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

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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.

## **Keywords**

coastal, level, response, rise, predicting, southeastern, wetlands, australia, sea

## **Disciplines**

Medicine and Health Sciences | Social and Behavioral Sciences

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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  $1.2 \text{ mm y}^{-1}$  around Australia 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 through 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 20<sup>th</sup> 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; Carama 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.

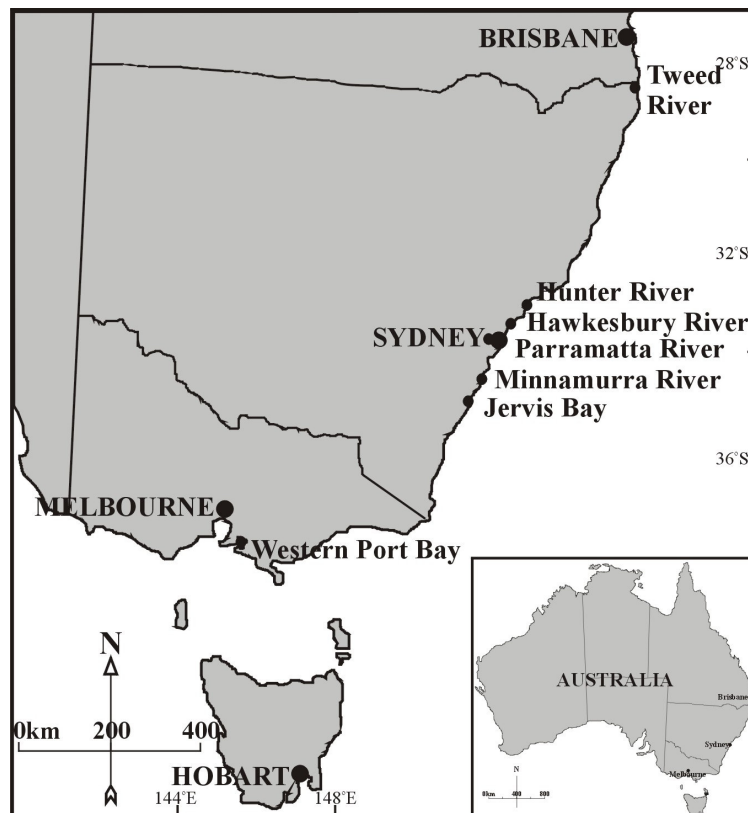


Figure 1: Location of study sites in Southeastern Australia

### 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.

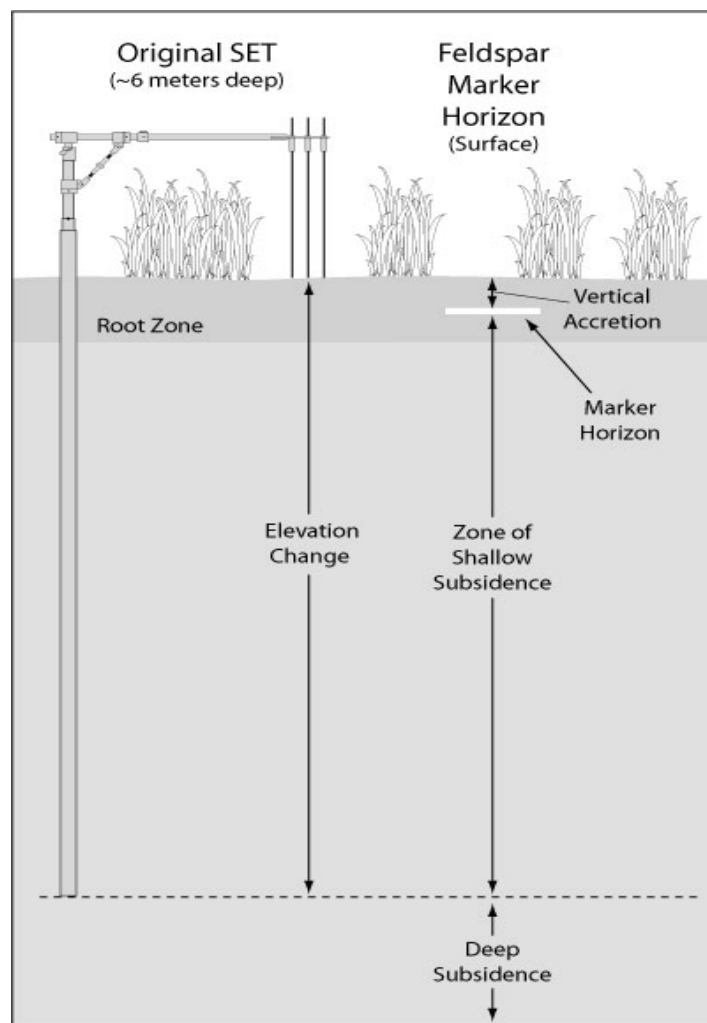


Figure 2: Overview of the Surface Elevation Table. Source: Cahoon (2006).

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 <sup>1</sup>
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 <sup>2</sup>
Cararma Inlet, Jervis Bay	Mangrove Saltmarsh	6	2/8/01	26/10/02, 14/8/03	1948, 1999 <sup>1</sup>
Currumbene Creek, Jervis Bay	Mangrove Mixed Saltmarsh	9	3/2/01	4/2/02, 4/2/03, 3/9/03, 4/2/04	1949, 1993 <sup>1</sup>
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

<sup>1</sup>Data sourced from Wilton (2002), <sup>2</sup>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 ( $\text{mm y}^{-1}$ ). 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 Currumbene 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, Carama Inlet and Currumbene 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 Carama 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 <sup>-1</sup> )	Accretion over Time P-value	Rate of Elevation Change (mm y <sup>-1</sup> )	Elevation Change over Time P-value	Compaction (mm y <sup>-1</sup> )	Accretion v. Elevation (within sites) P-value	Accretion v. Elevation (within zones) P-value	Elevation Deficit (long-term, Short-term)
Ukerebagh Island	Mangrove Saltmarsh	-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
			0.50±0.23		0.49±0.68		-0.01		P=0.100	0.89, 0.96
Kooragang Island	Mangrove Mixed Saltmarsh	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
			4.19±1.25		2.05±0.63		-2.14		P<0.001	0.87, 2.60
			2.03±0.38		1.92±0.98		-0.11		P=0.281	0.74, 2.47
Berowra Creek	Mangrove Saltmarsh	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
			5.05±0.72		1.29±1.48		-3.76		P=0.165	0.60, -24.62
Marramarra Creek	Mangrove Saltmarsh	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
			1.79±0.56		-2.53±1.27		-4.32		P<0.001	-3.22, -28.44
Homebush Bay	Mangrove Mixed Saltmarsh	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
			3.33±0.81		4.66±1.16		1.33		P=0.654	3.75, 14.18
			2.20±0.29		2.92±1.59		0.72		P=0.905	2.01, 12.44
Minnamurra River	Mangrove Saltmarsh	-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
			5.93±1.21		0.26±0.87		-5.67		P<0.001	1.42, 6.43
Carama Inlet	Mangrove Saltmarsh	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
			1.27±0.13		3.25±0.71		1.98		P=0.004	2.34, 38.18
Currambene Creek	Mangrove Mixed Saltmarsh	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
			1.37±0.48		0.07±1.49		-1.30		P=0.287	-0.84, 27.56
			0.33±0.11		0.14±1.48		-0.19		P=0.429	-0.77, 27.62
Rhyll	Mangrove Saltmarsh	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
			1.59±0.19		0.64±0.75		-0.95		P=0.110	0.38, 4.69
Kooweerup	Mangrove Saltmarsh	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
			2.03±0.32		-0.16±0.94		-2.19		P=0.022	-0.42, 3.89
French Island	Mangrove Saltmarsh	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
			4.07±0.25		5.27±0.96		1.20		P=0.176	5.01, 9.32
Quail Island	Mangrove Saltmarsh	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
			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 <sup>-1</sup> )	Long-term Sea-level Rise (mm y <sup>-1</sup> )
		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 ( $\text{mm y}^{-1}$ )  
 $m$  = constant, estimated at  $0.88 \text{ mm y}^{-1}$   
 $a$  = eustatic rates of sea-level rise ( $\text{mm y}^{-1}$ )  
 $b$  = rates of saltmarsh surface elevation change ( $\text{mm y}^{-1}$ )  
 $c$  = constant, estimated at  $3.11 \text{ mm y}^{-1}$

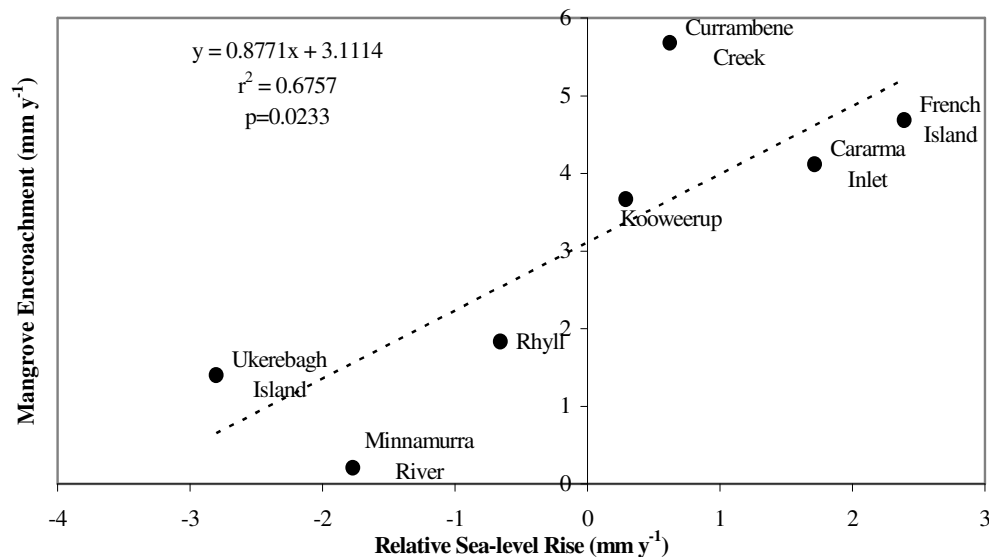


Figure 3: Relationship between mangrove encroachment, estimated as the annual change in mean inundation elevation of the mangrove zone; and relative sea-level rise, estimated as the annual eustatic component of sea-level rise plus the mean annual change in saltmarsh surface elevation.

## 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 Currumbene 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.

#### Mangrove encroachment of saltmarsh

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 20<sup>th</sup> 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.

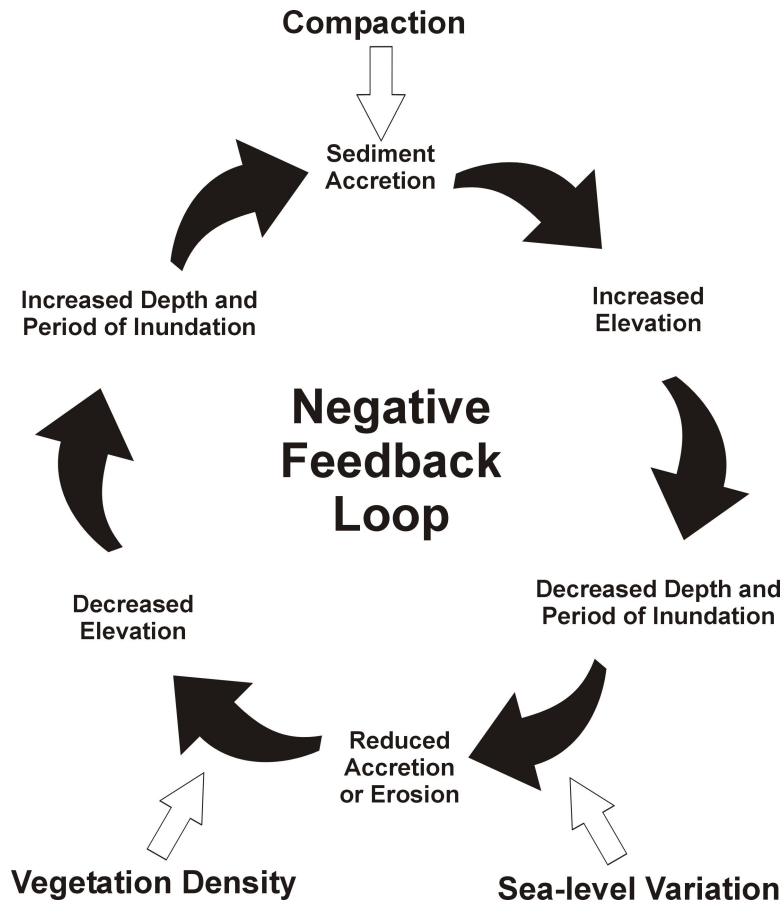


Figure 4: Relationships between sedimentation and elevation in a coastal saltmarsh.  
 Source: Saintilan *et al.* (2009).

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