

Part II: Species and species groups

Chapter 9

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

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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 (CO₂) 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 Australia¹⁸⁶. 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	<ul style="list-style-type: none"> - Forest growth - Recruitment reduced - Reduced sediment retention - Subsidence 	<ul style="list-style-type: none"> - Reduced forest cover 	Woodroffe and Grime ¹⁸⁹ , Baldwin et al. ¹⁶ , Cahoon et al. ⁴²
Increased waves and wind	<ul style="list-style-type: none"> - Sedimentation - Recruitment 	<ul style="list-style-type: none"> - Changes in forest coverage, depending on whether coasts are accreting or eroding (interaction with sediment stabilisation from seagrass loss) 	Semeniuk ¹⁵⁸
Reduced rainfall	<ul style="list-style-type: none"> - Reduction in sediment supply - Reduced ground water - Salinisation 	<ul style="list-style-type: none"> - 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	<ul style="list-style-type: none"> - Photosynthesis - Productivity 	<ul style="list-style-type: none"> - Reduced productivity - Species turnover - Loss of diversity 	Ball et al. ²⁰ , Clough and Sim ⁵⁵ , Cheeseman et al. ⁴⁹ , Cheeseman ⁴⁸
Enhanced rainfall	<ul style="list-style-type: none"> - Increased sedimentation - Enhanced ground-water - Less saline habitats - Productivity 	<ul style="list-style-type: none"> - 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 effects 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 edge¹. 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 mangroves⁹³ 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 south⁶². Mangrove tree species diversity is also influenced by rainfall, with higher diversity of mangrove tree species in moist compared to arid estuaries¹⁶⁸. Additionally, intertidal microbial mat community diversity declines with longer periods of desiccation higher in the intertidal¹⁵³.

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 height¹¹⁵. 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^{87,184,158} 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 productivity¹⁵⁶. 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. Steers¹⁷² 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, Neil¹³⁰ 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 species¹⁶⁸. Sedge-like salt marshes also occur on the landward edge of mangroves, and are well developed where fresh water inputs are high¹³⁵. Australian tropical salt marsh communities are characterised by low stature but highly productive species that support a wide range of fauna¹. Salt marsh and salt flat habitats are among the most vulnerable to climate change. They are often highly disturbed by human activities³. 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 change³.

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, pneumatophores, 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 enhanced¹⁸⁵.

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^{90,109}. They provide sites for associated flora (eg macroalgae), that adhere to above ground roots¹⁴⁹, 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 sediments¹¹. 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 availability³¹. (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 exchange⁷ due in part to the high efficiency of internal cycling within tree tissues^{90,91} and sediments¹³. Development within the catchments of the GBR and nutrient enrichment of coastal waters can alter nutrient cycling in mangroves, resulting in leakage through enhanced denitrification¹³ 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 inputs¹⁴¹. These materials accumulated on salt flats can also be released in seasonal pulses with fresh water flow or during high tides¹⁴¹.

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 flow¹³⁷.

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 propagules¹⁶⁷, 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 waters¹⁴¹. Crabs are consumed by large predatory fish¹⁶⁰ but also produce copious larvae, which are an important food source for many juvenile fish



utilising mangroves¹⁴³. Mangroves also support a wide diversity of other invertebrates, for example¹⁵³ species of macrobenthic species were recorded from Missionary Bay⁶.

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 mangroves⁸⁷, 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 fish¹²⁴. Moreover, some invertebrate species appeared to be confined to feeding in the salt marsh – mangrove ecotone¹⁰⁰ 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 mangroves¹²⁵. The single offshore commercially important species included in Manson et al's¹¹⁹ 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 productivity¹²⁴ (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 level 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 CO₂ via their stomata during photosynthetic carbon gain. Stomata are sensitive to CO₂ concentrations, temperature, humidity and salinity of soils, and thus mangrove and salt marsh productivity is likely to be affected by enhanced CO₂, 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 disturbances¹¹⁸. 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 estuaries¹⁸⁵, 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 Hacker¹⁰¹, 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 latitudes¹⁷³. 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 (CO₂ efflux) from plants and microbial communities in sediments approximately doubles with every 10°C increase in temperature. The predicted 2°C 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 storage⁶⁴. 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 Clark⁵³ 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 CO₂, primary production in plant communities are highly sensitive to atmospheric CO₂ concentrations^{68,86,20,70}. Concentrations of CO₂ 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 CO₂ 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 CO₂ 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 CO₂ concentrations that are in the order of approximately 20 percent⁷⁰. In mangroves, elevated CO₂ 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 humidity²⁰. Faster growing, less salt tolerant species were more responsive to elevated CO₂ 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 CO₂ 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 consumers¹⁷⁵ and on decomposition processes²⁸. Elevated CO₂ 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 CO₂ primary production is likely to be enhanced, although not uniformly over the range of mangrove environments within the GBR. Increases in CO₂ concentrations may partially reduce the negative effects of reduced humidity and rainfall expected where temperatures increase in northern regions. Increasing levels of CO₂ 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 high¹¹³. Impacts of enhanced UVB radiation are most likely to affect plants in temperate regions. Anticipated effects include small reductions in photosynthetic rates and altered morphology⁴⁴. Although, UVB radiation is predicted to have a large effect on subtidal primary producers, effect on intertidal plants is not expected to be large⁶⁶.

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 (Bermuda⁷⁹). 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 Australia¹⁴.

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 range¹³² (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 Fitzroy River⁷¹). 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 Australia¹⁵⁸; Mary River, Northern Territory¹⁴; southern Australian salt marshes^{157,152}), resulting in significant changes in diversity and ecosystem function, often necessitating changes in human utilisation of the coast^{c77,105,106,131}.

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 Millennium 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

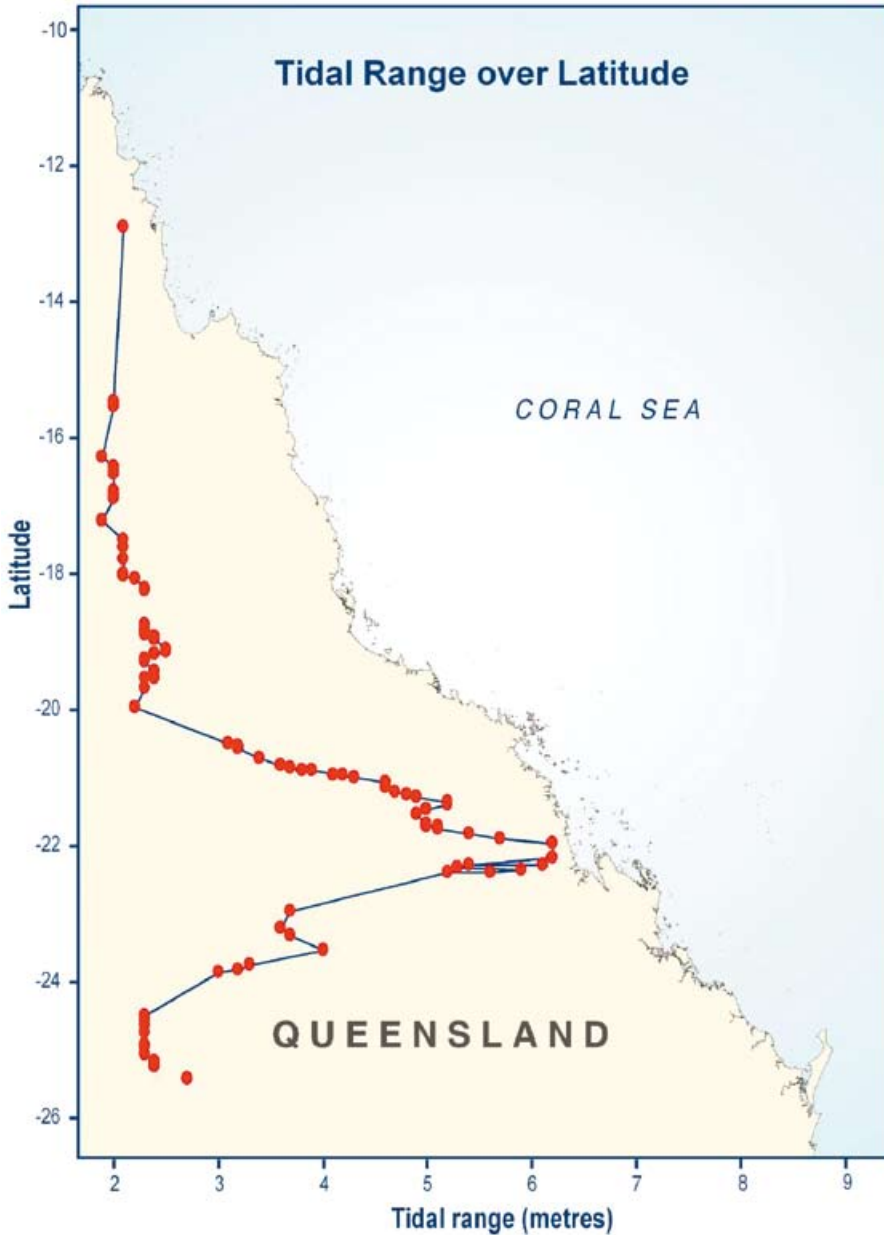


Figure 9.2 Model indicating the processes influencing vertical accretion in mangrove ecosystems (Adapted from Cahoon et al. 1999 by Diane Kleine)

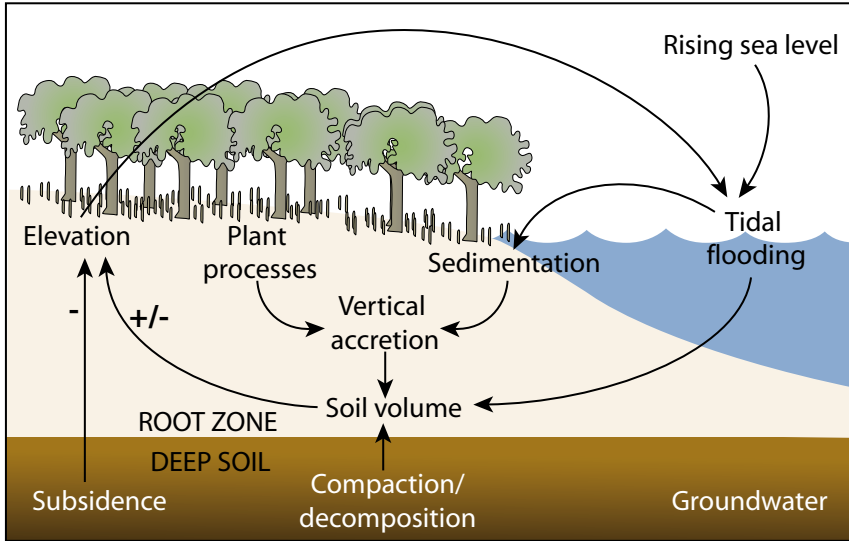
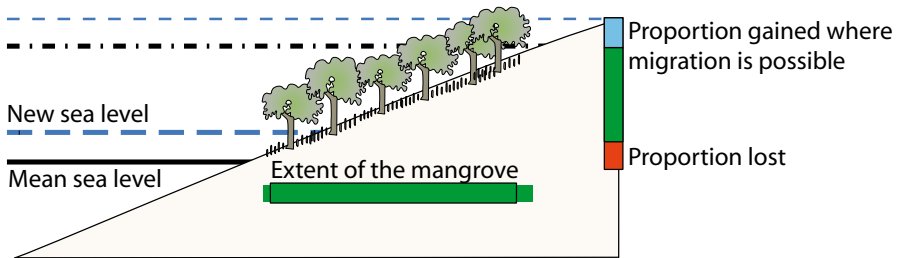


Figure 9.3 Effects of tidal range on the proportion of mangroves affected by rising sea level. With similar bathymetry a greater proportion of mangrove forest will be lost in settings with low (microtidal) compared to high (macrotidal) tidal ranges

MACROTIDAL



MICROTIDAL

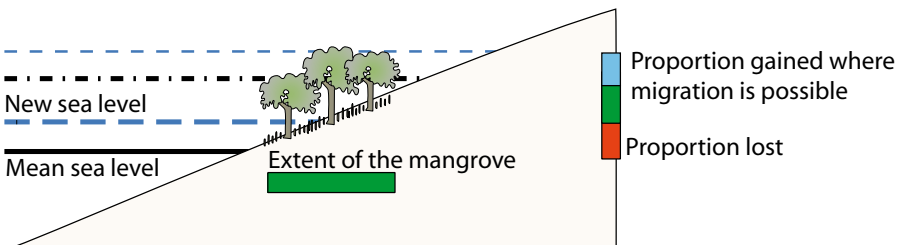


Table 9.4 Projected changes in estuaries with sea level rise exceeding vertical accretion (no changes in rainfall, temperature or storms are considered)*

Mangrove: tidal flat+salt marsh area (km ²)	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, Nicholls¹³¹). 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 volume¹⁰⁹. 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 pneumatophore type (ie mangrove species) plays an important role in the maintenance of surface elevation through differential abilities of species to promote sedimentation and sediment binding¹⁰⁹.

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 Semeniuk¹⁵⁸ and Woodroffe¹⁸⁸, 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 ($RSLR^* = RSLS^e / \text{tidal range}$) with a critical value ($RSLR^*_{crit}$) 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.ozestuaries.org

e Relative Sea Level State



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

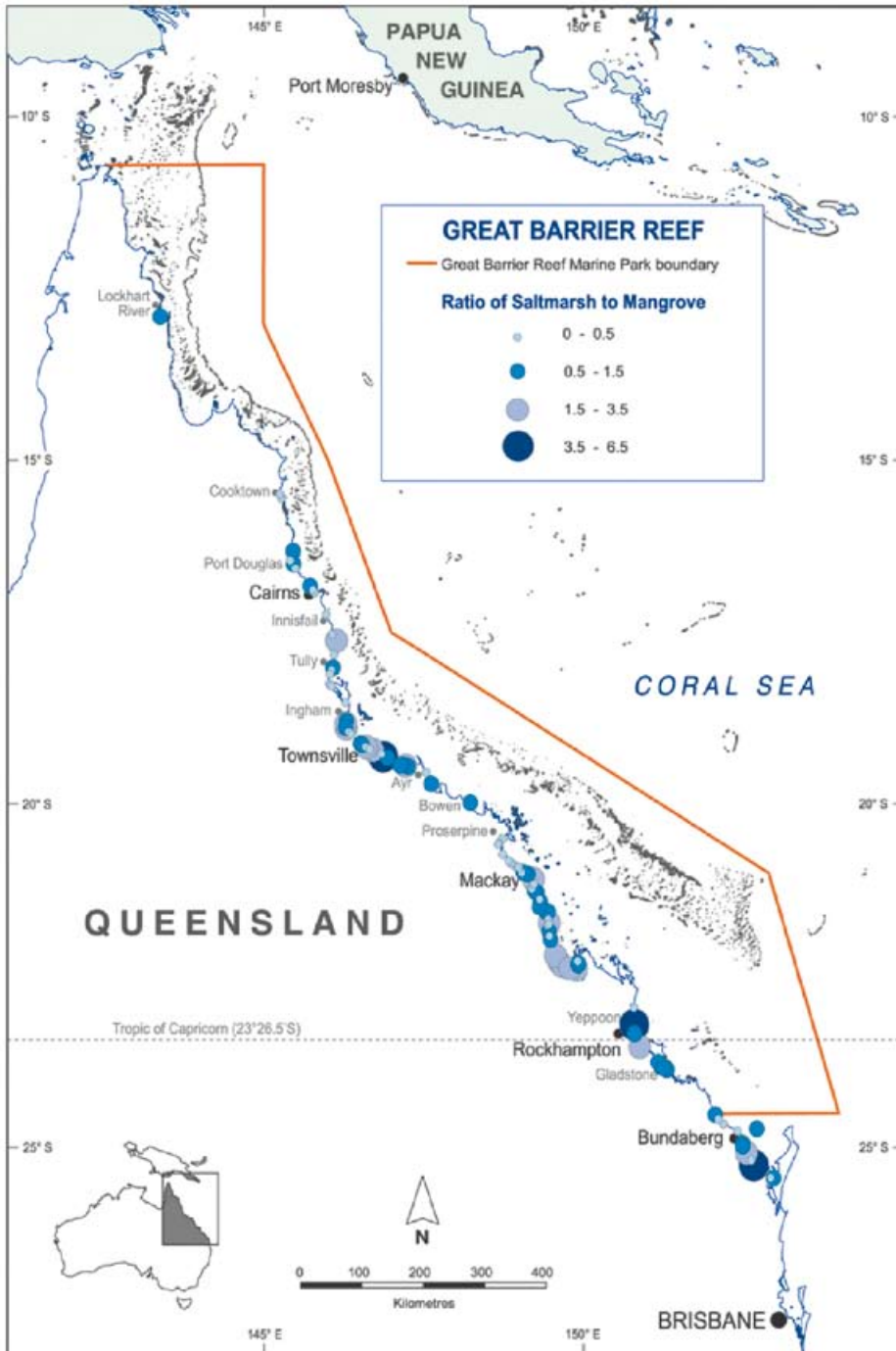
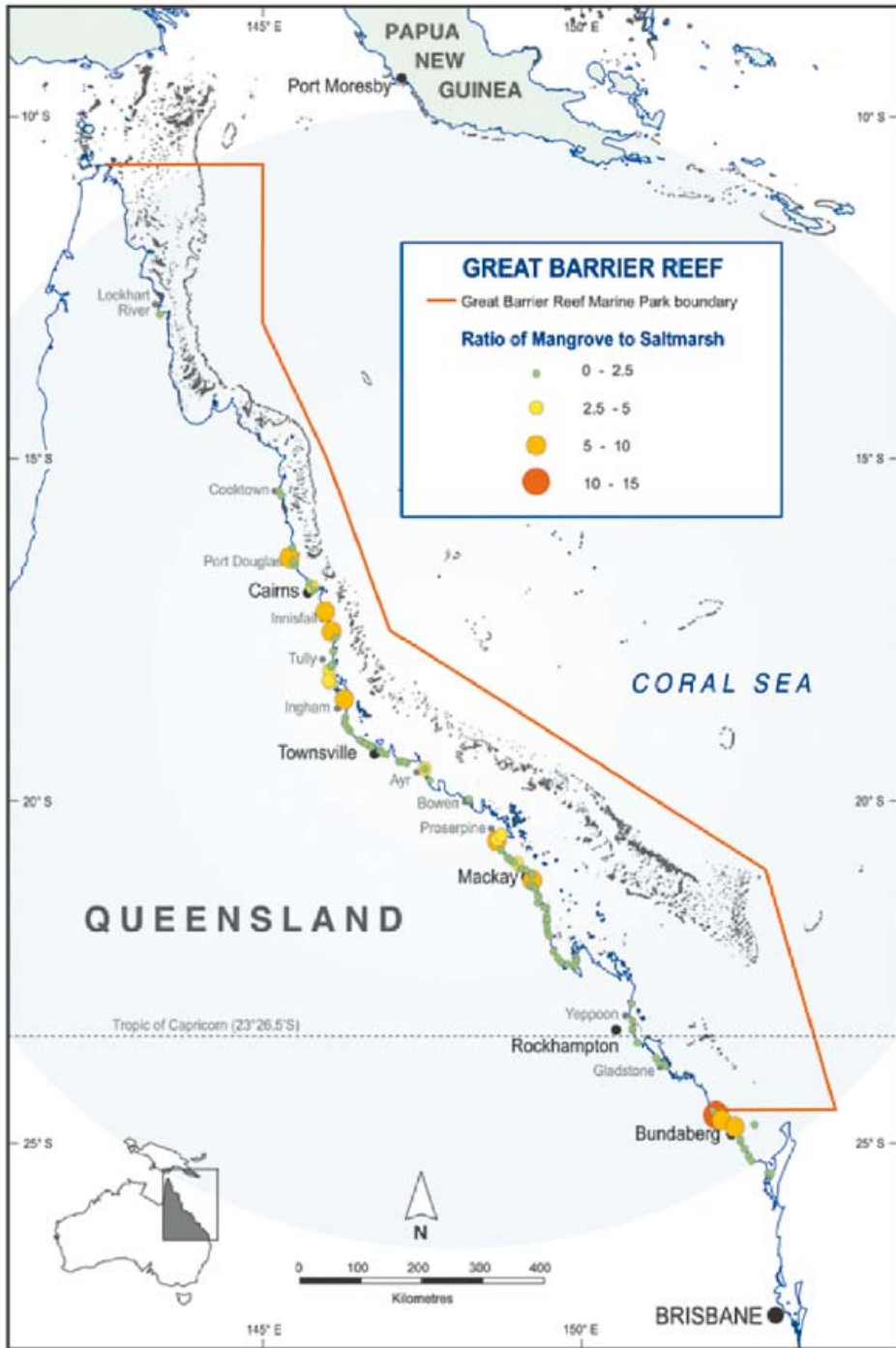


Figure 9.5 Ratio of mangrove to salt marsh in the GBR



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 all⁴². Intense storms can strongly influence surface elevation of wetlands through erosion, deposition and subsurface processes that can subsequently influence rates of recovery³⁶. 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 Rhiphoraceae being particularly vulnerable as they are unable to resprout¹⁶. 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 rainfall¹⁴¹ (see chapter 19).

In the GBR and other locations, sediment delivery to the estuary co-varies with rainfall⁶⁵ and increases with human development of the catchment⁹⁴. 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 fauna⁷⁸ and tree mortality if sedimentation is excessive⁸⁰. 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 growth¹¹⁴, however excessive sedimentation events could result in forest losses⁸⁰.

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 flats¹⁶⁸. 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 marsh¹⁵⁰). Sedimentation increased linearly with tidal range (sedimentation in mm per year = $-4 + 3.7 \times$ 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 CO₂, 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 CO₂ 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 losses⁷⁶. 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 CO₂, 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 forests⁹⁵. 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.⁷³) 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.

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