Predicting the response of coastal wetlands of southeastern Australia to sea-level rise

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Abstract
Coastal saltmarsh is an endangered ecological community in New South Wales and sea-level rise has been listed as a key threatening process. Over the previous five decades moderate rates of sea-level rise have coincided with the invasion of saltmarsh by mangrove. Surface elevation tables (SETs) were installed in 12 coastal wetlands in Southeastern Australia to establish elevation and accretion trajectories for comparisons with mangrove encroachment of saltmarsh and sea-level rise. SETs confirmed that the elevational response of wetlands is more complex than accretion alone and elevation changes may also be attributed to below-ground processes that alter the soil volume such as subsidence/compaction, groundwater volume fluctuations, and below-ground biomass changes. A simple modelling approach was employed to establish a relationship between the observed rate of mangrove encroachment of saltmarsh and relative sea-level rise, which incorporates the eustatic component of sea-level rise and changes in the marsh elevation. Increasing access to high resolution digital elevation models will enhance our capacity to predict the response of coastal wetlands to sea-level rise. Long-term datasets of elevation dynamics and improved understanding of the feedback mechanisms influencing marsh elevations will further enhance our modelling capacity.

Introduction

Mangrove and saltmarsh communities in southeastern Australia are typically located within the intertidal zone of estuaries, including barrier estuaries, drowned river valleys and coastal embayments (Roy *et al.* 2001). Due to their location within the intertidal zone, they are particularly susceptible to decline in quality and extent due to changing water levels and other changes to the tidal prism. Over the past five decades a trend of mangrove encroachment of saltmarsh and corresponding decline in saltmarsh extent has been identified (Saintilan and Williams 1999; Saintilan and Williams 2000). Proposed causes of mangrove encroachment includes sea-level rise (Saintilan and Hashimoto 1999), subsidence/compaction (Burton 1982; Saintilan 1998; Vanderzee 1988), elevated nutrient levels (McLoughlin 1988; McLoughlin 2000), altered tidal regimes (Morton 1994) and increased precipitation (McTainsh *et al.* 1986). The observed expansion of mangrove has coincided with a period of moderate rates of sea-level rise, with average relative sea-level increasing estimated to increase at 1.2 mm y^{-1} around Australian between 1920 and 2000 (CSIRO and BOM 2007). To protect coastal saltmarsh from further decline in NSW, coastal saltmarsh has been listed as an endangered ecological community and sea-level rise has been identified as a key threatening process under the NSW Threatened Species Act (1995).

Mangrove and saltmarsh communities in Southeastern Australia are diurnally inundated by turbid tidal waters. As tidal flow moves over the vegetation, friction and marsh elevation diminishes the flow velocity and enables sediment and organic material to settle on the marsh surface. In Southeastern Australia where saltmarsh communities are typically located at higher elevations within the tidal prism, vertical accretion is typically lower than adjoining mangrove communities, despite vegetation density generally being greater (Rogers 2004). This relationship between vertical accretion, tidal flow and marsh elevation has been recognised for some time and marshes have been found to accumulate sediment and organic material at rates equivalent to historic rates of sea-level rise (Bricker-Urso *et al.* 1989; McCaffrey and Thomson 1980; Oertel *et al.* 1989).

Due to this relationship, it has been predicted that the capacity of a wetland to keep pace with sea-level depended on its ability to maintain elevation though processes of vertical accretion (Kearney *et al.* 1994; Reed 1990; Reed 1995). Wetland vulnerability was determined on the basis of comparisons between accretion and sea-level rise. . When sea-level rise exceeded rates of accretion, sites were identified as having an accretion deficit and were therefore identified as being vulnerable to submergence. Global sea-level rise of about 17 cm in the 20th century (CSIRO and BOM 2007) has been implicated in the submergence of coastal wetlands throughout the world (Reed 1988; Reed 1989; Reed and Cahoon 1993).

However, recent research has identified that the elevational response of wetlands to water level changes may be more complex over shorter temporal scales. Sub-surface processes such as compaction, plant growth, plant and peat decomposition, and shrink-swell of sediments associated with water storage may also influence the soil volume of coastal wetlands (Cahoon *et al.* 1999). These processes may cause a disparity between marsh elevation change and accretion/erosion, a phenomenon first identified in the marshes of Boston, Massachusetts, USA more than 40 years ago Kaye and Barghoorn (1964). Since this time, numerous studies have identified that shallow compaction/subsidence of marsh soils may cause a significant deficit between elevation gain and sea-level rise, which is known as an “elevation deficit”. Elevation deficits have been implicated in the inundation and loss of wetlands in the USA (Cahoon *et al.* 1999; Cahoon *et al.* 1995), Honduras (Cahoon *et al.* 2003), Italy (Day *et al.* 1999) and France (Hensel *et al.* 1999).

Surface elevation tables and marker horizons (SET-MH) are a technique employed both within Australia and globally to explore the relationship between accretion and elevation gain within coastal wetlands. A SET-MH network was established in Southeastern Australia in 2000 to provide information on the elevational and accretionary response of mangrove and saltmarsh communities to sea-level rise. In this paper we explore the elevational and accretionary response of mangrove and saltmarsh in southeastern Australia with respect to the observed changes in mangrove and saltmarsh extent over the previous five decades. With global sea-level projected to increase by 18 to 59 cm relative to 1990 levels by 2100 (CSIRO and BOM 2007), understanding the mechanisms that contributed to the recent expansion of mangrove in Southeastern Australia may provide important insights into the future stability of these system.

METHODS

Study site

The study extends over 12 sites and includes 7 estuaries, including Ukerebagh Island, Tweed River; Kooragang Island, Hunter River; Berowra Creek and Marramarra Creek, Hawkesbury River; Homebush Bay, Parramatta River; Minnamurra River; Cararma Inlet and Currambene Creek, Jervis Bay; Rhyll, Quail Island, French Island and Kooweerup, Westernport Bay, Victoria (Figure 1). Mangrove and saltmarsh are the typical intertidal vegetation at these study sites. Mangrove species diversity declines with increasing latitude, while saltmarsh species diversity increases with increasing latitude. All sites are inundation diurnally and exhibit a mesotidal regime.

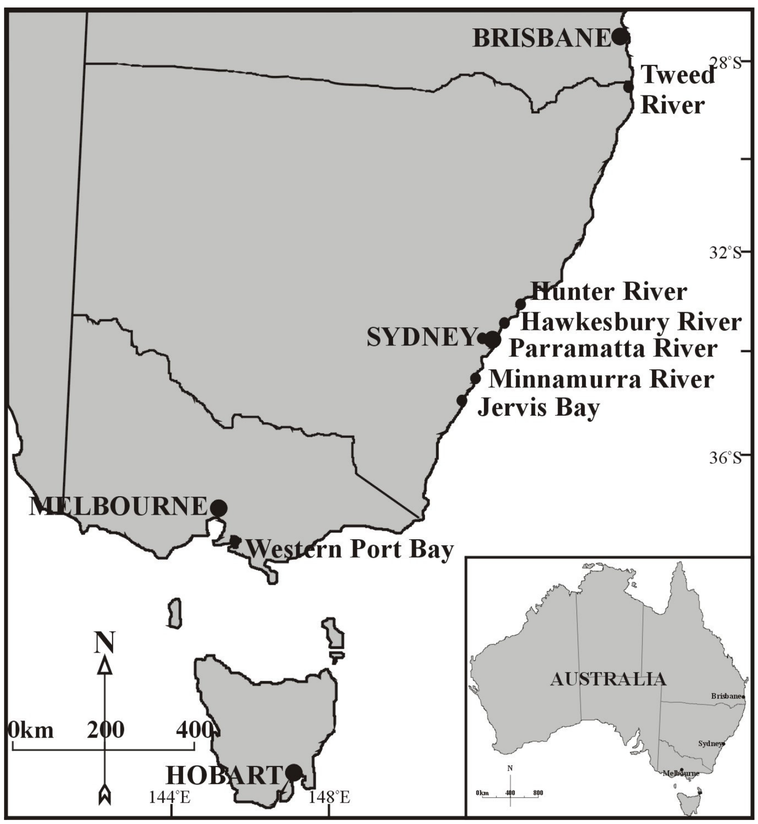

Figure 1: Location of study sites in Southeastern Australia

Surface elevation and accretion analyses

Surface Elevation Tables (SETs, version IV, Cahoon *et al.* 2002) were used to investigate surface elevation dynamics (Figure 2). SETs enable detection of changes in surface elevation in intertidal and shallow sub-tidal environments and have a confidence interval of 1.4 mm (Cahoon *et al.* 2002). SETs were installed according to the techniques of Boumans and Day (1993). A total of 72 SET monitoring stations were established within mangrove, saltmarsh and mixed mangrove-saltmarsh communities at study sites (Table 1). Measures were taken at biannual to annual frequency, commencing in 2000.

Vertical accretion was determined in conjunction with each SET monitoring station. Three feldspar marker horizons (MH) were established on the marsh surface at the perimeter of each SET monitoring station at the time of the initial SET measurements (i.e. 29 January 2002). MHs serve as a marker against which vertical accumulation of sediment and organic matter can be determined. Accretion was determined by the distance between the marsh surface and the horizon within the mini core. Cores were collected in conjunction with SET measures, at a biannual to annual frequency.

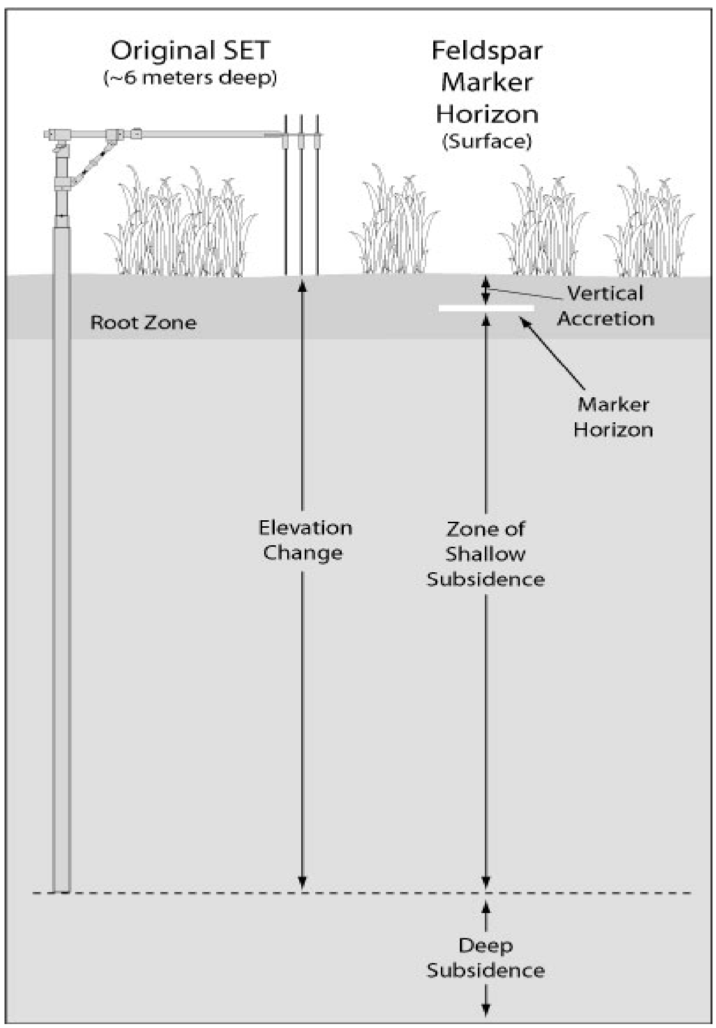

Figure 2: Overview of the Surface Elevation Table. Source: Cahoon (2006).

Table 1: Surface Elevation Table monitoring stations and sampling dates; and historic and contemporary aerial photograph dates.

Site	Zones	SETs (3/zone)	Baseline measures	Sampling dates	Aerial Photograph Dates (time 1, time 2)
Ukerebagh Island, Tweed River	Mangrove Saltmarsh	6	30/11/00	8/12/01, 4/11/02, 1/10/03	1948, 1998[1]
Kooragang Island, Hunter River	Mangrove Mixed Saltmarsh	9	29/1/02	4/3/03, 18/11/03	
Berowra Creek, Hawkesbury River	Mangrove Saltmarsh	6	11/12/02	14/3/03, 10/7/00	
Marramarra Creek, Hawkesbury River	Mangrove Saltmarsh	6	20/12/02	2/4/03, 17/7/03	
Homebush Bay, Parramatta River	Mangrove Mixed Saltmarsh	9	11/2/00	15/8/00, 16/3/01, 26/9/01, 19/4/02, 14/2/03, 7/8/03, 20/1/04	1930, 2000
Minnamurra River	Mangrove Saltmarsh	6	11/9/01	17/10/02, 5/8/03	1949, 1997[2]
Cararma Inlet, Jervis Bay	Mangrove Saltmarsh	6	2/8/01	26/10/02, 14/8/03	1948, 1999[1]
Currambene Creek, Jervis Bay	Mangrove Mixed Saltmarsh	9	3/2/01	4/2/02, 4/2/03, 3/9/03, 4/2/04	1949, 1993[1]
Rhyll, Westernport Bay	Mangrove Saltmarsh	6	15/10/00	18/11/01, 4/12/02, 12/11/03	1939, 1999
Kooweerup, Westernport Bay	Mangrove Saltmarsh	6	18/10/00	13/11/01, 4/12/02, 13/11/03	1939, 1999
French Island, Westernport Bay	Mangrove Saltmarsh	6	16/10/00	16/11/01, 3/12/02, 11/11/03	1967, 1999
Quail Island, Westernport Bay	Mangrove Saltmarsh	6	17/10/00	17/11/01, 13/1/03, 10/11/03	1973, 1999

[1]Data sourced from Wilton (2002), [2]Data sourced from Chafer (1998).

Statistical analyses

SET values that were not within two standard deviations of the mean for a sample were regarded as outliers and excluded from statistical analyses. These outliers may occur when SET pins are located on an obstruction, such as a pneumatophore or crab hole. The corrected data set was then used to determine surface elevation and accretion dynamics.

Measures of the change in surface elevation and vertical accretion were standardised by conversion to rates of surface elevation change and vertical accretion (mm y^{-1}). Two-way Analysis of Variances (ANOVAs) was used to identify statistical differences between rates of vertical accretion over time and rates of surface elevation change and over time within a site and within zones. Multivariate ANOVAs were used to identify statistical differences between rates of surface elevation change and vertical accretion within zones and over time.

Comparisons were made between rates of surface elevation change, rates of vertical accretion and rates of sea-level rise. Rates of sea-level rise were determined from reliable long-term water level data sets from nearby water level or ocean level gauges. Comparisons were made with long-term rates of sea-level rise, based on the entire length of the reliable data set, and short-term rates of sea-level rise, based on water level changes identified over the period of SET measures.

Tidal inundation models

Tidal inundation models (TIMs) were developed for the Ukerebagh Island, Minnamurra River, Cararma Inlet, French Island, Kooweerup, Quail Island and Rhyll study sites to provide information on the underlying topography. The technique employed was adapted from English *et al.* (1997) and applied by Saintilan and Wilton (2001). Stakes, marked with water soluble dye, were placed throughout the study sites in a systematic, grid-like manner prior to inundation from high spring tides. Following inundation from the tide, stakes were geopositioned and the inundation height recorded. TIMs were developed within an ArcView Geographic Information System (GIS) using the 3D analysis extension (ESRI Inc, version 3.2). Triangulated Irregular Networks (TINs) were developed by transforming the two dimensional stake location (x and y values) and inundation (z value) into 3 dimensional information. TIMs that could be used for further analysis were developed by converting 3 dimensional TINs into raster format using the Spatial Analysis extension. These TIMs complement the TIM developed by Wilton (2002) for Currambene Creek.

Aerial photograph interpretation and mangrove and saltmarsh extent mapping

Historic (time 1) and contemporary (time 2) aerial photographs of the study sites at French Island, Kooweerup, Quail Island and Rhyll (Table 1) were scanned and imported into an ArcView GIS (ESRI Inc. version 3.2) using the Image Analysis extension. Digital images were georectified, with a root mean square error of less than five pixels, considered appropriate.

Mangrove and saltmarsh community boundaries were delineated for historic and contemporary georectified digital images according to the protocols established by Wilton and Saintilan (2000). Individual themes (shapefiles), which contain spatial information, were created from historic and contemporary images for each study site. Individual themes were converted into raster format using the Spatial Analysis extension. These themes complemented similar themes prepared for Ukerebagh Island, Cararma Inlet and Currambene Creek by Wilton (2002) and Minnamurra River by Chafer (1998).

Rates of Vertical Upslope Mangrove Encroachment

The mean inundation elevation at which mangrove and saltmarsh occurred at each study site for the historic mapping period (time 1) and the contemporary mapping period (time 2) was estimated by overlaying mangrove and saltmarsh extent themes on TIMs using the Spatial Analysis extension. Rates of upslope migration were estimated as the difference between the mean inundation elevation at time 1 and time 2 and standardised for time.

RESULTS

Surface elevation, vertical accretion and sea-level rise

Both vertical accretion and surface elevation varied significantly over time for most study sites (Table 2) and relationships were not established between mean rates of surface elevation change and long-term sea-level change within the mangrove zone (R^2=0.0019, p=0.8940) and saltmarsh zone (r^2=0.0381, p=0.5430) or mean rates of surface elevation change and short-term sea-level change within the mangrove zone (R^2=0.0845, p=0.3593) and saltmarsh zone (r^2=0.14448, p=0.2224). Long-term rates of sea-level change exceeded rates of surface elevation change at 58% of mangrove sites and 33% of saltmarsh sites (Table 2).

Whilst vertical accretion contributes to marsh surface elevation changes, a relationship was not established between surface elevation change and vertical accretion for all study sites within southeastern Australia (r^2=0.0112, p=0.5998). At most sites, rates of vertical accretion were high than rates of surface elevation change, indicating significant shallow compaction of the soil volume (Table 2). Homebush Bay is regarded as relatively stable with rates of surface elevation change not significantly different to rates of vertical accretion (P=0.723). Some sites, namely the saltmarsh at Cararma Inlet and Homebush Bay, exhibited rates of surface elevation increase in excess of rates of vertical accretion. However, the general trend for all study sites was for marsh surface elevation changes to be dominated by vertical accretion and compaction.

Table 2: Mean (standard error) rates of vertical accretion and surface elevation change within zones at study sites throughout Southeastern Australia and p-values indicating differences in rates over time.

Site	Zone	Sea-level rise (long-term, short-term)	Rate of Accretion (mm y^{-1})	Accretion over Time P-value	Rate of Elevation Change (mm y^{-1})	Elevation Change over Time P-value	Compaction (mm y^{-1})	Accretion v. Elevation (within sites) P-value	Accretion v. Elevation (within zones) P-value	Elevation Deficit (long-term, Short-term)
Ukerebagh Island	Mangrove	-0.4, -0.47	2.21±0.30	P<0.001	2.40±1.39	P=0.041	0.19	P=0.014	P=0.030	2.80, 2.87
	Saltmarsh		0.50±0.23		0.49±0.68		-0.01		P=0.100	0.89, 0.96
Kooragang Island	Mangrove	1.18, -0.55	4.72±0.05	P<0.001	1.98±0.54	P=0.064	-2.74	P<0.001	P<0.001	0.80, 2.53
	Mixed		4.19±1.25		2.05±0.63		-2.14		P<0.001	0.87, 2.60
	Saltmarsh		2.03±0.38		1.92±0.98		-0.11		P=0.281	0.74, 2.47
Berowra Creek	Mangrove	0.69, 25.91	5.47±0.53	P=0.024	-1.51±2.68	P=0.308	-6.98	P=0.001	P=0.003	-2.20, -27.42
	Saltmarsh		5.05±0.72		1.29±1.48		-3.76		P=0.165	0.60, -24.62
Marramarra Creek	Mangrove	0.69, 25.91	0.49±0.49	P=0.572	-2.25±1.75	P=0.001	-2.74	P<0.001	P=0.031	-2.94, -28.16
	Saltmarsh		1.79±0.56		-2.53±1.27		-4.32		P<0.001	-3.22, -28.44
Homebush Bay	Mangrove	0.91, -9.52	4.58±0.28	P<0.001	5.64±2.15	P<0.001	1.06	P=0.723	P=0.840	4.73, 15.16
	Mixed		3.33±0.81		4.66±1.16		1.33		P=0.654	3.75, 14.18
	Saltmarsh		2.20±0.29		2.92±1.59		0.72		P=0.905	2.01, 12.44
Minnamurra River	Mangrove	-1.16, -6.17	6.64±0.52	P=0.557	0.61±0.44	P=0.352	-6.03	P<0.001	P<0.001	1.77, 6.78
	Saltmarsh		5.93±1.21		0.26±0.87		-5.67		P<0.001	1.42, 6.43
Cararma Inlet	Mangrove	0.91, -34.93	3.03±0.41	P<0.001	-0.81±1.00	P=0.006	-3.84	P=0.071	P<0.001	-1.72, 34.12
	Saltmarsh		1.27±0.13		3.25±0.71		1.98		P=0.004	2.34, 38.18
Currambene Creek	Mangrove	0.91, -34.93	0.65±0.34	P<0.001	0.29±2.02	P<0.001	-0.36	P=0.041	P=0.105	-0.62, 27.77
	Mixed		1.37±0.48		0.07±1.49		-1.30		P=0.287	-0.84, 27.56
	Saltmarsh		0.33±0.11		0.14±1.48		-0.19		P=0.429	-0.77, 27.62
Rhyll	Mangrove	0.26, -4.05	5.10±0.72	P=0.165	0.92±1.87	P<0.001	-4.18	P=0.001	P=0.003	0.66, 4.97
	Saltmarsh		1.59±0.19		0.64±0.75		-0.95		P=0.110	0.38, 4.69
Kooweerup	Mangrove	0.26, -4.05	7.20±0.85	P=0.053	-0.03±2.23	P<0.001	-7.23	P=0.001	P=0.002	-0.29, 4.02
	Saltmarsh		2.03±0.32		-0.16±0.94		-2.19		P=0.022	-0.42, 3.89
French Island	Mangrove	0.26, -4.05	9.49±2.69	P<0.001	-2.13±1.66	P<0.001	-11.62	P<0.001	P<0.001	-2.39, 1.92
	Saltmarsh		4.07±0.25		5.27±0.96		1.20		P=0.176	5.01, 9.32
Quail Island	Mangrove	0.26, -4.05	6.77±0.79	P=0.095	-2.60±2.07	P=0.009	-9.37	P<0.001	P<0.001	-2.86, 1.45
	Saltmarsh		2.35±0.96		-0.68±1.18		-3.03		P<0.001	-0.94, 3.37

Mangrove encroachment and sea-level rise

The TIMs typically showed a gradual elevation increase from seagrass beds and mudflat at the front of the mangrove zone, peaking within the saltmarsh zone. The mean inundation elevation of mangrove, saltmarsh and mixed mangrove-saltmarsh vegetation at study sites according to historic and contemporary aerial photography is detailed in Table 3. At all sites, except Quail Island, rates of upslope mangrove encroachment exceeded long-term estimates of sea-level rise, generated from reliable long-term water level data sets from water level and ocean level gauges located near the study sites (Table 3). Mangrove encroachment at Quail Island was not used for further analysis as mangroves had receded over time at the location site for SETs and inundation models. This recession was localised and Quail Island still exhibited a general trend of mangrove expansion into saltmarsh (Rogers *et al.* 2005b).

Table 3: Mean (standard deviation) inundation elevation for mangrove, saltmarsh and mixed mangrove-saltmarsh, rate of vertical upslope mangrove encroachment and long-term sea-level rise at study sites throughout southeastern Australia.

Sites	**Zone**	**Mean Inundation Elevation (m)**		**Upslope Mangrove Encroachment ($mm\ y^{-1}$)**	**Long-term Sea-level Rise ($mm\ y^{-1}$)**
		Historic	**Contemporary**		
Ukerebagh Island	Mangrove	1.12 (0.52)	1.19 (0.43)	1.4	-0.4
	Mixed		1.66 (0.04)		
	Saltmarsh	1.63 (0.20)	1.68 (0.09)		
Minnamurra River	Mangrove	1.18 (0.37)	1.19 (0.38)	0.2	-1.16
	Saltmarsh	1.45 (0.26)			
			1.51 (0.29)		
Cararma Inlet	Mangrove	1.33 (0.16)	1.54 (0.22)	4.1	0.91
	Mixed		1.72 (0.13)		
	Saltmarsh	1.76 (0.18)	1.84 (0.10)		
Currambene Creek	Mangrove	1.05 (0.49)	1.30 (0.51)	5.7	0.91
	Mixed	1.39 (0.37)	1.59 (0.28)		
	Saltmarsh	1.72 (0.26)	1.67 (0.32)		
French Island	Mangrove	1.91 (0.18)	2.06 (0.28)	4.7	0.26
	Saltmarsh	2.66 (0.19)	2.67 (0.15)		
Kooweerup	Mangrove	1.65 (0.31)	1.87 (0.45)	3.7	0.26
	Saltmarsh	2.47 (0.34)	2.57 (0.28)		
Quail Island	Mangrove	1.98 (0.21)	1.91 (0.18)	-2.7	0.26
	Saltmarsh	2.83 (0.23)	2.80 (0.26)		
Rhyll	Mangrove	2.18 (0.17)	2.29 (0.21)	1.8	0.26
	Saltmarsh	2.53 (0.21)	2.71 (0.15)		

However, comparisons of TIMs with rates of vertical upslope mangrove encroachment assumes that marsh surface elevations are static and that the recent marsh topography accurately represents historic marsh topography. More specifically, they rely on the assumption that sea level alone has risen relative to the marsh surface. Our analyses of surface elevation dynamics indicate that marsh surface elevations are not static and vary over time and that surface elevation dynamics can not be attributed to vertical accretion alone. To account for the dynamic nature of the marsh topography, rates of mangrove encroachment should therefore be compared to relative rates of sea-level rise, which incorporates the eustatic component of sea-level rise and changes in surface elevation. A significant correlation was established between rates of upslope mangrove encroachment (Table 3) and rates of relative sea-level rise (Figure 3), which incorporates long-term rates of sea-level rise and rates of surface elevation change according to the equation:

$$y = m (a + b) + c$$

Where: y = change in mean inundation elevation of the mangrove zone (mm y^{-1})

m = constant, estimated at 0.88 mm y^{-1}

a = eustatic rates of sea-level rise (mm y^{-1})

b = rates of saltmarsh surface elevation change (mm y^{-1})

c = constant, estimated at 3.11 mm y^{-1}

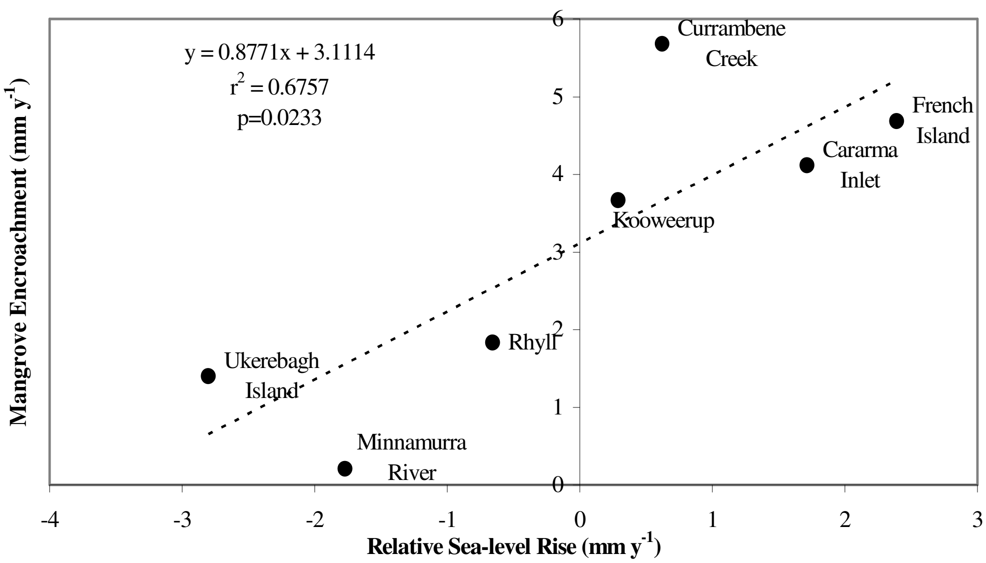

Figure 3: Relationship between mangrove encroachment, estimated as the annual change in mean inundation elevation of the mangrove zone; and relative sea-level rise, estimated as the annual eustatic component of sea-level rise plus the mean annual change in saltmarsh surface elevation.

DISCUSSION

Surface elevation dynamics

Our analyses of mangrove and saltmarsh surface elevation dynamics indicates that elevation changes within mangrove and saltmarsh are more complex than vertical accretion alone. Three possible accretion and elevation interaction scenarios were identified:

1. Vertical accretion = surface elevation change: This scenario was evident within all zones at Homebush Bay and Currambene Creek and within the saltmarsh zone at Ukerebagh Island, Kooragang Island, Berowra Creek, Rhyll and French Island. In these cases marsh elevation was largely controlled by surface processes of mineral and organic matter accumulation.
2. Vertical accretion > surface elevation change. This scenario occurred within the majority of zones within sites. The disparity between accretion and elevation change is largely attributed to below-ground processes that act to reduce the soil volume.
3. Vertical accretion < surface elevation change. This scenario was evident within the saltmarsh at Cararma Inlet and the mangrove Ukerebagh Island and to a small extent within the saltmarsh at French Island, although this was not significant. There was also significant uplift evident within the saltmarsh zone at Homebush Bay during the first sampling period.

These results support previous research indicating that marsh vulnerability to submergence from rising sea levels should account for below-ground processes as well as surface processes of vertical accretion.

Processes influencing marsh surface elevation dynamics

Processes that may influence marsh surface elevations may be attributed to geological, hydrological or biological processes (Cahoon *et al.* 1999) and all of these processes were observed at sites within southeastern Australia. The general trend to be dominated by surface processes of vertical accretion and compaction of the soil volume. Vertical accretion exceeded surface elevation gains at most sites and this was largely attributed to shallow compaction associated with consolidation and compaction of the soil volume, plant and peat decomposition and shrinkage of the soil volume associated with reduced water storage.

Many of the observed elevation changes were attributed to hydrological processes. An El Nino related drought and associated reduced rainfall and groundwater availability throughout Southeastern Australia over the study period caused a significant reduction in soil water storage and has been identified as significant driver of marsh surface elevation decline at study sites (Rogers *et al.* 2008; Rogers *et al.* 2005b; Rogers *et al.* 2006).

Hydrological processes were also identified as a significant influence on marsh uplift at Cararma Inlet, Ukerebagh Island and French Island. SET stations within the saltmarsh at Cararma Inlet are located immediately south of large natural saltwater ponds, SET stations within the mangrove at Ukerebagh Island are located near a small drainage creek, while SET stations within the saltmarsh at French Island are located immediately north of evaporation ponds that are an artefact from a salt extraction industry established within the saltmarsh in the 1850s. Uplift at these sites is largely attributed to ponding of water and an increase in soil pore water storage within the vicinity of SET monitoring stations. Increased pore water storage has been implicated in the uplift of marshes in numerous studies (Cahoon *et al.* 1999; Cahoon and Lynch 1997; Cahoon *et al.* 1995).

An observed increase in uplift event within the saltmarsh zone at Homebush Bay within the first year of sampling was attributed to biological processes (Rogers *et al.* 2005a). A measured increase in the above-ground biomass of mangroves within the saltmarsh zone and associated expansion of the root volume caused an increase in the saltmarsh surface elevation in excess of that attributed to vertical accretion.

<u>Mangrove encroachment of saltmarsh</u>

Previous comparisons between mangrove encroachment and sea-level rise did not establish a causal link between the two trends (Wilton 2002). Analyses of surface elevation dynamics within mangrove and saltmarsh in Southeastern Australia indicate that marsh surface elevations are not static but vary over time in response to both surface and below-ground processes. Comparisons of mangrove encroachment and sea-level rise should therefore incorporate marsh surface elevation changes that may act to alter water levels with respect to the marsh surface.

Rogers *et al.* (2006) established a relationship between contemporary rates of saltmarsh surface elevation change and long-term rates of mangrove encroachment into saltmarsh. In this paper a relationship was established between mangrove encroachment of saltmarsh and relative sea-level rise, which incorporates the eustatic component of sea-level rise and saltmarsh surface elevation changes. We propose that mangrove encroachment of saltmarsh can largely be attributed to eustatic sea-level rise and site specific factors that may act to alter marsh surface elevations. Site specific factors identified within this study include consolidation and compaction of the soil volume, plant and peat decomposition, plant productivity and shrink-swell of the soil volume associated with fluctuations in soil pore water storage.

Implications for assessing the vulnerability of coastal wetlands to sea-level rise

Technological improvements have lead to an evolution in the approach taken to assess the vulnerability of coastal wetlands to sea-level rise. Initial analyses of vertical accretion and sea-level lead to the concept that of marsh development keeping pace with sea-level rise (Mudge 1858). This concept was not challenged until moderate rates of sea-level rise in the latter half of the 20th century lead to the identification of accretion and sea-level disequilibrium's (Orson *et al.* 1985). Marsh vulnerability assessment relied on the determination of accretion deficits based on comparisons of vertical accretion to sea-level rise (Baumann *et al.* 1984; Cahoon and Turner 1989; DeLaune *et al.* 1983; Reed and Cahoon 1993). The development of SET-MH technology has enabled the differentiation between surface and below-ground processes that may alter marsh surface elevations and vulnerability assessments now rely on the determination of elevation deficits, defined as the difference between surface elevation changes and sea-level rise (Cahoon *et al.* 1999; Cahoon *et al.* 1995). In this paper we used a simple modelling approach to attribute mangrove encroachment of saltmarsh and loss of saltmarsh extent to relative sea-level rise. The development of LiDAR technology and associated high resolution digital elevation models will further enhance our ability to assess the vulnerability of coastal wetlands to sea-level rise.

However, our analyses of surface elevation dynamics indicate that projected sea-level rise may not result in an equivalent upslope translation of mangrove and saltmarsh communities. Rather surface and below-ground processes alter marsh elevations over time and modelling of the impacts of sea-level rise on mangrove and saltmarsh should incorporate surface elevation dynamics into digital elevation models. More specifically, models of the response of coastal wetlands to sea-level rise should be based on high resolution dynamic elevation models.

Vulnerability assessment based on dynamic elevation models have already begun to emerge within scientific literature. For example the Sea Level Affecting Marshes Model (SLAMM) incorporates factors that may influence marsh surface elevations and applies these to digital elevation models to project the distribution and loss of wetlands communities (Glick *et al.* 2007). This model has been applied to wetlands within Puget Sound, Chesapeake Bay and South Carolina, USA (SLAMM-view 2009). A 10 year surface elevation and vertical accretion data set is now being collated for study sites in Southeastern Australia. Collection of this data set coincides with wider coverage of coastal LiDAR surveys and greater access to high resolution digital elevation surveys. By applying our 10-year elevation data set to high resolution DEMs, we propose to develop dynamic elevation models for coastal wetlands to establish the likely impact of projected sea-level rise on mangrove and saltmarsh communities of Southeastern Australia.

A negative feedback loop was first proposed by Pethick (1981), whereby sedimentation causes marsh surface elevation increases, thereby decreasing the depth and period of tidal inundation and subsequently causing sedimentation to decrease. This negative feedback loop was further developed by Saintilan *et al.* (2009) to incorporate both surface and subsurface processes that may alter marsh elevations (Figure 4). More specifically, this adapted negative feedback loop incorporates the influence of compaction, sea-level variations and vegetation density on elevation gain. As our understanding of the processes influencing marsh surface elevation increase and the feedback mechanisms associated with changes in plant productivity, organic matter accumulation and decomposition and water level changes become evident, vulnerability assessment will undergo further evolution to incorporate these processes. We propose that the next evolution of coastal wetland vulnerability assessment will incorporate feedback mechanisms by the inclusion of dynamically projected changes in the rates of surface elevation gain/loss within models.

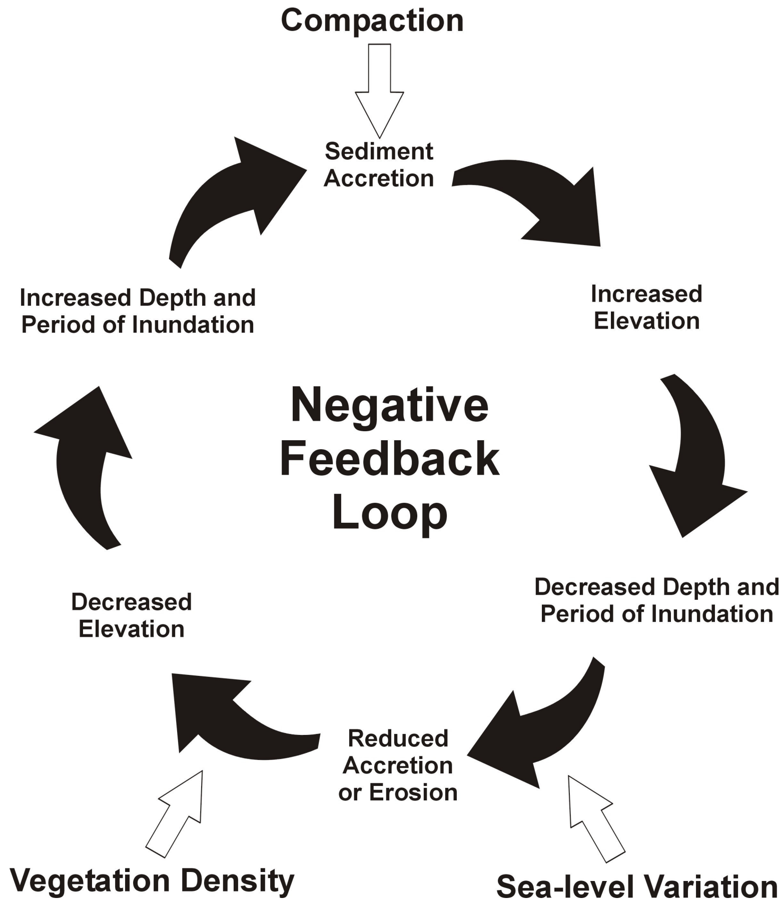

Figure 4: Relationships between sedimentation and elevation in a coastal saltmarsh. Source: Saintilan *et al.* (2009).

REFERENCES

Baumann RH, Day JWJ, Miller CA (1984) Mississippi Deltaic Wetland Survival: Sedimentation Versus Coastal Submergence. *Science* **224**, 1093-1095.

Boumans R, Day J (1993) High precision measurements of sediment elevation in shallow coastal areas using a sedimentation-erosion table. *Estuaries and Coasts* **16**, 375-380.

Bricker-Urso S, Nixon S, Cochran J, Hirschberg D, Hunt C (1989) Accretion rates and sediment accumulation in Rhode Island salt marshes. *Estuaries and Coasts* **12**, 300-317.

Burton T (1982) Mangrove changes recorded north of Adelaide. *Safic* **6**, 8-12.

Cahoon D (2006) *Surface Elevation Table (SET)*. Patuxent Wildlife Research Center, United States Geological Survey, Patuxent, <http://www.pwrc.usgs.gov/set/>.

Cahoon DR, Day JWJ, Reed DJ (1999) The influence of surface and shallow subsurface soil processes on wetland elevation: a synthesis. *Current topics in wetland biogeochemistry* **3**, 72-88.

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

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

Cahoon DR, Lynch JC, Hensel P, Boumans R, Perez BC, Segura B, Day JW, Jr. (2002) High-Precision Measurements of Wetland Sediment Elevation: I. Recent Improvements to the Sedimentation-Erosion Table. *JOURNAL OF SEDIMENTARY RESEARCH* **72**, 730-733.

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

Cahoon DR, Turner RE (1989) Accretion and Canal Impacts in a Rapidly Subsiding Wetland II. Feldspar Marker Horizon Technique. *Estuaries* **12**, 260-268.

Chafer CJ (1998) 'A spatio-temporal analysis of estuarine vegetation change in the Minnamurra River 1938-1997.' Wollongong.

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

Day JW, Rybczyk J, Scarton F, Rismondo A, Are D, Cecconi G (1999) Soil Accretionary Dynamics, Sea-Level Rise and the Survival of Wetlands in Venice Lagoon: A Field and Modelling Approach. *Estuarine, Coastal and Shelf Science* **49**, 607-628.

DeLaune RD, Baumann RH, Gosselink JG (1983) Relationships among vertical accretion, coastal submergence, and erosion in a Louisiana Gulf Coast marsh. *Journal of Sedimentary Research* **53**, 147-157.

English S, Wilkinson C, Baker V (1997) *Survey manual for tropical marine resources*. Australian Institute of Marine Science, Townsville.

Glick P, Clough J, Nunley B (2007) 'Sea-level Rise and Coastal Habitats in the Pacific Northwest An Analysis for Puget Sound, Southwestern Washington, and Northwestern Oregon.' National Wildlife Federation, Seattle, Washington, USA.

Hensel PF, Day JWJr, Pont D (1999) Wetland vertical accretion and soil elevation change in the Rhone River Delta, France: The importance of riverine flooding. *Journal of Coastal Research* **15**, 668-681

Kaye CA, Barghoorn ES (1964) Late Quaternary Sea-Level Change and Crustal Rise at Boston, Massachusetts, with Notes on the Autocompaction of Peat. *Geological Society of America Bulletin* **75**, 63-80.

Kearney MS, Stevenson JC, Ward LG (1994) Spatial and Temporal Changes in Marsh Vertical Accretion Rates at Monie Bay: Implications for Sea-Level Rise. *Journal of Coastal Research* **10**, 1010-1020.

McCaffrey RJ, Thomson J (1980) A record of the accumulation of sediments and heavy metals in a Connecticut salt marsh. In *Estuarine physics and chemistry: studies in Long Island*. (Ed. B Saltzman). (Academic Press: New York)

McLoughlin L (1988) Mangroves and grass swamps: changes in the shoreline vegetation of the Middle Lane Cover River, Sydney, 1780's-1880's. *Wetlands (Australia)* **7**, 13-24.

McLoughlin L (2000) Estuarine wetlands distribution along the Parramatta River, Sydney, 1788-1940: Implications for planning and conservation. *Cunninghamia* **6**, 579-610.

McTainsh G, iles B, Saffinga P (1986) Spatial and temporal patterns of mangroves at Oyster Point Bay, South East Queensland, 1944-1993. *Proceedings of the Royal Society of Queensland* **99**, 83-91.

Morton RM (1994) Fluctuations in wetlands extent in southern Moreton Bay. In *Future marine science in Moreton Bay*. (Eds GJ Greenwood and NJ Hall) pp. 145-150. (University of Queensland: Brisbane)

Mudge BF (1858) The salt marsh formations of Lynn, Massachusetts. *Proceedings of the Essex Institute* **2**, 117-119.

Oertel G, Wong G, Conway J (1989) Sediment accumulation at a fringe marsh during transgression, Oyster, Virginia. *Estuaries and Coasts* **12**, 18-26.

Orson R, Panageotou W, Leatherman SP (1985) Response of Tidal Salt Marshes of the U.S. Atlantic and Gulf Coasts to Rising Sea Levels. *Journal of Coastal Research* **1**, 29-37.

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

Reed DJ (1988) Sediment dynamics and deposition in a retreating coastal salt marsh. *Estuarine, Coastal and Shelf Science* **26**, 67-79.

Reed DJ (1989) Patterns of Sediment Deposition in Subsiding Coastal Salt Marshes, Terrebonne Bay, Louisiana: The Role of Winter Storms. *Estuaries* **12**, 222-227.

Reed DJ (1990) The impact of sea-level rise on coastal salt marshes. *Progress in Physical Geography* **14**, 465-481.

Reed DJ (1995) The response of coastal marshes to sea-level rise: Survival or submergence? *Earth Surface Processes and Landforms* **20**, 39-48.

Reed DJ, Cahoon D (1993) Marsh submergence vs. marsh accretion: Interpreting accretion deficit data in coastal Louisiana. In 'Coastal Zone 93'. (American Shore and Beach Preservation Association: New Orleans, Louisiana)

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

Rogers K, Ralph TJ, Miller L, Kelleway J (2008) 'Water regime requirements of selected floodplain wetland biota of the Macquarie Marshes, with implications for climate change.' Department of Environment and Climate Change, 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, 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.

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.

Saintilan N (1998) Photogrammetric survey of the Tweed River wetlands. *Wetlands (Australia)* **17**, 74-82.

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

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

Saintilan N, Williams RJ (2000) The decline of saltmarshes in Southeast Australi: Results of recent surveys. *Wetlands (Australia)* **18**, 49-54.

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

SLAMM-view (2009) *SLAMM-view: Sea Level Affecting Marshes Model Visualization*. US Fish and Wildlife Service, Chesapeake Bay, <http://www.slammview.org/>.

Vanderzee MP (1988) Changes in saltmarsh vegetation as an early indicator of sea-level rise. In *Greenhouse: Planning for climate change*. (Ed. GI Pearmen) pp. 147-160. (CSIRO: Melbourne)

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

Wilton KM, Saintilan N (2000) 'Protocols for mangrove and saltmarsh habitat mapping.' Australian Catholic University North Sydney.