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Mangroves and saltmarshes of Moreton Bay

Catherine E. Lovelock[1], Arnon Accad[2], Ralph M. Dowling[2], Norm Duke[3], Shing Yip Lee[4,5], Mike Ronan[6]

Author affiliations: 1. School of Biological Sciences, The University of Queensland, St Lucia Qld, 4072, Australia; 2. The Queensland Herbarium, Department of Environment and Science, Mount Coot-tha Road, Toowong Qld, 4066, Australia; 3. Centre for Tropical Water & Aquatic Research (TropWATER), James Cook University, Townsville Qld, 4811, Australia; 4. Griffith School of Environment, Griffith University, Gold Coast Campus, Parklands Drive, Southport Qld, 4222, Australia; 5. School of Life Sciences, The Chinese University of Hong Kong, Shatin N.T., Hong Kong; 6. Wetland Team, Environmental Policy and Programs, Department of Environment and Science, Queensland Government, Brisbane Qld, 4000, Australia

Corresponding author: c.lovelock@uq.edu.au

ORCID
Catherine Lovelock: https://orcid.org/0000-0002-2219-6855
Arnon Accad: https://orcid.org/0000-0001-9952-4995
Norm Duke: https://orcid.org/0000-0003-2081-9120
Shing Yip Lee: https://orcid.org/0000-0001-9336-2323
Mike Ronan: https://orcid.org/0000-0002-0199-2174

Abstract

The mangroves and saltmarshes of Moreton Bay comprising 18,400 ha are important habitats for biodiversity and providing ecosystem services. Government policy and legislation largely reflects their importance with protection provided through a range of federal and state laws, including the listing of saltmarsh communities in 2013 under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). Local communities also conserve and manage mangroves and saltmarshes. Recent scientific research on these ecosystems in Moreton Bay has described food webs, habitat use by fauna, carbon sequestration and effects of climate change. The area of saltmarsh has declined by 64% since 1955 due to mangrove encroachment into saltmarsh habitats and past conversion to rural and urban land uses. Mangrove encroachment into saltmarsh habitats, which has been reported in other locations in Australia and across the world, has increased the area of mangrove habitat by 6.4% over the same period. This is consistent with predictions of habitat changes under climate change, and demonstrates the need for management strategies that ensure these ecosystems are maintained.

Keywords: coastal wetlands, intertidal, wetland management, EPBC Act, wetland change, drivers of wetland change, South East Queensland, soil carbon stocks

Introduction

Mangroves and saltmarshes, which are components of the estuarine wetlands of Moreton Bay, are dominated by salt-tolerant vegetation that occurs from approximately mean sea level to the highest astronomical tidal plane. They occur within the river systems and tidal creeks of Moreton Bay as well as on the comparatively open coasts of the Bay where they fringe both islands and the mainland. Mangroves are distributed over the intertidal zone and can occur from approximately mean sea level to the elevation of the highest neap tides, with saltmarshes usually occurring at higher elevations up to the elevation of the highest astronomical tides (1). In 2012 mangroves covered 15,231ha and saltmarshes 3,171ha of the Moreton Bay area (Fig.1,

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(2)). These forests, shrublands, grasslands and sedgelands with their associated algal and microbial communities support a wide range of fauna, including many species of importance to commercial and recreational fisheries (3). Additionally, they provide a range of ecosystem services that arise from the structure and productivity of the vegetation, fauna and soils. These services include supporting biodiversity and fisheries, protecting coasts, mitigating floods, enhancing water quality and sequestering carbon. They are also important for cultural identity, recreational use, tourism and education (4). However, mangroves and saltmarshes are also habitats for mosquitoes, sandflies, weeds and feral animals, posing challenges to the highly urbanised environment of the catchments of Moreton Bay (5).

Since European colonisation of the region, mangroves and saltmarshes have been highly modified, having been affected by land use changes in the catchment and converted to alternative land uses (6) as has been observed elsewhere in Australia (7). Even though the remaining habitat is protected by legislation and international agreements (8), developments within mangrove and saltmarsh habitats still occur. This paper provides an overview of the state of mangroves and saltmarshes of Moreton Bay; it also discusses the current and future threats to these ecosystems. We review key aspects of recent research on these ecosystems which examine how to minimise the impacts of threats and maintain sustainable mangroves and saltmarshes for the Bay into the future.

Diversity of mangrove plant species

The mangrove plant community of Moreton Bay is typical of the low-energy coastlines of subtropical regions in Australia that support moderate tree species diversity. Moreton Bay has 7 tree species (Table 1) compared to 28 for the Daintree River in tropical north Queensland and 1 in the mangroves of southern Australia. Standing biomass and productivity of mangroves are also lower than observed in the wet tropics but higher than in southern Australia (9,10). The community includes additional primary producers such as algae and microphytobenthos that attach to pneumatophores and the sediment surface (11), and a diverse community of lichens growing on tree trunks (12). *Avicennia marina* subsp. *australasica* is both the most widely distributed and most abundant mangrove tree species in Moreton Bay. This species forms forests up to 15 m tall on the seaward edges of the mangrove zone and extensive scrub forests (trees <2 m tall) in the high intertidal zone where they mix with saltmarsh species and extend onto the high intertidal saltmarsh and salt flats often present as low, open-scrubland (Fig. 2). The net primary productivity of *A. marina* forests was observed to be 6.42 t dry biomass ha^{-1} yr^{-1} in seaward fringing forests declining to 3.4 t dry biomass ha^{-1} yr^{-1} for the closed-scrub and 1.94 t ha^{-1} yr^{-1} for the low, open-shrubland (9). These values are similar to those reported previously (8–9 t ha^{-1} yr^{-1} (13)) and typical for subtropical mangrove forests globally (14).

While *A. marina* dominates the mangroves of Moreton Bay, *Rhizophora stylosa* is abundant on soft unconsolidated marine clays or on sandy soils of the eastern and southern shores of the Bay, with other mangrove species having high fidelity to its other environments (15). For example, *Bruguiera gymnorhiza* is common in high intertidal sites with freshwater seepage (e.g. on North Stradbroke Island); *Ceriops australis* favours marine clay sites in the high intertidal zone; *Aegiceras corniculatum* occurs in brackish/riverine conditions, often as an understory of *A. marina*; *Excoecaria agallocha* is limited to the highest intertidal zone (usually at the marine–terrestrial interface) in brackish/riverine settings where *Crinum pedunculatum*, the swamp lily, may also occur.

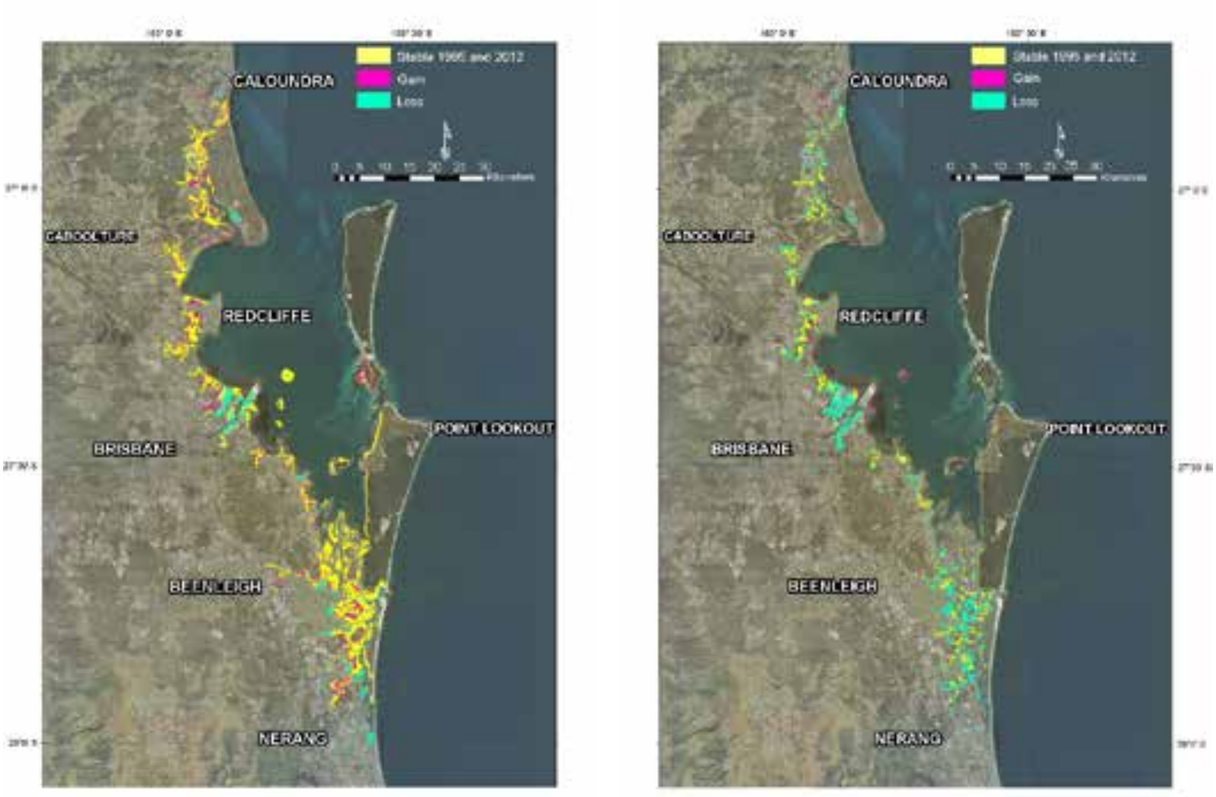

Figure 1. The distribution of mangrove forests (left) and saltmarsh (right) communities hroughout Moreton Bay and losses and gains in their cover from 1955–2012 (2).

Diversity of saltmarsh plants

The saltmarsh plant community has higher species richness than the mangroves (16). Its approximately 20 species represent 20% of the total saltmarsh species of Australia (17). Saltmarsh plant diversity within Australia increases with latitude (18) in contrast with the mangrove pattern of increasing species diversity towards the equator. Saltmarshes generally form at the high intertidal zone, at the landward edge of the mangroves in Moreton Bay (and regionally), and are submerged during high spring tides (1). The limited tidal inundation combined with moderate rainfall and high evaporation produces hypersaline conditions (i.e. salinity is higher than seawater) in some saltmarsh soils. These conditions are unfavourable for growth of species that do not have high physiological tolerance of highly saline soils. This leads to vegetation communities dominated by highly salt-tolerant herbs, for example *Sarcocornia quinqueflora*, *Suaeda* spp. and *Sporobolus virginicus* (Table 1).

Table 1. List of plant species typical of mangrove and saltmarsh ecosystems of Moreton Bay

Mangrove species	Common name
Acanthaceae	
Avicennia marina subsp. *australasica*	Grey mangrove
Combretaceae	
Lumnitzera racemosa	Black mangrove
Euphorbiacaeae	
Excoecaria agallocha	Blind-your-eye mangrove
Myrsinaceae	
Aegiceras corniculatum	River mangrove
Pteridaceae	
Acrostichum speciosum	Mangrove fern
Rhizophoraceae	
Rhizophora stylosa	Red mangrove (stilted mangrove)
Bruguiera gymnorhiza	Orange mangrove
Ceriops australis	Yellow mangrove
Saltmarsh species	
Aizoaceae	
Carpobrotus glaucescens	Pigface
Sesuvium portulacastrum	Sea purslane
Chenopodiaceae	
Tecticornia indica	Glasswort
Tecticornia pergranulata subsp. *queenslandica*	Glasswort
Tecticornia halocnemoides subsp. *tenuis*	Glasswort
Tecticornia indica	Glasswort
Cyperaceae	
Fimbristylis ferruginea	Rusty sedge
Fimbristylis polytrichoides	Rusty sedge
Isolepis cernua	Nodding club rush
Chenopodiaceae	
Sarcocornia quinqueflora	Bead weed
Suaeda australis	Seablite
Suaeda arbusculoides	Seablite
Juncaceae	
Juncus kraussii	Sea rush
Juncaginaceae	
Triglochin striata	Streaked arrow grass
Poaceae	
Phragmites australis	Common reed
Sporobolus virginicus	Saltwater couch
Portulacaceae	
Portulaca oleracea	Pigweed
Samolaceae	
Samolus repens	Creeping bushweed

Figure 2. Mangrove scrub of *Avicennia marina* encroaching into *Sarcocornia quinqueflora*-dominated saltmarsh at Tinchi Tamba Wetland Reserve.

Hypersaline salt flats occupied by *S. quinqueflora*, *Suaeda* spp. and *S. virginicus,* and often encrusted by cyanobacterial mats, are extensive in Moreton Bay, with particularly well-developed areas within the Tinchi Tamba Wetlands, Geoff Skinner Reserve and Point Halloran Reserve (Fig. 3). These hypersaline habitats tend to increase in area at the expense of mangrove forests during periods of prolonged drought (19) associated with El Niño phases of climate. However other factors, for example variation in sea level, may also be important. Mangrove encroachment into hypersaline marsh and high intertidal salt flats is occurring in Moreton Bay (2). This encroachment is consistent with the expected effects of increasing sea level. Higher sea level leads to increased frequency of inundation of the high intertidal zone. This aids the movement of mangrove propagules into the high intertidal zone and provides more favourable conditions for their growth.

Where soil salinity is ameliorated by the surface expression of groundwater (e.g. on the sand islands in the east of Moreton Bay) or by river flows (e.g. Boondall Wetlands and Point O'Halloran on the western side of the Bay), a broad range of reeds (e.g. *Juncus kraussii*), rushes and herbs can establish within the brackish soil. These brackish communities can have high diversity, but have been under intense pressure from urban development (2).

Figure 3. High intertidal, hypersaline saltmarsh and claypan at Point Halloran Reserve.

Fauna and food webs

Gastropods and crustaceans dominate the epibenthic macrofauna of estuarine wetlands in Moreton Bay. The relatively stable substratum, especially at the high intertidal saltmarsh, supports a high density (>350 individuals m^{-2}) of air-breathing pulmonate gastropod species grazing on the microphytobenthos and vascular plant detritus (20). Grapsoid (e.g. *Parasesarma, Neosarmatium, Metopograpsus*) and ocypodid (*Uca*) crabs dominate vegetated and open areas within mangroves and saltmarshes, respectively, reflecting segregation in their food sources (21). Some ocypodid crabs (e.g. *Australoplax*, *Heloecius*) occur in both vegetated and unvegetated habitats of the intertidal zone and may have a specialised mixed diet of microphytobenthos and fine vascular plant detritus.

The firm, high intertidal soils of mangroves and saltmarshes generally support a low abundance of infaunal species. Whereas diversity and abundance of burrowing and burying macrofauna, dominated again by brachyuran crabs, increase from the high to low intertidal zone. Polychaete and sipunculid worms may also be locally abundant within mangroves and saltmarsh. The meiofauna of mangroves and saltmarsh in Moreton Bay are dominated by nematodes and harpacticoid copepods (22). The macrofauna and meiofauna provide a trophic base for transient nektonic predators (fish and prawns) visiting these habitats during the high tide (20, 22).

Despite the limited research, other components of faunal diversity are being revealed. There are studies of insect diversity (23, 24) and discoveries such as finding the endangered Illidge's ant blue butterfly (25). Knowledge of the distribution of vertebrates, including the water mouse (*Xeromys myoides*) which is listed on the IUCN Red List (26, 27), is also increasing. Some insects (e.g. mosquitoes and biting midges) are, however, of considerable public health concern, prompting active management in local saltmarsh and mangrove habitats (28).

Research into estuarine food webs in Moreton Bay has found that saltmarshes are important habitats and provide food sources for fish, such as commercially important species such as whiting and mullet (29–31), and the giant mud crab (32). Abundant crab larvae are important resources from the saltmarsh (31, 33, 34). Mangroves encroaching into these habitats can reduce feeding and roosting sites for migratory shorebirds. This is of particular concern with several species being listed in 2013 as critically endangered under the *Environment Protection and Biodiversity Conservation Act 1999*. For mangrove forests, commercial fish catches are correlated with the area and perimeter of mangrove forests (3, 35, 36) as well as proximity to adjacent habitat (37). This highlights their importance as nurseries, refugia, and for food resources both within the habitat and organic matter, that is exported to adjacent habitats (38).

Habitats directly seaward of mangroves are generally comprised of intertidal sand and mud flats which are important for shore birds, including migratory species which are covered by international agreements with Japan (Japan–Australia Migratory Bird Agreement), China (China–Australia Migratory Bird Agreement) and Korea (Republic of Korea–Australia Migratory Bird Agreement) (39). The macroinvertebrate biomass and diversity of these low intertidal sand and mud flats is critical for maintaining shorebird populations (38). The connectivity of mangrove and saltmarsh habitats to subtidal habitats, such as reefs and seagrass meadows, also supports fish communities (40, 41).

Crabs are important ecosystem engineers that modify sediments and meiofauna through bioturbation and predation (22); this in turn provides food for mobile fauna (31). Many mangrove crab species bury and process decomposing mangrove leaves (21, 42), including fresh litter (43). Litter processing by crabs is an important process linking mangrove productivity to fisheries production prawns and fish. However, evidence for direct links between mangrove biomass and fisheries using tracers of naturally stable isotopes of carbon and nitrogen has been equivocal (44). But more recent evidence suggests that mangrove leaf material has a more important role in coastal food webs than previously thought. These new studies have found that there is isotopic fractionation of organic matter by crab bacterial gut symbionts or the crab's physiological pathway (45). Incorporating this new information into food-web studies indicates a strong role for mangrove biomass production and its consumption by crabs and possibly other invertebrate detritivores in coastal food webs (45, 46).

Threats and change over time

Globally, intertidal estuarine areas where mangroves and saltmarshes occur are under intense pressure because the coastal zone has high human population densities, which has led to urban, industrial and agricultural development that directly and indirectly affect mangroves and saltmarshes (47). Similar to other coastal and estuarine areas throughout the world, mangrove and saltmarsh habitats in Moreton Bay have been converted to alternative uses and degraded by a range of pressures that have varied over time (Tables 2 and 3). They are also influenced by extreme climatic events, natural variations in climate and climate change (Table 2). Losses of tidal wetlands since 1955 have been particularly evident for saltmarshes, which have been reduced in area by 64% (Table 3) due to encroachment by mangroves (47%) and conversion to urban and industrial uses (46%, Table 3 (2)). For mangroves there has been a net increase in area by 6.4% since 1955. However, losses have been largely matched by gains, indicating that approximately 28% of the current mangrove is relatively young (recruited since 1955). It may therefore have different characteristics and offer different ecosystem services than older forests that were present before 1955.

In addition to conversion to alternative land uses (Type 1, Table 2, e.g. the airport accounts for 12% of total losses), many mangrove and saltmarsh areas were used for dumping rubbish or specifically designated as landfill sites (Type 2, Table 2). In creating many of Moreton Bay's wetland parks and during the few restoration projects in the Bay, hundreds of wrecked cars have been removed (e.g. (48)). Currently saltmarshes, despite their protected status, are still vulnerable to direct disturbance by off-road vehicles and grazing by stock (49). Off-road vehicles directly disturb habitat. They also create depressions and ponds in the high intertidal zone harbouring mosquitoes that require control through enhanced management (see below).

While conversions and direct disturbance are relatively easy to observe, indirect effects that may also degrade the habitat are less easy to document, but are still apparent in the Bay (Table 3). The increased sediment supply to the coast after European settlement of Moreton Bay has increased rates of sediment accretion in intertidal habitats (50) and has therefore likely increased the area of mangrove habitat (6). However, high sediment loads may have also altered species composition and ecosystem functioning (51), as primarily sandy habitats have transitioned into more mud-dominated habitats, particularly in the western Bay.

Table 2. List of impacts for 11 key types of change affecting mangroves of the Moreton Bay region during three historical periods of the last two centuries. Types of change are grouped into four categories (A–D) based on human and natural influences on coastal and estuarine habitats. Updated from (6). Light green indicates no impact; yellow – minor impacts; dark green – moderate impact; red – severe impacts.

Type of change	**Pre 1860**	**1860–1946**	**1946–2016**
A. Direct – Intended and obviously human related			
1. Conversion to alternative land uses (Reclamation loss)	**Impact:** None/unknown	**Impact:** Moderate **Driver:** Chiefly industrial, upstream port development and river channel.	**Impact:** Severe **Driver:** Chiefly urban, industrial, airport and downstream port development – effects accumulative and irreversible.
2. Direct damage	**Impact:** Minor **Driver:** Occasional tree cutting, access paths and tracks.	**Impact:** Moderate **Driver:** Numerous access paths, tree cutting, access paths, tracks, trampled roots and soils, dumping.	**Impact:** Moderate **Driver:** Numerous access paths, trampled roots, although areas generally better protected than prior periods, dumping.
B. Direct – Unintended and obviously human related			
3. Altered tidal exchange	**Impact:** None/unknown	**Impact:** Minor **Driver:** Impoundment, built-up roads, drainage for agriculture.	**Impact:** Moderate **Driver:** Impoundment, drainage for mosquito control, built-up roads – proportional to urban growth.
4. Spill damage	**Impact:** None/unknown	**Impact:** Minor **Driver:** Occasional oil spills proportional to shipping volume.	**Impact:** Minor **Driver:** Oil spill incidents proportional to shipping volume – accumulation may exceed toxicant degradation rates.
C. Indirect – Unintended and less obviously human related			
5. Depositional gains and losses	**Impact:** Minor **Driver:** Increased frequency of fires in catchment reduced ground vegetation and increased sediment in run-off.	**Impact:** Minor **Driver:** Clearing of catchment vegetation and increased crop agriculture increased sediment run-off, resulting in shallower waters around the mouth of the Brisbane River. Dredging maintained channel	**Impact:** Moderate **Driver:** Hard surfaces of city-urban roads and built-up areas and reduction in catchment croplands, altered and increased sediment run-off. Dredging spoil from channel maintenance.

6. Mutations and genetic decline	**Impact:** None/unknown	**Impact:** None/unknown	**Impact:** Minor **Driver:** Loss of reproductive fitness and re-establishment of mangroves. Presence notable, but no apparent loss of natural regeneration or seed production.
7. Subsidence of soils associated with dieback	**Impact:** None/unknown	**Impact:** None/unknown	**Impact:** Locally severe **Driver:** Unknown but may be linked to high levels of nutrients and pesticides and extreme climatic events.
D. Not obviously human related			
8. Wrack accumulation	**Impact:** Minor **Driver:** Debris from blooms, storm waves – occasional.	**Impact:** Minor **Driver:** Litter debris, debris from increased number of blooms, storm waves.	**Impact:** Minor **Driver:** Litter debris, debris from increased number of blooms, storm waves. Recent *Lyngbya* blooms.
9.Herbivore /insect attack	**Impact:** Minor **Driver:** Insect plagues – occasional.	**Impact:** Minor **Driver:** Insect plagues – occasional.	**Impact:** Minor **Driver:** Insect plagues – occasional.
10. Storm damage	**Impact:** Minor **Driver:** Severe storm, hail, lightning, storm waves – occasional.	**Impact:** Minor **Driver:** Severe storms, hail, lightning, storm waves – occasional.	**Impact:** Minor **Driver:** Severe storms, lightning, storm waves – occasional. Notable hail damage in particular areas in Moreton Bay region.
11. Ecotone shift and zonal shifts in plant species	**Impact:** Minor **Driver:** Climate variability, including variation in sea level and rainfall.	**Impact:** Minor **Driver:** Climate variability, including variation in sea level and rainfall.	**Impact:** Moderate **Driver:** Climate variability and climate change, particularly sea-level rise and extreme drought. Sea-level rise linked to changes in bay hydrology – longer term responses.

The onset of industrialisation also led to increases in heavy metals in intertidal soils (Table 2), which may have negative impacts on all components of saltmarshes and mangroves (52). Increases in land cleared for agriculture and human populations in the catchments of the Bay over time have led to a rise in nutrients and sediments reaching the marine habitats of the Bay (53). This rise may increase mangrove growth, but high nutrient levels reduce the allocation of biomass to root systems (54). This may increase susceptibility of mangrove trees to drought and other stressors (55).

Table 3. Area in hectares, losses and gains in mangrove forests and saltmarshes from 1955–2012 (2). While high levels of loss have occurred in both ecosystems, there has been a large net loss of saltmarshes.

Ecosystem		1955 (ha)	Change between 1955 and 2012 (ha)	2012 (ha)	% net change
Mangrove		14,273		15,231	+6.4
	Mangrove losses		3282		
	Mangrove gains		4209		
Saltmarshes (including clay pan)		8901		3171	–64.0
	Saltmarsh losses		6410		
	Saltmarsh gains		710		
Total area		23,174		18,402	–20.6

Mangrove dieback events in Moreton Bay were responsible for 12% of mangrove losses from 1955–2012 (2). Although the causes are debatable, reduced groundwater and other freshwater flows due to drought and infrastructure interrupting groundwater flows may be important drivers. Groundwater is abundant in Moreton Bay (6.7×10^7 m^3/day, i.e.18 times greater than the average annual discharge of the major river inputs into the Bay (56)) and mangroves use groundwater to support their metabolism (57). Mangroves use combinations of fresh water and saline water, but fresh water has been shown to enhance growth rates in some species (58), suggesting that continued access to fresh water sources is important for maintaining mangrove productivity.

Other threats to mangroves and saltmarshes include local physical disturbances, which affect crab and mollusc communities (59). Introductions of non-native species are also likely to be important in mangrove and saltmarsh ecosystems. Foxes and cats exist in the tidal wetlands of Moreton Bay and have negative effects on native fauna, including IUCN-listed vulnerable species such as the water mouse *X. myoides* (60). Weeds also occur within saltmarshes and control measures, including herbicides and mechanical removal, are frequently used in Moreton Bay wetlands.

The Queensland Herbarium has monitored cover and change in cover of mangroves and saltmarshes reported this through State of the Environment reports and the annual Healthy Waterways Report Card (http://hlw.org.au/report-card). Since 2011, the Queensland Herbarium has established permanent monitoring sites across the Bay where floristics and biomass are measured every three years. Citizen science, including programs such as Mangrove Watch, has begun to emerge in the region (61). Individual researchers and community organisations have also conducted long-term monitoring (e.g. Queensland Wader Study Group).

Climate change

Increases in atmospheric carbon dioxide (CO_2) and associated increases in temperature and sea level, and expected reductions in rainfall (http://www.climatechangeinaustralia.gov.au/en/climate-projections/climate-futures-tool/projections/) will have a strong influence on mangroves and saltmarshes of the region (62, 63). Elevated levels of CO_2 (63) and elevated winter temperatures at subtropical and temperate locations can enhance plant growth rates (64). Increasing temperature may make the Bay more suitable for the growth of species that have more tropical distribution, for example *R. stylosa* (65). Plant growth and the extent of mangrove habitat (and the encroachment of mangroves into saltmarsh) are correlated with rainfall (19, 58). However, future rainfall projections have a high level of uncertainty and thus future changes in productivity and distribution in response to variation in rainfall are uncertain.

Climate change is an important driver of environmental change that will influence the distribution of mangroves and saltmarsh. The extent of mangrove and saltmarsh habitat is determined by the interactions between sea level and local topography because plants have specific tolerances to levels of inundation. Increasing sea levels could have negative effects on the distribution of mangroves if seaward fringing forests are submerged, but positive effects on mangrove area if higher sea levels promote invasion of mangroves into saltmarshes and landward expansion into other low-lying lands (60, 66, 67). Rising sea levels will have a negative influence on the area of saltmarshes in circumstances where mangroves encroach on land at a suitable elevation in the intertidal zone (Fig. 2), or if this land is unavailable due to human development on the landward edge. This reduction of available habitat between high intertidal barriers and encroaching mangroves is referred to as ‘coastal squeeze’ (68). It may already be evident as mangrove encroachment is responsible for approximately 50% of recent changes to saltmarshes cover (2).

To maintain mangroves and saltmarshes in their current position in the landscape with rising sea level, they must accrete vertically (raise the elevation of their soil surface) at the same rate as the level rises. Otherwise inundation tolerance will be exceeded and recruitment will be impeded. Monitoring accretion in mangroves and saltmarshes indicates it to be occurring at a rate similar to or exceeding that of sea-level rise in some sites, particularly on the sand islands (5.8 mm per year), while others are accreting at rates slightly lower than that of sea-level rise (1.7 mm per year (69)). In contrast, saltmarsh soil surface elevation gains are lower than local rates of sea-level rise (rates of accretion of 0.8–1.5 mm per year), suggesting that these habitats are likely becoming suitable for colonisation by mangroves as sea-level rise accelerates (69).

Ecosystem services – climate change mitigation, sediments and nutrients

Carbon stored in mangroves, saltmarshes and seagrass meadows has been called ‘blue carbon’. These ecosystems can be important in climate change mitigation strategies. This is due to the large carbon stocks that can be released as CO_2 emissions if the ecosystems are disturbed coupled with the high carbon sequestration rates when they are intact (70). They are also important in adaptation to climate change as they protect the coast against waves and storm surges and raise the seafloor through sediment accretion (71). An extensive survey of soil carbon stocks in Moreton Bay estimated between 4,100,000 and 5,200,000 Mg of sediment organic carbon (72) with mean carbon sequestration rates of 76 g C m^{-2} $year^{-1}$ for mangroves; 9 g C m^{-2} $year^{-1}$ for marshes dominated by *S. quinquefolia*, and 207 g C m^{-2} $year^{-1}$ for *J. krausii* marshes (62). Carbon sequestration rates for mangroves of the Bay are low to moderate compared to tropical mangrove forests (70), while *Juncus* marshes have similar rates to some of the highest carbon sequestration rates observed globally in saltmarshes (73, 74). The stocks of soil carbon over the landscape, being higher in landward compared to seaward mangroves (72, 75), reflect the sea level history of Moreton Bay (72) and the substantial risks from CO_2 emissions if these ecosystems are degraded and converted to alternative land uses (76).

In addition to their role in regulating CO_2, mangroves and saltmarshes regulate the greenhouse gases methane (CH_4) and nitrous oxide (N_2O), which are formed by microbial activity in their low oxygen soils. These greenhouse gases have warming potentials of 28–36 and 265–298 times that of CO_2 respectively (77). Methane emissions are very low when soil salinity is high; for example, on North Stradbroke Island methane and N_2O emissions were higher in brackish *Juncus* marshes (mean of 30 mg C-CH_4 m^{-2} h^{-1} and 50 µg N-N_2O m^{-2} h^{-1}, respectively) compared to the adjoining more saline mangrove, where emissions were very low, except in areas where groundwater emerged at the soil surface (78). For both methane and N_2O, the rates of emissions increased with added nutrients (79). Thus restoring mangroves and saltmarshes may reduce greenhouse gas emissions where these ecosystems have become brackish through altered hydrology (e.g. as a result of impoundment).

Mangroves and saltmarshes are also important for trapping sediments, particularly in fringing mangroves of riverine ecosystems (80) and for nutrient retention and cycling. Coastal wetlands are important sites of nitrogen retention in soils and plant biomass and for denitrification (81), where nitrogen in water and soil is converted to nitrogen gas (N_2) through microbial activity. Measurements in Moreton Bay waterways found that during a tidal cycle, mangroves retained up to 28% of nitrates (NO_x), 51% of soluble phosphorus, and 83% of the ammonium (NH_4) in tidal water (82). Thus losses of mangroves and saltmarshes over time (Table 3) are likely to have contributed to reduced water quality in the Bay, as has been observed in other estuaries globally (83).

Management

The Queensland Government shares responsibility for managing wetlands with the Australian Government, local governments, landholders and the wider community. These responsibilities are formalised in laws passed by the Queensland and Australian governments and through international obligations and management agreements such as Ramsar (Table 4).

Laws, policies and programs administered by government agencies manage our wetlands. These can be accessed through the portal on the Queensland Government's Wetland*Info* website (https://wetlandinfo.ehp.qld.gov.au/wetlands/management/policy-legislation/) which is updated regularly. The Wetland*Info* portal also provides a range of products that support wetland management, including mapping, fact sheets and guidelines (https://wetlandinfo.ehp.qld.gov.au/wetlands/).

Table 4. International, federal and state laws and policies relevant to the conservation and management of mangroves and saltmarshes in Moreton Bay. Modified from (8).

International	Reference or link
Ramsar Convention	http://www.environment.gov.au/water/wetlands/ramsar
A range of bilateral agreements on migratory birds with China, Korea and Japan (accommodated within the *Environment Protection and Biodiversity Conservation Act 1999* – see below)	http://www.environment.gov.au/biodiversity/migratory-species/migratory-birds
Convention on Biological Diversity (Bonn Convention)	http://www.environment.gov.au/biodiversity/international/un-convention-biological-diversity
Australian Government	
Environment Protection and Biodiversity Conservation Act 1999 (listed subtropical and temperate coastal saltmarsh communities as a nationally threatened ecological community in 2013)	http://www.environment.gov.au/epbc
State Government	
Fisheries Act 1994	https://www.daf.qld.gov.au/fisheries/consultations-and-legislation/legislation
Vegetation Management Act 1999	https://www.legislation.qld.gov.au/LEGISLTN/CURRENT/V/VegetManA99.pdf
Marine Parks Act 2004	https://www.legislation.qld.gov.au/Acts_SLs/Superseded/SUPERS_M/MarinePA04.htm
Planning Act 2016	https://www.legislation.qld.gov.au/LEGISLTN/CURRENT/P/PlanningA16.pdf
Environmental Protection (Water) Policy 2009	https://www.ehp.qld.gov.au/water/policy/seq-moretonbay.html

Mosquito control is one of the most intensive management activities in mangroves and saltmarshes in the Bay. These habitats harbour *Aedes vigilax* (Skuse) mosquitoes that are vectors for viruses causing the serious diseases of Ross River and Barmah Forest virus (84, 85). While other subtropical locations (e.g. Florida) achieved mosquito control by impounding and/or draining wetlands, in Moreton Bay an approach called ‘runnelling’ was developed. In this method, standing water in the saltmarsh is drained using small channels to dewater larval habitats and combined with aerial spraying of mosquito-specific insecticides (86). Successful models of mosquito habitat suitability are strongly linked to hydrological characteristics that can predict the need for larvicide applications based on rainfall and tidal inundation (87). 'Runnelling' is more compatible with maintaining wetlands in a state consistent with conservation goals compared to other methods of mosquito control (28), although there is some possibility that runnels have increased mangrove penetration into the saltmarshes of the region (88). Mosquito control is vital in urban settings where disease risks are high and thus developing management compatible with conservation goals is a high priority.

Restoration has been attempted to reduce the overall loss of saltmarsh and mangrove in Moreton Bay. The significant loss of mangroves during construction of the Brisbane Airport was followed by a large-scale restoration project (89), although the long-term success of this project is yet to be assessed. The Bulimba Creek Catchment Coordinating Committee restored mangroves and saltmarsh in the Bulimba Creek Oxbow that had previously been impounded for industry (48, 90). More recently, a small mangrove wetland was created in southern Moreton Bay as an offset measure for the construction of the Southport Park by the City of Gold Coast.

Given the losses experienced in saltmarsh habitats in Moreton Bay, future management actions could include increasing the size of the reserve network to accommodate landward migration of this ecosystem (91). However, the opportunities for this are rare as areas landward of saltmarsh have largely been developed or are habitat for rare freshwater wetlands and other species. Other interventions, for example adding sediment to build elevation of the saltmarsh, have been used in the USA (92) and could be appropriate in some locations. Recent research has shown that fisheries values and carbon sequestration (see above) could offset the costs of purchasing land to extend the reserve network for coastal wetlands (67). Additionally, explicitly considering the coastal protection functions and other ecosystem services in land-use planning can be highly cost-effective (66). A survey of how people in Moreton Bay value mangroves has indicated that the role of mangroves in coastal protection resonates with all stakeholder groups assessed, but these areas are highly contested for coastal development (5, 93, 94). Conserving and restoring coastal wetlands therefore depends on sound science and clear communication of the value of ecosystem services to the communities in specific locations and the various levels of government operating within Moreton Bay (94).

Conclusions

Mangrove forests and saltmarshes of Moreton Bay are clearly valuable environmental assets, and while they are dynamic systems, they have been subject to human-induced change over time with the loss of 64% of the area of saltmarshes observed since 1955. Even though a suite of laws, policies and international agreements protect mangroves and saltmarshes they continue to be lost. Little is being done to reverse these losses through restoration, and none has been initiated on a large scale. The ecosystem services provided by mangroves and saltmarshes, particularly those that are relatively well understood in the region (fisheries, carbon sequestration, nutrient cycling, cultural identity and education), provide the rationale for increasing the area allocated for mangroves and saltmarshes (e.g. increasing the reserve network, planning for landward migration). Given that sea-level rise will place pressure on saltmarshes due to coastal squeeze, this is a particularly important strategy to pursue. Benefits of maintaining or increasing the area of these habitats are consistent with society's aspirations for biodiversity, fish production and clean water, although they must be balanced with consideration of the vulnerability of adjacent freshwater wetlands and their dependent fauna.

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