estuary co-varies with rainfall[65] and increases with human development of the catchment[94]. Sedimentation increases surface elevation of wetland soils relative to sea level as well as increasing habitat for mangrove colonisation (eg Trinity Inlet, Cairns[71,74]). In addition to increasing soil surface elevation, delivery of sediments has a direct positive effect on plant growth[135,104,78,114], although it can lead to reduced diversity of fauna[78] and tree mortality if sedimentation is excessive[80]. Increases in frequency of intense rainfall events combined with land use change in catchments will increase sedimentation which will increase the availability of suitable mangrove habitat and enhance mangrove growth[114], however excessive sedimentation events could result in forest losses[80].

f http://www.marinamiragepd.com.au/cyclones.htm

Where rainfall is reduced, productivity, diversity and the area of wetlands will decline with possible increases in the area of salt flats[168]. Reduced rainfall will lead to reductions in sedimentation. Within the GBR, sedimentation in mangroves has been observed to vary between -11 mm per year (erosion) to 10 mm per year[95,26,171,34]. At the higher end, sedimentation is higher than projected sea level rise, but there is not sufficient data to determine what levels of sedimentation in mangroves occur over most of the GBR. In a study of sedimentation in southern Australia, sedimentation was higher in mangroves compared to salt marsh (approximately 5 mm per year in mangroves and 2.5 mm per year in salt marsh[150]). Sedimentation increased linearly with tidal range (sedimentation in mm per year = -4 + 3.7 x tidal range in metres). Extrapolation using the tidal range of the GBR, and assuming a similar sediment supply suggests sedimentation could vary from 1.6 to 2.8 mm per year, which is at the low end of the published range and is slightly lower than current rates of sea level rise. Thus areas of the GBR with low tidal ranges, low rainfall and limited sediment supply are more likely to experience retreat of seaward fringing mangroves with sea level rise compared to those areas with high tidal range, high rainfall and an ample sediment supply, which are conditions where mangrove expansion is likely to occur.

9.3 Threats to resilience

Overall our analysis leads us to predict that the total area of mangrove forest in the GBR is likely to increase with sea level rise, particularly as sedimentation, elevated CO_2, enhanced rainfall and nutrient enrichment have a positive influence on mangrove growth. Mangroves will migrate landward and will reoccupy salt marsh and other wetlands inland of current mangrove distributions, as has occurred in the past[186,188]. Large gains in mangrove area, possibly at the expense of salt marsh and salt flats, may be expected in the arid tropics, particularly in estuaries surrounding Townsville and Rockhampton (Figure 9.4). Increases are particularly likely if high sediment deposition rates due to land-use change in the catchments are sustained or increased with altered rainfall patterns, creating new habitat for mangrove colonisation. Additionally, high sedimentation and enhanced mangrove growth with elevated CO_2 and anthropogenic nutrient enrichment may enable mangrove fringes to maintain their position relative to sea level rise, reducing losses of seaward fringing forests due to submergence.

Losses in mangrove area may occur if high temperatures and aridity depress mangrove productivity and if sediment delivery is reduced. Pollution and storm damage could accentuate these losses[76]. Under scenarios of negative human influence (eg pollution and impoundment by building of barriers), reductions of fringing mangroves may be substantial, and forests establishing landward may have reduced productivity.

The largest threat to the resilience of intertidal wetlands with climate change is the presence of barriers that will prevent landward migration of intertidal wetland communities. Barriers to landward migration of intertidal communities can be imposed by natural features (eg steep slopes), but urban, agricultural and other human developments that build berms, bunds, seawalls and roads on coastal plains impose significant threats to resilience of mangroves, salt marsh and salt flats with sea level rise. Barriers also reduce connectivity between habitats and overall productivity (see chapter 19). Landward barriers to wetland migration will have particularly negative consequences for salt marsh and salt flat communities that are compressed between human imposed landward barriers and encroaching mangroves[157,3].

Reducing threats to resilience requires determining where barriers will lead to unacceptable changes in mangrove, salt marsh or salt flat communities followed by removal of barriers to landward migration. Areas of greatest concern are those that are highly developed (eg Cairns region) and which also have a relatively low tidal range and a high mangrove:salt marsh ratio. Additionally, where sediment and freshwater inputs (rivers and groundwater) are reduced, barriers to landward migration will have a greater negative impact on the intertidal wetlands of the GBR.

9.4 Summary and recommendations

9.4.1 Major vulnerabilities to climate change

Mangroves, salt marshes and salt flats are particularly vulnerable to sea level rise. Increases in sea level should lead to an increase in the area of mangroves, and migration of mangroves, salt marsh and salt flats upslope. This scenario is likely in areas of the GBR with high tidal ranges, where rainfall is predicted to increase and where there are no barriers to landward migration. Expansion of mangroves may be further enhanced with elevated CO_2, nutrient enrichment and warmer winter temperatures at southern latitudes. Reductions in area of mangroves, salt marsh and salt flats will occur in response to sea level rise if the soil surface elevation of the wetlands cannot keep pace with rising sea level. This is most likely to occur in areas with low tidal ranges, where rainfall is reduced, where sediment inputs are not sufficient to contribute to the maintenance of surface elevation and where groundwater depletion leads to subsidence of sediments. Additionally high temperatures, low humidity and more severe storms could also lead to reduced productivity, subsidence and erosion. The presence of human created barriers to landward migration of wetlands will have a significant negative impact on intertidal wetland cover.

Reductions in mangrove, salt marsh and salt flat area will decrease the level of ecosystem services they provide (Table 9.3), but we do not know quantitatively how reductions in area of wetland will equate to reductions in ecosystem services. This is partly because not all parts of the intertidal zone provide equivalent services, eg seaward fringes of mangroves provide disproportional level of sediment trapping compared to landward forests[95]. However, we expect that loss of diversity of flora and fauna is likely with reductions in salt marsh area and encroachment of mangroves into fresh water marshes. Sediment trapping, carbon sequestration and nutrient cycling will be reduced with declines in wetland cover resulting in higher turbidity and higher nutrient loading in nearshore waters. Carbon and nutrient subsidies to nearshore waters would also be reduced resulting in reductions in the productivity of nearshore food webs (see chapter 19).

9.4.2 Potential management responses

Increasing the resilience of GBR intertidal wetland habitats to climate change firstly requires attention to management actions that focus on responses to sea level rise. Particular attention should be focused on accommodating the landward migration of mangroves, salt marshes and salt flats. Management will be challenging. There are a wide range of current users of low elevation lands that will be directly affected by sea level rise, including farmers, large infrastructure (eg airports and ports), urban dwellers and indigenous communities. Additionally there are groups who benefit both directly

(eg fishers) and indirectly (eg water quality) from wetland ecosystem services. Currently no single regulatory body has a mandate to manage the terrestrial-marine interface or the issues arising from the competing interests of different interest groups. Given the magnitude of the expected sea level rise in the next century (Lough chapter 2), changes in the landward extent of the intertidal, the high value of the ecosystem services wetlands provide and the high value of coastal property to a range of stakeholders, the development of an organisation that can oversee management of current and future intertidal regions may be practical and desirable. Management responses should also include:

1. Quantitative assessment of lands that will become intertidal by 2080. Digital elevation models of estuaries are needed to augment and improve the OzEstuaries database.
2. Development of management processes that would a) create buffers around wetlands to increase resilience, and b) assist in relinquishing lands to accommodate landward migration of intertidal habitats.
3. Improving the knowledge of how wetlands are changing with rising sea level and with other environmental changes. This could be achieved through historical assessments (eg Duke et al.[75]) and by measuring current rates of surface elevation change relative to sea level rise in different wetland settings and under a range of environmental conditions.
4. Development of a management framework to aid decisions on whether and which wetlands should be conserved or restored in anticipation of rising sea level. Decision tools should incorporate valuation of diversity and ecosystem function and knowledge of the effects of extreme events (eg storms, pollution) on wetlands. The management framework could include consideration of the costs of restoration or defence against tidal incursions versus gains from sustaining current use and potential gains (eg fisheries habitat and carbon credits) from allowing mangrove and salt marsh landward migration.

9.4.3 Further research

The vulnerability assessment presented here is qualitative, but the information available for the GBR is extensive compared with many other tropical regions of the world. There are significant gaps in our knowledge that once filled would allow a quantitative assessment of the effects of climate change on mangroves and associated wetlands, knowledge that would aid in the development of much needed tools for managing wetlands in the GBR and elsewhere. Critical information gaps that need to be addressed include:

1. A capacity to model the effects of sea level rise on intertidal wetlands in detail in many areas of the GBR. Detailed digital elevation models of mangrove, salt marsh, salt flats and coastal plains and fine scale classification of the coast into typological units based on geomorphological characteristics would aid the development of models. Additionally more informed linkages between geomorphological classifications and ecological and physical processes would facilitate prediction of the effects of sea level rise on ecosystem services.
2. Rod surface elevation table installations that can measure the trajectory of wetland surface elevation relative to rising sea level and provide an experimental framework to link processes influencing surface elevation (eg variation in rainfall, nutrient enrichment and sedimentation) to wetland stability.

3. Knowledge of current sedimentation rates in mangroves and other wetlands (and differences from historical sedimentation rates) and the importance of sedimentation to wetland stability.
4. Understanding the magnitude of ground water inputs into mangroves and other tidal wetlands and the importance of this process to primary production, diversity and maintenance of surface elevation.
5. Improved knowledge of faunal responses to changing intertidal wetland plant species composition, changes in extent and connectivity of habitats and changes in productivity.
6. An enhanced understanding of how climate change factors interact with other human induced changes (eg nutrient enrichment) to influence productivity and stability.
7. Knowledge of the sensitivity of carbon and nutrient storage and cycling in intertidal wetland soils to climate change drivers (atmospheric changes, temperature and sea level rise) and how this varies spatially within GBR wetlands.
8. Quantitative understanding of the impacts of cyclones on intertidal wetlands, rates of recovery and interactions with other factors (eg sea level rise).
9. Development of decision tools for management of the GBR that incorporate biological, social and economic factors.

References

1 Adam P (1990) *Saltmarsh ecology*. Cambridge University Press, Melbourne.

2 Adam P (1995) Salt marshes. In: *PL Zann (ed) Our Sea, Our Future, Major findings of the State of the Marine Environment Report for Australia. Great Barrier Reef Marine Park Authority, Townsville.*

3 Adam P (2002) Saltmarshes in a time of change. *Environmental Conservation* 29, 39–61.

4 Alongi DM (1987) Intertidal zonation and seasonality in meiobenthos in tropical mangrove estuaries. *Marine Biology* 95, 447–458.

5 Alongi DM (2002) Present state and future of the world's mangrove forests. *Environmental Conservation* 29, 331–349.

6 Alongi DM and Sasekumar A (1992) Benthic Communities. In: AI Robertson and DM Alongi (eds) *Tropical Mangrove Ecosystems. Coastal and Estuarine Studies* 41. American Geophysical Union, Washington, DC, pp. 137-171.

7 Alongi DM, Boto KG and Robertson AI (1992) Nitrogen and phosphorus cycles. In: A Robertson and D Alongi (eds) *Tropical Mangrove Ecosystems*, Volume 41 American Geophysical Union, Washington DC, pp. 251-292.

8 Alongi DM, Ayukai T, Brunskill GJ, Clough BF and Wolanski E (1998) Sources, sinks and export of organic carbon through a tropical, semi-enclosed delta (Hinchinbrook Channel, Australia). *Mangroves and Salt Marshes* 2, 237–242.

9 Alongi DM, Wattayakorn G, Pfitzner J, Tirendi F, Zagorskis I, Brunskill GJ, Davidson A and Clough BF (2001) Organic carbon accumulation and metabolic pathways in sediments of mangrove forests in southern Thailand. *Marine Geology* 179, 85–103.

10 Alongi DM, Trott LA, Wattayakorn G and Clough BF (2002) Below-ground nitrogen cycling in relation to net canopy production in mangrove forests of southern Thailand. *Marine Biology* 140, 855–864.

11 Alongi DM, Clough BF, Dixon P and Tirendi F (2003) Nutrient partitioning and storage in arid-zone forests of the mangroves *Rhizophora stylosa* and *Avicennia marina*. *Trees* 17, 51–60.

12 Alongi DM, Sasekumar A, Chong VC, Pfitzner J, Trott LA, Terendi F, Dixon P and Brunskill GJ (2004) Sediment accumulation and organic material flux in a managed mangrove ecosystem, estimates of land-ocean-atmosphere exchange in peninsular Malaysia. *Marine Geology* 208, 383–402.

13 Alongi DM, Pfitzner J, Trott LA, Dixon P and Klumpp DW (2005) Rapid soil accumulation and microbial mineralization in forests of the mangrove *Kandelia candel* in the Jiulongjiang estuary, China. *Estuarine and Coastal Shelf Science* 63, 605–618.

14 Applegate RJ (1999) Saltwater intrusion and the Mary River Wetlands of the Northern Territory. In: WJ Streever (ed) *An International Perspective on Wetland Rehabilitation.* Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 113–120.

15 Ayukai T, Miller D, Wolanski E and Spagnol S (1998) Fluxes of nutrients and dissolved and particulate organic carbon in two mangrove creeks in northeastern Australia. *Mangroves and Saltmarshes* 2, 223–230.

16 Baldwin A, Egnotovich M, Ford M and Platt W (2001) Regeneration in fringe mangrove forests damaged by Hurricane Andrew. *Plant Ecology* 157, 149–162.

17 Ball MC (1988) Ecophysiology of mangroves. *Trees* 2, 129–142.

18 Ball MC (1998) Mangrove species richness in relation to salinity and waterlogging, a case study along the Adelaide River floodplain, northern Australia. *Global Ecology and Biogeography Letters* 7, 73–82.

19 Ball MC and Munns R (1992) Plant responses to salinity under elevated atmospheric concentrations of CO_2. *Australian Journal of Botany* 40, 515–525.

20 Ball MC, Cocharane MJ and Rawson HM (1997) Growth and water use of the mangroves *Rhizophora apiculata* and *R. stylosa* in response to salinity and humidity under ambient and elevated concentrations of atmospheric CO_2. *Plant Cell and Environment* 20, 1158–1166.

21 Baran E and Hambrey J (1999) Mangrove Conservation and Coastal Management in Southeast Asia, What Impact on Fishery Resources? *Marine Pollution Bulletin* 37, 431–440.

22 Barbier EB (2000) Valuing the environment as input, review of applications to mangrove-fishery linkages. *Ecological Economics* 35, 47–61.

23 Barbier EB and Strand I (1998) Valuing mangrove fishery linkages. A case study of Campeche, Mexico. *Environmental and Resource Economics* 12, 151–166.

24 Bardsley K (1985) The effects of Cyclone Kathy on mangrove vegetation. In: K Bardsley, J Davie and C Woodroffe (eds) *Coasts and tidal wetlands of the Australian monsoon region.* Canberra, Australian National University North Australia Research Unit, pp. 167–185.

25 Benzie JAH (1999) Genetic Structure of Coral Reef Organisms, Ghosts of Dispersal Past. *American Zoologist* 39,131–145.

26 Bird E and Barson M (1977) Measurement of physiographic changes on mangrove fringed estuaries and coastlines. *Marine Resources Indonesia* 18, 73–80.

27 Blaber SJM (2002) 'Fish in hot water': the challenges facing fish and fisheries research in tropical estuaries. *Journal of Fish Biology* 61, 1–20.

28 Bosire JO, Dahdouh-Guebas F, Kairo JG, Kazungu J, Dehairs F and Koedam N (2005) Litter degradation and CN dynamics in reforested mangrove plantations at Gazi Bay, Kenya. *Biological Conservation* 126, 287–296.

29 Boto KG and Bunt JS (1981) Tidal export of particulate organic matter from a Northern Australian mangrove system. *Estuarine, Coastal and Shelf Science* 13, 247–255.

30 Boto KG and Robertson AI (1990) The relationship between nitrogen fixation and tidal exports of nitrogen in a tropical mangrove system. *Estuarine, Coastal and Shelf Science* 31, 531–540.

31 Boto KG and Wellington JT (1983) Phosphorus and nitrogen nutritional status of a northern Australian mangrove forest. *Marine Ecology Progress Series* 11, 63–69.

32 Boto KG and Wellington JT (1988) Seasonal variation in concentrations and fluxes of dissolved organic and inorganic materials in a tropical, tidally-dominated, mangrove waterway. *Marine Ecology Progress Series* 50, 151–160.

33 Bouillon S, Koedam N, Raman AV and Dehairs F (2002) Primary producers sustaining macro-invertebrate communities in intertidal mangrove forests. *Oecologia* 130, 441–448.

34 Bryce S, Larcombe P and Ridd PV (2003) Hydrodynamic and geomorphological controls on suspended sediment transport in mangrove creek systems, a case study, Cocoa Creek, Townsville, Australia. *Estuarine, Coastal and Shelf Science* 56, 415–431.

35 Bucher D and Saenger P (1991) An inventory of Australian estuaries and enclosed marine waters, an overview of results. *Australian Geographical Studies* 29, 370–381.

36 Cahoon DR (2006) A review of major storm impacts on coastal wetland elevations. *Estuaries and Coasts* 29, 889-898.

37 Cahoon DR and Lynch JC (1997) Vertical accretion and shallow subsidence in a mangrove forest of southwestern Florida, U.S.A. *Mangroves and Salt Marshes* 1, 173–186.

38 Cahoon DR, Reed DJ and Day JW (1995) Estimating shallow subsidence in microtidal salt marshes of the southeastern United States, Kaye and Barghoorn revisited. *Marine Geology* 128, 1–9.

39 Cahoon DR, Day JW and Reed DJ (1999) The influence of surface and shallow subsurface soil processes on wetland elevation, a synthesis. *Current Topics in Wetland Biogeochemistry* 3, 72–88.

40 Cahoon DR, Lynch JC, Hensel P, Boumans R, Perez BC, Segura B and Day JW (2002a) High-precision measurements of wetland sediment elevation, I. Recent improvements to the sedimentation-erosion table. *Journal of Sedimentary Research* 72, 730–733.

41 Cahoon DR, Lynch JC, Perez BC, Segura B, Holland RD, Stelly C, Stephenson G and Hensel P (2002b) High-precision measurements of wetland sediment elevation, II. The rod surface elevation table. *Journal of Sedimentary Research* 72, 730–733.

42 Cahoon DR, Hensel P, Rybczyk J, McKee KL, Proffitt ED and Perez BC (2003) Mass tree mortality leads to mangrove peat collapse at Bay islands, Honduras after Hurricane Mitch. *Journal of Ecology* 91, 1093–1105.

43 Cahoon D, Hensel P, Spencer T, Reed DJ, McKee KL and Saintilan N (2006) Coastal wetland vulnerability to relative sea-level rise: Wetland elevation trends and process controls. In: JTA Verhoeven, B Beltman, R Bobbink and DF Whigham (eds) *Ecological Studies*, Volume 190 Wetlands and natural resource management, Springer-Verlag, Berlin, pp. 271–292.

44 Caldwell MM, Ballaré CL, Bornman JF, Flint SD, Björn LO, Teramura AH, Kulandaivelu G and Tevini M (2003) Terrestrial ecosystems, increased solar ultraviolet radiation and interactions with other climatic change factors. *Photochemical and Photobiological Science* 2, 29–38.

45 Carpenter SR, Walker BH, Anderies JM and Abal N (2001) From metaphor to measurement: Resilience of what to what? *Ecosystems* 4, 765–781.

46 Chapman VJ (1974) *Salt Marshes and Salt Deserts of the World.* 2nd Edition, J Cramer, supplemented reprint. Lehre, Germany.

47 Chappell J and Grindrod J (1985) Pollen analysis, a key to past mangrove communities and successional changes in North Australian coastal environments. In: KN Bardsley, JDS Davie and CD Woodroffe (eds) *Coasts and Tidal Wetlands of the Australian Monsoon Region.* Mangrove Monograph No. 1.1, North Australia Research Unit, Australian National University, Darwin, pp. 225–236.

48 Cheeseman JM (1994) Depressions of photosynthesis in mangrove canopies. In: NR Baker and JR Bowyer (eds) *Photoinhibition of Photosynthesis, From Molecular Mechanisms to the Field.* Bios Scientific Publishers, Oxford, pp. 377–389.

49 Cheeseman JM, Clough BF, Carter DR, Lovelock CE, Eong OJ and Sim RG (1991) The analysis of photosynthetic performance in leaves under field conditions, A case study using *Bruguiera* mangroves. *Photosynthesis Research* 29, 11–22.

50 Cheeseman JM, Herendeen LB, Cheeseman AT and Clough BF (1997) Photosynthesis and photoprotection in mangroves under field conditions. *Plant Cell and Environment* 20, 579–588.

51 Chitaro P, Usseglio P and Sale PF (2005) Variation in fish density, assemblage composition and relative rates of predation among mangrove, seagrass and coral reef habitats. *Environmental Biology of Fishes* 72, 175–187.

52 Chmura GL, Anisfeld SC, Cahoon DR and Lynch JC (2003) Global carbon sequestration in tidal, saline wetland soils. *Global Biogeochemical Cycles* 17, 1111–1120.

53 Clark DA (2004) Sources or sinks? The responses of tropical forests to current and future climate and atmospheric composition. *Philosophical Transactions of the Royal Society B, Biological Sciences* 359, 477–491.

54 Clough BF (1984) Growth and salt balance of the mangroves, *Avicennia marina* (Forsk.) Vieerh. and *Rhizophora stylosa* Griff. in relation to salinity. *Australian Journal of Plant Physiology* 11, 419–430.

55 Clough BF and Sim RG (1989) Changes in gas exchange characteristics and water use efficiency of mangroves in response to salinity and vapour pressure deficit. *Oecologia* 79, 38–44.

56 Costanza R, d'Arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill RVO, Paruelo J, Raskin RG, Sutton P and van den Belt M (1997) The value of the world's ecosystem services and natural capital. *Nature* 387, 253–260.

57 Crowley GM (1996) Late Quaternary mangrove distribution in northern Australia. *Australian Systematic Botany* 9, 219–225.

58 Dahdouh-Guebas F and Koedam N (2006) Coastal vegetation and the Asian tsunami. *Science* 311, 37–38.

59 Dahdouh-Guebas F, Verneirt M, Tack JF, Van Speybroeck D and Koedam N (1998) Propagule predators in Kenyan mangroves and their possible effect on regeneration. *Marine and Freshwater Research* 49, 345–350.

60 Dahdouh-Guebas F, Jayatissa LP, Di Nitto D, Bosire JO, Lo Seen D and Koedam N (2005a) How effective were mangroves as a defense against the recent tsunami? *Current Biology* 15, R443–447.

61 Dahdouh-Guebas F, Hettiarachchi S, Sooriyarachchi S, Lo Seen D, Batelaan O, Jayatissa LP and Koedam N (2005b) Transitions in ancient inland freshwater resource management in Sri Lanka affect biota and human populations in and around coastal lagoons. *Current Biology* 15, 579–586.

62 Dale P and Knight J (2003) *Coastal indicator knowledge and information system I: Biophysical Indicators*. Geoscience Australia, Canberra, www.ozestuaries.org/indicators.

63 Danielsen F, Sørensen MK, Olwig MF, Selvam V, Parish F, Burgess ND, Hiraishi T, Karunagaran VM, Rasmussen MS, Hansen LB, Quarto A and Suryadiputra N (2005) The Asian Tsunami, A Protective Role for Coastal Vegetation. *Science* 310, 643.

64 Davidson EA and Janssens IA (2006) Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature* 440, 165–173.

65 Davies PL and Eyre BD (2005) Estuarine modification of nutrient and sediment exports to the Great Barrier Reef Marine Park from the Daintree and Annan River catchments. *Marine Pollution Bulletin* 51, 174–185.

66 Day TA and Neale PJ (2002) Effects of UV-B radiation on terrestrial and aquatic primary producers. *Annual Review of Ecology and Systematics* 33, 371–396.

67 Dittmar T, Hertkorn N, Kattner G, Lara RJ (2006) Mangroves, a major source of dissolved organic carbon to the oceans. *Global Biogeochemical Cycles* 20,1–7.

68 Drake BG, Muehe MS, Peresta G, Gonzalez-Meler MA and Matamala R (1996) Acclimation of photosynthesis, respiration and ecosystem carbon flux of a wetland on Chesapeake Bay, Maryland to elevated atmospheric CO_2 concentration. *Plant and Soil* 187, 111–118.

69 Drake BG, Gonzalez-Meler MA and Long SP (1997) More efficient plants, a consequence of rising atmospheric CO_2? *Annual Review of Plant Physiology and Plant Molecular Biology* 48, 607–737.

70 Drake BG, Azcon-Bieto J, Berry J, Bunce J, Dijkstra P, Farrar J, Gifford RM, Gonzalez-Meler MA, Koch G, Lambers H, Siedow J and Wullschleger S (1999) Does elevated atmospheric CO_2 inhibit mitochondrial respiration in green plants? *Plant, Cell and Environment* 22, 649–657.

71 Duke NC (1997) Mangroves in the Great Barrier Reef World Heritage Area: current status, long-term trends, management implications and research. In: D Wachenfeld, J Oliver and K Davis (eds) *State of the Great Barrier Reef World Heritage Area Workshop*. Great Barrier Reef Marine Park Authority, Townsville, pp. 288–299.

72 Duke NC, Ball MC and Ellison JC (1998a) Factors influencing biodiversity and distributional gradients in mangroves. *Global Ecology and Biogeography Letters* 7, 27–47.

73 Duke NC, Benzie JAH, Goodall JA and Bailment ER (1998b) Genetic structure and evolution of species in the mangrove genus *Avicennia* (Avicenniaceae) in the Indo-Pacific. *Evolution* 52, 1612–1626.

74 Duke NC and Wolanski E (2001) Muddy coastal waters and depleted mangrove coastlines – depleted seagrass and coral reefs. In: E Wolanski (ed) *Oceanographic Processes of Coral Reefs*. CRC. Boca Raton. pp. 77–91.

75 Duke NC, Lawn P, Roelfsema CM, Zahmel KN, Pedersen D, Harris C, Steggles N and Tack C (2003) *Assessing Historical Change in Coastal Environments – Port Curtis, Fitzroy River Estuary and Moreton Bay Regions, Historical Coastlines. CRC for coastal zone, estuary and waterways management.* University of Queensland Press, St. Lucia.

76 Duke NC, Bell AM, Pedersen DK, Roelfsema CM and Bengston-Nash S (2005) Herbicides implicated as the cause of severe mangrove dieback in the Mackay region, NE Australia – serious implications for marine plant habitats of the GBR World Heritage Area. *Marine Pollution Bulletin* 51, 308–324.

77 Eliot C, Finlayson M and Waterman P (1999) Predicted climate change, sea-level rise and wetland management in the Australian wet-dry tropics. *Wetlands Ecology and Management* 7, 63–81.

78 Ellis J, Nicholls P, Craggs R, Hofstra D and Hewitt J (2004) Effects of terrigenous sedimentation on mangrove physiology and associated macrobenthic communities. *Marine Ecology Progress Series* 270, 71–82.

79 Ellison JC (1993) Mangrove retreat with rising sea-level, Bermuda. *Estuarine Coastal and Shelf Science* 37, 75–87.

80 Ellison JC (1998) Impacts of sediment burial on mangroves. *Marine Pollution Bulletin* 37, 8–12.

81 Ellison JC (2005) Holocene palynology and sea-level change in two estuaries in Southern Irian Jaya. *Palaeogeography, Palaeoclimatology, Palaeoecology* 220, 291–309.

82 Ellison AM and Farnsworth EJ (1996a) Anthropogenic disturbance of Caribbean mangrove ecosystems: past impacts, present trends, and future predictions. *Biotropica* 28, 549–565.

83 Ellison AM and Farnsworth EJ (1996b) Spatial and temporal variability in growth of *Rhizophora* mangle saplings on coral cays, Links with variation in insolation, herbivory, and local sedimentation rate. *Journal of Ecology* 84, 717–731.

84 Ellison JC and Stoddart DR (1991) Mangrove ecosystem collapse during predicted sea-level rise – Holocene analogs and implications. *Journal of Coastal Research* 7, 151–165.

85 Ewel KC, Twilley RR and Ong JE (1998) Different kinds of mangrove forests provide different goods and services. G*lobal Ecology Biogeography Letters* 7, 83–94.

86 Farnsworth EJ, Ellison AM and Gong WK (1996) Elevated CO_2 alters anatomy, physiology, growth, and reproduction of red mangrove (*Rhizophora mangle* L.). *Oecologia* 108, 599–609.

87 Faunce CH and Serafy JE (2006) Mangroves as fish habitat: 50 years of field studies. *Marine Ecology Progress Series* 318, 1–18.

88 Feller IC (2002) The role of herbivory by wood-boring insects in mangrove ecosystems in Belize. *Oikos* 97, 1657–176.

89 Feller IC and Mathis WN (1997) Primary herbivory by wood-boring insects along a tree-height architectural gradient of *Rhizophora mangle* L. in Belizean mangrove swamps. *Biotropica* 29, 440–451.

90 Feller IC, Whigham DF, O'Neill JP and McKee KM (1999) Effects of nutrient enrichment on within-stand nutrient cycling in mangrove ecosystems in Belize. *Ecology* 80, 2193–2205.

91 Feller IC, Whigham DF, McKee KL and Lovelock CE (2003a) Nitrogen limitation of growth and nutrient dynamics in a disturbed mangrove forest, Indian River Lagoon, Florida. *Oecologia* 134, 405–414.

92 Feller IC, McKee KL, Whigham DF and O'Neill JP (2003b) Nitrogen vs. phosphorus limitation across and ecotonal gradient in a mangrove forest. *Biogeochemistry* 62, 145–175.

93 Fosberg FR (1961) Vegetation-free zone on dry mangrove coastline. *United States Geological Society Professional Papers* 424(D), 216–218.

94 Furnas M (2003) *Catchments and Corals. Terrestrial Runoff to the Great Barrier Reef.* Australian Institute of Marine Science, Townsville.

95 Furukawa K and Wolanski E (1996) Sedimentation in mangrove forests. *Mangroves and Salt Marshes* 1, 3–10.

96 Furukawa K, Wolanski E and Mueller H (1997) Currents and sediment transport in mangrove forests. *Estuarine, Coastal and Shelf Science* 44, 310–310.

97 Galloway RW (1982) Distribution and physiographic patterns of Australian mangroves. *In: BF* Clough (ed) *Mangrove ecosystems in Australia, Structure, function and management.* Australian National University Press, Canberra, pp. 31–54.

98 Gattuso JP, Frankignoulle M and Wollast R (1998) Carbon and carbonate metabolism in coastal aquatic ecosystems. *Annual Review of Ecology and Systematics* 29, 405–434.

99 Grindrod J, Moss P and van der Kaars S (1999) Late Quaternary cycles of mangrove development and decline on the north Australian continental shelf. *Journal of Quaternary Science* 14, 465–470.

100 Guest MA, Connolly RM and Loneragan NR (2004) Carbon movement and assimilation by invertebrates in estuarine habitats at a scale of metres. Marine Ecology Progress Series 278, 27–34.

101 Hacker JB (1990) Drift seeds and fruits on Raine Island, northern Great Barrier Reef, Australia. *Journal of Biogeography* 17,19–24.

102 Hashimoto TR, Saintilan N and Haberle SG (2006) Mid-Holocene development of mangrove communities featuring Rhizophoraceae and geomorphic change in the Richmond River estuary, New South Wales, Australia. *Geographical Research* 44, 63–76.

103 Heap AD, Bryce S and Ryan DA (2004) Facies evolution of Holocene estuaries and deltas, a large-sample statistical study from Australia. *Sedimentary Geology* 168, 1–17.

104 Hemminga MA, Slim FJ, Kazungu J, Ganssen GM, Nieuwenhuize J and Kruyt NM (1994) Carbon outwelling from a mangrove forest with adjacent seagrass beds and coral reefs (Gazi Bay, Kenya). *Marine Ecology Progress Series* 106, 291–301.

105 IPCC (2002a) *Climate Change 2001, Impacts, Adaptation and Vulnerability*. JJ McCarthy, OF Canziani, NA Leary, DJ Dokken and KS White (eds) Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, UK.

106 IPCC (2002b) *Climate Change and Biodiversity*. H Gitay, A Suárez, RT Watson and DJ Dokken (eds) IPCC Technical Paper V.

107 Joye SB and Lee RY (2004) Benthic microbial mats, important sources of fixed nitrogen and carbon to the Twin Cays, Belize ecosystem. *Atoll Research Bulletin* 528, 1–24.

108 Kimani EN, Mwatha GK, Wakwabi EO, Ntiba JM and Okoth BK (1996) Fishes of a shallow tropical mangrove estuary, Gazi, Kenya. *Marine and Freshwater Research* 47, 857–868.

109 Krauss KW, Allen JA and Cahoon DR (2003) Differential rates of vertical accretion and elevation change among aerial roots types in Micronesian mangrove forests. *Estuarine Coastal Shelf Science* 56, 251–259.

110 Lee SY, Dunn RJK, Young RA, Connolly RM, Dale PER, Dehayr R, Lemckert CJ, McKinnon S, Powell B, Teasdale PR and Welsh DT (2006) Impact of urbanization on coastal wetland structure and function. *Austral Ecology* 31, 149–157.

111 Loneragan NR, Bunn SE and Kellaway DM (1997) Are mangroves and seagrasses sources of organic carbon for penaeid prawns in a tropical Australian estuary? A multiple stable-isotope study. *Marine Biology* 130, 289–300.

112 Lovelock CE and Feller IC (2003) Photosynthetic performance and resource utilization of two mangrove species coexisting in a hypersaline scrub forest. *Oecologia* 134, 455–462.

113 Lovelock CE, Clough BF and Woodrow IE (1992) Distribution and accumulation of ultraviolet-radiation-absorbing compounds in leaves of tropical mangroves. *Planta* 188, 143–154.

114 Lovelock CE, Feller IC, Ellis J, Hancock N, Schwarz AM and Sorrell B (2007) Mangrove growth in New Zealand estuaries: The role of nutrient enrichment at sites with contrasting rates of sedimentation. *Oecologia* doi 10.1007/s00442-007-0750-y.

115 Lugo AE and Snedaker SC (1974) The ecology of mangroves. *Annual Review of Ecology and Systematics* 5, 39–64.

116 McKee KL (1996) Growth and physiological responses of neotropical mangrove seedlings to root zone hypoxia. *Tree Physiology* 16, 883–889.

117 McKee KL, Cahoon DR, Feller IC (2007) Caribbean mangroves adjust to rising sea level through biotic controls on change in soil elevation. *Global Ecology and Biogeography* doi: 10.1111/j.1466-8238.2007.00317.x.

118 Manson FJ, Loneragan NR, Harch BD, Skilleter GA and Williams L (2005) A broadscale analysis of links between coastal fisheries production and mangrove extent, A case-study for northeastern Australia. *Fisheries Research* 74, 69–85.

119 Massel SR, Furukawa K and Brinkman RM (1999) Surface wave propagation in mangrove forests. *Fluid Dynamics Research* 24, 219–249.

120 Mastaller M (1996) Destruction of mangrove wetlands-causes and consequences. *Natural Resources and Development* 43/44, 37–57.

121 Mazda Y, Magi M, Kogo M and Hong PN (1997a) Mangroves as a coastal protection from waves in the Tong King delta, Vietnam. *Mangroves and Salt Marshes* 1, 127–135.

122 Mazda Y, Wolanski E, King B, Sase A, Ohtsuka D and Magi M (1997b) Drag force due to vegetation in mangrove swamps. *Mangroves and Salt Marshes* 1, 193–199.

123 Mazda Y, Magi M, Nanao H, Kogo M, Miyagi T, Kanazawa N and Kobashi D (2002) Coastal erosion due to long-term human impact on mangrove forests. *Wetlands Ecology and Management* 10, 1–9.

124 Mazumder D, Saintilan N and Williams RJ (2005) Temporal variations in fish catch using pop nets in mangrove and saltmarsh flats at Towra Point, NSW, Australia. *Wetlands Ecology and Management* 13, 457–467.

125 Melville AJ and Connolly RM (2003) Spatial analysis of stable isotope data to determine primary sources of nutrition for fish. *Oecologia* 136, 499-507.

126 Morris JT, Sundareshwar PV, Nietch CT, Kierfve B and Cahoon DR (2002) Responses of coastal wetlands to rising sea level. *Ecology* 83, 286–287.

127 Morton RM (1990) Community structure, standing crop and density of fishes in a subtropical Australian mangrove area. *Marine Biology* 105, 385–394.

128 Mumby PJ (2006) The impact of exploiting grazers (Scaridae) on the dynamics of Caribbean coral reefs. *Ecological Applications* 16, 747–769.

129 Mumby PJ, Edwards AJ, Arias-González JE, Lindeman KC, Blackwell PG, Gall A, Gorczynska MI, Harborne AR, Pescod CL, Renken H, Wabnitz CCC and Llewellyn G (2004) Mangroves enhance the biomass of coral reef fish communities in the Caribbean. *Nature* 427, 533–536.

130 Neil DT (2000) Characteristics and Significance of a Sub-tropical 'Low Wooded Island', Green Island, Moreton Bay, Australia. *Journal of Coastal Research* 16, 287–294.

131 Nicholls RJ (2004) Coastal flooding and wetland loss in the 21st Century, Changes under the SRES climate and socio-economic scenarios. *Global Environmental Change* 14, 69–86.

132 Nicholls RJ, Hoozemans MJ and Marchand M (1999) Increasing flood risk and wetland losses due to global sea-level rise, regional and global analyses. *Global Environmental Change* 9, S69–S87.

133 Onuf CP, Teal JM and Valiela I (1977) Interactions of nutrients, plant growth and herbivory in a mangrove ecosystem. *Ecology* 58, 514–526.

134 Paling EI, McComb AJ and Pate JS (1989) Nitrogen fixation (acetylene reduction) in non-heterocystous cyanobacterial mats from the Dampier Archipelago, Western Australia. *Australian Journal of Marine and Freshwater Research* 40, 147–153.

135 Pezeshki SR, DeLaune RD and Pardue IM (1992) Sediment addition enhances transpiration and growth of *Spartina alternijova* in deteriorating Louisiana Gulf Coast salt marshes. *Wetlands Ecology and Management* 1, 185–189.

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

137 Polis GA, Anderson WB and Holt RD (1997) Toward an integration of landscape ecology and food web ecology, the dynamics of spatially subsidized food webs. *Annual Review of Ecology and Systematics* 28, 289–316.

138 Poorter H and Perez-Soba M (2001) The growth response of plants to elevated CO_2 under non-optimal environmental conditions. *Oecologia* 129, 1–20.

139 Primavera JH (1996) Stable carbon and nitrogen isotope ratios of penaeid juveniles and primary producers in a riverine mangrove in Guimaras, Philippines. *Bulletin of Marine Science* 58, 675–683.

140 Ridd PV (1986) Flow through animal burrows in mangrove creeks. *Estuarine, Coastal and Shelf Science* 43, 617–625.

141 Ridd PV, Sandstrom MW and Wolanski E (1988) Outwelling from tropical tidal salt flats. *Estuarine Coastal and Shelf Science* 26, 243–253.

142 Rivera-Monroy VH, Twilley RR, Bone D, Childers DL, Coronado-Molina C, Davis S, Feller IC, Fitz C, Fourqurean J, Herrera-Silveira J, Jaffe R, Madden C, Mancera E, Medina E, Rejmankova E, Richards J, Salisbury JE, Spiniello P, Trexler J and Weil E (2004) A conceptual framework to develop long-term ecological research and management objectives in the wider Caribbean region. *Bioscience* 54, 843–856.

143 Robertson AI (1986) Leaf-burying crabs, their influence on energy flow and export from mixed mangrove forests (*Rhizophora* spp.) in northeastern Australia. *Journal of Experimental Marine Biology and Ecology* 102, 237–248.

144 Robertson AI (1988) Decomposition of mangrove leaf litter in tropical Australia. *Journal of Experimental Marine Biology and Ecology* 116, 235–247.

145 Robertson AI (1991) Plant–animal interactions and the structure and function of mangrove forest ecosystems. *Australian Journal of Ecology* 16, 433–443.

146 Robertson AI and Blaber SJM (1993) Plankton, epibenthos and fish communities. In: AI Robertson and DM Alongi (eds) *Tropical Mangrove Ecosystems*. Coastal and Estuarine Studies, Volume 41, American Geophysical Union, Washington DC, pp. 173–224.

147 Robertson AI and Duke NC (1987) Mangroves as nursery sites. Comparisons of the abundance and species composition of fish and crustaceans in mangroves and other nearshore habitats in tropical Australia. *Marine Biology* 96, 193–205.

148 Robertson AI, Alongi DM and Boto KG (1992) Food chains and carbon fluxes. In: AI Robertson and DM Alongi (eds) *Tropical Mangrove Ecosystems*. Coastal and Estuarine Studies, Volume 41, American Geophysical Union, Washington DC, pp. 293–326.

149 Rodriguez C and Stoner AW (1990) The epiphyte community of mangrove roots in a tropical estuary distribution and biomass. *Aquatic Botany* 36, 117–126.

150 Rogers K (2005) Mangrove and saltmarsh surface elevation dynamics in relation to environmental variables in Southeastern Australia. PhD Thesis. Earth and Environmental Sciences. University of Wollongong, Wollongong.

151 Rogers K, Saintilan N and Cahoon DR (2005a) Surface elevation dynamics in a regenerating mangrove forest at Homebush Bay, Australia. *Wetland Ecology and Management* 13, 587–598.

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

153 Rothrock MJ and Garcia-Pichel F (2005) Microbial diversity of benthic mats along a tidal desiccation gradient. *Environmental Microbiology* 74, 593–601.

154 Rützler K and Feller IC (1996) Caribbean swamp communities. *Scientific American* 274, 70–75.

155 Saenger P (2002) *Mangrove ecology, silviculture and conservation*. Kluwer Academic Publishers, Dordrecht, The Netherlands.

156 Saenger P and Snedaker SC (1993) Pantropical trends in mangrove above-ground biomass and annual litterfall. *Oecologia* 96, 293–299.

157 Saintilan N and Williams RJ (1999) Mangrove transgression into saltmarsh environments in south-east Australia. *Global Ecology and Biogeography* 8, 117–123.

158 Semeniuk V (1994) Predicting the effect of sea-level rise on mangroves in northwestern Australia. *Journal of Coastal Research* 10, 1050–1076.

159 Sheaves M (2005) Nature and consequences of biological connectivity in mangrove systems. *Marine Ecology Progress Series* 302, 293–305.

160 Sheaves M and Molony B (2000) Short-circuit in the mangrove food chain. *Marine Ecology Progress Series* 199, 97–109.

161 Sherman RE, Fahey TJ and Martinez P (2001) Hurricane impacts on a mangrove forest in the Dominican Republic, damage patterns and early recovery. *Biotropica* 33, 393–408.

162 Simas T, Nunes JP and Ferrier JG (2001) Effects of global change on coastal salt marshes. *Ecological Modeling* 139, 1–15.

163 Skilleter GA and Warren S (2000) Effects of habitat modification in mangroves on the structure of mollusc and crab assemblages. *Journal of Experimental Marine Biology and Ecology* 244, 107–129.

164 Skilleter GA, Olds A, Loneragan NR, Zharikov Y (2005) The value of patches of intertidal seagrass to prawns depends on their proximity to mangroves. *Marine Biology* 147, 353–365.

165 Smith JMB, Heatwole H, Jones M and Waterhouse BM (1990) Drift disseminules on cays of the Swain Reefs, Great Barrier Reef, Australia. *Journal of Biogeography* 17, 5–17.

166 Smith TJ (1987) Seed predation in relation to tree dominance and distribution in mangrove forests. *Ecology* 68, 266–273.

167 Smith TJ, III (1992) Forest structure. In: AI Robertson and DM Alongi (eds) *Tropical Mangrove Ecosystems*. Coastal and Estuarine Studies, Volume 41, American Geophysical Union, Washington DC, pp. 101–136.

168 Smith TJ, III and Duke NC (1987) Physical determinants of inter-estuary variation in mangrove species richness around the tropical coastline of Australia. *Journal of Biogeography* 14, 9–19.

169 Smith TJ, III, Robblee MB, Wanless HR and Doyle TW (1994) Mangroves, hurricanes and lightning strikes. *BioScience* 44, 256–262.

170 Spalding MD, Balsco F and Field CD (1997) *World mangrove atlas*. The International Society for Mangrove Ecosystems. Okinawa, Japan.

171 Spenceley A (1977) The role of pneumatophores in sedimentary processes. *Marine Geology* 24, 31–37.

172 Steers JA (1929) The Queensland coast and the Great Barrier Reefs. *Geographical Journal* 74, 232–257.

173 Steinke TD and Naidoo Y (1991) Respiration and net photosynthesis of cotyledons during establishment and early growth of propagules of the mangrove, *Avicennia marina*, at three temperatures. *South African Journal of Botany* 57, 171–174.

174 Steinke TD, Rajh A and Holland AJ (1993) The feeding behaviour of the red mangrove crab *Sesarma meinerti* De Man, 1887 (Crustacea, Decapoda, Grapsidae) and its effect on the degradation of mangrove leaf litter. *South African Journal of Marine Science* 13, 151–160.

175 Stiling P, Rossi AM, Hungate B, Dijkstra P, Hinkle CR, Knott WM and Drake B (1999) Decreased leaf-miner abundance in elevated CO_2, reduced leaf quality and increased parasitoid attack. *Ecological Applications* 9, 240–244.

176 Stoddart DR, McLean RF, Scoffin TP and Gibbs PE (1978) Forty five years of change on Low Wooded Islands, Great Barrier Reef. *Philosophical Transactions of the Royal Society* London B. 284, 63–80.

177 Tomlinson PB (1986) *The botany of mangroves*. Cambridge University Press, Cambridge.

178 Twilley RR, Lugo AE and Patterson-Zucca C (1986) Litter production and turnover in basin mangrove forests in southwest Florida. *Ecology* 67, 670–683.

179 Twilley RR, Chen R and Hargis T (1992) Carbon sinks in mangroves and their implication to carbon budgets of tropical ecosystems. *Water, Air and Soil Pollution* 64, 265–268.

180 Twilley RR, Rivera-Monroy VH, Chen R and Botero L (1998) Adapting an ecological mangrove model to simulate trajectories in restoration ecology. *Marine Pollution Bulletin* 37, 404–419.

181 Valiela I, Bowen JL and York JK (2001) Mangrove forests, one of the world's threatened major tropical environments. *BioScience* 51, 807–815.

182 Whelan KRT, Smith TJ, III, Cahoon DR, Lynch JC and Anderson GH (2005) Groundwater control of mangrove surface elevation, shrink and swell varies with soil depth. *Estuaries* 28, 833–843.

183 Woitchik AF, Ohowa B, Kazunga JM, Rao RG, Goeyens L and Dehairs F (1997) Nitrogen enrichment during decomposition of mangrove leaf litter in an East African coastal lagoon (Kenya), Relative importance of biological nitrogen fixation. *Biogeochemistry* 39, 15–35.

184 Wolanski E, Mazda Y and Ridd P (1992) Mangrove hydrodynamics. In: AI Robertson and DM Alongi (eds) *Tropical Mangrove Ecosystems.* Coastal and Estuarine Studies, Volume 41, American Geophysical Union, Washington DC, pp. 436–462.

185 Wolanski E, Mazda Y, Furukawa K, Ridd PV, Kitheka J, Spagnol S and Stieglitz T (20010) Water circulation in mangroves, and its implications for biodiversity. In: E Wolanski (ed) *Oceanographic Processes of Coral Reefs*, CRC Press, Boca Raton, pp. 53–76.

186 Woodroffe CD (1990) The impact of sea-level rise on mangrove shore lines. *Progress in Physical Geography* 14, 583–520.

187 Woodroffe CD (1992) Mangrove sediments and geomorphology. In: AI Robertson and DM Alongi (eds) *Tropical Mangrove Ecosystems.* Coastal and Estuarine Studies, Volume 41, American Geophysical Union, Washington DC, pp. 7–42.

188 Woodroffe CD (1995) Response of tide-dominated mangrove shorelines in northern Australia to anticipated sea-level rise. *Earth Surface Processes and Landform*s 20, 65–85.

189 Woodroffe CD and Grime D (1999) Storm impact and evolution of a mangrove-fringed chenier plain, Shoal Bay, Darwin, Australia. *Marine Geology* 159, 303-321.

190 Young BM and Harvey LE (1996) A spatial analysis of the relationship between mangrove (*Avicennia marin*a var australasica) physiognomy and sediment accretion in the Hauraki Plains, New Zealand. *Estuarine and Coastal Shelf Science* 42, 231–246.