UNIVERSITY
OF WOLLONGONG
AUSTRALIA

University of Wollongong
Research Online

Faculty of Science, Medicine and Health - Papers

Faculty of Science, Medicine and Health

2013

The significance and vulnerability of Australian saltmarshes: implications for management in a changing climate

Neil Saintilan

Office of Environment and Heritage (OEH)

Kerrylee Rogers

University of Wollongong, kerrylee@uow.edu.au

Publication Details

Saintilan, N. & Rogers, K. (2013). The significance and vulnerability of Australian saltmarshes: implications for management in a changing climate. *Marine And Freshwater Research*, 64 (1), 66-79.

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library:
research-pubs@uow.edu.au

The significance and vulnerability of Australian saltmarshes: implications for management in a changing climate

Abstract

We review the distribution, status and ecology of Australian saltmarshes and the mechanisms whereby enhanced atmospheric carbon dioxide and associated climate change have influenced and will influence the provision of ecosystem goods and services. Research in temperate and subtropical saltmarsh has demonstrated important trophic contributions to estuarine fisheries, mediated by the synchronised mass-spawning of crabs, which feed predominantly on the C-4 saltmarsh grass *Sporobolus virginicus* and microphytobenthos. Saltmarshes also provide unique feeding and habitat opportunities for several species of threatened microbats and birds, including migratory shorebirds. Saltmarshes increased in extent relative to mangrove in Australia in both tide- and wave-dominated geomorphic settings through the latter Holocene, although historic trends have seen a reversal of this trend. Australian saltmarshes have some capacity to maintain elevation with respect to rising sea level, although in south-eastern Australia, the encroachment of mangrove and, in Tasmania, conversion of shrubland to herbfield in the past half-century are consistent with changes in relative sea level. Modelling of the impacts of projected sea-level rise, incorporating sedimentation and other surface-elevation drivers, suggests that the survival of saltmarsh in developed estuaries will depend on the flexible management of hard structures and other impediments to wetland retreat.

Keywords

climate, australian, saltmarshes, implications, vulnerability, management, significance, changing

Disciplines

Medicine and Health Sciences | Social and Behavioral Sciences

Publication Details

Saintilan, N. & Rogers, K. (2013). The significance and vulnerability of Australian saltmarshes: implications for management in a changing climate. *Marine And Freshwater Research*, 64 (1), 66-79.

The significance and vulnerability of Australian saltmarshes: implications for management in a changing climate.

Neil Saintilan¹ and Kerrylee Rogers²

¹ Office of Environment and Heritage, Department of Premier and Cabinet. PO Box A290, Sydney South NSW 1232

². School of Earth and Environmental Science, University of Wollongong

ABSTRACT

We review the distribution, status and ecology of Australian saltmarshes and the mechanisms whereby enhanced atmospheric carbon dioxide and associated climate change has and will influence the provision of ecosystem goods and services. Research in temperate and subtropical saltmarsh has demonstrated important trophic contributions to estuarine fisheries, mediated by the synchronised mass spawning of crabs, which feed predominantly on the C₄ saltmarsh grass *Sporobolus virginicus* and microphytobenthos. Saltmarshes also provide unique feeding and habitat opportunities for several species of threatened microbats and birds, and migratory shorebirds. Saltmarshes increased in extent relative to mangrove in Australia in both tide and wave dominated geomorphic settings through the latter Holocene, though historic trends have seen a reversal of this trend. Australian saltmarshes have some capacity to maintain elevation with respect to rising sea level, though in southeastern Australia the encroachment of mangrove and, in Tasmania, conversion of shrubland to herbfield in the past half-century is consistent with changes in relative sea level. Modelling of the impacts of projected sea-level rise, incorporating sedimentation and other surface elevation drivers, suggests that the survival of saltmarsh in developed estuaries will depend upon the flexible management of hard structures and other impediments to wetland retreat.

KEY WORDS: accretion, temperature, wetland, sea-level rise,

RUNNING HEAD: Australian Saltmarsh Review

Introduction

The term saltmarsh refers to an ecosystem characterised by a taxonomically broad group of vascular plants occupying the intertidal shores of estuaries; characteristically herbs, grasses and shrubs, but excluding mangroves and other tree-form vegetation. For the purpose of this review saltmarsh also includes bare or sparsely vegetated hypersaline flats (including sabhka) where productivity is dominated by cyano-bacteria. Saltmarsh distribution globally favours regions where mangroves are excluded by frost (Long and Mason 1983; Mendelsohn and McKee 2000), and the Australian mainland littoral zone is one of a few regions globally where mangrove and saltmarsh show sympatric development. Mangroves have received the greater research and policy attention until recently: Fairweather (1990) described coastal saltmarsh as the least studied of coastal and marine ecosystems in Australia. Ignorance of the extent and ecological significance of coastal saltmarsh may have contributed to the widespread degradation and reclamation of this habitat over the past two centuries, and in recent years the need for urgent conservation action has been reflected in the 2004 listing of coastal saltmarsh as a threatened ecological community in New South Wales (Hughes 2004), and the inclusion in 2010 of temperate and subtropical saltmarsh on the Finalised Priority Assessment List for national listing under the Environmental Protection and Biodiversity Conservation (EPBC) Act.

To an appreciable extent our ignorance of the extent and ecology of coastal saltmarsh in Australia has been overcome in the past two decades, and this paper provides a review of recent work. The research has highlighted the vulnerability of Australian coastal saltmarsh to climate change impacts, in common with saltmarsh globally. Given their geomorphic situation within narrow elevation ranges in the intertidal zone, saltmarshes are sentinel ecosystems in the coastal zone and already the impacts of relative sea-level rise are being manifest (Lovelock *et al.* 2009; Saintilan *et al.* 2009b). Elevated atmospheric carbon dioxide, temperature rise, altered fire regimes, and a range of hydrological changes may also impact on saltmarshes, compounding the pressure of coastal development, vehicular impacts, pollution and invasive species (Adam 2009; McKee *et al.* 2012). The purpose of this review is to provide an overview of our understanding of Australian saltmarshes and their ecology, to identify the key climate change impacts and appropriate management strategies, and to highlight knowledge gaps that continue to hinder the sustainable management of this significant resource.

Distribution of Saltmarsh Plants

Saltmarsh vegetation globally can be classed into six biogeographical types: Arctic, Boreal, West Atlantic, Temperate, Dry Coast, and Tropical (Adam 1990), with consistent regional differences in dominant saltmarsh families. For example, Arctic saltmarshes are dominated by species of the genera *Puccinellia* and *Carex*, Boreal saltmarsh along the North American Atlantic coast is characterised by *Spartina patens*, *S. alterniflora* in the low marsh, and *Triglochin maritima*, *Salicornia virginica*, and *Distichlis spicata* on the Pacific coast (McKee *et al.* 2012). Temperate saltmarsh on the Atlantic coast is dominated by *S. alterniflora*, grading into *Juncus*, *Salicornia* and *Distichlis* in the higher marsh (Boon *et al.* 2011) *et al.* . Tropical saltmarshes are less well surveyed, and species composition varies between wetter communities (*Spartina patens*, *S. spartinae*, *D. spicata* in tropical America) and drier hypersaline environments where succulents dominate (*Batis maritima*, *Borrchia frutescens*, *Suaeda maritima*, and *Sesuvium portulacastrum*) (McKee *et al.* 2012).

Saintilan (2009) lists 103 species of vascular plants occurring in Australian saltmarshes, and presents their distribution by bioregion (using the Interim Bioregionalisation of Australia: IBRA). A more comprehensive list of 140 species for Victoria is presented by Boon *et al.* (2011) who noted, at a family level, strong affinities with saltmarshes on other continents. Adam (1990) explained some of these as a strong Gondwanan affiliation with similarities in the saltmarsh flora of temperate Australia, New Zealand and South Africa and temperate South America. For example, as much as 15% of the halophytic saltmarsh flora of Victoria is shared with New Zealand (Boon *et al.* 2011). A small number of less common species show remarkable trans-hemispheric disjunctions, such as the occurrence of *Limosella australis* on the south coast of New South Wales (NSW), but also in Wales, and *Eleocharis parvula*, rare in Australian saltmarshes but common in the northern hemisphere (Adam 2009). Both instances are thought to be the result of migratory birds transporting seeds between continents, most probably some time ago (Adam 2009).

Species Distribution and Temperature

There have been few systematic surveys of saltmarsh species distribution in Australia, and records of saltmarsh assemblages in individual estuaries remain scant. However, records of species occurrence have been compiled by herbaria since European colonisation and these are now linked in the Australian Virtual Herbarium to provide a national extent sufficient to

describe broad geographic trends. Saintilan (2009) used records from the Australian Virtual Herbarium to compare the distribution of 93 saltmarsh plant species across 36 coastal bioregions. The result was a clear distinction between a northern saltmarsh flora and a southern saltmarsh flora with only one quarter of species in common.

The northern and southern saltmarsh provinces are separated on the east coast immediately north of the South-east Queensland bioregion, where the Brigalow Belt bioregion reaches the coast. While *Sporobolus virginicus* continues to be the dominant saltmarsh species north of this point, several species characteristic of the northern saltmarsh become important, including *Tecticornia australasica*, *Fimbristylis polytrichoides*, *Fimbristylis ferruginea*, *Portulaca bicolor*, *Batis agrillicola*, *Xerochloa imberis* and *Sesuvium portulacastrum*. On the west coast of Australia the same distinction is made within the Carnarvon bioregion to the north of Shark Bay. On both coasts, the Tropic of Capricorn (23°30'S) provides a useful approximation of the point at which the northern and southern biogeographic provinces meet, and they may on this basis be more accurately described as a tropical and subtropical/temperate saltmarsh flora.

In contrast to mangroves (Saenger *et al.* 1977), and indeed most biota (Qian *et al.* 2007), saltmarsh species diversity increases with increasing latitude in Australia (Adam 1996; Saenger *et al.* 1977; Specht 1981). The increase in diversity appears strongly linked to mean minimum daily temperature, explaining nearly 80% of variation in diversity between bioregions (Saintilan 2009). Diversity increases linearly with declining mean minimum daily temperature until a threshold of 8°C is reached, after which point diversity declines. Few experimental studies have explored the relationship between temperature and germination in saltmarshes, and there are no comparable analyses for other continents. Some studies suggest an inverse relationship between temperature and germination success (Greenwood and MacFarlane 2006; Khan and Ungar 1984).

Species distribution and hydrology

Saltmarshes occur predominantly in low wave energy coastal environments, though the species occupying saltmarshes in Australia may be located across a broader range of landscape settings. For example, all of the species of saltmarsh shrubs (genera *Tecticornia* and *Maireana*) found in saltmarshes can be found in inland saline wetlands, and have no

obvious preference for coastal environments (Saintilan 2009). The diversity of saltmarsh shrubs and their frequent occurrence in southern Australian saltmarshes may reflect recruitment from interior arid and semi-arid wetlands. Most of the common saltmarsh grass and herb species are found predominantly but not exclusively in coastal saltmarsh environments (*Sarcocornia quinqueflora*; *Juncus kraussii*; *Ficinia nodosa*; *Selliera radicans*; *Gahnia filum*). Only a small proportion of species found in saltmarshes are found exclusively on the coast (these include *Austrastipa stipoides*; *Batis argillicola*, *Baumea juncea*; *Limonium australe*; *Limonium solanderi*, *Suaeda arbusculoides*; and *Sesuvium portulacastrum* (Saintilan 2009)).

Kirpatrick and Glasby (1981) in their study of Tasmanian saltmarshes classify the structural forms into four distinct groupings: communities dominated by succulent shrubs (e.g. *Tecticornia* spp.); communities dominated by low grasses (e.g. *Sporobolus virginicus*, *Zoysia macrantha*); communities dominated by sedges and tall grasses (e.g. *Juncus kraussii*; *Gahnia filum*); and communities dominated by herbs (e.g. *Sarcocornia quinqueflora*, *Wilsonia backhousei*, *Samolus repens*). The structural classification is useful in that these forms often present zonations across the intertidal zone, though the nature of these zonations varies between climatic regions.

Mangroves are absent from Tasmania, sections of the temperate West Australian coastline, and several intermittently closed/open lakes and lagoons on the temperate east coast. However, for most of the Australian mainland coastline, mangroves dominate the lower- to mid-intertidal zones, restricting saltmarsh development to elevations between mean high tide and the highest astronomical tides. In the temperate and subtropical east coast, a herbfield/grassland dominated by *Sarcocornia quinqueflora*, *Sporobolus virginicus*, *Samolus repens* and *Triglochin striata* gives way in the upper intertidal to tall sedges and grasses. In the cooler temperate saltmarshes of Victoria, Tasmania and South Australia, shrubs of the genus *Tecticornia* dominate the lower- and mid-intertidal zone, with diverse herbfields and grasses more common in the upper-intertidal (Boon *et al.* 2011).

The distribution of structural components of intertidal vegetation in Australian coastal wetlands appears related to the frequency of tidal inundation and aridity (Boon *et al.* 2011; Clarke and Hannon 1969; Clarke and Hannon 1970). Mangroves characteristically occupy flats inundated on most days, and this inundation reduces desiccation of propagules (Clarke

and Myerscough 1993), and variability in soil salinity. At higher elevations in the intertidal zone, inundation becomes increasingly infrequent and varies with phases of the monthly spring tide cycle. The lower inundation frequency of the upper intertidal corresponds to a change from nitrogen to phosphorus limitation in mangroves and their stunted growth (Feller *et al.* 2003). Salinity is more variable than in the lower intertidal, being more susceptible to evaporative concentration of salts, and rapid dilution following rainfall. The upper-intertidal zone is therefore more likely to reflect regional differences in aridity. The upslope zonation of ‘wet’ shrub-dominated marshes to herbfields in Victorian saltmarshes (Barson and Calder 1981) is also reflected in east-west transition to increasing herb-dominated arid saltmarshes (Boon *et al.* 2011).

While most saltmarsh plants are tolerant of salt water, and some species (including *Sarcocornia*) can germinate in seawater salinities or greater, many saltmarsh species require periodically fresher conditions to recruit sexually (Adam 1990; Boon *et al.* 2011). For example, *Juncus kraussii* shows optimal germination in brackish to fresh water (Greenwood and MacFarlane 2006; Naidoo and Kift 2006), and failed to germinate in seawater. Saltmarsh diversity may therefore be more vulnerable to the consequences of ground and surface water diversions than the prevailing salinity conditions may indicate.

Saltmarsh distribution and geomorphology

With the exception of Tasmania where mangroves are absent, saltmarsh typically occupies the upper intertidal zone, generally between mean high tide and mean spring tide, while mangrove occupies the lower intertidal zone. The interaction of hydrology and geomorphology controls the degree of marine and fluvial sedimentation, the development of intertidal flats and ultimately the conditions suitable for saltmarsh establishment. Harris and Heap (2003) conceptualised river, wave and tide power along the length of estuaries with optimal conditions for sediment deposition and saltmarsh development invariably occurring within the central mud basin of wave dominated estuaries and the meandering channels of tide dominated estuaries. The spatial distribution of depositional environments exhibits strong regional zonation and provides insight into the geomorphic settings of saltmarsh around Australia. Specifically, Harris *et al.* (2002) found that the southeast and southwest coasts of Australia are predominantly wave dominated environments, while northern coastal areas are tide dominated.

Estuaries of tropical Northern Australia are primarily tide dominated with macrotidal regimes and seasonal flooding (Harris *et al.* 2002). Woodroffe *et al.* (1993) demonstrate a consistent “big swamp” phase where mangrove dominated estuarine plains during the mid-Holocene for many tide dominated settings. This phase was succeeded by further infilling and the development of hypersaline flats in dryer areas and plains vegetated with salt tolerant plants in the upper intertidal and supra tidal environments. In contrast, the position of large sand islands (e.g. Moreton Island, North and South Stradbroke Island and Fraser Island) along the coastline of southeast Queensland shelters the coastal mainland and the leeward side of the islands from wave action (Saintilan *et al.* 2009a). This has created conditions suitable for the establishment of saltmarsh. Saltmarsh has developed on the leeward side of sand islands, on the back barrier deltaic deposits, and in the channels and channel-fringing flats of large mesotidal rivers.

The southeastern Australian coastline largely comprises wave dominated barrier estuaries in various evolutionary stages (Roy *et al.* 2001). Saltmarsh establishment is generally restricted to the central mud basin where low energy conditions prevail (Harris and Heap 2003). Where the entrance is open or more intermittently open, both mangrove and saltmarsh colonise the intertidal zone. Saltmarsh may dominate when tidal exchange is restricted by a closed or more intermittently closed entrance; under these conditions water levels may exceed the height of mangrove pneumatophores, thereby excluding their growth or causing widespread dieback. In Tasmania, the absence of mangroves allows saltmarsh to occupy a greater portion of the intertidal zone within wave dominated estuaries; here saltmarsh is common on the highly indented wave dominated southeastern coast (Kirkpatrick and Glasby 1981).

Tide dominated estuaries in NSW, classified as “drowned river valleys” (Roy 1984), occur along the central coast of NSW and at Batemans Bay in association with the Lachlan Orogen. These estuaries provide a range of settings suitable for saltmarsh establishment, though large intertidal flats rarely develop due to the deeply incised bedrock valleys that these estuaries occupy. Saltmarsh in these tide dominated settings occur on the meandering fluvial channel in the upper reaches of the estuary where tidal power diminishes, on fluvial deltas that develop where tributaries enter deeper waters within the drowned river valley, in the upper intertidal zone of cut-off embayments, and on back-barrier sands near the estuary mouth (Saintilan *et al.* 2009a). Tide dominated estuaries also occur in northwestern Tasmania where

entrances are protected from waves by large sand bars and islands, enabling saltmarsh to develop in the relatively protected environments on the open coast, though they are increasingly exposed to erosion.

The large marine embayments in Victoria and South Australia support wide fringing saltmarsh plains. These include wave-dominated estuaries, such as the Gippsland Lakes and Barwon River in Victoria, the Coorong in South Australia, and Davenport River near Ceduna in South Australia, and tide dominated estuaries, such as Corner Inlet, Westernport Bay and Port Phillip Bay in Victoria, and the Spencer Gulf and Gulf St. Vincent in South Australia (Saintilan *et al.* 2009a). Limited wave power in tide dominated estuaries allows extensive flats to develop in southern Australia; this is particularly prominent in Westernport Bay where saltmarsh occurs almost continuously around the shore in the upper intertidal zone and on the northern shores of French Island and Philip Island (Boon *et al.* 2011). Limited wave and river power on the tide dominated estuaries of Gulf St. Vincent and Spencer Gulf create conditions of increasing salinity with increasing distance from the ocean; these ‘inverse estuaries’ have vast low-lying areas and hyper saline soils able to support extensive saltmarsh vegetation (Saintilan *et al.* 2009a).

Extensive saltmarsh occurs throughout Western Australia, though its distribution is documented primarily in grey literature. Here, saltmarsh geomorphological settings largely mirror the east coast of Australia; extensive saltmarsh occurs within the tide dominated estuaries of the northern coastline such as the Ord and Fitzroy Rivers, while smaller areas are located within wave dominated estuaries and marine embayments of southwestern Australia, such as Peel-Harvey estuary and Leschenault Inlet (Pen *et al.* 2000; Bridgewater and Cresswell 2003).

Recent changes in the extent of Australian saltmarsh

The Holocene evolution of tide dominated and wave dominated environments provides valuable information regarding the response of saltmarsh to sea level and a context for the interpretation of recent change. Estuaries dominated by tidal processes, typical of the tropical north-west, are characterised by wide upper-intertidal and supratidal blacksoil plains, devoid of vegetation in drier climates, or supporting saltmarsh in wetter areas (Woodroffe *et al.* 1989). Mangroves are restricted to channel-fringing environments (Woodroffe *et al.* 1985)

but in the mid-Holocene were far more extensive, occupying the greater part of the floodplains of the Fitzroy, Ord, Daly and Alligator Rivers (Thom *et al.* 1975; Woodroffe *et al.* 1985). The replacement of mangrove by saltmarsh and salt flats occurred as a result of estuarine infilling (Woodroffe *et al.* 1985).

Wave dominated estuaries are largely comprised of a river dominated bay-head delta and alluvial plain at the head, a low energy central mud basin, and a coastal barrier with flood and ebb tide deltas at the entrance/mouth. Evolution of wave dominated estuaries is well documented (Roy *et al.* 2001; Roy 1984; Roy *et al.* 1980), particularly for southeastern Australia. Following barrier development under stable sea-level conditions, the central mud basin infills with sediment and diminishes in size due to the seaward expansion of the bay-head delta and landward extension of the flood tide delta. Saltmarsh and mangrove largely develop around the margins of the central mud basin: over time the extent of these intertidal communities gradually increases as the basin infills until the point when the intertidal zones succeed to supratidal alluvial floodplain (Hashimoto *et al.* 2006; Roy *et al.* 2001). The replacement of mangrove by saltmarsh has been demonstrated in stratigraphic studies in barrier estuaries (Saintilan and Wilton 2001) and drowned river valleys (Saintilan and Hashimoto 1999) in southeastern Australia.

In contrast to the longer-term Holocene trend of saltmarsh expansion within tidal and wave dominated estuaries, historical trends have seen mangrove replace saltmarsh. Saintilan and Williams (1999) reviewed 28 surveys of mangrove and saltmarsh extent in estuaries and embayments in temperate and subtropical Australia demonstrating a consistent pattern of mangrove expansion at the expense of saltmarsh. To these can be added surveys in Victoria for Westernport Bay (Rogers *et al.* 2005b); in NSW for Minnamurra River (Oliver *et al.* 2012), Homebush Bay (Rogers *et al.* 2005a), Jervis Bay (Saintilan and Wilton 2001), and multiple sites in NSW (Wilton 2002); and in Queensland for Moreton Bay (Eslami-Andargoli *et al.* 2009; Manson *et al.* 2003) and Pioneer River (Jupiter *et al.* 2007). A gradual extension of tidal marine influence has also been observed in the tide dominated estuaries and coastal plains of northern Australia, with saltwater intrusion causing widespread changes in coastal vegetation in the Alligator River region (Winn *et al.* 2006), and the Mary River (Knighton *et al.* 1991; Mulrennan and Woodroffe 1998). Mangroves in the Kakadu region have expanded their range into the upper intertidal environments by 16% over a 30-year period from 1974 (Williamson *et al.* 2011).

The causes of mangrove encroachment into saltmarsh remains a topic of active investigation. Research from southeast Queensland indicates that factors driving mangrove encroachment of saltmarsh may vary depending upon prevailing climatic conditions and catchment landuse patterns (Eslami-Andargoli *et al.* 2009; Eslami-Andargoli *et al.* 2010). In the Kakadu region, above average ocean water levels may be assisted by drier than average monsoonal conditions and the local influence of feral buffalo (Knighton *et al.* 1991; Winn *et al.* 2006). Mangrove expansion has been coincident with the expansion of woody terrestrial vegetation in the region, prompting Williamson *et al.* (2011) to propose that a common driver, such as elevated atmospheric carbon dioxide concentrations, might be at least partly responsible. Rogers *et al.* (2006) also demonstrated that observed rates of encroachment of mangrove into saltmarsh in southeastern Australia exhibited a strong relationship with relative sea-level rise, which accounted for both the eustatic component of sea-level rise and compaction of the saltmarsh surface; more-so the trend of mangrove encroachment of saltmarsh may be related to adjustment of mangrove within the tidal prism in association with recent rates of sea-level rise. Loss in saltmarsh extent and changes in saltmarsh community composition are also occurring in the absence of mangrove in southeast Tasmania and is attributed to sea-level rise, higher wave energy and direct human modification (Prahald *et al.* 2011).

Processes influencing marsh surface elevation

Saltmarshes will be impacted by sea-level rise if they are unable to sustain elevation with respect to water levels, (termed relative elevation (Reed 1990)). Surface Elevation Tables (SETs) have been employed in Australia (Lovelock *et al.* 2011; Rogers *et al.* 2006) and internationally (Cahoon *et al.* 2006) to investigate processes that may influence saltmarsh surface elevations. SETs are a precise and non-destructive method for measuring fine-scale changes in wetland surface elevations (Cahoon 2006b; Cahoon *et al.* 2002a; Cahoon *et al.* 2002b). The application of SETs in Australia has demonstrated a common discrepancy between the degree of elevation change and accretion, driven largely by processes that act to compact saltmarsh soils (Lovelock *et al.* 2011; Rogers *et al.* 2006). The degree of wetland compaction in mangrove and saltmarsh in southeastern Australia has been correlated to fluctuations in groundwater depth, rainfall and the Southern Oscillation Index (Rogers and Saintilan 2009; Rogers *et al.* 2005a), which all varied in association with a severe El Niño-Southern Oscillation (ENSO) related drought between 2001 and 2004. Lovelock *et al.* (2011)

attributed compaction of wetlands soils to soil characteristics, with muddy highly organic soils undergoing greater compaction than sandy soils. Instances where elevation gain exceeded the degree of accretion have been attributed to biological processes of below-ground root development (Rogers *et al.* 2005a) and abandoned salt evaporation ponds that altered the hydrological regime of saltmarsh (Rogers *et al.* 2005b).

While wetland hydrology and soil characteristics influence saltmarsh elevations, accretion of mineralogic and organic material is the dominant process of saltmarsh building in Australia (Lovelock *et al.* 2011; Rogers *et al.* 2006), which contrasts with peat-dominated settings in the northern hemisphere (McKee 2011; McKee *et al.* 2007; Nyman *et al.* 2006; Redfield 1972). Analysis of the SET record from southeastern Australia between 2000 and 2010 (Rogers and Saintilan 2011) indicates that saltmarshes (and mangroves) exhibiting a greater relative elevation gain also exhibited a greater contribution of accretion to elevation gain (Figure 1); hence sediment supply and accretion may be essential for the long-term maintenance of saltmarsh in southeastern Australia.

SUGGEST INSERT FIG 1

The maintenance of relative elevation in reasonably undisturbed saltmarshes in the northern hemisphere led to the concept of a marsh equilibrium elevation, whereby marsh surfaces fluctuate with sea-level change (Pethick 1981). The concept relies upon low elevation marshes building elevation (primarily through accretion) to be situated at an optimal height within the tidal prism; while high elevation marshes build elevation at a slower rate (or may be reworked) to water level changes. This inundation dependent accretion scheme (see Fagherazzi *et al.* 2012 for review of numerical marsh evolution models) appears to be holding true in Australia under current rates of sea-level rise: strong relationships have been established between accretion and tidal range or hydroperiod (Rogers *et al.* 2005a; Rogers *et al.* 2006); and there is little evidence of saltmarsh loss due to submergence. Preliminary assessments suggest that the few instances of saltmarsh loss related to water level changes may be driven by fetch related alterations to wind waves. Models of saltmarsh evolution are required to establish whether this equilibrium response fails when rates of saltmarsh elevation gain are too low (facilitated by insufficient sediment supply and/or plant productivity, or high soil compaction) or the rate of sea-level rise is too high for feedback between processes to respond accordingly.

Modelling marsh responses to sea-level rise

Models of saltmarsh response to sea-level rise incorporate relationships between saltmarsh elevation, processes that influence saltmarsh elevation (accretion, plant productivity, sediment supply etc.), and changes to the tidal prism. These models are becoming increasingly complex (Fagherazzi *et al.* 2012; Rybczyk and Callaway 2009), attempt to integrate both morphologic and ecological components of marsh evolution (D'Alpaos *et al.* 2007; Kirwan and Murray 2007), and have been coupled with models of adjoining systems, such as tidal flats (Mariotti and Fagherazzi 2010). This is an emerging area of saltmarsh research in Australia. SETs have been used to demonstrate that saltmarshes within southeastern Australia exhibit low vulnerability to submergence (Rogers 2004; Rogers and Saintilan 2011); though with the caveat that rates of accretion and elevation adjustment continue and that sea-level continues to rise at relatively low rates that are consistent with recent trends.

Projections of the likely response of saltmarsh to moderate rates of sea-level rise indicate that saltmarsh may be in serious decline by the end of the century. A number of techniques have been employed; including simple bath-tub techniques (Boon *et al.* 2011; Traill *et al.* 2010) that assume static wetland surfaces and do not account for morphological change occurring in conjunction with sea-level rise; the Sea-Level Affecting Marshes Model (SLAMM; Akumu *et al.* 2011; Clough *et al.* 2010; Traill *et al.* 2011); and statistical techniques relying on empirical data (Oliver *et al.* 2012; Rogers *et al.* 2012). Oliver *et al.* (2012) demonstrated that model responses are highly dependent upon the parameters employed within the model. However, with the exception of bath-tub techniques, all models indicate that coastal wetlands may have some capacity to adapt to low rates of sea-level rise. Under high rates of sea-level rise, the capacity to adapt is constrained by the morphology of coastal floodplains, development within coastal floodplains and management to facilitate wetland conversion. Rogers *et al.* (in review) explore the inherent adaptive capacity of estuarine wetlands on the Hunter River to demonstrate that under high and accelerating rates of sea-level rise, thresholds of resilience may become exhausted after 2060. By 2100 these wetlands were projected to be located behind existing levee banks; adaptation will be dependent upon the reinstatement of tidal exchange to these new communities.

Ecological Significance of Saltmarsh

Carbon and Aquatic Foodwebs

Mangroves have long been recognised as playing a significant role in estuarine and nearshore fisheries, and more recently the unique contribution of saltmarsh as a habitat for fish in Australian estuaries has been assessed. The density of fish recorded in Australian saltmarshes varies greatly between settings, with generally fewer individuals found in South Australian marshes than in the temperate and tropical marshes of the Australian east coast (Bloomfield and Gillanders 2005; Connolly 2005; Connolly *et al.* 1997). While the density of fish recorded in Australian saltmarshes appears to be lower than that encountered in mangroves on a unit area basis, and in comparison to northern hemisphere saltmarshes (Shenker and Dean 1979), this may largely be explained by the occurrence of saltmarsh in the upper intertidal zone in Australia, and the shallower depth and duration of inundation (Connolly 2009). When converted to density of fish per unit volume of water, fish density in saltmarsh in the Sydney region is comparable to adjacent mangroves (Mazumder *et al.* 2005). A study of fish assemblages in adjacent seagrass, mangrove and saltmarsh indicated that species appearing in the flooded mangrove and saltmarsh had left the seagrass habitat, which declined in fish abundance during spring tides (Saintilan *et al.* 2007).

Though systematic surveys of saltmarsh nekton diversity are scant, early evidence suggests a latitudinal cline, with higher diversity of species in lower latitudes than higher latitudes (Mazumder *et al.* 2006). The fact that latitudinal cline in fish diversity is inversely related to floristic diversity in Australian saltmarshes would indicate diversity is driven by a more diverse assemblage of species occupying tropical estuaries, rather than structural and niche diversity within the saltmarsh environment. Saltmarsh fish assemblages are dominated by small fish of the families Ambassidae, Atherinidae and Gobiidae (Connolly 2009). However, many species of commercial importance also visit the saltmarsh. Very high densities of banana prawns (*Fenneropenaeus merguensis*) have been observed (Connolly 2005), and the mullet *Liza argentea* is commonly found as juveniles in saltmarshes in temperate southeastern Australia. Surveys have recorded bream (*Acanthopagrus australis*), flathead (*Platycephalus fuscus*), whiting (*Sillago ciliata*), school prawns (*Metapenaeus macleayi*), (Connolly 2009; Mazumder *et al.* 2006) and squid (Mazumder unpublished data).

The inundated saltmarsh plain provides a unique feeding opportunity for fish. Crabs occupying the saltmarsh synchronise their larval production and release with the monthly spring tides (Mazumder *et al.* 2009), and the density of crab larvae within the saltmarsh during spring tide inundation is such that overall zooplankton density is higher at these times than in any other estuarine environment (Mazumder *et al.* 2009). Visiting zooplanktivorous fish are able to feed efficiently and voraciously during their brief residence on the saltmarsh plain (Hollingsworth and Connolly 2006; Platell and Freewater 2009), as do some species of commercial importance (Mazumder *et al.* 2006): gut fullness of Ambassids leaving the saltmarsh is consistently and substantially greater than fish sampled from other shallow estuarine environments (Hollingsworth and Connolly 2006). Snail larvae may similarly make a contribution to the diet of some species (Mazumder *et al.* 2009). Larger predatory fish are often observed at the mouths of tidal channels draining the saltmarsh, and Mazumder *et al.* (2011) were able to demonstrate a trophic relay from the saltmarsh to the broader estuary with zooplanktivores and omnivores feeding periodically within the inundated saltmarsh.

Grazing crabs therefore occupy a keystone position in the saltmarsh ecosystem, transforming carbon into forms utilised by a range of fish species. The most commonly encountered and wide-ranging saltmarsh crab is *Helograpsus haswellianus* (Grapsidae), being common in Tasmania (Richardson *et al.* 1998), South Australia (Imgraben and Dittman 2008), New South Wales (Mazumder and Saintilan 2003; Morrissey 1995), and southeast Queensland (Skilleter and Warren 2000). *H. haswellianus* was primarily responsible for larval export from the saltmarsh at Towra Point, NSW (Mazumder *et al.* 2006). Three other species of burrowing crab are common in temperate Australia: two Grapsidae (*Paragrapsus laevis* and *Parasesarma erythrodactyla*) and one Ocypodidae (*Heloecius cordiformis*). In southeast Queensland, *Australoplax tridentata* replaces *H. cordiformis* as the common Ocypodid in the saltmarsh (Skilleter and Warren 2000).

A range of food items are available to crabs in the saltmarsh: these include living saltmarsh plant material; plant detritus, including mangrove and seagrass detritus transported by the flood tide; microphytobenthos; and organisms deposited by the high tide, including copepods and amphipods, which comprise more than one third of the zooplankton entering with the flood tide (Mazumder *et al.* 2009). Shore crabs are opportunistic scavengers with wide dietary tolerances, and determining the relative contributions of these sources of nutrition can be challenging, given the highly masticated nature of crab gut contents. However, crab

foraging in saltmarsh is highly localised (Guest and Connolly 2004; Guest *et al.* 2004), and recent studies have utilised the contrasting stable isotope signatures of the common C₄ grass *Sporobolus virginicus* and C₃ plants, including mangroves and chenopod saltmarsh plants, which are relatively depleted in ¹³C (Guest and Connolly 2006; Guest *et al.* 2006; Mazumder and Saintilan 2010) to distinguish contributing food sources. Microphytobenthos is intermediate between these two signatures, though may be locally influenced by dissolved inorganic carbon from the C₄ grass (Alderson *et al.* submitted). These studies suggest that *S. virginicus* is an important source of nutrition for crabs in saltmarsh (Guest and Connolly 2004), though probably more-so in the subtropics where the grass is the dominant autotroph. In temperate latitudes, microphytobenthos appears more important, as does a broader range of saltmarsh plant and detrital sources (Saintilan and Mazumder 2010; Alderson *et al.* in review).

Saltmarsh molluscs, including snails, slugs, bivalves and limpets, predominantly live on saltmarsh surfaces and vegetation. These are generally regarded to be epifaunal, though some infaunal species may bury within saltmarsh soils (Ross *et al.* 2009). Saltmarsh vegetation creates a complex arrangement of microhabitats for molluscs, though a broad distribution pattern is apparent within wetlands of NSW with *Ophicardelus* species and *Littoraria luteola* restricted to saltmarsh habitats, and *Phallosmedusa solida*, *Cassidula zonata* and Assimineids largely occurring in the upper mangrove forest and saltmarsh (Kaly 1988; Ross *et al.* 2009). Studies suggest that the diversity and abundance of molluscs in saltmarsh correlates with vegetation (Ross *et al.* 2009). In contrast, research from Tasmania proposed that the composition of molluscs in saltmarshes was not related to plant assemblages (Richardson *et al.* 1998), though Ross *et al.* (2009) suggest that this may relate to the absence of mangrove from Tasmania and the occurrence of saltmarsh at higher elevations in New South Wales.

Molluscs in saltmarsh play an important trophic role as consumers and prey, yet relatively little research in Australia has focussed on their contribution to estuarine foodwebs. Observations reveal that snails and slugs consume plant detritus, microalgae and other organic matter from the saltmarsh surface or saltmarsh vegetation (Hutchings and Recher 1981; Ross *et al.* 2009). Direct herbivory of saltmarsh vegetation was confirmed by isotope analysis by Saintilan and Mazumder (2010), and there is evidence of correlations between food available for direct herbivory and mollusc density (Ross *et al.* 2009), though this may also relate to provision of shelter by specific saltmarsh plants (Richardson *et al.* 1998).

Recent research from the USA highlights the role of molluscs in saltmarsh die-off by selectively consuming saltmarsh vegetation (Gedan *et al.* 2009); however, the role of herbivorous molluscs as habitat modifiers and top-down consumers has not been observed in Australia, but requires further attention. Mollusc adults and larvae are also prey for a range of estuarine predators, including eels, crabs, fish, waterbirds and mammals (Hollingsworth and Connolly 2006; Mazumder *et al.* 2006; Roach 1998); these molluscs and other invertebrates appear to make an important contribution to the diet of fish feeding in saltmarsh (Mazumder *et al.* 2006).

Though saltmarshes provide habitat for a range of invertebrates, they are well known for the provision of habitat for pestiferous and vector mosquitoes; including *Aedes vigilax*, which largely occurs in tropical and subtropical climates; *Aedes camptorhynchus*, which occurs in cooler climates; and *Aedes alternans*, which is less common but has a wider distribution (Dale and Breitfuss 2009). These invertebrates transmit a variety of arbovirus diseases, including Ross River and Barmah Forest viruses, which are debilitating and have economic impact on healthcare resources and productivity. As a consequence saltmarsh mosquito research has largely focussed on strategies to limit mosquito abundance and the transmission of viruses (see for example Hu *et al.* 2010; Knight *et al.* 2012; Williams *et al.* 2009).

Strategies to control mosquito populations include habitat modification to maintain or restore tidal flooding, chemical control using non-specific chemicals to limit the abundance of adult mosquitoes, and biological control facilitated by the consumption of larvae by fish and shrimp (Morris *et al.* 2002; Morton *et al.* 1988; Morton *et al.* 1987). *Pseudomugil signifer*, a small fish commonly found in saltmarsh, was found in laboratory studies to prey on mosquito larvae but was satiated at moderate densities (Willems *et al.* 2005). Mosquito control in Australia has largely focussed on runnelling to promote tidal exchange; chemical control is generally only implemented under emergency situations where there is a risk of disease transmission to humans, while biological control is currently ineffective at controlling vector mosquitoes (Dale and Breitfuss 2009). It is apparent that integrated approaches have the greatest success, as in the Northern Territory where drainage channels are maintained annually and supplemented with aerial spraying. This research in Northern Territory also indicates that when undertaken effectively, the cost of large scale habitat modification to control mosquitoes may be offset by the added benefit of saltmarsh restoration facilitated by the reinstatement of tidal exchange (Jacups *et al.* 2012). However these management

approaches should also consider the impact on non-target species; such as fish, which have been found to exhibit lower abundance in the vicinity of saltmarsh runnels, perhaps in response to limited prey availability (Connolly 2005).

Physical habitat structure and itinerant vertebrates

Large vertebrate animals also use Australian saltmarshes. In this regard saltmarsh is perhaps best known for providing roosting and foraging habitat for waterbirds; however they also provide feeding habitat for terrestrial birds, insectivorous bats, the water mouse (*Xeromys myoides*) and a range of incidental visitors including macropods [e.g. swamp wallaby (*Wallabia bicolor*), eastern grey kangaroo (*Macropus giganteus*)], reptiles and amphibians [goannas and monitors (*Varanus* species), red-bellied black snakes (*Pseudechis porphyriacus*), estuarine crocodiles (*Crocodylus porosus*), eastern long-necked turtles (*Chelodina longicollis*)] and numerous introduced animals (rabbits, foxes, rats and hares) (Laegdsgaard *et al.* 2009). The habitat role that saltmarsh plays for these vertebrate species is significant; for example the water mouse, which nests within saltmarsh, mangrove and coastal freshwater wetlands, is vulnerable at international, national and state levels (IUCN; Commonwealth *Environmental Protection and Biodiversity Conservation Act 1999*; Queensland *Nature Conservation (Wildlife) Regulation 1994*). Availability of suitable habitat may be a strong limiting factor on the distribution and abundance of the water rat (Russell and Hale 2009). Few studies document the importance of saltmarsh to insectivorous bats; however, Gonsalves *et al.* (2009) detected 13 insectivorous bat species over saltmarsh, with saltmarsh noted to provide significant foraging benefit to *Chalinolobus gouldii*, *Mormopterus ridei* and *Vespadelus* species as they commonly avoid foraging in open habitats. Recorded feeding buzzes from insectivorous bats over saltmarsh reportedly coincide with the emergence of mosquitoes following spring high tides (Belbasé 2005).

The habitat role that saltmarsh plays for waterbirds is well-documented (Laegdsgaard *et al.* 2009); they provide feeding habitat for terrestrial birds, including birds of prey (e.g. swamp harrier (*Circus approximans*), whistling kite (*Haliastur spehnurus*)), small passerines (e.g. endemic species White-fronted chat (*Epthianura albifrons*), and little grassbird (*Megalurus gramineus*)); they act as a refuge for common colonial waterbird species when inland wetlands may be dry (e.g. Australian white ibis (*Threskiornis molucca*), cattle egret (*Ardea ibis*)) (Kingsford and Norman 2002); they act as a drought refuge for Australian breeding shorebird species, and some species are reported to breed in saltmarsh when conditions are

not favourable elsewhere (e.g. black winged stilt (*Himantopus himantopus*) and masked lapwing (*Vanellus miles*)) (Marchant and Higgins 1993). Migratory shorebird species roost and feed in intertidal environments, with many species avoiding mangrove in preference to the open expanse of saltmarsh (Zharikov and Milton 2009). Shallow saltmarsh pools are particularly important as a night roost in the Hunter estuary (Spencer *et al.* 2009). As signatory to agreements with China (China-Australia Migratory bird Agreement, CAMBA), Japan (JAMBA) and the Republic of Korea (ROKAMBA) aimed at maintaining migratory shorebird habitat, Australian authorities must consider the preservation of habitat values of saltmarsh. In addition, the habitat role that wetlands play for waterbirds has also ensured that a number of saltmarsh wetlands in Australia are included on the 'list of wetlands of international importance' identified under the Ramsar Convention, including Moreton Bay, Hunter Estuary Wetlands, Towra Point Nature Reserve, Corner Inlet, Western Port, The Coorong and Peel-Yalgorup System.

Despite these efforts to conserve saltmarsh as waterbird habitat, recent analyses highlight trends of declining abundance of many shorebird species that use the East Asian-Australasian flyway in Moreton Bay (Wilson *et al.* 2011) and other sites (Wetlands International 2006). A number of causes have been identified for this decline, including climate change influences on breeding habitat in the Arctic, loss of stopover sites throughout Asia, and reduction in area and quality of non-breeding grounds primarily in Australia (Wilson *et al.* 2011). An analysis of shorebird abundance data from Moreton Bay established that selection of safe and open supratidal roosting sites, including supratidal spits and sandbars and saltmarsh in the upper intertidal, was strongly affected by proximity to a large foraging area, field of view and the composition of the surrounding landscape (Zharikov and Milton 2009); decline in the availability of roosting sites with these characteristics may influence the abundance of shorebirds. Similarly, a recent study highlighted the decline in the Sydney region of the small passerine white fronted chat (*Epthianura albifrons*), which is predominantly found in saltmarsh, and found the species was particularly sensitive to human-induced disturbance and habitat loss. Population declines for birds relying on saltmarsh highlight the need for a review of existing management plans and a preparation of recovery plans for species in serious decline (Jenner *et al.* 2011).

Biomass, nutrient cycling and Carbon sequestration

Mangrove and saltmarsh are among the most efficient ecosystems globally at sequestering carbon (Pidgeon 2009), a capacity that currently places these wetlands at the forefront of scientific and policy interest. 'Blue Carbon', as it is commonly known, is the potential of marine ecosystems to trap and bury atmospheric carbon dioxide (Nellemann *et al.* 2009). This efficiency occurs because methane emissions are dramatically reduced in environments where methanogenic bacteria are inhibited by salt (Poffenbarger *et al.* 2011), and because the biogeochemical conditions in tidal wetlands are conducive to long-term carbon retention (DeLaune *et al.* 1990; Choi and Wang 2004). A review by Duarte *et al.* (2005a) reported a mean organic carbon burial rate of 1.51 Mg ha yr⁻¹ for saltmarsh (maximum 17.2 Mg ha yr⁻¹) exceeding the maximum burial rate of undisturbed Amazonian forest (1.02 Mg ha yr⁻¹) (Grace *et al.* 1993; Nellemann *et al.* 2009).

However, Australian saltmarsh communities are likely to vary greatly in their capacity to fix and bury carbon. Livesly and Andrusiak (2011) sampled in the *Sclerostegia* saltbush in Westernport Bay, Victoria, which they estimated to be relatively high in carbon store (105.7 Mg C ha⁻¹). Saltbushes of the genus *Sclerostegia* and *Halosarcia* (or *Tecticornia* following Shepherd and Wilson 2007) dominate saltmarsh communities in southern Australia, and Livesly and Andrusiak (2011) provide the only quantified record for this community type to date. The saltmarsh rush *Juncus kraussii* maintains a high above-ground productivity in NSW (0.81 kg m⁻² yr⁻¹) (Clarke and Jacoby 1994), and southwestern Australia (0.3-1.3 kg m⁻² yr⁻¹) (Congdon and McComb 1980), a figure higher than the above-ground productivity estimates for the two sympatric species of mangrove, *Avicennia marina* (0.31 kg m⁻² yr⁻¹) and *Aegiceras corniculatum* (0.21 kg m⁻² yr⁻¹) (Clarke 1994). The high rate of productivity translates into a relatively high carbon concentration in sediment accumulated in *Juncus* wetlands on the Hawkesbury River (Saintilan and Rogers unpublished data). However, as the occurrence of *J. kraussii* may be indicative of the presence of low soil salinities (Naidoo and Kift 2006; Zedler *et al.* 1995), perhaps associated with fresh groundwater intrusions or contribution of fresh surface water run-off, these wetlands may yield greater methane emissions than the saltmarsh grasses and herbs found elsewhere. A comparison of soil carbon budgets across saltmarsh communities in the region would be an important avenue for further investigation. The *Sporobolus virginicus*/*Sarcocornia quinqueflora* association is the most widespread saltmarsh vegetation community on the Australian east coast (Adam *et al.* 1988), and contributes carbon to estuarine foodwebs across the region (Guest and Connolly 2004; Mazumder *et al.* 2011). The standing biomass of this community is relatively low (Clarke and

Jacoby 1994), and roots are shallow, suggesting that the rate of accumulation of recalcitrant carbon in the soil may be low for these communities, though no measures have been published.

Much of this carbon is stable if soil conditions are preserved though several factors may threaten the longevity of carbon preserved in estuarine soils. The dynamic geomorphology to which mangroves and saltmarshes are adapted is one such factor; eroding shorelines act to reset carbon stores (Alongi 2011). However, the temperate setting, limited catchment area and protected entrance of many of the east-flowing rivers of eastern Australia have given rise to relatively quiescent conditions for carbon accumulation in estuaries. For example, at several locations on the Hawkesbury River, Saintilan and Hashimoto (1999) found well preserved mangrove soils 70 cm below the contemporary saltmarsh surface dating from 1700 ± 90 years to 490 ± 70 years BP. The size of the carbon store at one site is approximately 260 Mg C ha^{-1} . Similarly, Saintilan and Wilton (2001) found well preserved peats at Carama Inlet and Curremembene Creek, Jervis Bay, preserved beneath the saltmarsh.

Summary of Climate Change Vulnerability

The ecosystem goods and services provided by saltmarsh in Australia are likely to be impacted by environmental changes related to enhanced levels of atmospheric carbon. Elevated carbon dioxide potentially has direct effects on the competitive advantage of plant species in the intertidal zone. The growth of mangroves is enhanced by elevated carbon dioxide, particularly in low salinity conditions (Ball *et al.* 1997; Farnsworth *et al.* 1996), and may partly explain the proliferation of woody vegetation over non-woody vegetation in the Kakadu region (Williamson *et al.* 2011), as has been postulated for the expansion of woody vegetation into terrestrial grasslands (Bond and Midgley 2000; Eamus and Palmer 2007). The efficacy of this mechanism may be reduced in competition with some saltmarsh species (McKee and Rooth 2008) and more experimental data are required for Australian species interactions. Equally, elevated carbon dioxide may promote the growth of C_3 photosynthesising plants over C_4 saltmarsh plants, which may have flow-on effects to estuarine foodwebs given the proven trophic significance of the dominant C_4 grass *Sporobolus virginicus* in Australian estuaries (Guest and Connolly 2006; Saintilan and Mazumder 2010).

Increased temperature associated with elevated greenhouse gas concentrations has the potential to influence saltmarsh extent and diversity. The strong inverse relationship between minimum monthly temperature and saltmarsh species diversity in Australia would suggest that significant warming might threaten the survival of some cold-dependant species, while further promoting the proliferation of the essentially tropical mangrove genera. The invasive saltmarsh plant *Spartina* spp. is currently restricted to small but dense patches in several Tasmanian and Victorian estuaries (Adam 2009; Williamson 1996), and higher temperatures may promote its further proliferation (Boon *et al.* 2011), as has been observed in the Netherlands (Loebl *et al.* 2006).

Sea-level rise presents an opportunity and threat to coastal saltmarsh, depending on rates of sediment supply, local topographic conditions and barriers to transgression. Several studies have strongly implicated relative sea-level rise as a driver of changes already observed, including, tidal creek reactivation and saline intrusion in brackish wetlands in tropical Australia (Winn *et al.* 2006), mangrove encroachment in southeastern Australia (Rogers *et al.* 2006), and conversion of *Tecticornia* shrubland to *Sarcocornia* herbfield and open water in Tasmania (Prahalad *et al.* 2011). In many developed coastal lowlands, the fate of coastal saltmarsh as an ecological community rests with local planning instruments. As climate change related sea-level rise is projected to accelerate in the 21st century (Meehl *et al.* 2007), there is an urgent need to explore adaptation options for these communities, particularly through management actions that promote the accommodation and retreat of saltmarsh to higher elevations (Rogers *et al.* in press). In addition, as climate change may increase the frequency and intensity of storm events (CSIRO and BOM 2007) which may contribute to saltmarsh maintenance by enhancing sedimentation, or saltmarsh loss by compressing saltmarsh surfaces or causing erosion (Cahoon 2006a). Other factors, such as altered rainfall patterns and catchment land use change, may also alter sediment supply to estuaries and the capacity of saltmarsh to remain in-situ as sea levels rise.

Management implications, recommendations and knowledge gaps

Climate change is occurring against the backdrop of multiple threats to saltmarsh, resulting from the situation of saltmarsh occurring in the heavily populated coastal zone. Several reviews have documented the impacts of reclamation, pollution, recreation use and grazing on coastal saltmarsh in Australia (Adam 2009; Boon *et al.* 2011; Laegdsgaard *et al.* 2009),

and recovery times from small disturbances in the upper intertidal zone can extend to years (Laegdsgaard 2002). Improved legislative protection and inclusion in regional planning policies has done much to arrest the incremental loss of saltmarsh in Australia (Laegdsgaard *et al.* 2009). However, sea-level rise poses a new set of planning challenges, changing the focus from the protection of existing saltmarsh to the protection of opportunities for adaptation. Models of the impact of sea-level rise on wetlands in the region have indicated that further losses of saltmarsh are inevitable. Rogers *et al.* (2012) demonstrated that a continuation of current sea-level trends for the Hunter estuary will lead to an increase in land available for mangrove and saltmarsh if passive retreat is allowed. The continuing survival of mangrove and saltmarsh will depend on the managed retreat of these ecosystems, currently inhibited in NSW by in excess of 4000 impediments to tidal flow (Williams and Watford 1997). One third of these impediments, if removed or regulated, would provide opportunities for wetland restoration (Williams and Watford 1997), though opportunities for retreat are incrementally removed as ‘sea-change’ population growth continues along the coast. Appropriate zoning by local planning agencies is hampered by restricted coverage of detailed (LiDAR-derived) elevation modeling and limited application of dynamic wetland response modeling.

The removal of impediments to tidal inundation of coastal lowland has the dual benefit of climate change adaptation and mitigation. Rates of accumulation of carbon and loss will vary within estuaries (Alongi 2012), as will rates of gaseous flux (Poffenbarger *et al.* 2011), with some mangroves and saltmarshes being net exporters or emitters of carbon. The success of mangrove and saltmarsh restoration programs under REDD+ and PES frameworks will be linked to long-term stability of the site and the soil carbon stores being accumulated (Alongi 2011). Careful site selection is important in this context. Upstream sites within estuaries represent a higher risk, with more dynamic fluvial drivers of geomorphic change and greater likelihood of methanogenesis. Restoring mangrove and saltmarsh wetland within reclaimed lowland floodplains protected by floodgates presents a high likelihood of success in controlled environments amenable to experimental manipulation. Careful monitoring of carbon benefits derived from such projects leading to improved predictive modeling of carbon flux will increase confidence in the market over time.

Due to competing pressure on coastal land, saltmarsh management responses to climate change must be innovative, with consideration given to win-win options, as described above,

or ‘no regrets’ options where a net social or economic benefit is gained irrespective of the influence of climate change (Parry *et al.* 2007). ‘Living shorelines’, a term used to describe the protective effect that vegetation can have on shorelines by binding soils, trapping sediments, and baffling tidal flow and wave action, are gaining in popularity internationally (Currin *et al.* 2010; Gedan *et al.* 2011). This ‘no regrets’ option is yet to be fully explored in Australia due to community misconceptions on the value of shoreline vegetation and loss of visual amenity; however, management actions that create or maintain vegetated shorelines not only acts as a defense to sea-level rise, erosion and storm surge; they also provide multiple ecosystem services, including habitat creation and carbon sequestration.

References

- Adam P (1990) 'Saltmarsh ecology.' (Cambridge University Press: Cambridge)
- Adam P (1996) Saltmarsh. In 'State of the Marine Environment Report for Australia. Technical Annexe 1'. (Eds LP Zann and P Kailola). (Department of Environment, Sport and Territories: Canberra, Australia)
- Adam P (2009) Australian saltmarshes in global context. In 'Australian saltmarsh ecology'. (Ed. N Saintilan) pp. 1-22. (CSIRO Publishing: Collingwood, Victoria, Australia)
- Adam P, Wilson NC, Huntley B (1988) The phytosociology of coastal saltmarsh vegetation in New South Wales. *Wetlands (Australia)* **7**, 35-57.
- Akumu C, Pathirana S, Baban S, Bucher D (2011) Examining the potential impacts of sea level rise on coastal wetlands in north-eastern NSW, Australia. *Journal of Coastal Conservation* **15**, 15-22.
- Alongi DM (2011) Carbon payments for mangrove conservation: ecosystem constraints and uncertainties of sequestration potential. *Environmental Science and Policy* **14**, 462-470.
- Alongi DM (2012) Carbon Sequestration in Mangrove Forests. *Carbon Management* **3**, 313-322.
- Ball MC, Cochrane MJ, Rawson HM (1997) Growth and water use of the mangroves *Rhizophora apiculata* and *R. stylosa* in response to salinity and humidity under ambient and elevated concentrations of atmospheric CO₂. *Plant, Cell and Environment* **20**, 1158-1166.
- Barson MM, Calder DM (1981) The vegetation of the Victorian coast. *Proceedings of the Royal Society of Victoria* **92**, 55-65.
- Belbasé S (2005) Presence and activity of insectivorous bats in saltmarsh habitat at Kooragang Nature Reserve, Newcastle. Australian Catholic University.

Bloomfield A, Gillanders B (2005) Fish and invertebrate assemblages in seagrass, mangrove, saltmarsh, and nonvegetated habitats. *Estuaries and Coasts* **28**, 63-77.

Bond WJ, Midgley GF (2000) A proposed CO₂ controlled mechanism of woody plant invasion in grasslands and savannas. *Global Change Biology* **6**, 865-869.

Boon PI, Allen T, Brook J, Carr G, Frood D, Harty C, Hoye J, McMahon A, Mathews S, Rosengren N, Sinclair S, White M, Yugovic J (2011) 'Mangroves and coastal saltmarsh of Victoria: distribution, condition, threats and management.' Institute for Sustainability and Innovation, Victoria University, Melbourne.

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

Cahoon D (2006b) Surface Elevation Table (SET). Available at <http://www.pwrc.usgs.gov/set/> [accessed 25 October 2012]

Cahoon DR, Hensel PF, Spencer T, Reed DJ, McKee KL, Saintilan N (2006) Coastal wetland vulnerability to relative sea-level rise: Wetland elevation trends and process controls. In 'Wetlands and natural resource management'. (Eds JTA Verhoeven, B Beltman, R Bobbink and DF Whigham) pp. 271-292. (Springer Berlin Heidelberg)

Cahoon DR, Lynch JC, Hensel P, Boumans R, Perez BC, Segura B, Day JW, Jr. (2002a) High-precision measurements of wetland sediment elevation: I. Recent improvements to the Sedimentation-Erosion Table. *Journal of Sedimentary Research* **72**, 730-733.

Cahoon DR, Lynch JC, Perez BC, Segura B, Holland RD, Stelly C, Stephenson G, Hensel P (2002b) High-precision measurements of wetland sediment elevation: II. The rod Surface Elevation Table. *Journal of sedimentary research* **72**, 734-739.

Clarke LD, Hannon NJ (1969) The Mangrove Swamp and Salt Marsh Communities of the Sydney District: II. The Holocoenotic Complex with Particular Reference to Physiography. *Journal of Ecology* **57**, 213-234.

Clarke LD, Hannon NJ (1970) The Mangrove Swamp and Salt Marsh Communities of the Sydney District: III. Plant Growth in Relation to Salinity and Waterlogging. *Journal of Ecology* **58**, 351-369.

Clarke PJ (1994) Baseline studies of temperate mangrove growth and reproduction: demographic and litterfall measures of leafing and flowing. *Australian Journal of Botany* **42**, 37-48.

Clarke PJ, Jacoby CA (1994) Biomass and Above-ground Productivity of Salt-marsh Plants in South-eastern Australia. *Australian Journal of Marine and Freshwater Research* **45**, 1521-1528.

Clarke PJ, Myerscough PJ (1993) The intertidal distribution of the grey mangrove (*Avicennia marina*) in southeastern Australia: The effects of physical conditions, interspecific competition, and predation on propagule establishment and survival. *Australian Journal of Ecology* **18**, 307-315.

Clough JS, Park RA, Fuller R (2010) 'SLAMM 6 beta Technical Documentation, Release 6.0 beta.' Warren Pinnacle Consulting, Inc, USA, Warren, Vermont.

Congdon RA, McComb AJ (1980) Productivity and nutrient content of *Juncus kraussii* in an estuarine marsh in south-western Australia. *Australian Journal of Ecology* **5**, 221-234.

Connolly R (2009) Fish on Australian Saltmarshes. In 'Australian Saltmarsh Ecology'. (Ed. N Saintilan). (CSIRO Publishing: Melbourne)

Connolly RM (2005) Modification of saltmarsh for mosquito control in Australia alters habitat use by nekton. *Wetlands Ecology and Management* **13**, 149-161.

Connolly RM, Dalton A, Bass DA (1997) Fish use of an inundated saltmarsh flat in a temperate Australian estuary. *Australian Journal of Ecology* **22**, 222-226.

CSIRO, BOM (2007) 'Climate change in Australia.' Commonwealth Scientific and Industrial Research Organisation and the Australian Bureau of Meteorology, Canberra.

Currin CA, Chappell WS, Deaton A (2010) Developing alternative shoreline armoring strategies: The living shoreline approach in North Carolina. In 'Puget Sound Shorelines and the Impacts of Armoring'. (Ed. H Shipman, Dethier, M.N., Gelfenbaum, G., Fresh, K.L., and Dinicola, R.S.) pp. 91-102. (U.S. Geological Survey Scientific Investigations Report 2010-5254)

D'Alpaos A, Lanzoni S, Marani M, Rinaldo A (2007) Landscape evolution in tidal embayments: Modeling the interplay of erosion, sedimentation, and vegetation dynamics. *Journal of Geophysical Research* **112**.

Dale P, Breidfuss M (2009) ecology and management of mosquitoes. In 'Australian saltmarsh ecology'. (Ed. N Saintilan). (CSIRO Publishing: Collingwood, Vic)

Eamus D, Palmer AR (2007) Is climate change a possible explanation for woody thickening in arid and semi-arid regions? *Research Letters in Ecology* **2007**, 5.

Eslami-Andargoli L, Dale P, Sipe N, Chaseling J (2009) Mangrove expansion and rainfall patterns in Moreton Bay, Southeast Queensland, Australia. *Estuarine, Coastal and Shelf Science* **85**, 292-298.

Eslami-Andargoli L, Dale PER, Sipe N, Chaseling J (2010) Local and landscape effects on spatial patterns of mangrove forest during wetter and drier periods: Moreton Bay, Southeast Queensland, Australia. *Estuarine, Coastal and Shelf Science* **89**, 53-61.

Fagherazzi S, Kirwan ML, Mudd SM, Guntenspergen GR, Temmerman S, D'Alpaos A, van de Koppel J, Rybczyk JM, Reyes E, Craft C, Clough J (2012) Numerical models of salt marsh evolution: Ecological, geomorphic, and climatic factors. *Reviews of Geophysics* **50**, RG1002.

Fairweather PG (1990) Ecological changes due to our use of the coast: research needs versus effort. *Proceedings of the Ecological Society of Australia* **16**, 71-77.

Farnsworth EJ, Ellison AM, Gong WK (1996) Elevated CO₂ alters anatomy, physiology, growth and reproduction of red mangroves (*Rhizophora mangle* L.). *Oecologia* **108**, 599-609.

Feller IC, McKee KL, Whigham DF, O'Neill JP (2003) Nitrogen versus Phosphorus limitation across and ecotonal gradient in a mangrove forest. *Biogeochemistry* **62**, 145-175.

Gedan K, Kirwan M, Wolanski E, Barbier E, Silliman B (2011) The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm. *Climatic Change* **106**, 7-29.

Gedan KB, Silliman BR, Bertness MD (2009) Centuries of Human-Driven Change in Salt Marsh Ecosystems. *Annual Review of Marine Science* **1**, 117-141.

Grace J, Lloyd J, MacIntyre J, Miranda AC, Meir P, Miranda HS, Mobre C, Moncrieff J, Massheder J, Malhi Y, Wright I, Gash J (1993) Carbon dioxide uptake by undisturbed tropical rain forest in southwest Amazonia, 1993 to 1992. *Science* **270**, 778-780.

Greenwood ME, MacFarlane GR (2006) Effects of Salinity and Temperature on the Germination of *Phragmites australis*, *Juncus kraussii*, and *Juncus acutus*: Implications for Estuarine Restoration Initiatives. *Wetlands* **26**, 854-861.

Guest MA, Connolly RM (2004) Fine-scale movement and assimilation of carbon in saltmarsh and mangrove habitat by resident animals. *Aquatic Ecology* **38**, 599-609.

Guest MA, Connolly RM (2006) Movement of carbon among estuarine habitats: the influence of saltmarsh patch size. *Marine Ecology Progress Series* **310**, 15-24.

Guest MA, Connolly RM, Lee SY, Loneragan NR, Breitfuss MJ (2006) Mechanism for the small-scale movement of carbon among estuarine habitats: organic matter transfer not crab movement. *Oecologia* **148**, 88-96.

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

Harris PT, Heap AD (2003) Environmental management of clastic coastal depositional environments: inferences from an Australian geomorphic database. *Ocean and Coastal Management* **46**, 457-478.

Harris PT, Heap AD, Bryce SM, Porter-Smith R, Ryan DA, Heggie DT (2002) Classification of Australian Clastic Coastal Depositional Environments Based Upon a Quantitative Analysis of Wave, Tidal, and River Power. *Journal of Sedimentary Research* **72**, 858-870.

Hashimoto TR, Saintilan N, Haberle SG (2006) Mid-Holocene Development of Mangrove Communities Featuring Rhizophoraceae and Geomorphic Change in the Richmond River Estuary, New South Wales, Australia. *Geographical Research* **44**, 63-76.

Hollingsworth A, Connolly RM (2006) Feeding by fish visiting inundated subtropical saltmarsh. *Journal of Experimental Marine Biology and Ecology* **336**, 88-98.

Hu W, Mengersen K, Dale P, Tong S (2010) Difference in Mosquito Species (Diptera: Culicidae) and the Transmission of Ross River Virus between Coastline and Inland Areas in Brisbane, Australia. *Environmental Entomology* **39**, 88-97.

Hughes L (2004) Coastal saltmarsh in the NSW North Coast, Sydney Basin and SE Corner Bioregions – endangered ecological community listing. NSW Scientific Committee – final determination. . In. (NSW Office of Environment and Heritage)

Hutchings PA, Recher HF (1981) The fauna of Australian mangroves. *Proceedings of the Linnean Society of New South Wales* **106**, 83-121.

Imgraben S, Dittman S (2008) Leaf litter dynamics and litter composition in two temperate South Australian mangrove forests. *Journal of Sea Research* **59**, 83-93.

Jacups S, Warchot A, Whelan P (2012) Anthropogenic Ecological Change and Impacts on Mosquito Breeding and Control Strategies in Salt-Marshes, Northern Territory, Australia. *EcoHealth*, 1-12.

Jenner B, French K, Oxenham K, Major RE (2011) Population decline of the White-fronted Chat (*Epethianura albifrons*) in New South Wales, Australia. *Emu* **111**, 84-91.

Jupiter S, Potts D, Phinn S, Duke N (2007) Natural and anthropogenic changes to mangrove distributions in the Pioneer River Estuary (QLD, Australia). *Wetlands Ecology and Management* **15**, 51-62.

Kaly UL (1988) Distribution, abundance and size in mangrove and saltmarsh gastropods. University of Sydney.

Khan MA, Ungar IA (1984) The effect of salinity and temperature on the germination of polymorphic seeds and growth of *Atriplex triangularis* Willd. *American Journal of Botany* **71**, 481-489.

Kingsford RT, Norman FI (2002) Australian waterbirds - products of the continent's ecology. *Emu* **102**, 47-69.

Kirkpatrick JB, Glasby J (1981) 'Saltmarsh in Tasmania: distribution, community, composition and conservation.' Occasional paper no. 8. Department of Geography, University of Tasmania, Hobart.

Kirwan ML, Murray AB (2007) A coupled geomorphic and ecological model of tidal marsh evolution. *Proceedings of the National Academy of Sciences* **104**, 6118-6122.

Knight J, Griffin L, Dale P, Phinn S (2012) Oviposition and larval habitat preferences of the saltwater mosquito, *Aedes vigilax*, in a subtropical mangrove forest in Queensland, Australia. *Journal of Insect Science* **12**, available online: insectscience.org/12.6.

Knighton AD, Mills K, Woodroffe CD (1991) Tidal-creek extension and saltwater intrusion in northern Australia. *Geology* **19**, 831-834.

Laegdsgaard P (2002) Recovery of small denuded patches of the dominant NSW coastal saltmarsh specie (*Sporobolus virginicus* and *Sarcocornia quinqueflora*) and implications for restoration using donor sites. *Ecological Management & Restoration* **3**, 200-204.

Laegdsgaard P, Kelleway J, Williams RJ, Harty C (2009) Protection and management of coastal saltmarsh. In 'Australian Saltmarsh Ecology'. (Ed. N Saintilan) pp. 149-166. (CSIRO Publishing: Collingwood, Melbourne)

Livesley SJ, Andrusiak SM (2011) Temperate mangrove and salt marsh sediments are a small methane and nitrous oxide source but important carbon store. *Estuarine, Coastal and Shelf Science* **97**, 19-27.

Loebl M, van Beuskon JEE, Reise K (2006) Is spread of the neophyte *Spartina anglica* recently enhanced by increasing temperatures? *Aquatic Ecology* **20**, 315-324.

Long SP, Mason CF (1983) 'Saltmarsh Ecology.' (Blackie and Son Ltd: Glasgow and London)

Lovelock C, Bennion V, Grinham A, Cahoon D (2011) The Role of Surface and Subsurface Processes in Keeping Pace with Sea Level Rise in Intertidal Wetlands of Moreton Bay, Queensland, Australia. *Ecosystems* **14**, 745-757.

Lovelock CE, Skilleter G, Saintilan N (2009) Tidal Wetlands and Climate Change. In 'Marine Climate Change Impacts and Adaptation Report Card for Australia 2009.'. (Eds ES Poloczanska, AJ Hobday and AJ Richardson). (National Climate Change Adaptation Research Facility)

Manson FJ, Loneragan NR, Phinn SR (2003) Spatial and temporal variation in distribution of mangroves in Moreton Bay, subtropical Australia: a comparison of pattern metrics and change detection analyses based on aerial photographs. *Estuarine, Coastal and Shelf Science* **57**, 663-666.

Marchant S, Higgins PJ (1993) 'Handbook of Australian, New Zealand and Antarctic Birds. Volume 2: Raptors to Lapwings.' (Oxford University Press: Melbourne)

Mariotti G, Fagherazzi S (2010) A numerical model for the coupled long-term evolution of salt marshes and tidal flats. *Journal of Geophysical Research* **115**, F01004.

Mazumder D, Saintilan N (2003) A comparison of sampling techniques in the assessment of burrowing crab abundance in saltmarsh and mangrove environments. *Wetlands (Australia)* **21**, 1-15.

Mazumder D, Saintilan N (2010) Mangrove leaves are not a significant source of carbon and nitrogen for temperate mangrove crabs in Australia. *Wetlands* **30**, 375-380.

Mazumder D, Saintilan N, Williams JR, Szymczak R (2011) Trophic importance of a temperate intertidal wetland to resident and itinerant taxa: evidence from multiple stable isotope analyses. *Marine and Freshwater Research* **62**, 11-19.

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

Mazumder D, Saintilan N, Williams RJ (2006) Trophic relationships between itinerant fish and crab larvae in a temperate Australian saltmarsh. *Marine and Freshwater Research* **57**, 193-199.

Mazumder D, Saintilan N, Williams RJ (2009) Zooplankton inputs and outputs in the saltmarsh at Towra Point, Australia. *Wetlands Ecology and Management* **17**, 225-230.

McKee K, Rogers K, Saintilan N (2012) Response of Salt Marsh and Mangrove Wetlands to Changes in Atmospheric CO₂, Climate, and Sea Level. In 'Global Change and the Function and Distribution of Wetlands'. (Ed. BA Middleton) pp. 63-96. (Springer Netherlands)

McKee KL (2011) Biophysical controls on accretion and elevation change in Caribbean mangrove ecosystems. *Estuarine, Coastal and Shelf Science* **91**, 475-483.

McKee KL, Cahoon DR, Feller IC (2007) Caribbean mangroves adjust to rising sea level through biotic controls on change in soil elevation. *Global Ecology and Biogeography* **16**, 545-556.

McKee KL, Rooth JE (2008) Where temperate meets tropical: multi-factorial effects of elevated CO₂, nitrogen enrichment, and competition on a mangrove-salt marsh community. *Global Change Biology* **14**, 971-984.

Meehl GA, Stocker TF, Collins WD, Friedlingstein P, Gaye AT, Gregory JM, Kitoh A, Knutti R, Murphy JM, Noda A, Raper SCB, Watterson IG, Weaver AJ, Zhao Z-C (2007) Global Climate Projections. In 'Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change'. (Eds S Solomon, D Qin, M Manning, Z Chen, M Marquis, KB Averyt, M Tignor and HL Miller). (Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA.)

Mendelssohn IA, McKee KL (2000) Salt marshes and mangroves. In 'North American Terrestrial Vegetation'. (Ed. MG Barbour, Billings, W.D.) pp. 501-563. (Cambridge University Press: Cambridge)

Morris CD, Dale PER, Stanfast H (Eds) (2002) 'Australian mosquito control manual.' (Mosquito Control Association of Australia: Brisbane)

Morrissey D (1995) Saltmarshes. In 'Coastal Marine Ecology of Temperate Australia'. (Eds AJ Underwood and MG Chapman) pp. 205-220. (University of New South Wales Press: Sydney)

Morton R, Beumer J, Pollock B (1988) Fishes of a subtropical Australian saltmarsh and their predation upon mosquitoes. *Environmental Biology of Fishes* **21**, 185-194.

Morton RM, Pollock BR, Beumer JP (1987) The occurrence and diet of fishes in a tidal inlet to a saltmarsh in southern Moreton Bay, Queensland. *Australian Journal of Ecology* **12**, 217-237.

Mulrennan ME, Woodroffe CD (1998) Saltwater intrusion into the coastal plains of the Lower Mary River, Northern Territory, Australia. *Journal of Environmental Management* **54**, 169-188.

Naidoo G, Kift J (2006) Responses of the saltmarsh rush *Juncus kraussii* to salinity and waterlogging. *Aquatic Botany* **84**, 217-225.

Nellemann C, Corcoran E, Duarte CM, Valdés L, DeYoung C, Fonseca L, Grimsditch GE (2009) 'Blue Carbon. A Rapid Response Assessment.' (United Nations Environment Programme, GRID-Arendal, Norway)

Nyman JA, Walters RJ, Delaune RD, Patrick Jr WH (2006) Marsh vertical accretion via vegetative growth. *Estuarine, Coastal and Shelf Science* **69**, 370-380.

Oliver T, Rogers K, Chafer C, Woodroffe C (2012) Measuring, mapping and modelling: an integrated approach to the management of mangrove and saltmarsh in the Minnamurra River estuary, southeast Australia. *Wetlands Ecology and Management*, 1-19.

Parry MK, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (2007) 'Appendix 1: Glossary. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.' (Cambridge University Press: Cambridge UK)

Pethick JS (1981) Long-term accretion rates on tidal salt marshes. *Journal of Sedimentary Research* **51**, 571-577.

Pidgeon E (2009) Carbon Sequestration by Coastal Marine Habitats: Important Missing Sinks. In 'The management of national Coastal Carbon Sinks'. (Eds D Laffoley and G Grimsditch). (IUCN: Gland, Switzerland)

Platell ME, Freewater P (2009) Importance of saltmarsh to fish species of a large south-eastern Australian estuary during a spring tide cycle. *Marine and Freshwater Research* **60**, 936-941.

Poffenbarger H, Needelman B, Megonigal J (2011) Salinity Influence on Methane Emissions from Tidal Marshes. *Wetlands* **31**, 831-842.

Prahalad VN, Kirkpatrick JB, Mount RE (2011) Tasmanian coastal saltmarsh community transitions associated with climate change and relative sea level rise 1975â€“2009. *Australian Journal of Botany* **59**, 741-748.

Qian H, Fridley JD, Palmer MW (2007) The latitudinal gradient of species-area relationships for vascular plants of North America. *American Naturalist* **170**, 690-701.

Redfield AC (1972) Development of a New England Salt Marsh. *Ecological Monographs* **42**, 201-237.

Richardson AMM, Swain R, Wong V (1998) Relationship between the crustacean and molluscan assemblages of Tasmanian saltmarshes and the vegetation and soil conditions. *Marine and Freshwater Research* **49**, 785-799.

Roach AC (1998) Effects of predation on the size structure of the gastropod *Salinator solida* (Martens) populations at Towra Point, NSW, Australia. *Marine and Freshwater Research* **49**, 779-784.

Rogers K (2004) Mangrove and saltmarsh surface elevation dynamics in relation to environmental variables in Southeastern Australia. University of Wollongong.

Rogers K, Saintilan N (2009) Relationships between Surface Elevation and Groundwater in Mangrove Forests of Southeast Australia. *Journal of Coastal Research* **24**, 63-69.

Rogers K, Saintilan N (2011) 'Coastal wetland vulnerability to sea-level rise in southeastern Australia.' Final report prepared for the Environmental Trust. NSW Department of Environment, Climate Change and Water, Sydney.

Rogers K, Saintilan N, Cahoon D (2005a) Surface Elevation Dynamics in a Regenerating Mangrove Forest at Homebush Bay, Australia. *Wetlands Ecology and Management* **13**, 587-598.

Rogers K, Saintilan N, Copeland C (2012) Modelling wetland surface elevation and its application to forecasting the effects of sea-level rise on estuarine wetlands. *Ecological Modelling* **244**, 148-157.

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

Rogers K, Wilton KM, Saintilan N (2006) Vegetation change and surface elevation dynamics in estuarine wetlands of southeast Australia. *Estuarine, Coastal and Shelf Science* **66**, 559-569.

Ross P, Minchinton T, Ponder W (2009) The ecology of molluscs in Australian saltmarshes. In 'Australian saltmarsh ecology'. (Ed. N Saintilan). (CSIRO Publishing: Collingwood, Vic)

Roy PS (1984) New South Wales Estuaries: Their origin and evolution. In 'Coastal geomorphology in Australia'. (Ed. BG Thom) pp. 99-121. (Academic Press: Sydney, Australia)

Roy PS, Thom BG, Wright LD (1980) Holocene sequences on an embayed high-energy coast: an evolutionary model. *Sedimentary Geology* **26**, 1-19.

Roy PS, Williams RJ, Jones AR, Yassini I, Gibbs PJ, Coates B, West RJ, Scanes PR, Hudson JP, Nichol S (2001) Structure and Function of South-east Australian Estuaries. *Estuarine, Coastal and Shelf Science* **53**, 351-384.

Russell TL, Hale PT (2009) Conservation of the false water rat (*Xeromys myoides*) depends on landscape complementation. *Australian Mammalogy* **31**, 81-87.

Rybczyk JM, Callaway JC (2009) Surface elevation models. In 'Coastal wetlands: An integrated ecosystem approach'. (Eds GME Perillo, E Wolanski, DR Cahoon and MM Brinson). (Elsevier: Amsterdam, The Netherlands)

Saenger P, Specht MM, Specht RL, Chapman VJ (1977) Mangal and coastal saltmarsh communities in Australasia. In 'Ecosystems of the World I: Wet Coastal Ecosystems'. (Ed. VJ Chapman). (Elsevier: Amsterdam)

Saintilan N (2009) Biogeography of Australian saltmarsh plants. *Austral Ecology* **34**, 929-937.

Saintilan N, Hashimoto TR (1999) Mangrove-saltmarsh dynamics on a bay-head delta in the Hawkesbury River estuary, New South Wales, Australia. *Hydrobiologia* **413**, 95-102.

Saintilan N, Hossain K, Mazumder D (2007) Linkages between adjacent seagrass, mangrove and saltmarsh as fish habitat in the Botany Bay estuary, New South Wales. *Wetlands Ecology and Management* **15**, 277-286.

Saintilan N, Mazumder D (2010) Fine-scale variability in the dietary sources of grazing invertebrates in a temperate Australian saltmarsh. *Marine and Freshwater Research* **61**, 615-620.

Saintilan N, Rogers K, Howe A (2009a) Geomorphology and habitat dynamics. In 'Australian saltmarsh ecology'. (Ed. N Saintilan). (CSIRO Publishing: Collingwood, Victoria, Australia)

Saintilan N, Rogers K, McKee K (2009b) Salt-marsh-mangrove interactions in Australia and the Americas. In 'Coastal wetlands: an integrated ecosystem approach'. (Eds GME Perillo, E Wolanski, DR Cahoon and MM Brinson) pp. 855-883. (Elsevier: Amsterdam, The Netherlands)

Saintilan N, Williams RJ (1999) Mangrove Transgression into Saltmarsh Environments in South-East Australia. *Global Ecology and Biogeography* **8**, 117-124.

Saintilan N, Wilton K (2001) Changes in the distribution of mangroves and saltmarshes in Jervis Bay, Australia. *Wetlands Ecology and Management* **9**, 409-420.

Shenker JM, Dean JM (1979) The utilisation of an intertidal salt marsh creek by larval and juvenile fishes: abundance, diversity and temporal variation. *Estuaries and Coasts* **2**, 154-163.

Shepherd KA, Wilson PG (2007) Incorporation of the Australian genera *Halosarcia*, *Pachycornia*, *Sclerostegia* and *Tegicornia* into *Tecticornia* (Salicornioideae, Chenopodiaceae). *Australian Systematic Botany* **20**, 319-331.

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

Specht RL (1981) Biogeography of halophytic angiosperms (salt-marsh, mangrove and sea-grass). In 'Ecological Biography of Australia'. (Ed. A Keast) pp. 575-589. (Dr. W. Junk Publishers: The Hague)

Thom BG, Wright LD, Coleman JM (1975) Mangrove Ecology and Deltaic-Estuarine Geomorphology: Cambridge Gulf-Ord River, Western Australia. *Journal of Ecology* **63**, 203-232.

Traill LW, Bradshaw CJA, Delean S, Brook BW (2010) Wetland conservation and sustainable use under global change: a tropical Australian case study using magpie geese. *Ecography* **33**, 818-825.

Traill LW, Perhans K, Lovelock CE, Prohaska A, McFallan S, Rhodes JR, Wilson KA (2011) Managing for change: wetland transitions under sea-level rise and outcomes for threatened species. *Diversity and Distributions*, **17**, 1255-1233.

Wetlands International (2006) 'Waterbird population estimates.' Wetlands International, Wageningen, The Netherlands.

Willems KJ, Webb CE, Russell RC (2005) A comparison of mosquito predation by the fish *Pseudomugil signifier* Kner and *Gambusia holbrooki* (Girard) in laboratory trials. *Journal of Vector Ecology* **30**, 87-90.

Williams RJ, Watford FA (1997) 'Change in the distribution of mangrove and saltmarsh in Berowra and Marramarra Creeks. 1941-1992.' NSW Fisheries Office of Conservation, Fisheries Research Institute, Cronulla, NSW.

Williams SR, Kokkinn MJ, Fricker SR, Schneemilch MJ, Humphrey MJ, Williams CR (2009) Mosquitoes (Diptera: Culicidae) of the Spencer Gulf Coast of South Australia. *Transactions of the Royal Society of South Australia* **133**, 51-56.

Williamson G, Boggs G, Bowman D (2011) Late 20th century mangrove encroachment in the coastal Australian monsoon tropics parallels the regional increase in woody biomass. *Regional Environmental Change* **11**, 19-27.

Williamson R (1996) *Spartina* in Victoria- an overview. In 'Proceedings of the Australasian conference on *Spartina* control (10-12 May 1995)'. (Eds JAE Rash, RC Williamson and SJ Taylor) pp. 26-29. (Department of Conservation and Natural Resources: Yarrum)

Wilson HB, Kendall BE, Fuller RA, Milton DA, Possingham HP (2011) Analyzing Variability and the Rate of Decline of Migratory Shorebirds in Moreton Bay, Australia. *Conservation Biology* **25**, 758-766.

Wilton KM (2002) Coastal wetland habitat dynamics in selected New South Wales estuaries. Australian Catholic University.

Winn KO, Saynor MJ, Eliot MJ, Elio I (2006) Saltwater Intrusion and Morphological Change at the Mouth of the East Alligator River, Northern Territory. *Journal of Coastal Research*, 137-149.

Woodroffe CD, Chappell J, Thom BG, Wallensky E (1989) Depositional model of a macrotidal estuary and floodplain, South Alligator River, Northern Australia. *Sedimentology* **36**, 737-756.

Woodroffe CD, Mulrennan ME, Chappell J (1993) Estuarine infill and coastal progradation, southern van diemen gulf, northern Australia. *Sedimentary Geology* **83**, 257-275.

Woodroffe CD, Thom BG, Chappell J (1985) Development of widespread mangrove swamps in mid-Holocene times in northern Australia. *Nature* **317**, 711-713.

Zedler JB, Nelson P, Adam P (1995) Plant community organisation in New South Wales saltmarshes: species mosaics and potential causes. *Wetlands (Australia)* **14**, 1-18.

Zharikov Y, Milton DA (2009) Valuing coastal habitats: predicting high-tide roosts of non-breeding migratory shorebirds from landscape composition. *Emu* **109**, 107-120.

FIGURES

Figure 1: Relationship between the contribution of accretion to elevation gain and elevation deficit within mangrove and saltmarsh at study sites in southeastern Australia.