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PREFACE

This proceedings volume includes six papers presented at the *Symposium on Mangrove Responses to Relative Sea-level Rise and Other Climate Change Effects*, held at the Society of Wetland Scientists 2006 conference in Cairns, Australia. Presentations discuss anticipated mangrove responses to changes in sea-level and other climate change effects based on (i) reconstructions of mangrove response to change in Holocene sea-levels using stratigraphic records, (ii) observations of mangrove responses to relative sea-level rise over human time scales, and (iii) trends in changes in the elevation of the surface of mangrove wetlands based on surface elevation table – marker horizon technology from sites in 11 countries. Presentations also describe the state of readiness of Pacific Island Countries and territories to assess vulnerability and adapt to mangrove responses to climate change effects and identify current and planned regional and international initiatives available to assist these countries and territories to augment mangrove resistance and resilience to climate change effects. Support for the symposium was kindly provided by the Western Pacific Regional Fishery Management Council, Secretariat of the Pacific Regional Environment Programme and United Nations Environment Programme.

Global sea-level rose 10-20 cm during the last century, which is one outcome of global warming. Several climate models project an accelerated rate of sea-level rise over coming decades. Accurate predictions of mangrove responses to changes in relative sea-level enable advance planning to minimize and offset anticipated mangrove losses. When sea-level rise is the predominant force causing a change in mangrove position, the mangrove's natural response is to migrate landward. Depending on the ability of individual mangrove species to colonize new habitat at a rate that keeps pace with the rate of relative sea-level rise, the slope of adjacent land and the presence of obstacles to landward migration of the landward boundary of the mangrove, such as seawalls and other erosion control structures, some sites will revert to a narrow mangrove fringe, possible survival of individual trees, or even experience local extirpation of the mangrove community. Regionally, assessments of mangrove response to sea-level and climate change facilitate identifying critical areas to mitigate anticipated mangrove losses. Small island developing states and low-lying coastal areas of continents are particularly vulnerable to small increases in sea-level. Establishing mangrove baselines and monitoring these gradual changes to coastal habitats through regional networks using standardized techniques will enable the separation of site-based influences from global changes to provide a better understanding of the response of coastal habitats to global climate and sea-level change, and alternatives for mitigating adverse effects.

This collection of papers highlights the importance of assessing mangrove vulnerability to relative sea-level rise and other climate change effects as a way of designing coastal land use policies to conserve mangroves and minimize problems to be faced by local communities. Management authorities, especially of small island countries and territories, are encouraged to assess shoreline responses to projected relative sea-level rise and adopt appropriate policies to provide adequate lead time to minimize social disruption and cost, minimize losses of valued coastal habitats and maximize available options. It will be physically and economically difficult for many small island communities to retreat from landward migrating coastal ecosystems and to establish zoning setbacks from coastal habitats for new development. However, some sections of coastline that aren't highly developed may be suitable for "managed retreat." "Managed retreat" involves implementing land-use planning mechanisms before the effects of rising sea-level become apparent, which can be planned carefully with sufficient lead time to enable economically viable, socially acceptable, and environmentally sound management measures.

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CONTENTS

Mangrove Palaeoenvironmental Response to Climate Change

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Abstract

Mangrove systems occur extensively on low gradient tropical shorelines, where sedimentation enables resilience during sea-level rise (SLR). Within mangroves, inundation frequencies across the intertidal slope cause zonation of different species with elevation. This tight sea-level control of the seaward margin and zones within mangroves has been demonstrated by precise EDM survey. Hence species zones in mangroves are definitive indicators of sea-level position, and pollen distributions record the locations of different zones in the sedimentary record. Pollen stratigraphic records can be used to reconstruct Holocene sea-levels and show mangrove response to change. Mangrove response to sea-level rise has been investigated in Bermuda, the Cayman Islands, Tonga and southern New Guinea. Radiocarbon dating of stratigraphy determined a sediment accretion rate of 1 mm a^{-1} for the low island locations, and up to 1.5 mm a^{-1} in two estuaries of southern New Guinea. The IPCC SLR projections of 9-88 cm by 2100 equate to a rate of 0.9-8.8 mm a^{-1}. Mangrove recession events and replacement by lagoon environments are shown to occur during more rapid sea-level rise. In Bermuda rates of SLR exceed 2 mm a^{-1} and the largest mangrove area having existed for the last 2000 years lost 26% area in retreat of its seaward edge during the last century. In Tonga, a large mangrove swamp persisted 7000-5500 yr BP during SLR of 1.2 mm a^{-1}, then retreated when the rate increased. In Cayman 20 km^2 of mangroves died back between 4080 and 3230 yr BP, during SLR of 2.8-3.3 mm a^{-1}, to become a lagoon. In extensive swamps of southern New Guinea gradual Late Holocene retreat of mangrove zones occurred with SLR of 0.67 mm a^{-1}. Hence while low island mangroves are likely to be the most sensitive to projected SLR, continental margin mangroves will also suffer disruption and retreat.

1. Introduction

Mangrove forests occur on low energy, sedimentary shorelines of the lower latitudes, between mean tide and high tide elevations. Mangroves in Australia and elsewhere are valued primarily for their importance as fish and crab habitats, and outwelling of mangrove detritus has been shown to support foodchains including commercial species offshore. Mangroves also stabilize and trap sediments, lowering suspended sediment levels in coastal waters to benefit shallow water communities such as coral reefs. Furthermore, mangrove shorelines provide protection for inland areas from storm surges and flooding.

There is increasing evidence that mangroves may be affected by coastal environmental change, including hydrological variations and sea-level rise (Ellison and Farnsworth, 1997). The response of mangroves to such impacts tends to be gradual and, particularly in undisturbed systems, is manifested typically as a change in their extent, structure and species composition and hence their distinct zonation. As mangroves are sensitive to even minor transitions in coastal conditions (e.g., altered drainage patterns, saltwater intrusion, accretion or erosion in response to sea-level variations), changes in the zonation of these ecosystems are often indicative of broader scale changes and associated impacts in coastal regions (Blasco *et al*., 1996; Ellison and Farnsworth, 1997). The fate of mangrove habitats to climate change will depend on a number of factors, including current tidal range, sedimentology, salinity regime, community composition and shore profile. Mangrove response to increased CO_2 and temperatures, changed precipitation and rising sea-level will also vary with each factor.

As sedimentary systems, mangroves have a palaeoenvironmental record both as a recognizable type of sedimentary deposits, and through microfossils that occur in this particularly pollen. Being a wet environment, anaerobic conditions allow the long term preservation of these microfossil records. This paper uses some of these published records of past distributions of mangroves to show their past responses to climate change, particularly sea-level change.

The pollen record does not show clear trends of mangrove migration with climate change, more distributions have changed over time more due to biogeographic factors and habitat availability. This is exemplified by records in the Pacific Islands, where mangroves of the New Guinea center of biodiversity reach a eastern limit at American Samoa (Ellison, 1995). Leopold (1969) showed distributions of mangroves in the west and south Pacific to be far more extensive in the past than at present, recording *Rhizophora, Sonneratia, Avicennia* and *Scyiphora* pollen from the Miocene of Enewetok Atoll, Marshall Islands. All of these species have more restricted distributions today. In Miocene dark peat sediments on Viti Levu, Fiji, Ladd (1965) found pollen of *Sonneratia*, which today extends only east as far as Vanuatu. Leopold suggested that, at times, post-Miocene Enewetok was completely submerged, necessitating later recolonization by plants, which may explain the local extinction of *Rhizophora*.

Further evidence of more recent increased ranges of mangroves comes from Mangaia in the Cook Islands, where Ellison (1994) found *Rhizophora* pollen (probably *R. stylosa*) for periods during the Holocene. This reached a maximum concentration of 2691 grains/ cm^3 and occurred around 7250, 5000 and 2000 yrs BP. *Rhizophora* was not previously believed to be indigenous east of Samoa (Ellison, 1991), and seems to have colonised the inner swamps of Mangaia through conduit caves. The loss of *Rhizophora* from Mangaia shown in the pollen diagrams could have been caused by decreasing salinity of the inner swamps with sea-level fall, and closure of the conduit caves by sedimentation. This record lends support to Taylor's (1979) view that *R. stylosa* in Moorea and Bora Bora is not introduced. It seems that Pacific mangrove ranges are more controlled by availability of habitats and less by dispersal capability than was previously thought (Mepham, 1983).

The paleoecological record rather gives strong evidence that habitat suitability for mangroves is controlled by sea-level elevation relative to land surfaces, and rates of sea-level change. This is investigated below through two lines of inquiry, first establishing sea-level/ elevation control in current mangroves, and second, using this to interpret mangrove responses to past sea-level change from the palaeorecords.

2. Sea-Level Control of Mangroves

Within the intertidal habitat of mangroves, species have different preferences for elevation, salinity and frequency of inundation, resulting in species zones (Duke et al., 1998). This zonation is largely controlled by the elevation of the substrate surface relative to mean sea-level. Elevation of the ground surface can be raised under mangroves, by accumulation of vegetative detritus to form a mangrove peat or mud, which may also contain matter brought in by the tides and by rivers. If the sedimentation rate keeps pace with rising sea-level, then the salinity and frequency of inundation preferences of mangrove species zones will remain largely unaffected. If the rate of sea-level rise exceeds the rate of sedimentation, then mangrove species zones will migrate inland to their preferred elevation, and seaward margins will die back. The accumulation of sediment under mangroves will help to compensate for rising sea-levels. However, expected rates of sedimentation must be established to assess the vulnerability of mangrove ecosystems.

While mangroves are widely recognised in the literature to occur between mean tide and high tide elevations, this has been demonstrated in relatively few studies. Accurate survey of mangrove substrate elevations in microtidal Bermuda demonstrated elevations of -0.2 m below MSL at the seaward edge of mangroves, and 0.3 m above MSL at the landward edge (Ellison, 1993). In extensive continental mangroves of southern Irian Jaya, the elevation of the seaward edge of mangroves was surveyed accurately at the mouth of two adjacent estuaries. At both locations the transition from dense forest to scattered pioneer trees occured at 0.15 m above MSL, and scattered trees occur seaward to –0.35 or 0.40 m below MSL (Ellison, 2005). The landward edge of mangroves with freshwater forest was found to occur at +1.6 m above MSL, within a tidal range of 3.3-3.6 m.

Several surveys from large mangrove systems in northern Queensland as well as Darwin Harbour have shown that the mangrove seaward edge occurs at MSL, which supports the widespread understanding of mangrove habitat occurrence in the tidal spectrum. Mangroves of Coral Creek, northern Hinchinbrook Island, were surveyed in detail in 1978 by the Australian Survey Office. This showed the mangrove seaward edge to occur mangrove at –0.18 to +0.07 m relative to MSL (Boto and Bunt, 1981; Wolanski, et al., 1992). Similar surveys were carried out by the Australian Survey Office in 1974 at Zoe Bay, SE Hinchinbrook Island, showing the mangrove seaward edge to occur at –0.18 to +0.02 m above MSL, and in 1985 the Murray River estuary just north of Hinchinbrook, finding the mangrove seaward margin to be at approximately 0.0 AHD, which is at sea-level (Priest, 1990).

Offshore in ths GBR, three marine-dominated low island mangrove systems on the were accurately surveyed at Low Isles (16° 23'S, 145°34'E), Three Isles (15°06'S, 145.25'E) and Pipon (14°07'S, 145.12'E). The mean elevation of the mangrove/ lagoon margins was found to be 0.36 m below MSL, and using ANOVA the differences in means were not significant between islands. These elevation studies indicate the sensitivity of mangrove zones to sea-level position, hence inferring disruption and relocation with small amounts of sea-level change.

The control of sea-level elevation on the seaward margin of mangroves has been demonstrated by the author in detailed survey of marine-dominated low island mangrove systems on the Northern Great Barrier Reef. The mean elevation of the mangrove/ lagoon margins at Low Isles, Three Isles and Pipon was found to be 0.36 m below MSL, with insignificant differences in means between islands. Mangroves are therefore shown to be closely controlled by sea-level elevation at their seaward margin, which demonstrates the importance of stable sea-level in controlling mangrove distributions.

3. Past Records of Mangrove Response to Sea-Level Rise

Comparing present trends in species and communities with palaeo-ecological records of past extents provides excellent information on how they may respond to climate change (Hansen et al., 2001; Hansen and Biringer, 2003). Mangrove response to sea-level rise has been investigated by the author by reconstruction of Holocene analogues in the Cayman Islands, Tonga and southern New Guinea as well as Bermuda. In summary radiocarbon dating of stratigraphy determined a sediment accretion rate of 1 mm a^{-1} for the low island locations, and up to 1.5 mm a^{-1} in two estuaries of southern New Guinea.

This rate is of significance because as established above, within the intertidal habitat of mangroves, species have different preferences for elevation, salinity and frequency of inundation, resulting in species zones. Elevation of the ground surface under mangroves can be raised, by accumulation of vegetative detritus to form a mangrove peat or mud, which may also contain matter brought in by the tides and by rivers. If the sedimentation rate keeps pace with rising sea-level, then the salinity and frequency of inundation preferences of mangrove species zones will remain largely unaffected. If the rate of sea-level rise exceeds the rate of sedimentation, then mangrove species zones will migrate inland to their preferred elevation, and seaward margins will die back. The accumulation of sediment under mangroves will help to compensate for rising sea-levels. The net rates at which mangroves build up sediment over long periods of time is indicated by sedimentation rates as shown by analysis of Holocene mangrove stratigraphy.

In Bermuda, tide guage measured rates of sea-level rise over the last century have been within the rates projectioned fr this century. This allows assessment of mangrove response to rising sea-level at a location that has been experiencing sea-level rise in the past, at a rate within the ranges projected for this century elsewhere in the world. The largest mangrove area at Hungry Bay had existed for the last 2000 years, and during the last century lost 26% of its area due to retreat of its seaward edge (Figure 1). Survey showed that swamp elevations were lower in the tidal spectrum than normal, and mangroves at the seaward margin were under inundation stress (Ellison 1993, 1996).

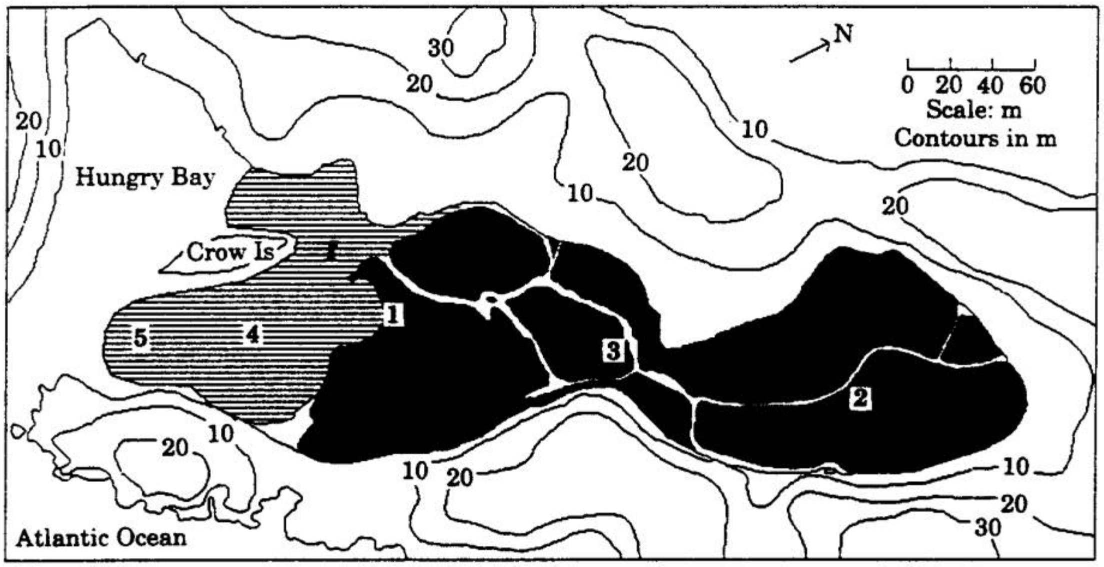

Fig. 1. Current mangrove extent at Hungry Bay, Bermuda shown in black, and died back areas of mangroves shown striped (from Ellison 1993).

This Bermuda site demonstrated that mangrove sediment is subject to erosion by rising sea-levels, with removal of mangrove substrate (above MSL) and with some deposition subtidally offshore of the mangroves (Ellison, 1993). Accelerated coastal erosion is known to be associated with rising sea-level (Stewart, et al., 1990), with removal of sediment from the upper part of the tidal spectrum and deposition in the lower part (Bruun, 1962). The Bruun rule is expected to cause significant coastal erosion problems if projected sea-level rise occurs.

Mangrove recession events and replacement by lagoon environments are shown to occur during more rapid sea-level rise, the largest in Cayman, where 20 km^2 of mangroves under the present North Sound receded between 4080 and 3230 years before present (Figure 2). This was found by coring beneath the current lagoon to find mangrove peat buried beneath seagrass beds.

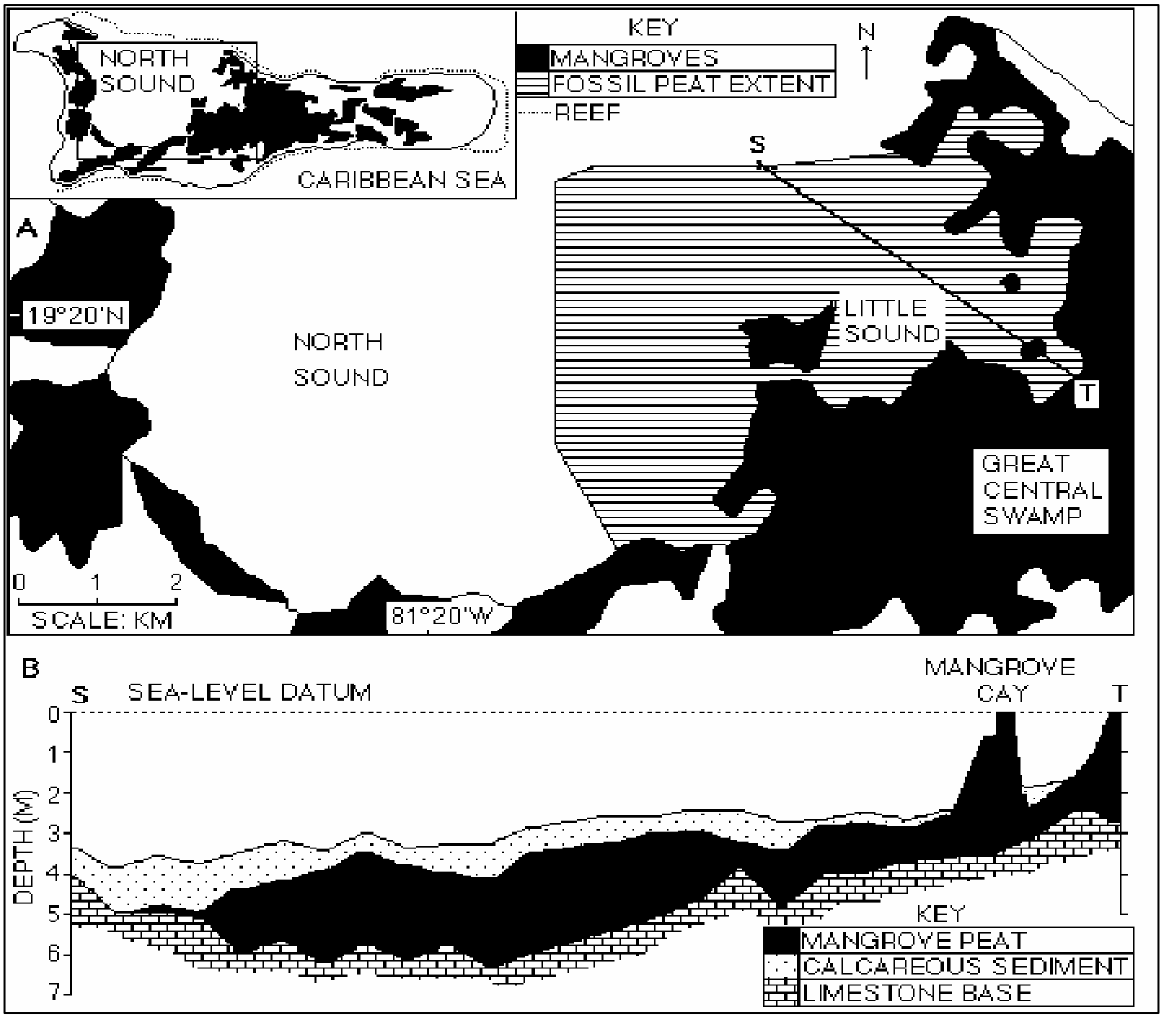

Fig. 2. Current mangrove extent in the North Sound, Grand Cayman shown in black, and died back areas of mangroves shown striped.

In Tonga, , then retreated when the rate of sea-level rise increased (Ellison, 1989). This is the largest pocket of mangroves in Tonga, in the Fanga'uta Lagoon. The stratigraphic diagram in Figure 3 shows mangrove peat between about 2.5 and 1.5 m below present sea-level, indicating a large mangrove swamp that persisted between 7000 and 5500 yr BP during sea-level rise reconstructed to be at a rate of 1.2 mm a^{-1}. Around 5500 yr BP this mangrove area died back to become a lagoon, persisting above this level as just a narrow fringe. The mangrove swamp later re-established over the whole site following sea-level fall in the later Holocene.

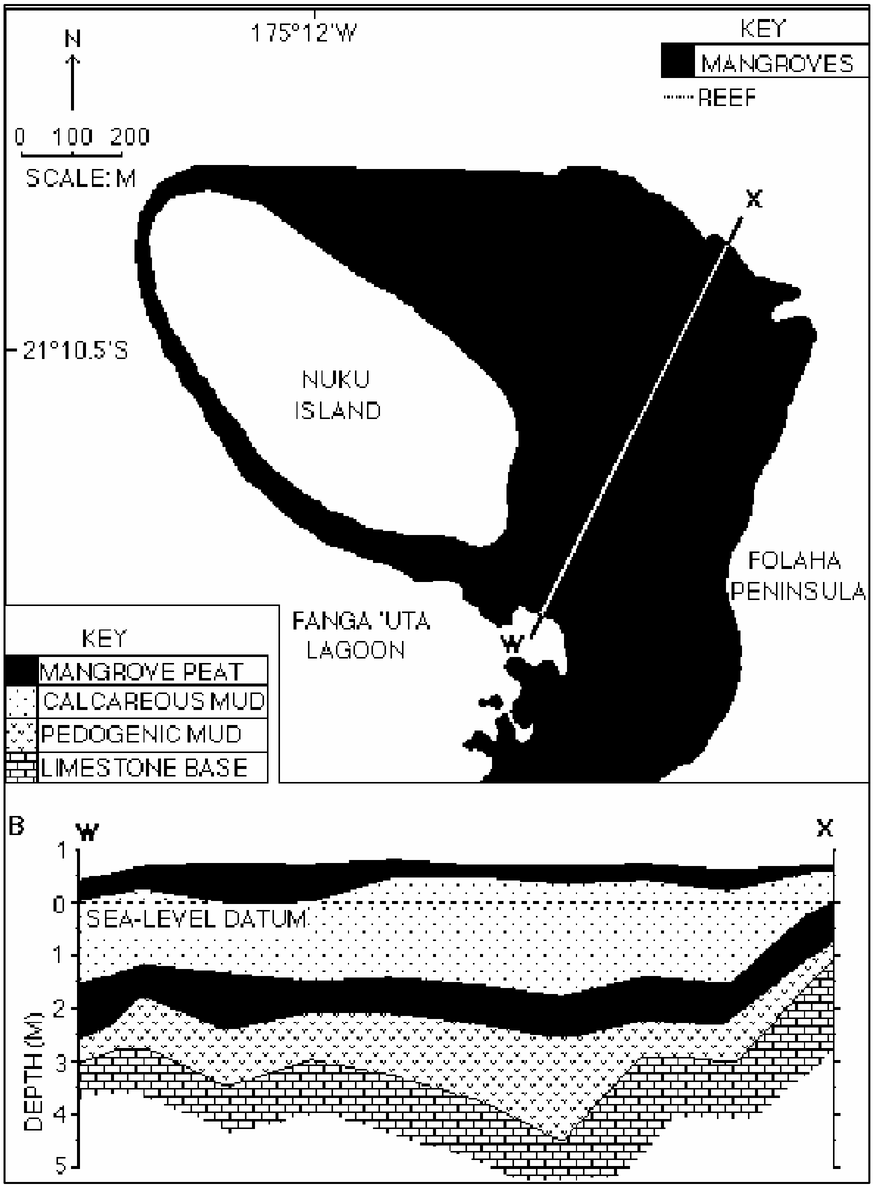

Fig. 3. Location diagram for a coring transect at Folaha, Tangatapu (top) and stratigraphy along this transect (bottom) (from Ellison, 1989).

Gradual retreat of mangrove zones with slowly rising sea-level has more recently been demonstrated from the extensive coastal swamps of southern New Guinea (Irian Jaya) (Ellison, 2005). Figure 4 is a pollen diagram showing a *Bruguiera* zone present at the core site for most of the Holocene, replaced around 3000 years ago by a *Rhizophora* zone, and this occurrence was replicated at 4 other core sites throughout this and the adjacent Ajkwa Estuary. Landward Bruguiera being replaced by seaward *Rhizophora* indicates landward retreat of the mangroves, at a rate of sea-level rise determined to be only 0.67 mm a^{-1} .

Comparison of these Holocene palaeorecords indicates that while low island mangroves are likely to be the most sensitive to sea-level rise, continental margin mangroves will also suffer disruption and retreat.

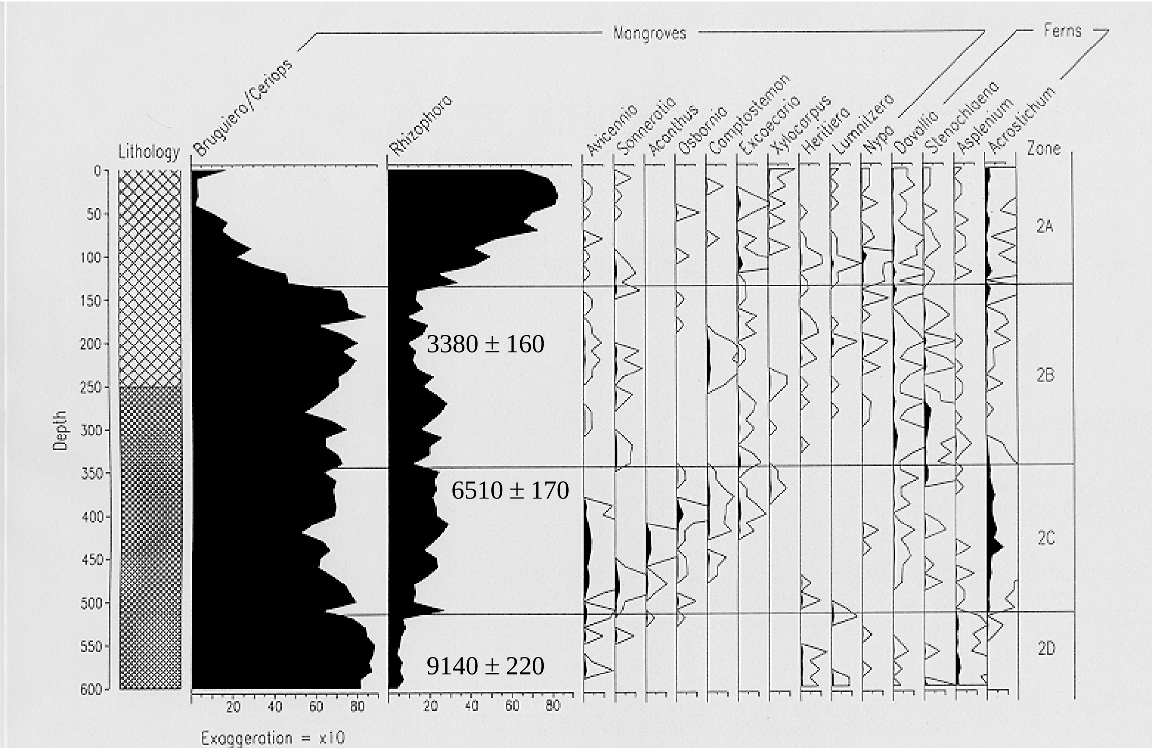

Fig. 4. Core site 2 percentage pollen diagram from the Tipoeka Estuary, southern New Guinea (from Ellison, 2005).

4. Conclusions

The palaeoenvironmental record of mangroves shown sensitivity to sea-level rise, including dieback and massive mortality events within the rates of sea-level rise currently projected for this century. Sediment supply determines mangrove ability to keep up with sea-level rise. Mangroves of low relief islands in carbonate settings that lack rivers are likely to be the most sensitive to sea-level rise, owing to their sediment-deficit environments. However, as demonstrated from southern New Guinea, continental mangroves (such as mainland Australia) will also demonstrate significant mortality and attempted relocation inland.

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High-Resolution Global Assessment of Mangrove Responses to Sea-Level Rise: A Review

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Abstract

Predicted acceleration in sea-level rise has raised concerns worldwide about the stability of mangrove habitats and the ecological services they provide (e.g., fisheries). But mangrove elevation responses to current and future rates of sea-level rise and the potential for mangrove submergence are poorly understood. We review the findings from a recently developed global network of high-resolution accretion and elevation monitoring stations using surface elevation table – marker horizon (SET – MH) technology, and the recent literature on process controls of mangrove elevation dynamics, to evaluate the vulnerability of mangrove forests to sea-level rise. Preliminary analyses of the SET - MH network reveal there exists a direct positive relationship between vertical accretion and both sea-level rise and tidal range. But elevation change is not related to either variable, and the majority of sites in the network are experiencing an elevation deficit in relation to sea-level, because of significant rates of shallow subsidence (accretion minus elevation). These findings indicate that local subsurface processes, such as root growth, root decomposition, compaction, and soil-shrink swell driven by groundwater flux control mangrove elevation, not surface accretionary processes. An improved understanding of mangrove elevation dynamics is needed to develop best management practices to maintain these systems under future climate change scenarios.

1. Introduction

Mangroves provide a suite of critical ecological services (Ewel et al. 1998, Alongi 2002), including nursery habitat for juvenile fishes, especially coral reef fishes (Nagelkerken et al. 2002). Worldwide loss of mangrove forests is largely driven by human alterations and impacts related to resource use (Alongi 2002). But projections of acceleration in eustatic sea-level rise from a current rate of ~ 15 cm/century to a best estimate of 48 cm/century by 2100 (range = 11 – 77 cm/century) (Church et al. 2001) have raised concerns worldwide about the stability and potential for further loss through submergence of mangrove habitats. Soil elevation relative to sea-level varies among individual mangrove sites as a result of local geomorphologic, climatic, and hydrologic controls on sediment supply, primary production and decomposition, subsidence, and autocompaction. In addition, mangrove forests develop in areas that present multiple physiological stressors for the dominant tree species (e.g., water logging, salinity, sedimentation, reduced soils, and high energy storms). The combination of various local controls and multiple stressors means that individual mangrove sites show different degrees of vulnerability to relative sea-level rise (RSLR), which is the combined effect of sea and land level change (Cahoon et al. in press). A better understanding of mangrove accretionary dynamics in response to sea-level rise is needed to better inform the development of management practices to maintain these systems under future climate change scenarios.

Many processes control mangrove elevation dynamics (Figure 1), most of which are not well quantified. Thus mangrove elevation responses to current and future rates of sea-level rise are poorly understood. Site-specific data are needed on the local geomorphic, climatic, and hydrologic controls of mangrove elevation. In addition, the relationships among sedimentation, soil organic matter accumulation, vertical accretion, and soil elevation change require more research, as well as how these processes interact with local relative sea-level rise. The surface elevation table – marker horizon (SET – MH) method was developed to provide high resolution, site-specific data on mangrove accretion, soil elevation change and shallow subsidence. In this paper we evaluate the vulnerability of mangrove forests to current rates of sea-level rise through a review of the literature on trends in mangrove accretion, elevation change, shallow subsidence, and subsurface process controls on elevation dynamics. We describe data gaps and shortcomings in our knowledge, and identify future research directions, including general approaches for managing current vulnerabilities to sea-level rise.

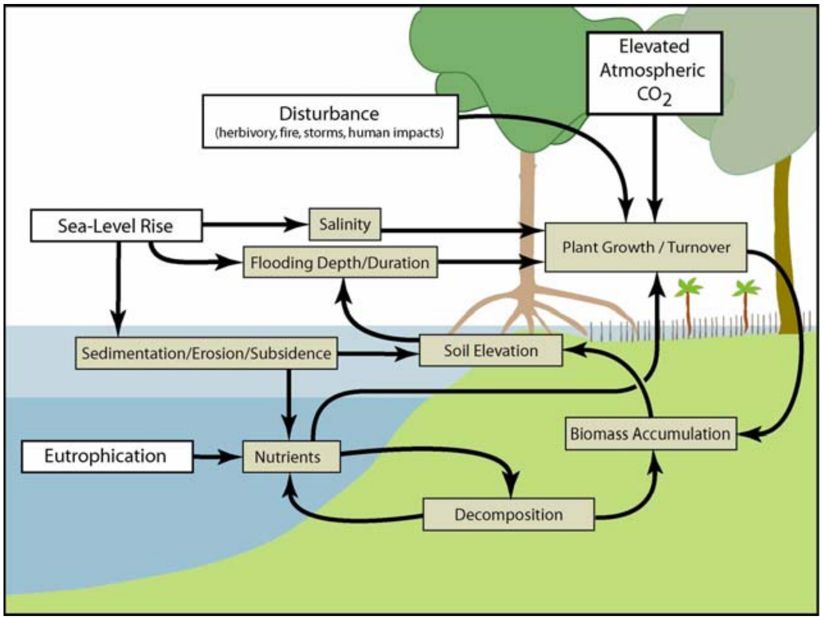

Fig. 1. Linkages and feedback relationships among factors controlling mangrove habitat stability, soil elevation, and nutrient and carbon dynamics. (Modified from Guntenspergen, G.R., Cahoon, D. R., McKee K. L., and Grace, J. B. unpublished data).

2. Methods

2.1. SET – MH methodology

The SET – MH method includes simultaneous, high-resolution (1-2 mm) measures of vertical accretion from artificial soil marker horizons (e.g., Cahoon and Turner 1989) and soil elevation change from a surface elevation table (Boumans and Day 1993, Cahoon et al. 2002a, b). Multi-year datasets are compared with sea-level trends derived from local tide gauges to determine how closely mangrove accretion and elevation trends match sea-level rise. Equally important, the SET – MH method can be used to quantify the amount of surface and subsurface process controls on mangrove surface elevation by comparing accretion and elevation trends (Cahoon et al. 1995). The collective influence on soil elevation of subsurface processes occurring between the marker horizon and the bottom of the SET benchmark (Figure 2), which is calculated as vertical accretion (A) minus elevation change (E), is called shallow subsidence (SS) when elevation change is negative or shallow soil expansion (SE) when elevation change is positive. Shallow subsidence or expansion can be calculated over different depths of the soil profile depending on which SET is used (Figure 2), shallow rod SET (< 6 m maximum depth, typically depth of the live root zone, or < 0.5 m), original SET (maximum depth of 6-9 m), or deep rod SET (maximum depth > 9 m). When E = A, surface processes (e.g., sediment deposition or erosion) control the elevation trend. When E < A, shallow soil subsidence, driven singly or in combination by sediment compaction, decomposition, or soil shrinkage (groundwater flux), controls the elevation trend. When E > A, shallow soil expansion, driven by a net increase in soil organic matter accumulation (root growth > decomposition) or soil swelling, controls the elevation trend. Understanding the amount and direction of surface and subsurface controls on elevation is critical for developing appropriate management practices to mitigate the vulnerability of mangroves to sea-level rise.

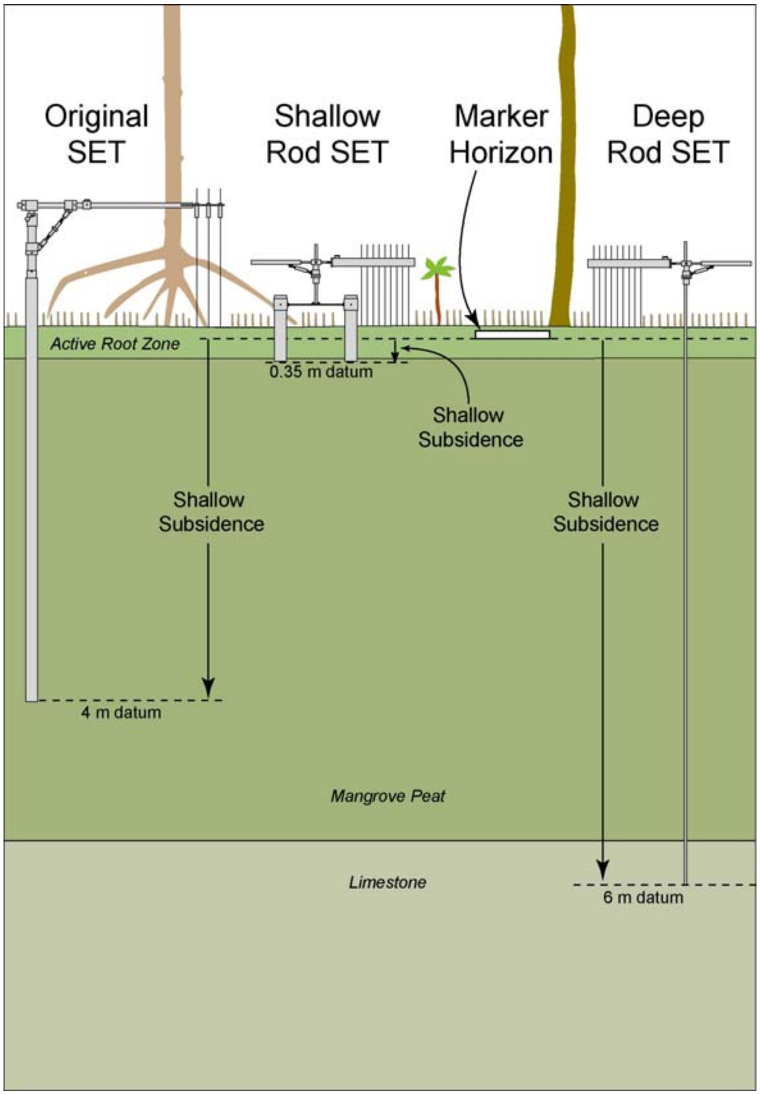

Fig. 2. The relationship between measures of surface elevation change and vertical accretion made with the surface elevation table – marker horizon (SET – MH) approach at Shark River, Everglades National Park, Florida, USA (modified from Whelan et al. 2005), and how these measures are used to calculate shallow subsidence over different depths of the soil profile.

2.2. Global SET – MH Network

During the past 14 years, > 65 scientists have adopted the SET – MH method for use in their field investigations of salt marshes and mangroves. The common use of the original SET and rod SET methodology in individual studies of coastal wetland processes has led to the development of a global *ad hoc* network of wetland elevation monitoring stations, which can be used to compare elevation dynamics among sites, wetland types, and regions of the world. The global *ad hoc* network consists of > 90 sites in 19 countries. The mangrove SET – MH network consists of > 30 sites in 11 countries (Figure 3).

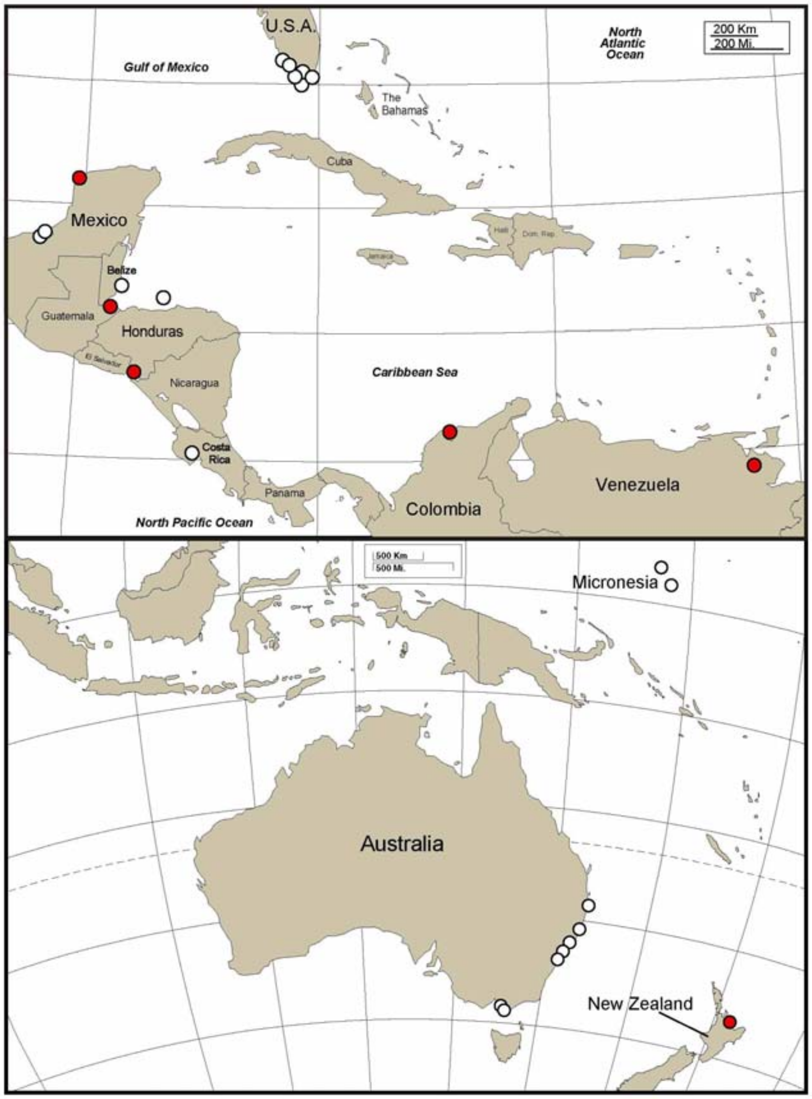

Fig. 3. Global distribution of mangrove surface elevation table – marker horizon (SET – MH) sampling stations in 2006. Top: Wider Caribbean Region. Bottom: Western Pacific Region. White circles indicate sites included in the analyses; red circles indicate sites not included in the analyses.

2.3. Data Analyses

Not every dataset from the *ad hoc* mangrove SET network was included in this global analysis. In all, data from 28 sites in 7 countries were analyzed (Table 1). Some datasets were not available from the global network, while others did not conform to predetermined selection criteria. In order to be included in the analysis, the available datasets were restricted to natural mangrove settings that had not been overtly altered by either chronic human impacts or natural catastrophic events. Sites impacted by hypersalinization due to human-induced hydraulic modification, and sites altered by clear cutting serve as two examples non-conforming to this selection criterion. In addition, data records had to be longer than one year, and have a minimum of three measurement events. Analysis was conducted on original SET and deep rod SET data, but not on shallow rod SET data (see Figure 2), which is used primarily to evaluate the influence of live root zone processes on elevation.

A number of different benchmark plots (Figure 2) are customarily distributed within a site, often spanning different habitats within a flooding gradient (e.g. fringe, basin, riverine, overwash forests), or being subjected to different energy regimes (exposed, protected forests). For the purposes of this analysis, sites were therefore divided into different settings based on these differences in hydrology or energy regimes. A total of 60 settings thus emerged from the 28 sites. All settings contributed elevation data and 41 settings also contributed accretion data.

Sediment accretion and surface elevation change may be influenced by variables such as sediment type and sediment supply, hydrology, and energy regime (tides, floods, wave exposure), variables closely associated with the coastal geomorphology. For this reason, the relationships among accretion and elevation change were investigated according to geomorphic classes. Of the many classification schemes available, the one developed by Woodroffe (2002) was chosen because of its wide applicability and its incorporation of previous classifications. Geomorphic classes include: back barrier, embayment, estuarine, deltaic, open coast, and drowned valley. None of the selected mangrove network sites corresponded to the deltaic setting; the one Australian drowned river site was included within the estuarine class. An additional class, “oceanic island,” was added, yielding a total of five classes. Classification of each site was determined in consultation with the data contributors.

To more closely investigate the processes influencing sediment accretion and elevation change, several covariates were added to the datasets. Rates of local RSLR and tide ranges were obtained from the data contributors, or from published literature. Soil bulk density and soil percent organic matter were obtained for a small subset of the chosen network sites.

Table 1. List of Mangrove Sites and Settings included in the global analysis (Cahoon et al. in press).

Caribbean Region

Country	Area, State	Site	Investigators
USA	Rookery Bay, FL	Rookery Bay NERR	D. Cahoon
USA	10,000 Islands NWR, FL	Blackwater River	D. Cahoon
USA	10,000 Islands NWR, FL	Faka Union River	D. Cahoon
USA	Everglades NP, FL	Lostmans River	T.J. Smith / D. Cahoon
USA	Everglades NP, FL	Shark River	T.J. Smith / D. Cahoon
USA	Everglades NP, FL	Taylor Slough	C. Coronado / F. Sklar
BLZ	Twin Cays		K. McKee / D. Cahoon
MEX	Campeche	Terminos Lagoon	J.W. Day / C. Coronado
HND	Roatan Island		D. Cahoon

Pacific Region

Country	Area, State	Site	Investigators
HND	Gulf of Fonseca		D. Cahoon
CRI	Guanacaste	Bebedero River	P. Delgado
CRI	Guanacaste	Tempisque River	P. Delgado
FSM	Yela, Kosrae	Yela River	D. Cahoon / K. Ewel
FSM	Utwe, Kosrae	Utwe River	D. Cahoon / K. Ewel
FSM	Pukusrik, Kosrae	Lela Lagoon	D. Cahoon / K. Ewel
FSM	Enipoas, Pohnpei	Enipoas River	D. Cahoon / K. Ewel
FSM	Sapwalap, Pohnpei	Sapwalap River	D. Cahoon / K. Ewel
AUS	Hawkesbury R., NSW	Berowra Creek	K. Rogers / N. Saintilan
AUS	Hawkesbury R., NSW	Marramarra Creek	K. Rogers / N. Saintilan
AUS	Jervis Bay, NWS	Cararma Inlet	K. Rogers / N. Saintilan
AUS	Sydney Harbour, NSW	Homebush Bay	K. Rogers / N. Saintilan
AUS	Hunter River, NSW	Kooragang Island	K. Rogers / N. Saintilan

AUS	Kiama, NSW	Minnamurra R.	K. Rogers / N. Saintilan
AUS	Tweed River, NSW	Ukerebagh Island	K. Rogers / N. Saintilan
AUS	Westernport Bay, VIC	French Island	K. Rogers / N. Saintilan
AUS	Westernport Bay, VIC	Kooweerup	K. Rogers / N. Saintilan
AUS	Westernport Bay, VIC	Quail Island	K. Rogers / N. Saintilan
AUS	Westernport Bay, VIC	Rhyll/Phillip Island	K. Rogers / N. Saintilan

Each mangrove setting within the analysis was represented by several (typically three) replicate plots. Each plot consisted of one SET benchmark and generally three feldspar marker horizons. Linear regressions were used on cumulative accretion and elevation change data to estimate linear trajectories over the available time series. To minimize serial correlation, regressions were run at the plot level using the individual marker horizons as sample replicates for accretion, and the different orientations of the SET as sample replicates for elevation change at the plot level. Linear trajectory estimates were then averaged over the replicate plots within a setting. An overall accretion rate was estimated over the 41 settings with accretion data, and its significance was evaluated by a one-sided *t*-test. Similarly, an average elevation change rate was estimated over the 60 settings with elevation data, and compared via a two-sided *t*-test. Shallow subsidence was calculated as the difference between the linear accretion rate and the linear elevation change rate at the plot level, and then averaged over the 41 settings and evaluated with a 2-sided *t*-test. Rates of accretion, elevation change, and shallow subsidence were also averaged over the different geomorphic classes and compared to zero via similar *t*-tests. The same analysis was conducted for geographic classes: Caribbean, New South Wales (Australia), Victoria (Australia), Micronesia, and Pacific Central America. Due to the fact that there are generally more settings for elevation data compared to accretion data (e.g. 21 Caribbean accretion settings vs. 27 Caribbean elevation change settings), the difference between averaged values of accretion and elevation change are not equal to the calculation of average shallow subsidence.

Simple linear regressions were used to test the relationships between RSLR and both accretion and elevation change rates. Likewise, the relationships of accretion rates and elevation change rates to tide range were tested with simple linear regressions. The same analysis was followed for soil bulk density and percent organic matter. The nature of the relationship between soil organic matter and accretion was decidedly not linear, and a negative exponential curve provided a very satisfactory fit.

3. Mangrove Vulnerability to Current RSLR

Cahoon et al. (in press), in the first analysis of the mangrove *ad hoc* global SET – MH sampling network, reported significant (1) relationships among the trends in accretion, elevation change, and relative sea-level rise (RSLR), (2) regional and geomorphic influences on accretion and elevation trends, and (3) physical and biotic subsurface process controls on elevation.

3.1. Vertical accretion and elevation trends

For the entire mangrove network, vertical accretion increased with increasing rates of RSLR and, on average, accretion rates exceeded RSLR. In addition, vertical accretion was positively related to tidal range and soil bulk density, and negatively correlated with soil organic matter content. Conversely, elevation change across the entire network was not positively related to RSLR, tidal range, or soil bulk density; and a majority of sites experienced elevation deficits with respect to sea-level. The distinctly different responses between vertical accretion and elevation change resulted in a significant rate of shallow subsidence for the entire network. Across the network, vertical accretion averaged 5 mm/yr, elevation change 1 mm/yr, and shallow subsidence 4 mm/yr.

3.2. Regional, geomorphic and species comparisons

Of the five geomorphic settings included in the network, only mangroves growing in estuarine and embayment settings exhibited significant linear relationships between accretion and RSLR. Mangroves growing in embayments were the only class to exhibit a positive relationship of elevation to RSLR and tidal range. In addition, mangrove forests in this class were the only forests to exhibit a positive relationship between accretion and tidal range. Regional comparisons revealed that the highest rates of accretion were found in the sediment-rich settings of eastern Australia and the Pacific coast of Central America. These areas also exhibited the highest rates of shallow subsidence, due to compaction and decomposition. The mineral soils of the riverine mangroves on the Pacific Central America coast had the highest bulk densities, lowest organic matter contents, and highest accretion rates in the network. Conversely, the peat-based soils of oceanic islands in the Caribbean had the lowest bulk density, highest organic matter content, and lowest accretion rates in the network. Lastly, there were no strong species effects on accretion and elevation trends. *Avicennia* and *Rhizophora*, the two most commonly represented species in the network, exhibited similar trends with respect to RSLR and tidal range.

3.3. Process controls

Analysis of the SET – MH network reveals that relative sea-level rise (RSLR) is a primary controlling factor of vertical accretion in mangrove forests through the increase in accommodation space (i.e., the difference between sea-level and land level). The resulting increase in flooding frequency leads to increased opportunity for sediment deposition. In contrast, the lack of influence of RSLR on elevation, coupled with high rates of shallow subsidence in sediment-rich settings and the ability of mangroves in sediment-poor settings to build vertically through peat formation, indicates that subsurface processes are primary controlling factors of elevation change. A review of recent literature reveals that soil organic matter accumulation and groundwater flux exert significant control over elevation.

Soil organic matter accumulates when root growth exceeds root decomposition. Under anaerobic soil conditions, decomposition occurs slowly. Thus variation in root growth can influence soil elevation through root inputs to soil volume. For example, in Honduras where Hurricane Mitch caused mass tree mortality, elimination of root inputs led to loss of elevation through peat collapse driven by decomposition (Cahoon et al. 2003). Similarly, Sherman et al. (2000) and Whelan (2005) report that formation of canopy gaps through lighting strikes (i.e., lightning-induced tree death) lead to as much as 60 mm of soil elevation loss within the gap through death of tree roots. However, root recolonization (from the surrounding forest) is rapid in the canopy gaps and elevation recovers to pre-gap levels within 7-10 years (Whelan 2005). In contrast, elevation recovery will not occur following mass tree mortality unless new trees colonize the site and new root input is initiated. To determine the direct influence of root growth on soil elevation, K. L. McKee (in Cahoon et al. in press) analyzed data on root production and vertical accretion from 30 mangrove sites, 18 of which had measures of surface elevation change. The root contribution to vertical soil expansion ranged from 0 mm/yr to 3 mm/yr, and there was a significant correlation between elevation change and root production in some settings. Thus root growth, or the lack thereof, can have a substantial effect on mangrove soil elevation.

Groundwater flux influences mangrove elevation through soil shrink – swell. Mangrove soil elevation is directly correlated with seasonal changes in groundwater pressure in a *Rhizophora*-dominated mangrove forest on the Shark River, Florida, USA (Whelan et al. 2005) and with total monthly rainfall during a severe El Nino drought event in a mangrove forest in eastern Australia (Rogers et al. 2005). Although these findings highlight the importance of groundwater recharge to mangrove soil elevation, the effect on elevation is transitory (e.g., seasonal) and apparently does not affect the long-term trajectory. But the timescale of SET – MH sampling must be taken into account when collecting and interpreting elevation data.

3.4. Research needs

Preliminary analysis of the *ad hoc* global network revealed several shortcomings or limitations of the current network database. (1) The *ad hoc* nature of the network means that individual project site selection criterion has led to the non-systematic development of the network, resulting in large geographic gaps. The current mangrove network is concentrated in the western Pacific Ocean and the wider Caribbean region, with no data from Asia, Africa, and the Pacific coast of South America. The network needs to expand to fill these gaps. There is also uneven distribution among the geomorphic settings, with some types more commonly represented than others (e.g., estuarine, and embayment). (2) Another limitation to data interpretation is data record length. The majority of SET – MH databases are < 5 years duration, with many < 3 years duration. Like sea-level records from tide gauges, the longer the elevation record the more reliable the regression trend. Consequently, as the network matures, the predictive quality of the data should improve. But funding for many projects in the *ad hoc* network has ended, so monitoring of many benchmarks has ceased or is intermittent at best. (3) Interpretations of vulnerability to sea-level rise are limited for some sites by lack of reliable, proximal tide gauge data. Extrapolating sea-level rise trends from a tide gauge located in a different geomorphic and/or hydrologic setting from the SET – MH sampling stations reduces the reliability and resolution of the vulnerability estimate. Reliable sea-level rise trends are needed for all sites in the network. (4) Lastly, predictive wetland elevation models (Morris et al. 2002, Rybczyk and Cahoon 2002) used to predict salt marsh elevation responses to future sea-level rise scenarios have not been applied to mangrove systems, except to model peat collapse after Hurricane Mitch (Cahoon et al. 2003). Until predictive elevation models are applied to mangrove systems, we can only guess how mangroves will respond to accelerated increases in RSLR.

4. Management Implications

The findings from the preliminary analysis of the SET – MH network have important implications for the sustainable management of mangrove resources during current and predicted future increases in sea-level rise. Elevation trends for the majority of sites in the network are not keeping pace with current rates of RSLR, even though vertical accretion rates are keeping pace. Predicted acceleration in the rate of eustatic sea-level rise (Church et al. 2001) will presumably result in both an increase in the size of the current elevation deficits and the number of sites experiencing an elevation deficit, although predictive elevation models are needed to confirm this presumption. More importantly, managing long-term mangrove sustainability under these elevation deficit scenarios requires an understanding of key subsurface process influences on elevation such as soil organic matter accumulation, especially in sediment-poor settings. Land use practices and other human activities that affect soil organic matter accumulation (e.g., timber harvesting, pollution, eutrophication, groundwater extraction, coastal development that forms a barrier to mangrove transgression upslope) can directly influence mangrove vulnerability to sea-level rise and should be managed appropriately. Future research should determine the effects of common land use practices on soil organic matter accumulation and mangrove elevation. Management practices and policies should be based on local knowledge of mangrove elevation dynamics and with a focus to maximize sediment deposition and soil organic matter accumulation.

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Recent Historical Reconstruction of Mangrove Position and Assessment of Mangrove Responses to Projected Relative Sea-level Rise[1]

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Abstract:

We predict the decadal change in position of three American Samoa mangroves from analysis of a time series of remotely sensed imagery, a geographic information system, tide gauge data, and projections for change in sea-level relative to the mangrove surface. Accurate predictions of changes to coastal ecosystem boundaries, including in response to projected relative sea-level rise, enable advanced planning to minimize and offset anticipated losses and minimize social disruption and cost of reducing threats to coastal development and human safety. The observed mean landward migration of three mangroves' seaward margins over four decades was 25, 64, and 72 mm a^{-1}, 12 to 37 times the observed relative sea-level rise rate. Two of the sites had clear trends in reductions in mangrove area, where there was a highly significant correlation between the change in position of the seaward mangrove margin and change in relative sea-level. Here it can be inferred that the force of sea-level rise relative to the mangrove surface is causing landward migration. Shoreline movement was variable at a third site and not significantly correlated with changing sea-level, where it is likely that forces other than change in relative sea-level are predominant. Currently, 16.5%, 23.4%, and 68.0% of the three mangroves' landward margins are obstructed by coastal development from natural landward migration. The three mangroves could experience as high as a 50.0% reduction in area by the year 2100.

1. Introduction

Accurate predictions of changes to coastal ecosystem boundaries, including in response to projected relative sea-level rise, enables advanced planning appropriate for specific sections of coastline to minimize and offset anticipated losses, and reduce threats to coastal development and human safety (Titus, 1991; Mullane and Suzuki, 1997; Ramsar Bureau, 1998; Hansen and Biringer, 2003; Ellison, 2004; Gilman, 2004). Relative sea-level rise is a major factor contributing to recent losses and projected future reductions in the area of valued coastal habitats, including mangroves and other tidal wetlands, with concomitant increased threat to human safety and shoreline development from coastal hazards (Gilman, 2004). Global sea-level rise is one of the more certain outcomes of global warming, it is already likely taking place, and several climate models project accelerated rate of sea-level rise over coming decades (Church et al., 2001 and 2004a; Cazenave and Nerem, 2004; Holgate and Woodworth, 2004; Thomas et al., 2004). Small island developing states and low-lying coastal areas of continents are particularly vulnerable to small increases in sea-level.

Here we predict the future change in position of three American Samoa mangroves from analysis of a time series of recent historical remotely sensed imagery, a geographic information system (GIS), tide gauge data, and projected relative sea-level. Remotely sensed imagery and a GIS have been used broadly to assess changes in mangrove and other habitat boundaries over time (e.g., Woodroffe, 1995; Solomon et al., 1997; El-Raey et al., 1999; Wilton and Saintilan, 2000; Saintilan and Wilton, 2001). Local and regional implications of results are discussed. A predictive

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[1] This paper is based on:
Gilman, E., J. Ellison, R. Coleman. In Press 2006. Assessment of mangrove response to projected relative sea-level rise and recent historical reconstruction of shoreline position. *Environmental Monitoring and Assessment*.

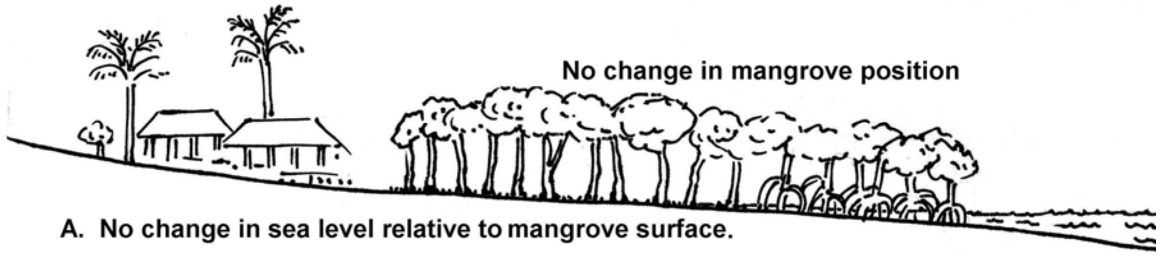
model for site-specific mangrove response to changes in relative sea-level is described, with a caveat on suitable temporal and spatial scales.

1.1. Predictive model for site-specific mangrove response to relative sea-level rise

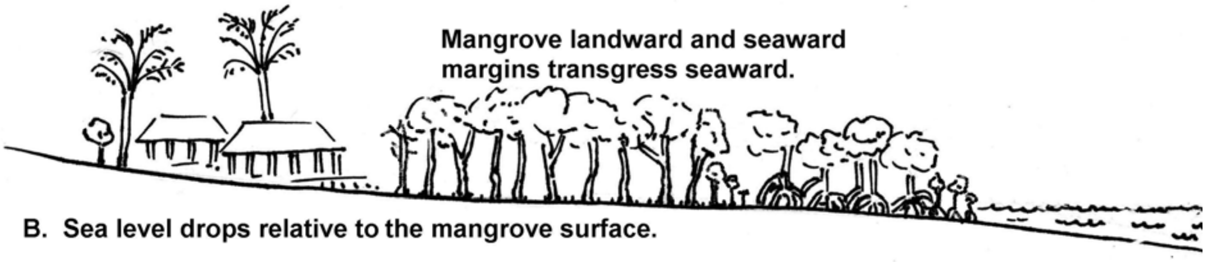
When relative sea-level rise is the predominant force shaping mangrove position, the landscape-level responses of mangroves over decadal and longer periods can be predicted based on reconstruction of the paleoenvironmental response of mangroves to past sea-level fluctuations (Ellison and Stoddart, 1991; Woodroffe, 1995; Ellison, 1993, 2000; Berdin et al., 2003). Such predictions can be based on (a) the mean sea-level change rate relative to the mangrove surface, (b) the mangrove's physiographic setting (slope of the land adjacent to the mangrove, slope of the mangrove, and presence of obstacles to landward migration), and (c) erosion or progradation rate of the mangrove seaward margin (Ellison and Stoddart, 1991; Ellison, 1993, 2000, and 2001; Woodroffe, 1995; Alleng, 1998; Lucas et al., 2002).

This model is based on the understanding that mangroves respond passively to changes in hydrogeomorphic processes and conditions, including changes in relative sea-level (Ellison and Stoddart, 1991; Ellison, 1993, 2000, and 2001; Woodroffe, 1995; Alleng, 1998; Lucas et al., 2002). This has replaced the classical, successional model where mangroves are understood to actively move towards a climax community through sediment accumulation and colonization (Woodroffe, 1995; Alleng, 1998).

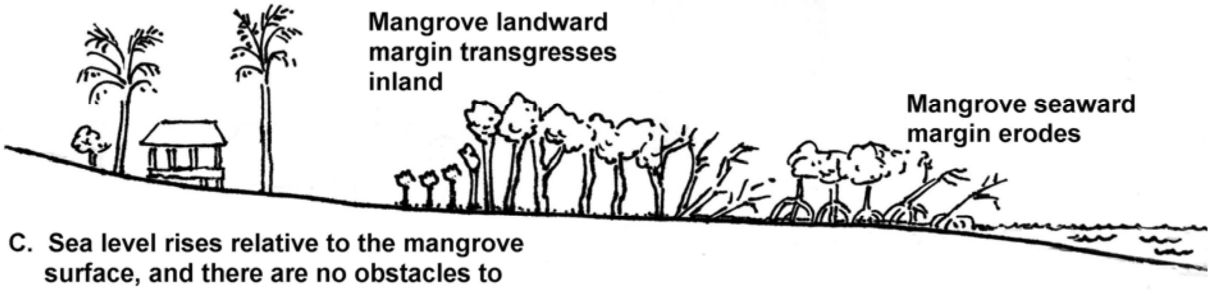
There are three general scenarios for mangrove response to relative sea-level rise, given a landscape-level scale and time period of decades or longer (Fig. 1):



A. No change in sea level relative to mangrove surface.



B. Sea level drops relative to the mangrove surface.



C. Sea level rises relative to the mangrove surface, and there are no obstacles to the mangrove's landward transgression.

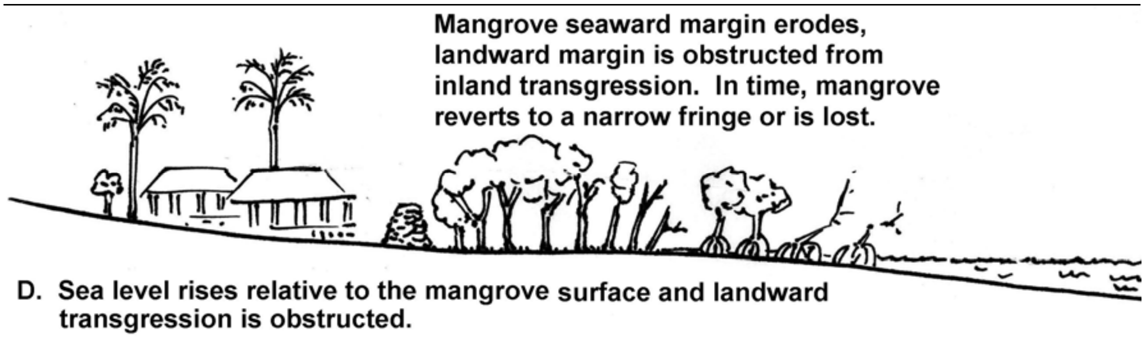


Fig. 1. Four scenarios for generalized mangrove response to relative sea-level rise.

- No change in relative sea-level: When sea-level is not changing relative to the mangrove surface, mangrove elevation; salinity; frequency, period, and depth of inundation; and other factors that determine if a mangrove community can persist at a location will remain relatively constant and the mangrove margins will remain in the same location (Fig. 1A) (Blasco, 1996; Alleng, 1998; Ellison, 2000);
- Relative sea-level lowering: When sea-level is dropping relative to the mangrove surface, this forces the mangrove margins to migrate seaward (Fig. 1B). This has been observed in Fiji (Nunn, 2000), and may explain observed mangrove progradation in Florida (Snedaker et al., 1994). The mangrove may also expand laterally if areas adjacent to the mangrove, which are currently at a lower elevation than the mangrove surface, develop hydrologic conditions (period, depth, and frequency of inundation) suitable for mangrove establishment; and
- Relative sea-level rising: If sea-level is rising relative to the mangrove surface, the mangrove's seaward and landward margins retreat landward, the mangrove species zones migrate inland as they maintain their preferred period, frequency and depth of inundation, as the seaward margin dies back, and tidal creeks widen (Fig. 1C) (Semeniuk, 1980; Ellison, 1993, 2000, 2001; Woodroffe, 1995). For instance, in Bermuda, mangroves have been documented to not be keeping pace with relative sea-level rise (Ellison, 1993). The mangrove may also expand laterally if areas adjacent to the mangrove, which are currently at a higher elevation than the mangrove surface, develop a suitable hydrologic regime.

The seaward mangrove margin migrates landward from mangrove tree dieback due to stresses caused by a rising sea-level such as erosion resulting in weakened root structures and falling of trees, increased salinity, and too high a period, frequency, and depth of inundation (Naidoo, 1983; Ellison, 1993, 2000, 2004; Lewis, 2005).

Mangrove zones migrate landward via seedling recruitment and vegetative reproduction as new habitat becomes available landward through erosion, inundation, and concomitant change in salinity (Semeniuk, 1994). Depending on the ability of individual true mangrove species to colonize newly available habitat at a rate that keeps pace with the rate of relative sea-level rise, slope of adjacent land and the presence of obstacles to landward migration of the landward boundary of the mangrove, such as seawalls and other shoreline protection structures, some sites will revert to a narrow mangrove fringe, possible survival of individual trees, or even experience extirpation of the mangrove community (Fig. 1 D) (Ellison and Stoddart, 1991). The sediment composition of the upland habitat where the mangrove is migrating may also influence the migration rate (Semeniiuk, 1994).

As observed in salt marshes, as wave energy increases when sea-level rises relative to the wetland surface, mangroves transgress landward through the erosion of sediment at the mangrove seaward margin and along tidal creeks. Eroded mangrove sediment is likely processed by nearshore waves and currents, with coarser sediment retained in the mangrove system, while finer material is transported offshore (SCOR Working Group, 1991). The eroded coarser sediment is deposited across the mangrove (Semeniuk, 1980; SCOR Working Group, 1991; Ellison, 1993; Woodroffe, 1995; Pethick, 2001).

1.2. Exceptions to the generalized predictive model

Change in mangrove position will be variable over relatively small temporal and spatial scales (SCOR Working Group, 1991; Woodroffe, 1995; Gilman, 2004). The larger the temporal and spatial scales employed to observe trends in change in relative sea-level and shoreline position, the more likely the predictive model for site-specific mangrove response to changing relative sea-level employed in this analysis will be accurate. Trends will be more apparent, while signals from short-term, episodic, cyclical, and small-scale events will be less apparent (SCOR Working Group, 1991; Semeniuk, 1994; List et al., 1997; Pethick, 2001; Pilkey and Cooper, 2004). Shorelines are expected to take decades to reach equilibrium from increased sea-level (Komar, 1998). Retreat of the seaward margin of mangroves resulting from a long-term rise in relative sea-level will likely result from a process of short-term episodic spurts of erosion and accretion with a long-term mean trend of landward transgression, rather than a continuous gradual landward migration (SCOR Working Group, 1991). These episodic events range from events that occur over days such as storms, to seasonal events such as variations in the strengths and prevailing directions of coastal currents and winds, to events that last over a few months such as El Nino and La Nina phases. These forces affect sediment-budget balances, result in short-term changes in sea-level, and result in pulses in erosion and accretion along the seaward margin of mangroves. Over short time periods of years or less, relative sea-level rise is small against these shorter-term changes in local sea-level (SCOR Working Group, 1991).

In addition, mangrove response and resilience to relative sea-level rise over a small spatial scale will be variable. Spatially variable environmental conditions within a mangrove may result in variable response to change in relative sea-level over small areas. The site-specific hydrogeomorphic setting, including small topographic features within the wetland, slope of land adjacent to and upslope of the mangrove, presence of obstacles to landward migration (buildings, roads, seawalls), tidal range, and groundwater and soilwater hydrologic dynamics affect localized mangrove response to change in sea-level (Semeniuk, 1994; Woodroffe, 1995; List et al., 1997; Komar, 1998; Donnelly and Bertness, 2001; Nurse et al., 2001; Saintilan and Wilton, 2001; Wilton, 2002; Ellison, 2004). Spatially variable differences in changing elevation of the mangrove surface and rate of erosion of the seaward mangrove margin will produce variable response to change in sea-level over small scales. Additional important variables include slope of the mangrove surface and the types of coastal ecosystems that border the mangrove (Semeniuk, 1994). For instance, mangroves bordering rocky hinterland will migrate landward more slowly than when the adjacent habitat has unconsolidated coastal deposits.

Mangrove boundary position will also be variable where other natural and anthropogenic forces exert a larger influence on mangrove margin position than changing sea-level. Mangrove species have specific tolerance levels for period, frequency, and depth of inundation; salinity regime; wave energy; soil and water pH; sediment composition and stability; nutrient concentrations; and degree of faunal predation; resulting in zonal distribution of mangrove species and determining if a mangrove wetland can become established and survive in a specific location (Tomlinson, 1986; Naidoo, 1985 and 1990; Wakushima et al., 1994a and 1994b). While there is still incomplete understanding of what combination of factors control mangrove establishment and health, changes in any of these factors can result in changes in the location of mangrove margins (Donnelly and Bertness, 2001; Saintilan and Wilton, 2001; Wilton, 2002). For example, forces affecting sediment-budget balances, including changes in sediment inputs from rivers, variations in coastal currents and wind directions and strength, variations in regional climate and resulting storms, and construction of seawalls and other shoreline erosion control structures, can produce erosion or accretion of the mangrove seaward margin irrespective of any sea-level rise.

In addition to altered sediment inputs, several other forces can affect mangrove margin position, as well as structure and health. These include other outcomes of global climate change besides global sea-level rise; changing nutrient, freshwater, and pollutant inputs; clearing mangrove vegetation; filling; displacing native species with alien invasive species; and harming vegetation from insect infestations, fungal flora pathogens, and other diseases (United Nations Environment

Programme, 1994; Ellison, 1993, 1996, 1999; Gilman, 1999a, 1999b; Donnelly and Bertness, 2001; Saintilan and Wilton, 2001). These pressures can also reduce mangrove resilience to the additional stress of sea-level and climate change. Projected increases in frequency and elevations of extreme high water events in response to climate change (Church et al., 2004b, Woodworth and Blackman, 2004) could also affect the position and health of mangroves by altering salinity, recruitment, and inundation, in addition to changing the wetland sediment budget. Furthermore, degradation of adjacent coastal ecosystems from relative sea-level rise and climate change may reduce mangrove health. Mangroves are functionally linked to neighboring coastal ecosystems, including seagrass beds, coral reefs, and upland habitat, although the functional links are not fully understood (Mumby et al., 2004). For instance, mangroves of low islands and atolls, which receive a proportion of sediment supply from productive coral reefs, may suffer lower sedimentation rates and increased susceptibility to relative sea-level rise if coral reefs become less productive from climate change and sea-level rise.

Outcomes of global climate change besides global sea-level rise, such as changes in precipitation, increases in air and sea-surface temperatures, changes in frequency and intensity of storms, changes in prevailing ocean wave heights and direction, and changes in tidal regimes may affect coastal systems, including mangroves. However, projected changes in these parameters are less certain than global change in sea-level, and the response of mangroves and other coastal systems to changes in these parameters are not well understood (McLean et al., 2001). Increases in temperature and direct effects of increased atmospheric CO_2 concentration are expected to increase mangrove productivity, change phenological patters (e.g., timing of flowering and fruiting), and expand mangrove ranges to higher latitudes (Ellison, 2000). Snedaker (1993) hypothesizes that changes in regional precipitation will have a larger influence on mangrove survival than any change in relative sea-level and temperature. The Intergovernmental Panel on Climate Change found evidence of increased precipitation in the equatorial Pacific and decreased precipitation to the north in the last few decades, and predicts that El Nino conditions will become more persistent over coming decades, resulting in a general increase in precipitation in the tropical Pacific (Houghton et al., 2001). It is uncertain how precipitation patterns will change in for individual Pacific island States over coming decades. Areas with decreased precipitation will have a smaller water input to groundwater and less freshwater surface water input to mangroves, increasing salinity. Increased salinity decreases mangrove net primary productivity, growth, and seedling survival, and may possibly change competition between mangrove species (Ellison, 2000, 2004). Decreased rainfall and increased evaporation will reduce the extent of mangrove areas, with a conversion of landward zones to hypersaline flats, and there will be a decrease in diversity of mangrove zones and growth (Ellison, 2000). Mangrove areas experiencing increased rainfall will experience an increase in area, with mangrove colonization of previously unvegetated areas of the landward fringe, and there will an increase in diversity of mangrove zones and growth rates (Ellison, 2000). Areas with higher rainfall have higher mangrove diversity and productivity due to higher supply of fluvial sediment and nutrients, as well as reduced exposure to sulfate and reduced salinity (McKee, 1993; Ellison, 2000 and 2004). Mangrove will likely increase peat production with increased freshwater inputs (for instance, if precipitation increases or relative sea-level is dropping), but will experience a net loss of peat if salinity increases (for instance, if relative sea-level is rising or precipitation is decreasing), as the increased availability of sulfate in seawater would increase anaerobic decomposition of peat, increasing the mangrove’s vulnerability to any rise in relative sea-level (Snedaker, 1993).

There is little quantitative information available on land use changes in American Samoa’s watersheds. Williams (2004) quantified land uses in 1961, 1984, and 2001 for the Tafuna Plain, Tutuila Island, American Samoa, which is adjacent to the Nu’uuli mangrove study site, finding that over the four decades the area of forested land decreased by 52%, and the area of developed land increased by 367%. This may have altered sediment, freshwater, and pollutant input levels into mangroves, forcing change in position of margins as well as affecting health and resilience. Qualitative analysis of a recent historical time series of images of the three mangrove study sites reveals direct losses of mangrove area from filling, such as placement of fill within the Leone mangrove, as well as activities that likely altered mangrove functions, such as development of the

Pago Pago airport runways across Pala Lagoon, dredging to create the runways, and increasing development of the Tafuna coastal plain within the Nu'uuli mangrove watershed contributing area. These activities may have reduced the lagoon water turnover rate, altered the tidal range, increased the sedimentation rate in the lagoon, and altered the sediment, nutrient, freshwater, and pollutant input levels into the mangrove.

2. Methods

2.1. Study area

American Samoa is the eastern portion of the Samoa archipelago, located in the central western Pacific (Fig. 2). Samoa is the eastern limit for indigenous mangroves in the Pacific (Ellison, 1999). There are nine mangrove wetlands in American Samoa, located on Tutuila and Aunu'u islands, with an estimated combined area of 52.3 ha (Fig. 3) (Bardi and Mann, 2004). While mangroves were once prominent features at the mouths of most freshwater streams in American Samoa, the majority of mangrove area has been filled since the early 1900s, and losses continue (Amerson et al., 1982; American Samoa Coastal Management Program 1992).

Fig. 2. Location of American Samoa, the Eastern portion of the Samoa archipelago, located between 168 and 173 W longitude and 13 and 15 S latitude.

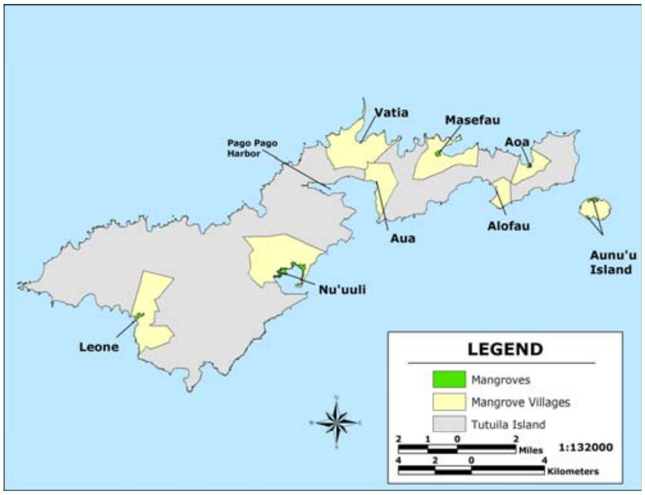


Fig. 3. Location of American Samoa's nine mangroves, including the three study sites, Leone, Nu'uuli, and Masefau mangroves, on Tutuila and Aunu'u Islands.

Three true mangrove species and several mangrove associate species are present in American Samoa's mangrove communities (Amerson et al., 1982; Bardi and Mann, 2004). American Samoa mangroves are dominated by a single tree species, *Bruguiera gymnorrhiza* (oriental mangrove), with *Rhizophora mangle* (red mangrove) found primarily along mangrove seaward margins (Amerson et al., 1982). *Xylocarpus moluccensis* (puzzle-nut tree) is rare, with only a few individual trees found at Nu'uuli and Aunu'u mangroves (Amerson et al., 1982; Bardi and Mann, 2004). The predominant soil type of American Samoa mangrove is Ngerungor Variant organic peat (U.S. Soil Conservation Service, 1984), a mixture of peat and basaltic and calcareous sand, comprised of 10-30% organic matter (Ellison, 2001). Tidal range is about 1.1 m. Mean annual rainfall is 312 to 563 cm. Mean annual temperature is 26.7 degrees C (U.S. Soil Conservation Service, 1984).

Three study sites include the three largest mangrove areas of American Samoa, located on the main island of Tutuila. The largest of these is Nu’uuli (30.69 ha), a fringing, tide-dominated mangrove (Bardi and Mann, 2004), with an approximate center at 170 42.766’ W, 14 18.844’ S. This mangrove area receives drainage from a watershed contributing area of approximately 1,760 ha. Six streams provide a surface supply of freshwater. Large portions of Nu’uuli mangrove have been filled for development since the early 1900’s (Amerson et al., 1982; American Samoa Coastal Management Program 1992). This site is representative of a Pacific high island coastal fringing mangrove with high degree of development in the contributing watershed area.

Masefau mangrove, a partially enclosed basin or interior mangrove, is about 6.38 ha (Bardi and Mann, 2004), is the second largest mangrove of American Samoa, with an approximate center at 170 38.048’ W, 14 15.421’ S. Masefau mangrove receives drainage from a watershed contributing area of approximately 362 ha. One stream passes through the site, which transitions into an estuarine inlet from the ocean. This site is representative of a Pacific high island basin mangrove in a relatively less disturbed watershed contributing area.

Leone mangrove, like Masefau, is a partially enclosed basin or interior mangrove with a stream passing through the site, which transitions into an estuarine inlet from the ocean, is about 5.76 ha (Bardi and Mann, 2004), is the third largest mangrove of American Samoa, with an approximate center at 14 20.173’ S, 170 47.132’ W. Leone mangrove receives drainage from a watershed contributing area of approximately 1,467 ha. This site has a similar hydrogeomorphic setting as Masefau but higher degree of development in its watershed.

2.2. Tide gauge data analyses

A trend in the rate of relative sea-level change for American Samoa was calculated using mean monthly relative sea-levels obtained from analysis of data from the Pago Pago, American Samoa tide gauge. Data sources, corrected for changes in local datum, are the Permanent Service for Mean Sea-level and the University of Hawaii Sea-level Center Joint Archive for Sea-Level and GLOSS/CLIVAR Research Quality Data Set databases. Linear and second order polynomial regression models are fit to the mean monthly relative sea-level data from October 1948 through May 2004, an elapsed period of 55.6 years.

The observed American Samoa mean relative sea-level rise trend is compared to the globally calculated rate of past sea-level change determined by the Intergovernmental Panel on Climate Change (IPCC) (Church et al., 2001). The global sea-level rise minimum and maximum projections through the year 2100 (Church et al., 2001) are then applied to the American Samoa observed rate of change in relative sea-level to determine a range of relative sea-level projections for American Samoa through the year 2100.

2.3. Time series analysis of mangrove seaward margins

Aerial photos showing the seaward boundary of Masefau mangrove are available from 1961, 1971, 1990, and 1994. Aerial photos showing the seaward boundary of Nu’uuli mangrove are available from 1961, 1971, 1984, 1990, and 1994. Aerial photos showing the seaward boundary of Leone mangrove are available from 1961, 1966, 1971, 1984, 1990, and 1994. Ikonos space imaging from 2001 and QuickBird space imaging from 2003-2004 are also available for the three study sites. The IKONOS and QuickBird satellite imagery have been geo-referenced to the UTM NAD83 Zone 2 South HARN projection and coordinate system. ERDAS Imagine 8.7 software was used to co-register the aerial photos to the georeferenced 2001 Ikonos satellite imagery. A minimum of twenty ground control points were used per aerial photo for co-registration. A third order polynomial model was used to co-register the aerial photos.

The mangrove seaward margins and margins of major tidal creeks for the three study sites were identified from each co-registered aerial photo and space imaging. The seaward margin was defined as the unbroken canopy edge, thus excluding opportunistic, pioneer mangrove vegetation. ArcGIS software was used to calculate the area between the seaward mangrove margin and a fixed line seaward of the mangrove for each remotely sensed image. Change in the area of open water between the seaward mangrove margin and the fixed line is caused by change in position of the mangrove seaward margin. It was not possible to accurately identify the position of the landward mangrove margins from interpretation of the remotely sensed images. The length of each study site's seaward margin was measured for each historical image using a GIS. Mean length of seaward margins and observed change in mangrove area from movement of the seaward margin are used to estimate the distance the margin moved over the observed period.

2.4. Significance of correlation between changes in position of seaward mangrove margins and relative sea-level

Linear regression analysis was conducted to determine if there is a significant correlation between the change in mangrove area caused by movement of the seaward mangrove margin and change in relative sea-level for the three study sites.

2.5. Year 2100 mangrove margins

2.5.1. Seaward margin

Projections for the retreat of the seaward mangrove margin are made through the year 2100 using information on observed mean rate of change in shoreline position and projected relative sea-level rise scenarios.

For a mangrove site where there is a significant correlation between changes in relative sea-level and position of the seaward margin, a range of projections for the year 2100 seaward mangrove margin position is made by: (i) extrapolating from the observed rate of change in shoreline position into the future, (ii) and (iii) applying the IPCC lower and upper global sea-level projections (Church et al., 2001) to American Samoa, and (iv) extrapolating from a linear regression model fit to the observed mean monthly relative sea-levels from a tide gauge at Pago Pago, American Samoa. IPCC models A2 and B1 provide the minimum projections for the change in global mean sea-level, and models A1T and A1FI provide the maximum projections (Appendix II.5, Table II.5.1, Church et al., 2001).

The IPCC's best estimate of global average sea-level change during the 20th century, based mainly on tide gauge observations, is 1.5 ± 0.5 mm a^{-1} (Church et al., 2001; Cazenave and Nerem, 2004), while Church et al. (2004a) provide an estimate of 1.8 +/- 0.3 mm a^{-1} from 1950 – 2000. The observed American Samoa rate of relative sea-level change during the 20th century (October 1948 through December 2000) of 1.77 mm a^{-1} (1.41 – 2.12 95% CI, N = 581) over the observed 51.83 years (based on fitting a linear regression model to mean monthly relative sea-levels) is within the IPCC's (Church et al., 2001) and Church et al.'s (2004a) uncertainties for the rate of change of global average sea-level, justifying use of the IPCC range of projections for change in global sea-level to American Samoa.

When there is a significant correlation between the change in relative sea-level and change in mangrove area resulting from the landward transgression of the seaward mangrove margin for a mangrove site, we infer that the ratio of change in mangrove area to change in relative sea-level over an observed historical time period will be equal to the ratio of the future change in mangrove area to projected change in relative sea-level. Using a simple hypothetical example to demonstrate this method using the IPCC high projection, the following equation is used:

$$\frac{25{,}000\text{ m}^2\text{ observed change mangrove area 16 Sept 1961 – 15 Dec. 2003}}{0.083\text{ m change relative sea-level 16 Sept. 1961 – 15 Dec. 2003}} =$$

$$\frac{X\text{ m}^2\text{ change mangrove area 15 Dec. 2003 – 15 June 2100}}{0.82\text{ m projected change relative sea-level 15 Dec. 2003 – 15 June 2100}}$$

Where X = 246,988 m^2, the predicted change in mangrove area resulting from the landward transgression of the seaward mangrove margin from 15 December 2003 to 15 June 2100 using the IPCC upper projection. Similar calculations could be made using the IPCC low projection for global sea-level rise through 2100.

Otherwise, for a mangrove site with no significant correlation between relative sea-level and position of the seaward margin, the projection for the year 2100 seaward mangrove margin position is made by extrapolating only from the observed rate of change in shoreline position into the future.

2.5.2. Landward margin

Using the estimated change in mangrove area through the year 2100 resulting from movement of the mangrove seaward margin, and using a GIS to determine the length of the seaward margin in the most current satellite image, we determine the mean distance that the seaward mangrove margin will migrate over this time period.

The mean slope of the land immediately adjacent to the landward mangrove margins is estimated using a GIS including the delineation of 2002 landward mangrove margins (Bardi and Mann, 2004) and topography (3.048 m (10 foot) contour interval, American Samoa 1962 datum). Every 50 m along the landward mangrove margin the distance between the landward mangrove margin and 3.048 m contour is measured. We estimate that the 2002 landward mangrove margins are located at 0.62 m above the 1962 mean sea-level. Mangroves are generally located between the level of mean high water spring tides (just above the high tide line) and mean sea-level, the upper half of the tidal range (Ellison, 2001 and 2004). In American Samoa the tidal range is 1.07 m, placing the delineated landward mangrove margin roughly at 0.54 m above mean sea-level in 2002, when the mangrove boundary was mapped. Using the observed relative sea-level rise rate of 1.97 mm a^{-1}, the 2002 mangrove landward margin was 0.62 m above the 1962 mean sea-level, the height datum used in the topographic map. The average of the slopes of the points 50 m along the landward mangrove margin is then determined.

Alternative scenarios for projected relative sea-level rise are then used to estimate the distance that the landward mangrove margin will transgress landward. A GIS is used, including layers for buildings, roads, 2002 landward mangrove margin, and space imaging, to identify the location of any buildings, seawalls, and roads that present obstacles to mangrove landward migration through the upper projection for landward transgression of the landward mangrove margin. This information is incorporated into the calculation of predictions of the year 2100 position of the landward mangrove margin.

Main assumptions in conducting this analysis are that the landward mangrove margin is actually located at just above the mean high tide line, and has not been altered by human activities such as filling and placement of seawalls; the elevation of the mangrove surface at the mangrove landward margin is not changing (change in elevation from sediment accretion or erosion and subsurface processes, such as organic matter decomposition, sediment compaction, fluctuations in sediment water storage and water table levels, and root production balance exactly), so that the change in sea-level relative to the mangrove surface is 1.97 mm a^{-1}; the sediment composition of the upland habitat where the mangrove might migrate is suitable for mangrove establishment; and that there will be no new obstacles to landward migration of the landward mangrove margins between now and the year 2100.

3. Results

3.1. Tide gauge analyses

Fig. 4 presents the mean monthly relative sea-level from October 1948 through May 2004 for Pago Pago, American Samoa. A linear regression model fit to the mean monthly sea-levels indicates a mean relative sea-level rise trend of 1.97 mm a^{-1} (1.650 - 2.285 95% CI, N = 619) over the observed 54.67 years. Based on the linear regression model (which does not include an acceleration term), mean sea-level in American Samoa will rise 189 mm between 2004 and 2100.

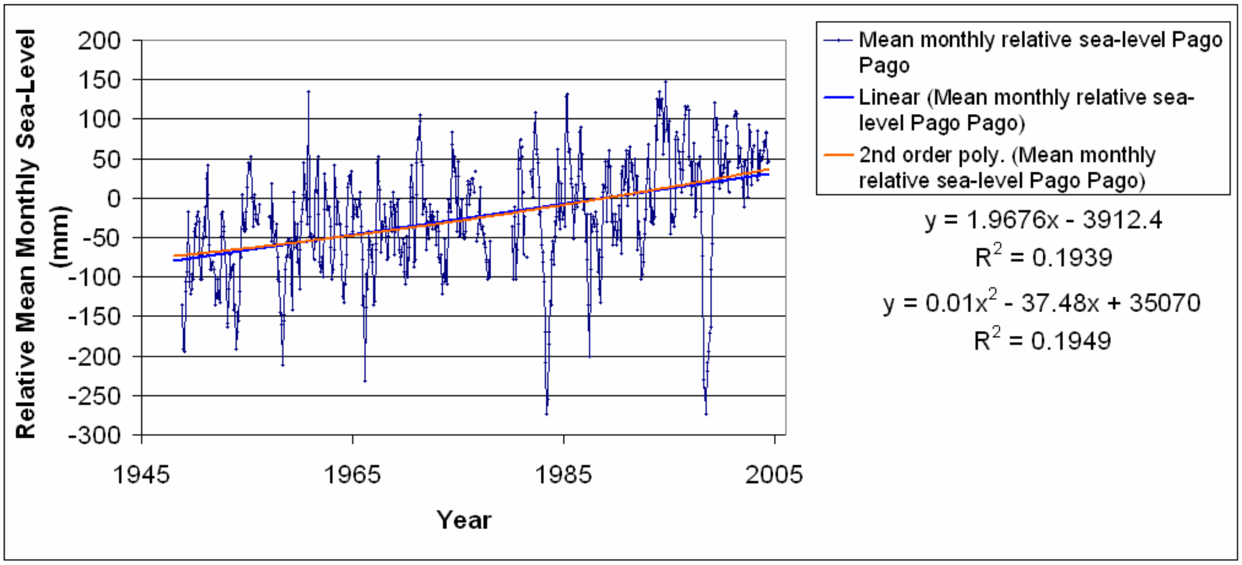


Fig. 4. Mean monthly relative sea-level from a tide gauge located in Pago Pago harbor, American Samoa, from October 1948 – May 2004. Gaps appear in the data plots where there were not enough data to produce a reliable monthly mean. Linear and second order polynomial regression models are fit to the data. The relative sea-level 0 mm mark is an arbitrary benchmark.

Fig. 5 shows the IPCC projections for American Samoa range between 92 and 859 mm rise in relative sea-level from 1990 to 2100, and a rise of between 64 mm and 831 mm between 2004 and 2100 (Church et al., 2001). The second order polynomial model of the mean monthly sea-levels has a variable slope, and shows a variable average sea-level trend, where the x term is -37.48 mm a^{-1} (-126.4 – 51.4 95% CI). Mean monthly relative sea-level data, calculated by averaging hourly sea-levels by month, adequately removes cyclical tidal constituents. Removal of El Nino Southern Oscillation phase signals may result in the data fitting better to the regression models, better estimate for the trend in change in relative sea-level, and smaller error interval around the point estimate. However, if El Nino Southern Oscillation events are undergoing a trend in frequency and intensity, then these data should remain in the data series for assessment for trend in mean sea-level.

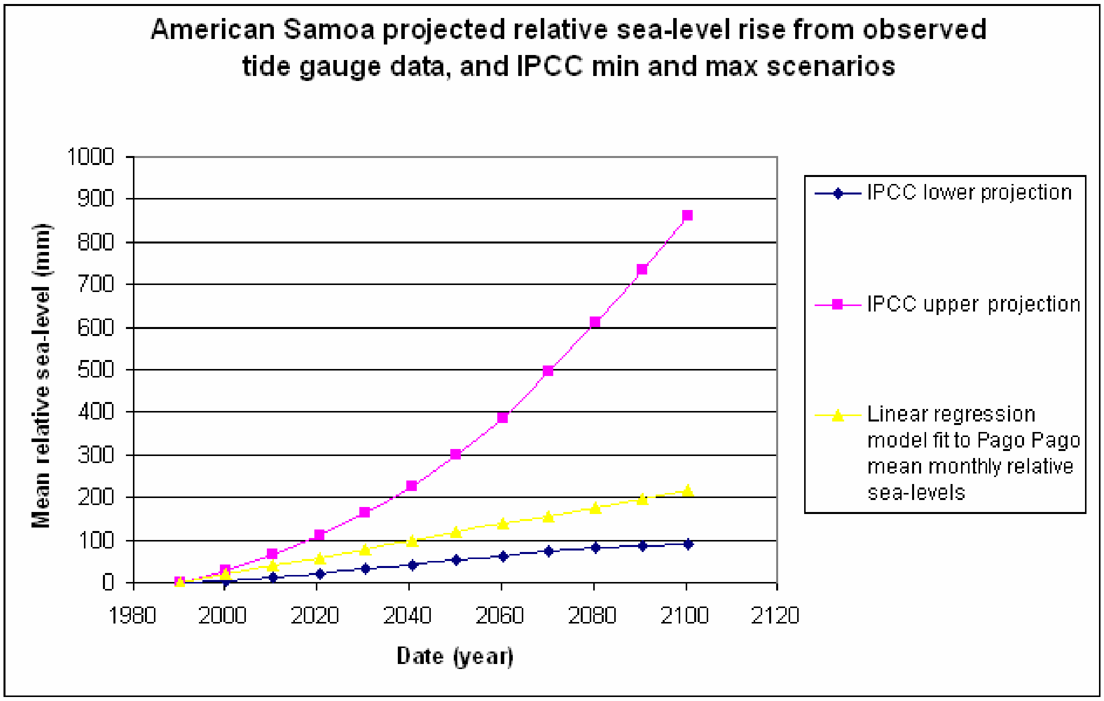


Fig. 5. Plot of a linear regression model fit to the mean monthly relative sea-level tide gauge data for Pago Pago, American Samoa from 1948-2004 (y = 1.97(x) – 3921.3) plotted from the middle of 1990 through the middle of 2100, where the relative sea-level 0 mm benchmark is set to the middle of 1990, and plots of the IPCC upper and lower projections for the change in mean global sea-level from 1990 through 2100 (Church et al., 2001).

3.2. Time series analysis of mangrove seaward margins

Figs. 6-8 present the observed change in position of the mangrove seaward margins. Table 1 presents the change in mangrove area resulting from the movement of the seaward mangrove margin and change in relative sea-level over the four decades for the three mangrove study sites.

Table 1. Change in mangrove area resulting from movement of the seaward mangrove margin and change in relative sea-level, for Masefau, Nu'uuli, and Leone mangroves, American Samoa from 1961-2003/4.

Date of Image (month/day/ year)	**Cumulative change in mangrove area from movement of the seaward mangrove margin (m^2)**	**Cumulative change in relative mean sea-level (mm)** [a]
Masefau		
9/16/1961	0	0
7/11/1971	-441.37	19.34
9/18/1990	-781.22	14.73
6/30/1994	-1210.47	64.59
9/15/2001	-1901.97	78.80
11/9/2003	-2203.43	83.03

Nu'uuli		
9/16/1961	0	0
7/11/1971	-8,950.91	19.34
11/7/1984	-13,818.43	45.60
8/27/1990	-14,140.16	56.64
6/17/1994	-18,312.63	64.52
9/15/2001	-19,719.88	78.80
12/15/2003	-23,160.22	83.23
Leone		
9/16/1961	0	0
3/31/1966	937.40	8.94
8/17/1971	984.63	19.54
11/7/1984	-2,150.33	45.60
9/27/1990	-3,466.10	57.19
6/30/1994	-53.01	64.59
9/15/2001	652.65	78.80
5/20/2004	198.67	84.07

[a] Based on a 1.97 mm a^{-1} relative sea-level rise trend from fitting a linear regression model to mean monthly relative sea-levels observed from the Pago Pago, American Samoa tide gauge, October 1948 – May 2004.

The trend in change in Masefau's mangrove area resulting from movement of the seaward mangrove margin, based on linear regression analysis, is 46.98 $m^2 a^{-1}$ (23.4 - 70.6 95% CI, R^2 = 0.88). Nu'uuli's trend is 483.85 $m^2 a^{-1}$ (364.15 – 603.55 95% CI, R^2 = 0.96). Leone's trend is 20.34 $m^2 a^{-1}$ (-75.85 – 116.53 95% CI, R^2 = 0.043).

The Masefau mangrove seaward margin migrated landward about 3.0 m over the observed 42.1-year period, a rate of 63.9 mm a^{-1}. The Leone mangrove seaward margin migrated landward about 9.3 m over the observed 42.7-year period, a rate of 24.5 mm a^{-1}. The Nu'uuli mangrove seaward margin migrated landward about 138.1 m over the observed 42.2-year period, a rate of 72.3 mm a^{-1}.

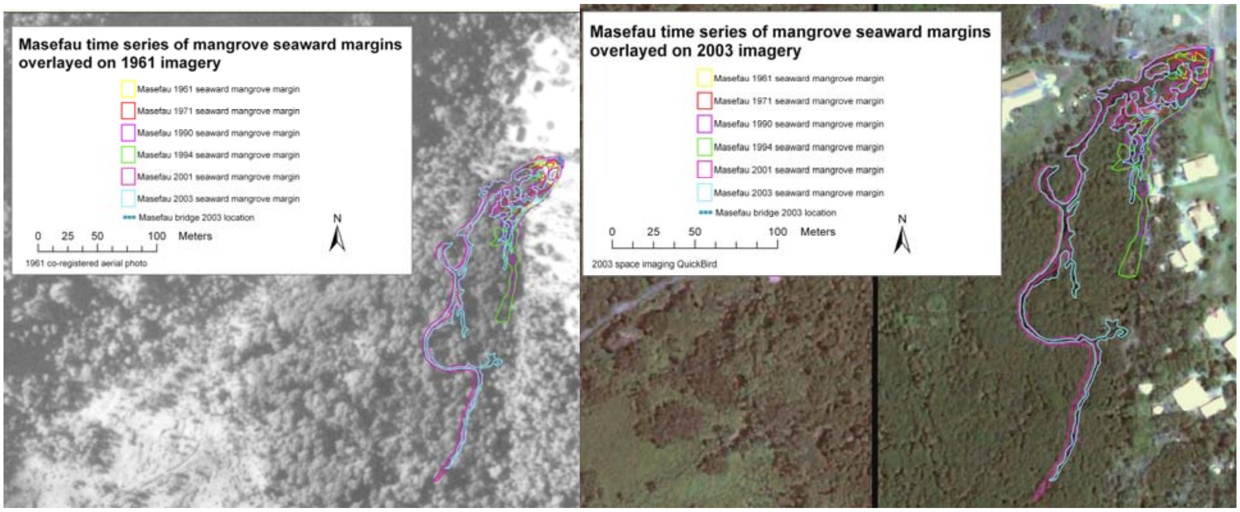


Fig. 6. Time series of Masefau mangrove seaward margin at six points in time from 1961 – 2003 overlayed on a 1961 co-registered aerial photo and 2003 QuickBird space imaging.

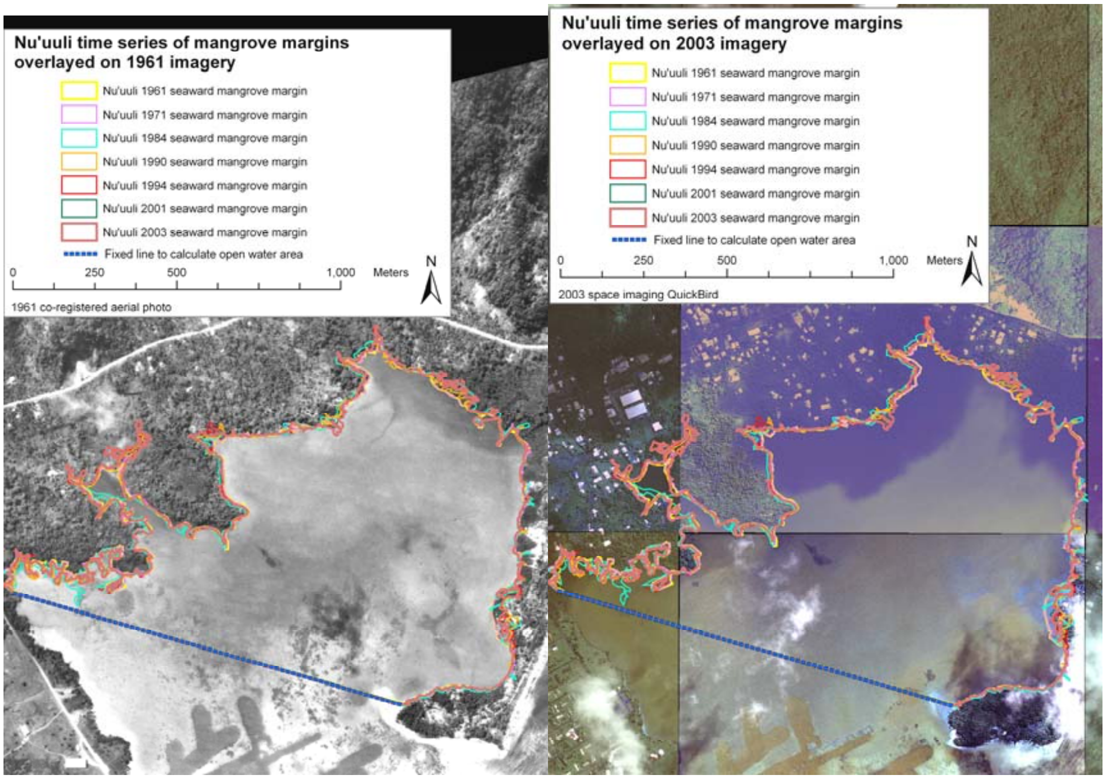


Fig. 7. Time series of Nu'uuli mangrove seaward margin at seven points in time from 1961 – 2003 overlayed on a 1961 co-registered aerial photo and 2003 QuickBird space imaging.

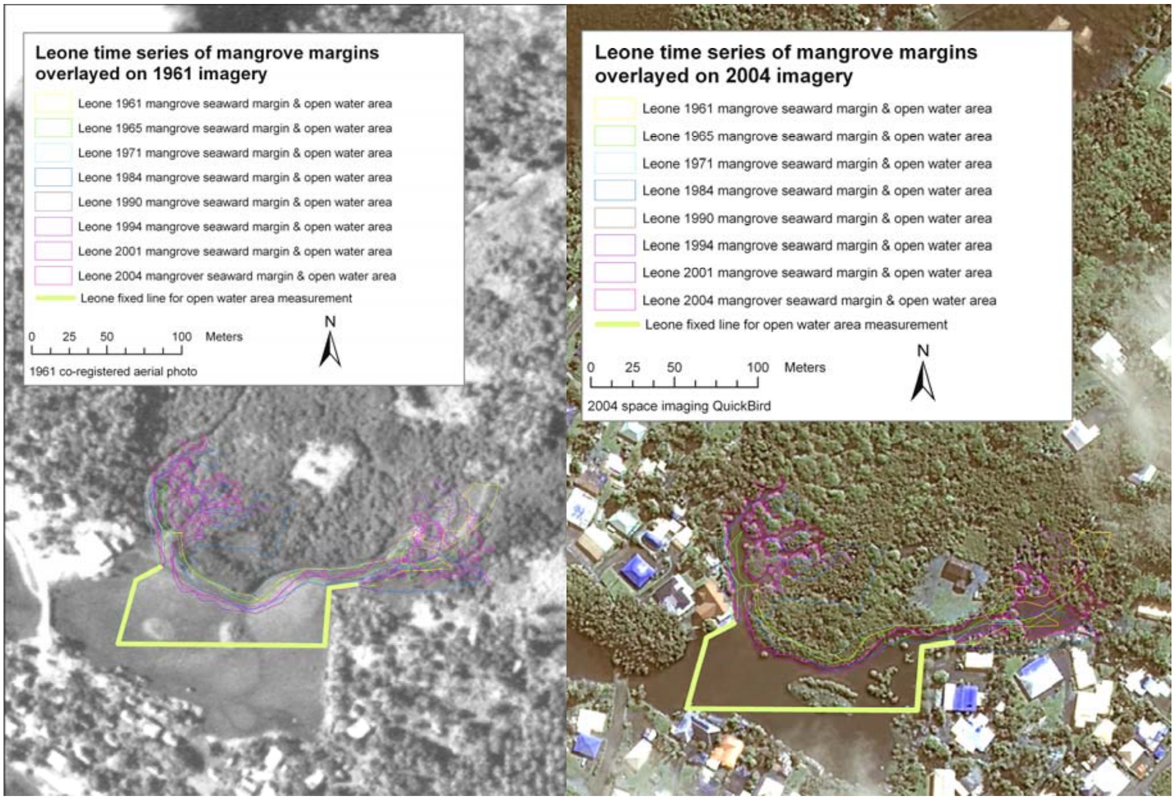


Fig. 8. Time series of Leone mangrove seaward margin at eight points in time from 1961 – 2004 overlayed on a 1961 co-registered aerial photo and 2004 QuickBird space imaging.

3.3. Significance of correlation between change in relative sea-level and change in position of mangrove seaward margins

For Masefau mangrove, there is a highly significant correlation between the change in mangrove area due to migration of the mangrove seaward margin and change in relative sea-level over the observed 42.1-year period, based on linear regression analysis ($P<0.01$, $r = 0.956$, $R^2 = 0.913$, $N = 6$). Nu'uuli mangrove also demonstrated a highly significant correlation over the observed 42.2-year period ($P<0.01$, $r = 0.978$, $R^2 = 0.957$, $N = 7$). For Leone mangrove, the correlation over the observed 42.7-year period is not significant ($P>0.05$, $r = 0.207$, $R^2 = 0.043$, $N = 8$).

3.4. Mangrove margin changes through year 2100

Table 2 presents predicted reductions in area of the three mangrove study sites as a result of projected landward migration of the seaward mangrove margin through the middle of the year 2100, the rate of change in area, and the rate of landward transgression of the seaward landward margin. For Masefau and Nu'uuli, sites shown to have highly significant correlations between change in mangrove area resulting from movement of the seaward mangrove margin and observed change in relative sea-level, the (i) IPCC's lower and (ii) upper projections for change in sea-level through the year 2100, (iii) extrapolation through the year 2100 of the linear regression model fit to the observed mean monthly relative sea-levels from the Pago Pago tide gauge, and (iv) extrapolation from the observed recent historical erosion rate are used to predict a range of year 2100 seaward margin positions. For Leone, where there was no significant correlation between change in mangrove area resulting from migration of the seaward mangrove margin and change in relative sea-level, the observed recent historical erosion rate of the mangrove seaward margin is extrapolated through the year 2100.

Table 2. Scenarios for change in mangrove area resulting from migration of the seaward mangrove margin, and rate of movement of the seaward mangrove margin, through the middle of 2100.

Mangrove site	**Reduced mangrove area by mid-2100 (m^2)[a]**	**Annual rate of reduction in mangrove area ($m^2 a^{-1}$)**	**Rate of landward migration of seaward mangrove margin ($mm a^{-1}$)[b]**
Leone[c]	1,955	20	19
Masefau[d]			
Lower projection IPCC	2,203	29	16
Extrapolate observed historical erosion rate	4,540 6,451	47 67	34 48
Extrapolate using observed trend in relative sea-level from American Samoa tide gauge	21,663	224	161
Upper projection IPCC			
Nu'uuli[d]			
Lower projection IPCC	23,160	240	30
Extrapolate observed	46,729	484	64

historical erosion rate	53,073	550	70
Extrapolate using observed trend in relative sea-level from American Samoa tide gauge	228,812	2,370	310
Upper projection IPCC			

[a] Change in mangrove area from 20 May 2004, 9 November 2003, and 15 December 2003 for Leone, Masefau, and Nu'uuli mangrove study sites, respectively, through the middle of 2100.

[b] Assumes an equal rate of erosion along the seaward mangrove margin. Uses the 2003 length of the Masefau and Nu'uuli mangrove seaward margins of 1,390 m and 7,568 m, respectively, and the 2004 length of the Leone mangrove seaward margin of 1,081 m.

[c] Extrapolation from observed erosion rate. The correlation between change in mangrove area from movement of the seaward margin and change in relative sea-level was not significant for this study site.

[d] Extrapolation employing three scenarios for projected relative sea-level rise, as well as directly extrapolating the observed historical erosion rate. There was a highly significant correlation between change in mangrove area due to movement of the seaward margin and change in relative sea-level for these two study sites.

Table 3 presents predicted increases in mangrove area through the year 2100 resulting from the landward migration of the landward margins of the three study sites.

The slope of the upland adjacent to the landward mangrove margin at Leone mangrove is a mean of 0.06 (standard deviation of the mean = 0.02, N = 25). Approximately 23.4% of the Leone landward mangrove margin is obstructed from natural landward transgression. The slope of the upland adjacent to the landward mangrove margin at Masefau mangrove is a mean of 0.27 (standard deviation of the mean = 0.06, N = 25). Approximately 16.5% of the Masefau landward mangrove margin is obstructed from natural landward transgression. The slope of the upland adjacent to the landward mangrove margin at Nu'uuli mangrove is a mean of 0.077 (standard deviation of the mean = 0.02, N = 128). Approximately 68% of the Nu'uuli landward mangrove margin is obstructed from natural landward transgression.

Table 3. Scenarios for change in mangrove area resulting from migration of the landward mangrove margin, and rate of movement of the landward mangrove margin, through the middle of 2100.

Mangrove site	**Increased mangrove area by mid-2100 (m^2)[a]**	**Annual rate of increase in mangrove area (m^2 a^{-1})**	**Rate of landward migration of landward mangrove margin (mm a^{-1})**
Leone			
Lower projection IPCC	1,404	14.6	15.0
Extrapolate observed trend in relative sea-level from American Samoa tide gauge	3,081 13,291	32.1 138.3	32.9 141.8
Upper projection IPCC			
Masefau			

Lower projection IPCC	326	3.4	3.2
Extrapolate observed trend in relative sea-level from American Samoa tide gauge	747	7.7	7.3
Upper projection IPCC	3,207	33.2	31.2
Nu’uuli			
Lower projection IPCC	2,218	23.0	11.2
Extrapolate observed trend in relative sea-level from American Samoa tide gauge	5,077	52.6	25.6
Upper projection IPCC	21,910	226.9	110.4

[a] Change in mangrove area from 20 May 2004, 9 November 2003, and 15 December 2003 for Leone, Masefau, and Nu’uuli mangrove study sites, respectively, through the middle of 2100. Uses the 2003 length of the Masefau and Nu’uuli mangrove landward margins of 1,272 m and 6,423 m, respectively, and the 2004 length of the Leone mangrove landward margin of 1,273 m, reduced by the length of the margin that is obstructed from migrating landward. Assumes that the elevation of the mangrove surfaces at their landward margins is not changing over time (change in elevation from sedimentation and subsurface processes, such as root production, decomposition, compaction, and dewatering, balance exactly), so that the change in sea-level relative to the mangrove surface is 1.97 mm a^{-1}.

If the observed trend in relative sea-level over the previous 55 years continues at the same rate through the year 2100, and no new obstacles to natural mangrove migration are constructed, based on these estimated movements of the landward and seaward margins, Leone mangrove will experience a net gain in area of 1,126 m^2, while Masefau and Nu’uuli mangroves will experience a net loss in area of 5,704 m^2 and 47,996 m^2, respectively. Using the IPCC’s upper projection for sea-level rise by the year 2100, if no new obstacles to natural mangrove migration are constructed, Leone mangrove will increase in area by 11,336 m^2, while Masefau and Nu’uuli mangroves will lose 18,456 m^2 and 206,902 m^2, respectively. Where unobstructed by development, by the year 2100, the landward mangrove margins of Leone, Masefau, and Nu’uuli could migrate landward as much as 14 m, 3 m, and 11 m, respectively, under IPCC’s upper projection.

4. Discussion - Year 2100 Mangrove Margin Positions

If there were a way to reconstruct the position of the mangrove landward margins over recent decades to observe a trend in movement, as we did for the seaward mangrove margins, this would account for all forces affecting the position of the mangrove landward margin, and would provide an accurate way to predict future movement. Unfortunately, it is usually not possible to identify the landward mangrove margin with any confidence from interpretation of aerial photos or satellite imagery, as was the case for the three mangrove study sites in American Samoa.

Alternatively, we have predicted the future position of the mangrove landward margin based on (a) a current boundary delineation, (b) the mangroves’ physiographic setting (slope of the adjacent land and presence of any obstacles (e.g., roads, development, seawalls) to landward mangrove migration, and (c) projections for sea-level rise relative to the mangrove surface.

In estimating the distance that the landward mangrove margins will transgress over coming decades it is assumed that there will be no net change in elevation of the mangrove surfaces, so that the change in elevation from sediment accretion and subsurface processes, such as organic matter decomposition, sediment compaction, fluctuations in sediment water storage and water table levels, and root production, will balance exactly.

Subsurface processes can lower the elevation of a wetland's surface (Lynch et al., 1989; Donnelly and Bertness, 2001; Krauss et al., 2003; Rogers et al., 2005). Krauss et al. (2003) found that, at three mangrove sites in the Federated States of Micronesia, shallow sediment subsidence was between 4.9 and 11.2 mm a^{-1}, based on a comparison of observed vertical sediment accretion measured using a horizon marker and change in elevation of the mangrove surface measured using stakes inserted 0.7 m into the sediment. At these same sites, shallow sediment subsidence to a depth of 5.2 m has been observed to range from 2.8-16.0 mm a^{-1} (J.A. Allen and D.R. Cahoon, unpublished data, referenced in Krauss et al., 2003). Rogers et al. (2005) also found that sediment accretion rates at four mangrove sites in Australia significantly exceeded surface elevation change.

For this estimate of change in position of American Samoa mangrove landward margins over coming decades, we make the rough estimate that sediment subsidence near the landward mangrove margin is counterbalancing sediment accretion, so that the relative sea-level rise rate measured by a tide gauge in nearby Pago Pago harbor is also the mangrove relative sea-level rise rate. The observation that there has been a trend in erosion of the seaward mangrove margins over the past four decades for all three study sites supports the assumption that sea-level relative to the mangrove surface is rising at the three study sites at their seaward margins, at least for Nu'uuli and Masefau mangroves where we observed relative sea-level rise to be a significant force explaining the observed landward migration of the seaward mangrove margin.

Information on trends in the change in elevation of the mangrove surface is needed to determine how sea-level has been changing in recent decades relative to the mangrove surface, to enable future projections. The most precise method to obtain this information is to install an array of tide gauges throughout a site, but this is expensive, laborious, and a minimum of a 20-year local tide gauge record is required to obtain an accurate trend in relative sea-level (Church et al., 2004a). Measurement of ^{137}Cs and excess ^{210}Pb activity in shallow sediment cores, observing sedimentation stakes, and using soil horizon markers can provide an accurate estimate of rates of change in mangrove surface elevation over recent decades (e.g., Krauss et al., 2003), which can then be compared to the relative sea-level change rate as measured by the closest tide gauge. The measurement of radioisotope activity in mangrove sediment cores is expensive, especially if multiple cores are taken in an attempt to characterize an entire mangrove site, this method does not account for subsurface processes that affect the elevation of the mangrove surface that occur below the depth of the cores, and there are several potential sources of error, including that the sediment profile can be disturbed from bioturbation as well as abiotic processes. Alternatively, precision surveying from a benchmark to points throughout a mangrove site could provide information on trends in elevation of the mangrove surface (Cahoon et al., 2002), which could then be compared to the relative sea-level change rate from a nearby tide gauge.

Some of the observed areas of smaller polygons in co-registered aerial photos used in the analysis are within the co-registration root-mean-square (RMS) error, reducing confidence in estimates of trends in mangrove area. However, a comparison of coordinates of fixed features, such as corners of buildings, road intersections, and bridges, located around the boundaries of the mangrove sites between the co-registered aerial photos and the IKONOS imagery indicates that the error is generally small, within a few meters and in some cases as small as a few millimeters. Some error is also introduced from human error in digitizing the mangrove boundary line. Interpretation of some of the images to identify the mangrove seaward margin was difficult due in part to the poor image contrast and resolution.

5. Conclusions - Implications for Managing Mangrove Response to Relative Sea-level Rise

Reduced mangrove area and health will increase the threat to human safety and shoreline development from coastal hazards such as erosion, flooding, and storm waves and surges. Mangrove loss will also reduce coastal water quality, reduce biodiversity, eliminate fish nursery habitat, adversely affect adjacent coastal habitats (Mumby et al., 2004), and eliminate a major resource for human communities that traditionally rely on mangroves for numerous products and services (Satele, 2000; Gilman and Sauni, 2005). Management authorities, especially of small island countries and territories, are encouraged to assess shoreline response to projected relative sea-level rise and adopt appropriate policies to provide adequate lead time to minimize social disruption and cost, minimize losses of valued coastal habitats, and maximize available options. The policy adopted to manage site-based shoreline response to rising sea-level will be made as part a broader coastal planning analysis. This analysis requires balancing multiple and often conflicting objectives of allowing managers and stakeholders to sustain the provision of ecological, economic, and cultural values; address priority threats to natural ecosystem functioning; maintain ecological processes and biodiversity; achieve sustainable development; and fulfill institutional, policy, and legal needs (Gilman, 2002).

Site planning for some sections of shoreline containing mangroves will call for abandonment and adaptation to manage long-term retreat with relative sea-level rise (Mullane and Suzuki, 1997; Dixon and Sherman, 1990; Ramsar Bureau, 1998; Gilman, 2002). “Managed retreat” involves implementing land-use planning mechanisms before the effects of rising sea-level become apparent, which can be planned carefully with sufficient lead time to enable economically viable, socially acceptable, and environmentally sound management measures. Coastal development can remain in use until the eroding coastline becomes a safety hazard or begins to prevent landward migration of mangroves, at which time the development can be abandoned or moved inland. Adoption of legal tools, such as rolling easements, can help make such eventual coastal abandonment more acceptable to coastal communities (Titus, 1991). Zoning rules for building setbacks and land use for new development can be used to reserve zones behind current mangroves for future mangrove habitat. Managers can determine adequate setbacks by assessing site-specific rates for landward migration of the mangrove landward margin. Construction codes can be instituted to account for relative sea-level rise rate projections to allow for the natural inland migration of mangroves based on a desired lifetime for the coastal development (Mullane and Suzuki, 1997). Any new construction of minor coastal development structures, such as sidewalks and boardwalks, should be required to be expendable with a lifetime based on the assessed sites’ erosion rate and selected setback. Otherwise, the structure should be portable. Rules should prohibit landowners of parcels along these coasts from constructing coastal engineering structures to prevent coastal erosion and the natural inland migration of mangroves. This managed coastal retreat will allow mangroves to migrate and retain their natural functional processes, including protecting the coastline from wind and wave energy.

Employing shoreline erosion control measures can help reduce the rate of coastal erosion (Mullane and Suzuki, 1997). Use of hard engineering technology, including groins, seawalls, revetments, and bulkheads, a traditional response to coastal erosion and flooding, are likely to result in increased coastal vulnerability (Tait and Griggs, 1990; Fletcher et al., 1997; Mullane and Suzuki, 1997; Mimura and Nunn, 1998; Nurse et al., 2001). These coastal engineering structures usually can effectively halt erosion as relative sea-level rises, but often lead to the loss of the coastal system located in front of and immediately downstream in the direction of longshore sediment transport from the structure, converting the seaward coastal system into deepwater habitat (Tait and Griggs, 1990; Fletcher et al., 1997; Mullane and Suzuki, 1997). For some sites, it may be less expensive to avoid hard solutions to relative sea-level rise and instead allow coastal ecosystems to migrate inland. These ecosystems provide natural coastal protection that may be more expensive to replace with artificial structures (Mimura and Nunn, 1998; Ramsar Bureau, 1998). However, results of site planning may justify use of hard engineering technology and shoreline erosion control measures to prevent erosion for some sections of highly developed coastline adjacent to mangroves. As a result, the mangroves' natural landward migration will be prevented and the mangrove fronting the development will eventually be lost.

Management authorities are also encouraged to support rehabilitating mangroves as a means to mitigate predicted mangrove losses resulting from relative sea-level rise. Restoring areas where mangrove habitat previously existed and creating new mangrove habitat will help offset anticipated reductions in mangrove area from relative sea-level rise. Enhancing degraded mangroves by removing stresses that caused their decline will increase their resilience to climate change effects (Hansen and Biringer, 2003; Ellison, 2004).

Observations support that sea-level is rising relative to the surface of American Samoa mangroves, forcing mangrove margins to migrate landward. We employed a generalized predictive model of site-specific mangrove response to projected change in relative sea-level over temporal and spatial scales of decades and entire mangrove sites by considering physiographic settings, erosion rates of seaward margins, and sea-level change rates relative to the mangrove surface.

Based on general estimates of mangrove sedimentation rates (Ellison and Stoddart, 1991), and the possibility that subsurface sediment subsidence from decomposition, compaction, and dewatering may result in substantially higher rates of sea-level rise relative to the mangrove surface (Krauss et al., 2003), island mangroves could experience serious problems due to rising sea-level, and low island mangroves may already be under stress. Based on results from the assessment in American Samoa, in areas where sea-level is rising relative to the elevation of the mangrove surface, we can expect reductions in mangrove area and concomitant increased risk to coastal development from coastal hazards.

Relative to other Pacific island countries and territories, American Samoa possesses abundant technical resources that enabled this comprehensive assessment to predict mangrove response to relative sea-level rise (Gilman et al., In Press). Disseminating lessons learnt from this study and instituting programs to transfer technical skills and share resources will augment the region's capacity to manage coastal ecosystems' response to projected relative sea-level rise.

Projections are available over coming decades for rising sea-level and changes in climate and weather (Church et al., 2001). These changes are expected to alter the position, area, structure, species composition, and health of most coastal communities, including mangroves. Establishing mangrove baselines and monitoring these gradual changes to coastal habitats through regional networks using standardized techniques will enable the separation of site-based influences from global changes to provide a better understanding of the response of coastal habitats to global climate and sea-level change, and alternatives for mitigating adverse effects (Ellison, 2000; Nurse et al., 2001). The monitoring network, while designed to distinguish climate change effects on mangroves, would also therefore show local effects, providing coastal managers with information to abate these sources of degradation. Establishing a regional wetland monitoring network for the Pacific Islands region has been proposed in the *Action Strategy for Nature Conservation in the Pacific Islands Region* (South Pacific Regional Environment Programme, 1999a), and the *Regional Wetlands Action Plan for the Pacific Islands* (South Pacific Regional Environment Programme, 1999b).

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Coastal Wetland Elevation Trends in Southeast Australia

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Abstract

Situated within narrow elevation gradients, coastal saltmarsh is vulnerable to moderate rates of sea-level rise. Encroachment of saltmarsh by mangrove, documented for many estuaries of Southeastern Australia, has been postulated as evidence of the effect of relative sea-level rise over the historic timeperiod. In a large-scale experiment to test this hypothesis, sedimentation and surface elevation trends were studied in mangrove and saltmarsh wetlands in Southeastern Australia. A total of 81 surface elevation tables, each associated with feldspar marker horizons, were deployed in 12 wetlands across 7 estuaries, and monitored for three years. Saltmarsh and mangrove vegetation distribution were mapped for the same estuaries, and elevation characteristics of the wetlands were modeled. A positive relationship was demonstrated between saltmarsh subsidence and mangrove encroachment into saltmarsh, and between the rate of mangrove upslope migration and relative sea-level rise. The result suggests that saltmarshes vary in their capacity of respond to sea-level rise due to local factors such as groundwater flow, sedimentation and below-ground productivity.

1. Introduction

The prospect of accelerated sea-level rise has focused recent scientific attention on the ecological services provided by coastal wetland ecosystems, including coastal saltmarsh. Saltmarshes in Australia occupy an inter-tidal niche between mangrove and the upper limits of spring tide inundation. Recent research has demonstrated the significance of coastal saltmarsh to estuarine fish (Mazumder *et al*. 2005), with high numbers of many species visiting flooded saltmarsh during the spring tide. Mazumder *et al.* (2006) demonstrated a direct trophic link between itinerant fish and zooplankton produced in the saltmarsh, particularly crab larvae.

Saltmarsh also provides a unique habitat for many terrestrial invertebrates. Insectivorous bats utilise saltmarsh as a feeding habitat (Laegdsgaard *et al.* 2004). Migratory shorebirds use saltmarsh as a roosting habitat (Lawler 1996, Saintilan 2003), particularly at night (J. Spencer, unpublished data).

Many of these ecological values are threatened by sea-level rise. Given time, it might be supposed that saltmarsh would transgress landward, occupying low-lying elevations accessed by tides under elevated sea-level conditions. However, barriers to landward transgression, either natural or artificial, may prevent this, and the encroachment of saltmarsh by mangrove would yield a net decline in this resource. Mangrove does not substitute for all of the values provided by saltmarsh, particularly in their roosting function for shorebirds. Many species of shorebird actively avoid mangroves and other tree-form vegetation, possibly to avoid predation by raptors (Lawler 1996).

Planning for sea-level change is therefore an issue with direct consequences for the management of wildlife. Australia has obligations under the Ramsar convention and international agreements (JAMBA and CAMBA) to protect critical wetland habitat for shorebirds. While not being able to control the diffuse source of sea-level rise, planning decisions must be made which accommodate, as far as possible, the new landscape imposed by sea-level rise. This involves an identification of where coastal wetlands might be distributed under a range of scenarios.

To model the predicted distribution of coastal wetlands in 50 or 100 years time, a sound knowledge of the elevation of coastal lowlands needs to be supplemented with an understanding of processes which contribute to the elevation trajectories. The purpose of this paper is to describe some of these processes derived from measurements taken in a range of Southeastern Australian settings over the past 5 years.

2. Mangrove and Saltmarsh Trends

Some indication of the degree of change possible under future scenarios can be gauged by the dynamics of coastal wetlands over the previous five decades. Nearly all aerial photograph based surveys of mangrove and saltmarsh distribution in Southeastern Australia have demonstrated a consistent trend of saltmarsh decline and mangrove increase since the earliest available air photographs (Saintilan and Williams 1999, 2000). The median rate of decline of saltmarsh has been in the vicinity of 30%. Wilton (2002) demonstrated that the concurrent decline of saltmarsh and increase in mangrove was primarily due to the replacement of saltmarsh by mangrove as mangroves have encroached landward. There has been no loss of mangrove at the seaward edge, and in many cases mangroves have prograded into estuaries and along estuarine foreshores. Table 1 is a recent compilation of mangrove proliferation for the region.

Table 1. Mangrove percentage increase in the estuaries of Southeastern Australia and New Zealand.

LOCATION	Mangrove increase (percent)	Period	Source
Queensland			
Johnstone River	15	1943-1991	Duke 1995
Hinchinbrook Channel	6	1943-1991	Duke 1995
Coolangatta to Caloundra	-8	1974-1987	Hyland and Butler 1988
Oyster Point	119	1944-1983	McTainsh *et al.* 1988
Moreton Bay	10	1944-1983	Morton 1994
New South Wales			
Tweed River	86	1930-1994	Saintilan 1998
Hunter estuary (overall)	31	1954-1994	Williams *et al.* 1999
Couranga Point, Hawkesbury	30	1954-1994	Saintilan and Hashimoto
Berowra Creek, Hawkebury	30	1941-1994	Williams and Watford 1997b
Careel Bay	551	1940-1996	Wilton 2001
Homebush Bay	65	1930-2000	Rogers and Saintilan 2001
Port Jackson/Parramatta R.	-19	1930-1985	Thorogood 1985
Kurnell Peninsula Botany Bay	33	1956-1996	Evans and Williams 2001
Towra Point, Botany Bay	36	1942-1997	Mitchell and Adam 1989
Minnamurra River	70	1938-1997	Chafer 1998
Currambene Creek, Jervis Bay	32	1949-1993	Saintilan and Wilton 2001
Cararma Inlet, Jervis Bay	15	1949-1993	Saintilan and Wilton 2001
Moruya River	43	1949-1999	Phillips 2001
Merimbula River	122	1948-1994	Meehan 1997
Pambula River	84	1948-1994	Meehan 1997
Victoria			
Kooweerup, Westernport Bay	60	1940-1999	Rogers and Saintilan 2001
Rhyll, Westernport Bay	20	1939-1999	Rogers and Saintilan 2001
French Is. Westernport Bay	2	1967-1999	Rogers and Saintilan 2001
Quail Is. Westernport Bay	32	1973-1999	Rogers and Saintilan 2001
South Australia			
North Arm Creek	20	1979-1993	Coleman 1998
Swan Alley	189	1935-1979	Burton 1982
River Light	117	1949-1979	Burton 1982
New Zealand			
Rangaanu Harbour	33	1944-1981	Shaw and Maingay 1990
Whangarei Harbour	20	1942-1966	Smith and McNaught 1976
Mangemangeroa estuary	54	1955-1997	Craggs et al 2001
Waikopua estuary	72	1955-2000	Craggs et al 2001
Puhinui Ck Manukau Harbour	161	1939-1996	Morrisey et al. 2003
Ohiwa	440	1945-1992	Park 2001
Tauranga	220	1943-1991	Park 2001

3. Eustatic Sea-level Trends in Southeastern Australia

A *prima facie* case can be made relating mangrove transgression to sea-level rise over the period. Figure 1 shows the sea-level trend for Fort Denison, Sydney Harbour, for the period 1915-2000. An increase in sea-level is evident, particularly for the period 1940-1970, representing a rise of approximately 7cm over the period. Given that the saltmarsh occupies elevations between mean high water and mean high water springs (a vertical range of approximately 30cm), the proportionate rise in sea-level is close to the proportion of saltmarsh lost over the period.

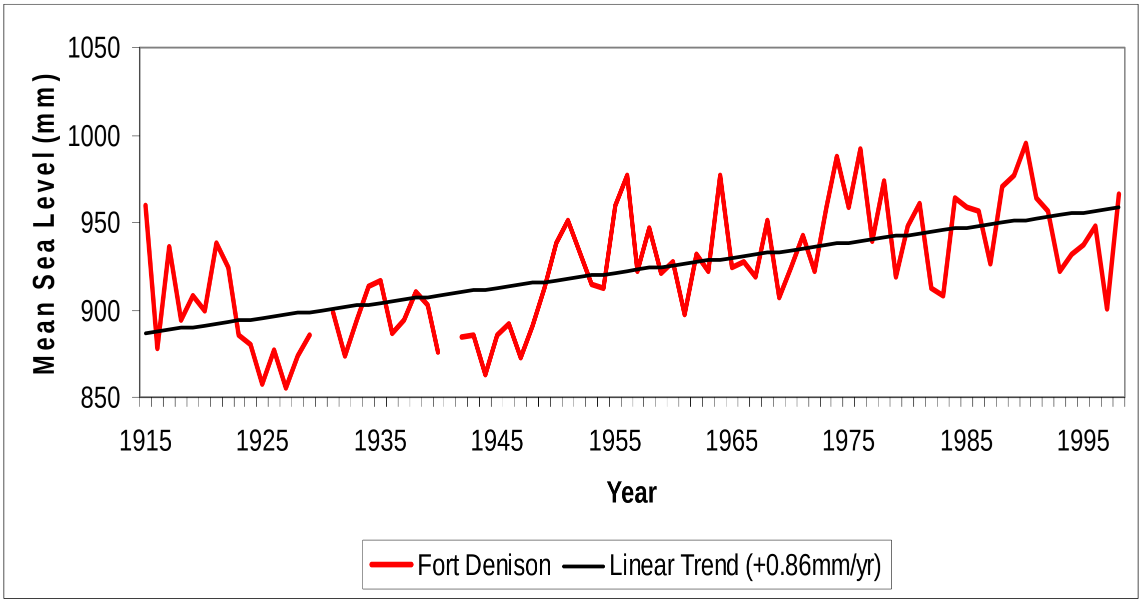

Fig. 1. Sea-level curve for Fort Denison, Sydney Harbour

There are obvious limitations to such a coarse approach. Firstly, a degree of variation exists between sites in the proportion of saltmarsh lost to mangrove. Secondly, there is no simple translation between eustatic sea-level trends and relative sea-level, because of the number of factors influencing surface elevation which also relate to sea-level , including sedimentation (inundation frequency and duration), above and below-ground plant productivity, and groundwater (Figure 2). To understand the relationship between surface elevation and sea-level trends, surface elevation must be directly measured.

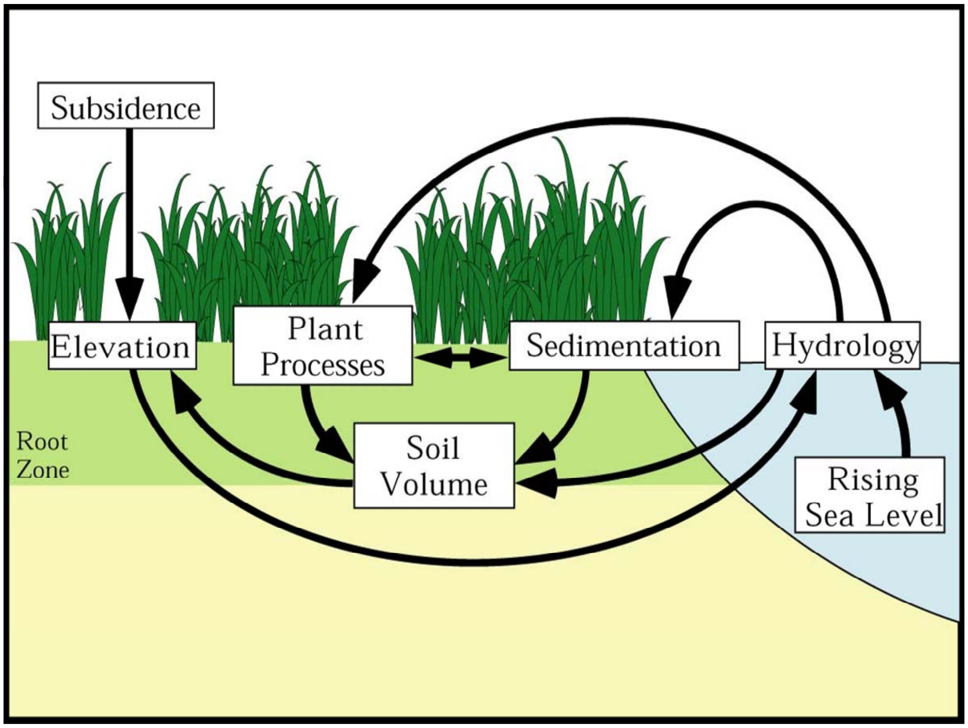

Fig. 2. Processes influencing surface elevation in an intertidal marsh (courtesy of Don Cahoon and used with permission).

4. Study Sites

Study sites were selected on the basis of four criteria (Table 2). Firstly, since the observed trend of mangrove encroachment of saltmarsh is largely limited to Southeastern Australia, sites were selected from a number of regions throughout temperate Southeastern Australia. Secondly, sites were included from a number of geomorphic settings, as described by Roy *et al.* (2001). Sites were also chosen on the basis of the degree of interest and involvement of local management agencies, as it was anticipated that this research would provide useful information relevant to the management of mangrove and saltmarsh communities. Finally, where possible, sites of international, national or state significance have been selected. For this reason, study sites include a Ramsar wetland (Kooragang Island) and are located within Marine Parks, National Parks, Nature Parks or State Environmental Planning Policy 14 Coastal wetlands under the NSW Environmental Planning and Assessment Act (1979) (Figure 3).

Table 2: Study sites, their geomorphic setting and significance. * From Roy *et al.* 2001.

Region	**Site**	**Geomorphic Setting* (group/type)**	**Significance**
North NSW	Ukerebagh Is., Tweed R.	Barrier Estuary (III/5)	SEPP 14
Central NSW	Kooragang Is., Hunter R.	Barrier Estuary (III/5)	RAMSAR, SEPP 14
Sydney	Berowra Cr., Hawkesbury R.	Drowned River Valley (II/3)	
	Marramarra Cr., Hawkesbury R.	Drowned River Valley (II/3)	SOPA
	Homebush Bay, Parramatta	Drowned River Valley	

	R.	(II/3)	
Southern NSW	Minnamurra R.	Barrier Estuary (III/5)	SEPP 14
	Cararma Cr., Jervis Bay	Barrier Estuary (III/5)	Marine Park, SEPP 14
	Currambene Cr., Jervis Bay	Barrier Estuary (III/5)	Marine Park, SEPP 14
Victoria	French Is., Western Port Bay	Coastal Embayment (I/1)	Marine Park
	Kooweerup, Western Port Bay	Coastal Embayment (I/1)	Nature Reserve
	Quail Is., Western Port Bay	Coastal Embayment (I/1)	Nature Park
	Rhyll, Western Port Bay	Coastal Embayment (I/1)	

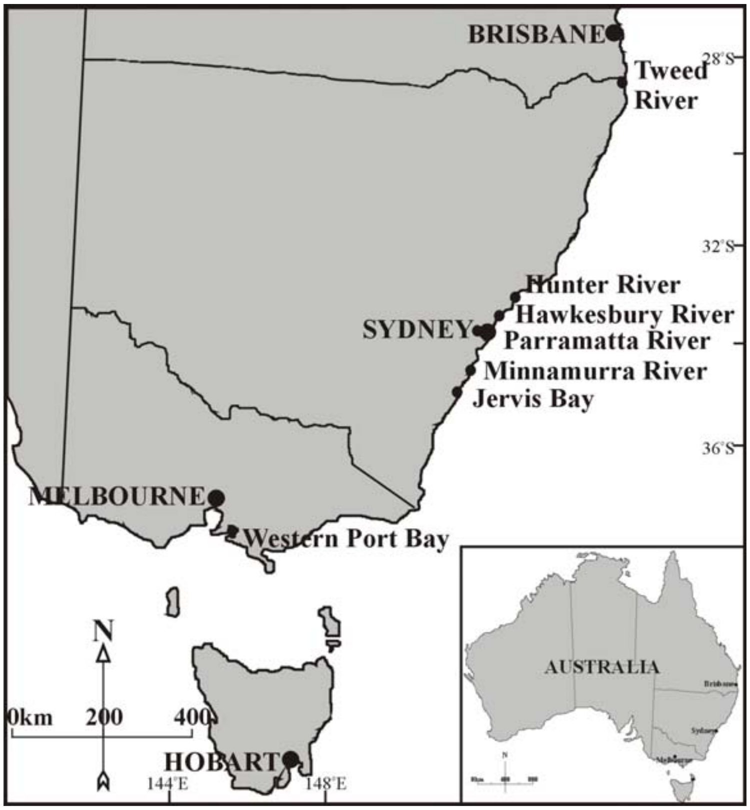

Fig. 3. Study site locations throughout Southeastern Australia.

5. Measuring Marsh Surface Elevation

Surface Elevation Tables (SET version IV, Cahoon *et al*. 2002a) were installed at study sites in order to determine surface elevation trends. The SET reportedly has a confidence interval of 1.4 mm (Cahoon *et al.* 2002a). The version IV SET utilises a benchmark pole driven 4-6 metres into the marsh. A detachable arm extends parallel to the marsh, with sliding vertical pins used to measure changes in the marsh surface elevation.

SET stations were established according to two layout strategies; either in replicated sets of three within mangrove, mixed mangrove and saltmarsh and saltmarsh zones where mangrove encroachment had given rise to a wide ecotone (Kooragang Island, Currambene Creek, and Homebush Bay) or within both mangrove and saltmarsh zones (Ukerebagh Island, Berowra Creek, Marramarra Creek Minamurra River, Cararma Inlet, French Island, Rhyll, Kooweerup and Quail Island). Due to the potential influence of dilation on surface elevation, measures were taken at low tide. Surface elevation measurements were taken at least once a year from 2000 to 2003.

Vertical accretion was also measured at each SET station. At the time of SET installation, three 0.25 m^2 feldspar marker horizons were established on the marsh surface around the perimeter of each SET station. These horizons served as markers against which vertical accretion was measured. Mini cores were taken from each feldspar marker horizon at the time of surface elevation measurements. The distance from the marsh surface to the marker horizon was measured in order to establish the vertical thickness of sediment accreted.

Elevation and vertical accretion trends were established and rates of surface elevation change and vertical accretion were estimated for mangrove and saltmarsh zones or mangrove, mixed and saltmarsh zones at each study site. Randomised block design analysis of variance was used to determine whether surface elevation change and vertical accretion varied consistently within sites and between zones within sites.

To examine the influence of groundwater height on marsh surface elevation, marsh surface elevation measures were taken in conjunction with measures of groundwater depth at five SET stations at Homebush Bay, one in the saltmarsh zone, one in the mixed zone, and 3 in the mangrove zone. Measurements were taken on 2 February 2004, 16 February 2004, 1 March 2004, 29 March 2004 and 31 May 2004.

To measure groundwater depth, perforated plastic pipes were inserted vertically into the marsh surface at approximately the same depth as SET aluminium poles. The groundwater height was then determined at the time of SET measurement by lowering a weighted string into the groundwater pipe until contact was made with the groundwater. The length of the weighted string was measured from the marsh surface to the groundwater.

Regression analysis was performed on mean incremental change in groundwater depth and marsh surface elevation to determine whether a significant relationship existed between changes in groundwater depth and marsh surface elevation.

6. SET Results

6.1. Factors controlling surface elevation

It may be supposed that ground surface elevation is primarily a function of sedimentation rate. This may well prove to be true over longer temporal scales, as suggested by Saintilan and Hashimoto (1999) for the Hawkesbury in the latter stages of the Holocene highstand. However, over inter-annual periods the no relationship can be demonstrated between sedimentation rate and marsh surface elevation increase (Rogers *et al*. 2006).

Marsh surface elevation appears to be influenced primarily by below-ground processes, at least over the time-period of the survey.

Over inter-annual time periods, marsh surface elevation in Westernport Bay tracked against the southern oscillation index (Rogers *et al.* 2005a, Figure 5).

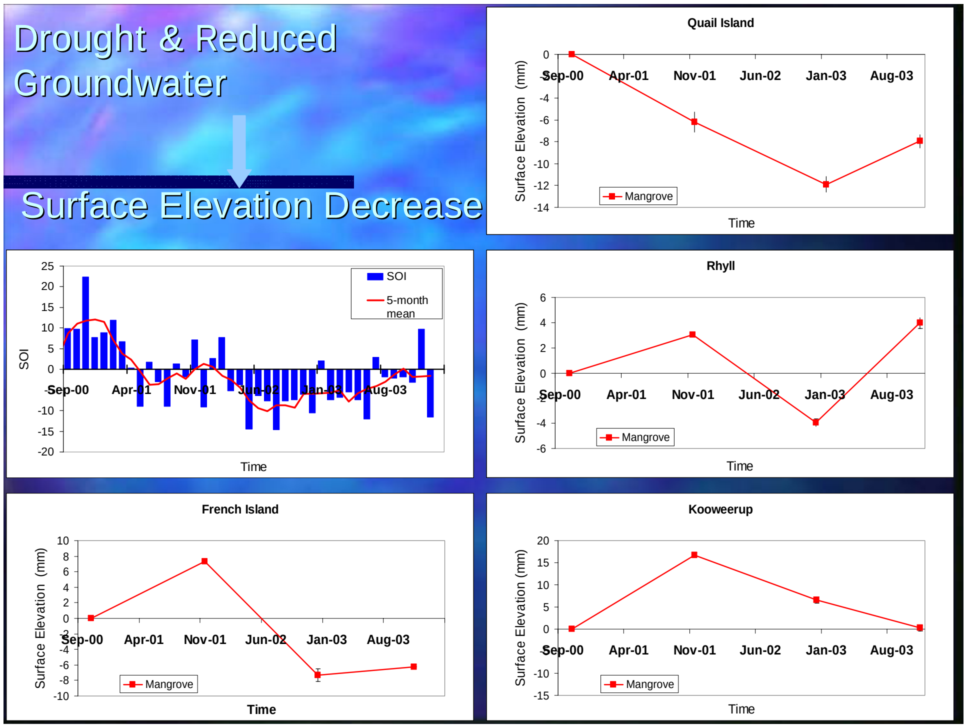

Fig. 5. Marsh surface elevation trends in Westernport Bay, and the Southern Oscillation Index.

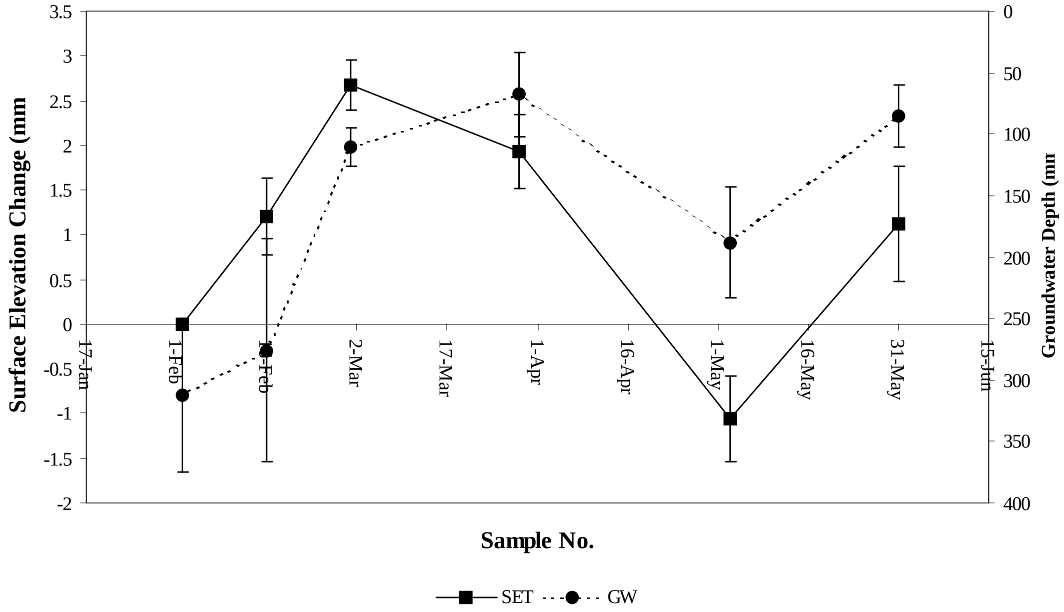

Fig 6. Variation in surface elevation (SET) and groundwater (GW) for the mangrove at Sydney Olympic Park.

Over the period of two weeks, marsh surface elevation closely followed groundwater measured for the same locations at Homebush Bay (Rogers and Saintilan 2006, Figure 6).

Mangrove below-ground productivity can influence ground surface elevation, as demonstrated in an experiment which captured a period of regrowth in a forest of *Avicennia* *marina* at Homebush Bay. During the regrowth period, ground surface elevation increased at a greater rate than the sedimentation rate (Rogers *et al.* 2005b, Figure 7).

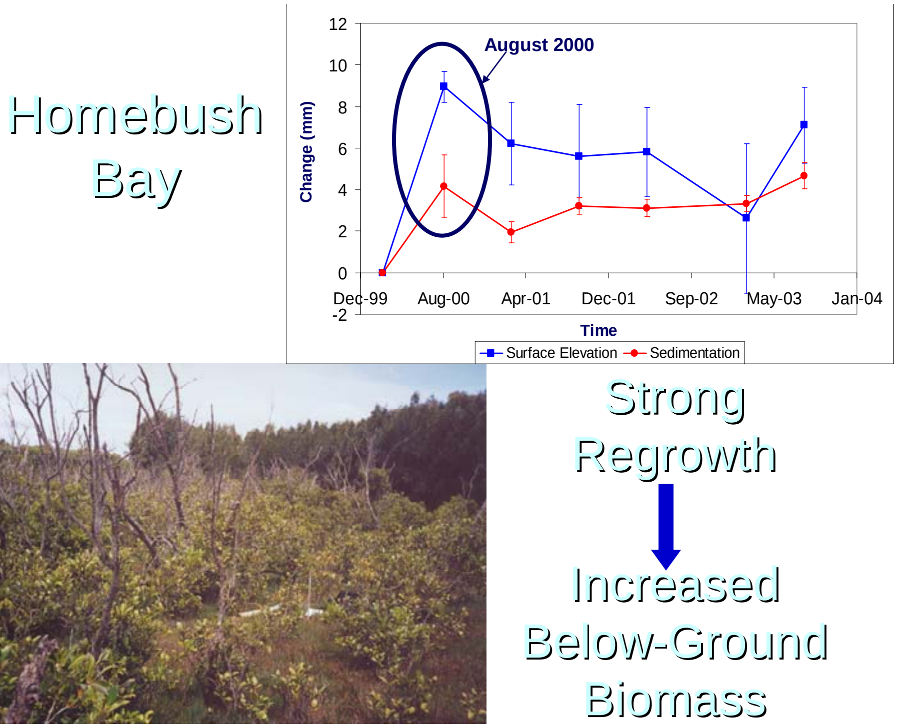

Fig 7. Marsh surface elevation and plant regrowth, Homebush Bay.

So what have we learnt? Primarily, that marsh surface elevation is variable, and that eustatic sea-level trends cannot be directly translated into relative sea-level trends for coastal marshes. Marsh survival must be understood in relation to relative sea-level, which factors in the trends in marsh surface elevation. Secondly, that the factors which influence relative sea-level at inter-annual time-periods are primarily below-ground, being groundwater and below-ground biotic processes. This conclusion is in concordance with results from a global analysis of SET data (Cahoon *et al.* 2006).

That is to say, we can refine our assessment of the relationship between saltmarsh decline and sea-level rise by factoring in the trends of surface elevation. Do different sites vary in their relative sea-level trends, based on variability in, for example, groundwater extraction during drought?

6.2. Saltmarsh decline and relative sea-level

The final stage in the analysis has been to explore the relationship between relative sea-level trends and vegetation dynamics. This involves two components:

(i) The calculation of relative sea-level by factoring in the eustatic component and the marsh surface trajectory, for a range of sites in Southeastern Australia
(ii) Calculate the rate mangrove encroachment into saltmarsh for the same range of sites.

This analysis has revealed a startling but not wholly unexpected result. Though mangrove encroachment into saltmarsh is a widespread phenomenon and corresponds broadly to the degree of sea-level rise in the period, a correlation exists between the extent of mangrove encroachment and relative sea-level rise, when marsh surface processes have been included in the analysis.

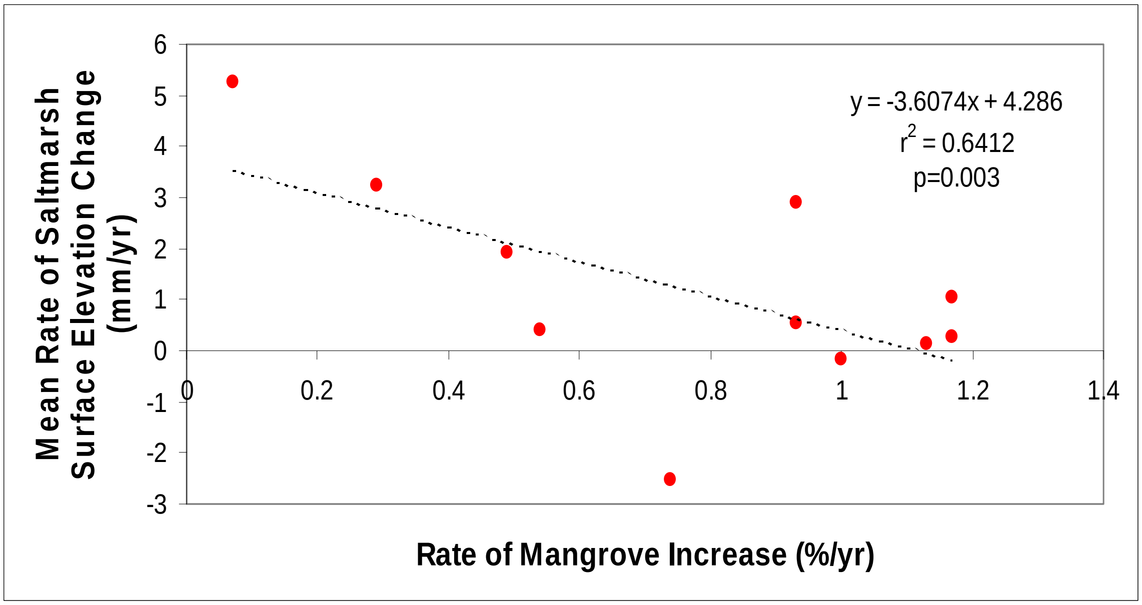

Fig 8. Marsh surface elevation and sea-level.

Sites which maintained a strong pattern of elevation increase sustained the lowest rates of mangrove encroachment.

7. Conclusions

A consistent pattern of saltmarsh decline has been demonstrated for the estuaries of Southeastern Australia. Comparisons of contemporary distributions with those gauged from historical aerial photography, now extending back five decades for most sites, reveals replacement of saltmarsh by mangrove over a time-period in which sea-levels were higher than the previous first half of the 20th century. The encroachment of saltmarsh by mangrove has led to a decline of important migratory shorebird roosting habitat, and threatens the availability of habitat important for itinerant fish and crustaceans.

Using the Surface Elevation Table and associated marker horizon technique, Rogers *et al.* (2006) were able to demonstrate that inter-estuary variability in the rate of saltmarsh decline was correlated with the degree of relative sea-level rise, factoring in surface elevation trends and regional eustatic sea-level trends. Those sites in which surface elevation declined were those experiencing the most rapid rate of mangrove encroachment, when mangrove encroachment was estimated in terms of vertical migration. This implicates relative sea-level rise as the primary driver of mangrove encroachment, as opposed to regional climatic trends.

The trend of mangrove encroachment and saltmarsh decline would be expected to continue with accelerated sea-level rise, predicted for the coming century by the Intergovernmental Panel on Climate Change (Houghton *et al.* 2001). In this sense, the evidence of the past 50 years, and the associated ecological impacts, might be seen as an early indicator of future trends. The rate of sea-level rise has been moderate by global standards (1.18 mm yr^{-1}), and to date *Casuarina* and *Melaleuca* forests have shown no signs of dieback in the region, nor has the seaward fringe of mangrove. The subtle gradients separating mangrove from saltmarsh serves as a sentinel for a trend which in time would be expected to cause the movement of adjacent vegetation zones. Whether saltmarsh has extended beneath the canopy of *Melaleuca* and *Casuarina* is difficult to determine from aerial photography.

The variability of saltmarshes in the degree of decline is controlled by local factors influencing below-ground processes, such as groundwater flow and below-ground productivity. This trend is consistent with evidence emerging from the global SET network. In a recent global analysis of SET data, Cahoon *et al.* (2006) demonstrated a poor correlation between surface elevation trajectories and sedimentation, but closer associations with below-ground processes.

There are a number of implications for the management of coastal saltmarsh in the prospect of anticipated sea-level trends. Thought must be given to accommodating the landward encroachment of coastal wetland communities. In some places, this would require landward buffers, the size of which might be determined by high resolution elevation modeling, and surface elevation trend modeling (incorporating trajectories derived from SET data). In many of the deeply incised sandstone valleys of the central NSW coast, natural barriers exist to landward encroachment, and the best prospect for saltmarsh accommodation is on headward floodplains. In many situations, landward and headward accommodation of saltmarsh is restricted by agricultural, residential and industrial development. Planning instruments should be invoked to prevent closing options for future movements of these vital wetland communities. At a minimum, residential development and transport corridors should be prohibited within a vertical range of 50 cm of the upper spring tide inundation bordering existing saltmarsh.

The management of wetlands also requires attention to the sources of sediment and water which influence the condition of the wetland. For coastal saltmarsh, groundwater is emerging as an important control for many communities, both in maintaining vegetation composition and also surface elevation. The diversion of groundwater poses challenges for the sustainability of coastal saltmarsh, possibly promoting subsidence, and promoting mangrove encroachment. The relationship between saltmarsh species composition, surface elevation and groundwater is poorly understood.

Marshes also require sediment to compensate for autocompaction and maintain surface elevation. The sediment requirements of coastal wetlands should be considered when managing the movement of sediment through the catchment. The prevailing paradigm of trapping sediment in catchments and minimizing delivery of sediment to estuaries, and the coastal wetlands which represent the end-point of sediment movement, should be reconsidered in the context of accelerated sea-level rise.

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Opportunities to Increase Mangrove Resilience to Sea-level and Climate Change in the Pacific Islands Region

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1. Introduction

This paper provides an overview of current and planned regional and international initiatives and tools that present opportunities for increasing the resilience of mangrove ecosystems of Pacific Island Countries and Territories (PICTs).

PICTs share similar characteristics, those of small physical size and geographical remoteness, fragile biodiversity, exposure to natural hazards, high population growth, limited natural resource base, remoteness from world markets and small economies of scale. The social and economic development of PICTs are closely linked to their natural environment. Agriculture and fisheries form the basis of most economies and supports both subsistence and commercial production. However, PICTs face significant pressures on the their natural environment, which are largely driven by socio-economic factors, including population increase, insufficiently planned economic development, and poverty. Such pressures present a major impediment to the achievement of sustainable development in PICTs.

Addressing these pressures in PICTs has been constrained by limited human and institutional capacity, scarcity of financial resources, inadequate data and information, poor governance, weak regulatory frameworks and the displacement of traditional natural resource governance systems (UNEP, 2005). Perhaps a major constraint though has been the slow progress of integrating the environment agenda into national development planning processes and other sectoral policies.

2. PICTs and Climate Change

It is widely recognized that climate change and its associated impacts presents one of the most serious emerging threats to the Pacific Islands region, which is one of the most vulnerable regions of the world to climate-related risks. This increased recognition has seen a significant number of Pacific Island Countries joining up to the Climate Change Convention (UNFCCC) since the last decade, with 12 Island Countries ratifying the UNFCCC so far. This concern is also reflected in most regional strategies including the Pacific Islands Regional Wetlands Action Plan (1999); The Pacific Plan for greater regional cooperation and integration (2005); the Action Strategy for Nature Conservation in Pacific Islands region (2003-2007); The Pacific Islands Framework for Action on Climate Change (2006-2015). Considerable assistance from the international community has also enabled national level work within PICTs to be undertaken such as the development of National Adaptation Programmes of Action (NAPAs), Vulnerability and Adaptation (VandA) assessments, pilot community adaptation projects, Greenhouse Gas (GHG) Inventories, National Communications reporting, hazard and risk management assessments and Cyclone Emergency Recovery Projects (CERPs), among others.

The extreme vulnerability of PICTs to Climate Change may result in them being among the first to adapt to its impacts, these being extreme climatic events, increased natural disasters, habitat destruction, saltwater intrusion into groundwater, increase in vector-borne diseases and effects on crops and fisheries. Low lying Atolls, many of which are hardly three metres above sea-level, are at risk of total inundation during very strong storm surges. The scientific community predicts that the tropical Pacific region will continue to warm and this may very well exert more pressure on already stressed coastal and marine environments. A recent estimate of PICTs vulnerability to specific natural hazards (UNDP South Pacific Office, 2002), particularly those relevant to the coastal zone (tropical cyclone, storm surge, coastal flood and tsunami) reports a 'high' value for most Island countries.

3. Pacific Island Mangroves and Climate Change

Mangroves occur across the Pacific with attenuation in diversity from west to east. Independent Samoa is considered to contain the largest tract of mangrove in eastern Polynesia while American Samoa is the eastern-most limit of mangrove occurrence. The largest mangrove areas occur in Melanesia, King (2004) reports that Papua New Guinea has 45 species, Solomon Islands (33 species) and Fiji (7 species). Lacerda et al. (1992) estimated the global mangrove area to be 14, 197, 635 hectares, based on this global estimate, SPREP (1999) approximated that the Pacific Islands region contained about 2.42 percent of the global coverage of mangroves. However, there has not been a substantial follow-up to verify if this percentage has increased or declined in recent years, although anecdotal evidence and observations suggest the latter.

Mangroves provide many benefits and services for PICTs, including shoreline stabilization, improvement of lagoon water quality, a protective buffer to wind and wave energy, a source of traditional medicines and a significant role in maintaining cultural practices. Perhaps most importantly, the associated fishery resources of mangrove ecosystems provide PICTs with a major source of their daily protein intake. A recent study estimated losses to subsistence and commercial fisheries based on a scenario of one hectare of mangrove habitat removal per year due to coastal erosion (World Bank, 2000). For Fiji, the estimated value of loss ranged between FJ$464 (AUD$358) and FJ$702 (AUD$542) per hectare per year for subsistence fishing and a slightly lower value of loss for commercial fishing, being between FJ$179 (AUD$138) and FJ$272 (AUD$210) per hectare per year. An analysis of the results of a household fisheries and dietary survey in Samoa by Passfield et al. (2000) revealed that the percentage of total catches of inshore and offshore fish species were higher in villages which rely on mangroves for subsistence fishing than those villages which rely on lagoons for the same purpose.

Climate related shifts may impact mangrove productivity, which in turn may lead to a decline in subsistence fisheries where "food shortages could become particularly acute if declines in marine resources used for subsistence coincided with reduced agricultural productivity" (Hay et. al, 2003). Rising sea-levels are of concern if the rate of rise exceeds the natural ability of mangroves to adapt. Furthermore, since mangroves are fixed in locality they must adjust to changing conditions on site.

The University of Tasmania, SPREP, and UNEP Regional Seas Programme conducted a recent study of the impacts on mangroves from climate change and sea-level rise (Gilman et al., 2006). The study provides a clear understanding of the capacity of PICTs to assess and manage shoreline response to relative sea-level and climate change. In addition, the study identifies priority capacity-building needs to enable PICTs to manage shoreline response to relative sea-level rise and climate change. The results of the study will assist participating countries in developing, updating, and implementing plans for National Adaptation Programmes of Action established under the UNFCCC, and contributes to the Intergovernmental Panel on Climate Change's preparation of their Fourth Assessment Report. It is envisaged that current funding agencies will consider supporting a second phase of this project to assist participating countries to address their identified priority capacity-building needs.

Except for some larger Islands in Melanesia, most infrastructure and settlements in PICTs are concentrated along coastal areas. For example, Nunn et al. (1994) confirmed that 73 percent of schools and 60 percent of churches on the island of Savaii, Samoa were located along the coastal area. Furthermore, Taule'alo and Crawley (2002) pointed out that most of the population in Samoa, as well as the majority of the social and economic infrastructure are concentrated near the sea. Since horizontal/landward migration is a response of mangroves to sea-level rise, an apparent problem is presented in accommodating this response. The continued degradation and loss of mangroves coupled with limits to their horizontal migration 'mean that many mangrove forest communities are unlikely to survive into the next century' (Hay et. al, 2003).

4. Opportunities for Increasing Mangrove Resilience

There are a number of current and planned regional initiatives as well as tools that contribute, either directly or indirectly, to enhancing mangrove resilience to climate change and associated sea-level rise.

4.1. Current regional projects and initiatives

4.1.1. The Pacific Islands Framework for Action on Climate Change (2006-2015)

The main aim of this framework is to ensure that Pacific Island people build their capacity for resilience. The framework was endorsed by PICTs in 2005 and focuses on the following: implementing adaptation measures; governance and decision making; improving understanding of climate change; education, training and awareness; contributing to global greenhouse gas reduction; and partnerships and cooperation.

4.1.2. SOPAC/EC Initiative – reducing vulnerability in Pacific ACP States

This project, executed by SOPAC, addresses vulnerability reduction in the Pacific ACP States through the development of an integrated planning and management system, Island Systems Management enhance capacity at the national level for hazard risk management. The objective is to strengthen integrated development in Pacific ACP States by concentrating on three key focal areas in the island system:

(i) Hazard mitigation and risk assessment;
(ii) Aggregates for construction; and
(iii) Water resources supply and sanitation.

The Project addresses problems such as: unavailability of accurate and timely data; weak human resource base; limited resources (money and infrastructure); and lack of appropriate management plans, policies and regulatory frameworks to deal with these three focal areas. All 14 beneficiary Pacific ACP countries are involved - Fiji, Kiribati, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu and Vanuatu, Cook Islands, Federated States of Micronesia, Marshall Islands, Nauru, Niue and Palau.

4.1.3. UNDP-GEF International Waters Project for the Pacific Islands (IWP)

The IWP, executed by SPREP is a seven-year initiative (1999-2006) dedicated to enhancing global environment benefits, through two components, oceanic and coastal. The overall focus is on the management and conservation of tuna stocks and Integrated Coastal Watershed Management. Through the project, community mangrove replanting activities have been carried out for Fiji and the Solomon Islands.

4.1.4. The Action Strategy for Nature Conservation in the Pacific Islands Region 2003-2007

The current version of this strategy was endorsed by PICTs in 2002, with relevant actions focusing on the preparation of adaptation and contingency plans to address impacts of climate change on society and biodiversity and the integration of impacts of climate change on biodiversity in national and community conservation plans in all PICTs. The Action Strategy will be revisited again at the Eighth South Pacific Conference on Nature Conservation and Protected Areas in 2007.

4.1.5. Pacific Plan for strengthening regional cooperation and integration (2005)

The Pacific Plan is the regional blueprint for increasing cooperation within the Pacific on priority issues including economic growth, sustainable development, good governance and security. The Plan was endorsed by Pacific Island leaders in October 2005 has as an immediate priority the facilitation of international financing for sustainable development, biodiversity and environmental protection and Climate Change in the Pacific, including through the Global Environment Facility. The Plan also calls for the further development of adaptation and mitigation efforts linked to Pacific

Islands Climate Change Framework (2006-2015), which includes public awareness, improving governance, capacity building, and risk and vulnerability assessments.

4.2. Upcoming regional projects/Initiatives

4.2.1. Pacific Adaptation to Climate Change project (UNFCCC-PACC)

This project is a collaborative effort between SPREP and UNDP designed to implement long-term adaptation measures to increase resilience of a key number of sectors to Climate Change. This project falls under the Global Environment Facility Strategic Priority area ‘ Adaptation to Climate Change’. The project will complement the work on adaptation initiated by the Canadian Government funded CBDAMPIC (2002-2005) Project in enhancing resilience to the impacts of Climate Change. The project will engage 11 Pacific Island Countries and planning for its commencement has already begun with in-country consultations currently in progress to finalize implementation details.

4.2.2. CBD Island Biodiversity Programme of Work (2006)

The CBD Conference of the Parties in 2004 at its seventh meeting (CoP7) adopted a multi-year programme of work up to 2010 and established a new thematic programme of work on Island Biodiversity (IB-POW), a draft of which was considered at CoP8 of the CBD in early 2006. The IB-POW aims to assist Small Island Developing States to significantly reduce the loss of their biodiversity by 2010 and beyond at global, regional and national levels, through the implementation of the three main objectives of the Convention, for the benefit of all forms of life on islands and, in particular, as a contribution to poverty alleviation and their sustainable development.

The particular benefit for Pacific Island Countries will be in efforts to implement current national biodiversity strategies and action plans (NBSAPs). Pacific Island countries will be able to use the IB-POW to assist in securing funding as well as technical and other assistance from other CBD Parties in order to address island biodiversity priorities. Relevant actions of the IB-POW focus on researching and implementing adaptation and mitigation measures in land-use and coastal zone planning and strategies to strengthen local-level biodiversity resilience to climate change as well as the creation, where feasible, of viable national systems of protected areas that are resilient to climate change.

4.3. Relevant tools and guidance

4.3.1. Ramsar ‘Wise Use’ Toolkit of the Ramsar Convention on Wetlands

These guidelines are in the form of 14 handbooks prepared by the Ramsar Secretariat following COP7 (1999) and COP8 (2002), with the second edition (2004) being the most current. The toolkit/guidelines are primarily designed to assist contracting parties to the Ramsar convention with implementation, however, the toolkit provides flexibility in that it is also well suited for use for national planning for wetland conservation, even in non-parties. The toolkit contains practical guidance relevant to planning for increased mangrove resilience. Relevant guidance includes – developing and implementing wetland policies; Reviewing laws and Institutions; Strengthening local communities participation; Communication Education and Public Awareness (CEPA); Wetland management; Impact assessment; wetland issues in coastal management.

The toolkit has been disseminated to all PICTs (21 in total) and it is expected that future mangrove-related training in the region would incorporate elements of this toolkit. A challenge in the meantime though is encouraging PICTs to make full use of the toolkit, including for planning specific components of national mangrove conservation programmes.

4.3.2. Comprehensive Hazard and Risk Management (CHARM)

CHARM is a comprehensive hazard and risk management tool and / or process, administered by SOPAC, which aims to facilitate greater collaboration between risk reduction projects at all levels and across sectors to improve sustainable development within the SOPAC member countries. Of relevance to planning for increasing mangrove resilience, the CHARM seeks to ensure that national programmes and processes:

- Address all hazards (natural, anthropogenic, technological, biological and environmental);
- Adopt all appropriate measures that reduce risk, such as prevention / mitigation, preparedness, response and recovery;
- Integrate the efforts of all relevant regional and national organizations and agencies, public sector, NGO, and community organizations;
- Link to national development planning and decision-making processes / systems
- Seek to develop prepared communities with reduced vulnerability to risk and with increased resilience to the impacts of hazards; and
- Seek to enhance collaboration and partnerships across all sectors.

4.3.3. CVandA: A Guide to Community Vulnerability and Adaptation Assessment and Action

This guide was funded by the Canadian Government as part of the CBDAMPIC project and was developed by SPREP (Nakalevu, 2006). The primary purpose of the guide is to assist community vulnerability and adaptation work carried out by the four pilot Pacific Island Countries that participated in this project. Three of these four participating countries have indigenous mangroves. The guide is a tool to increase understanding of Pacific communities' vulnerability to climate change, variability and sea-level change and contains six main stages for conducting a CVandA assessment at the local community level. In addition, the guide complements other participatory tools that have been introduced into the Pacific, including the CHARM process outlined above.

5. Conclusions

There are significant opportunities at regional and national levels that, in whole or in part, contribute to increasing mangrove resilience to climate change and sea-level rise. Although some major challenges linger, the momentum of forging new partnerships and strengthening collaboration between (and across) all key players at the local, national, regional and international levels for mangrove conservation is increasing. Such concerted efforts will provide further opportunities and an enabling environment to ensure that mangroves do not disappear under the waves, but continue to provide their valuable functions and services to Pacific Island peoples well into the future.

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Capacity of Pacific Island Countries and Territories to Adapt to Mangrove Responses to Changes in Sea-level and Other Climate Change Effects[1]

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Abstract

Stresses associated with effects from climate change, including rise in relative mean sea-level, present one set of threats to mangroves. Coastal development and ecosystems are particularly vulnerable to climate change effects in the Pacific islands region. We investigate the capacity of Pacific Island Countries and territories to assess mangrove vulnerability to climate change effects and adapt to mangrove responses to these forces. Technical and institutional capacity-building priorities include strengthening management frameworks to conduct site-specific assessment of mangrove vulnerability and incorporate resulting information into land-use plans to prepare for any landward mangrove migration and offset anticipated losses; reducing and eliminating stresses on and rehabilitating mangroves, in part, to increase mangrove resilience to climate change effects; and augmenting abilities to establish mangrove baselines and monitor gradual changes using standardized techniques through a regional network to distinguish local and climate change effects on mangroves. Other priorities are to assess how mangrove margins have changed over recent decades, determine projections of trends in mean relative sea-level and frequency and elevation of extreme high water events, measure trends in changes in elevations of mangrove surfaces, and incorporate this information into land-use planning processes. Some locations require spatial imagery showing topography and locations of mangroves and coastal development. Land-use planners can use information from assessments predicting shoreline responses to projected sea-level and climate change to reduce risks to coastal development, human safety, and coastal

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[1] This paper is based on:
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ecosystems. This advanced planning enables coastal managers to minimize social disruption and cost, minimize losses of valued coastal ecosystems, and maximize available options.

1. Introduction

Accurate predictions of changes to coastal ecosystem area and health, including in response to climate change effects such as projected relative sea-level rise, enables advanced planning appropriate for specific sections of coastline to minimize and offset anticipated losses, and reduce threats to coastal development and human safety (Titus, 1991; Mullane and Suzuki, 1997; Ramsar Bureau, 1998; Hansen and Biringer, 2003; Ellison, 2004; Gilman et al., In Press). Relative sea-level rise is a major factor contributing to recent losses and projected future reductions in the area of valued coastal habitats, including mangroves and other tidal wetlands, with concomitant increased threat to human safety and shoreline development from coastal hazards (Gilman et al., In Press). Global sea-level rise is one of the more certain outcomes of global warming, 10-20 cm occurred during the last century, and several climate models project an accelerated rate of sea-level rise over coming decades (Church et al., 2001 and 2004a; Cazenave and Nerem, 2004; Holgate and Woodworth, 2004; Thomas et al., 2004).

Over the past few decades, the average change in relative sea-level of the 10 countries and territories in the Pacific Islands region with native mangroves that are experiencing a rise in relative sea-level was 2.0 mm a^{-1}. Based on general estimates of mangrove sedimentation rates (Ellison and Stoddart, 1991), and the possibility that subsurface sediment subsidence from organic matter decomposition, sediment compaction, and fluctuations in sediment water storage and water table levels may result in substantially higher rates of sea-level rise relative to the mangrove surface (Krauss et al., 2003), island mangroves could experience serious problems due to rising sea-level, and low island mangroves may already be under stress. Gilman et al. (In Press) determine that American Samoa could experience a 50% loss in mangrove area and a 12% reduction is possible in the Pacific Islands region due to mangrove responses to relative sea-level rise when employing the Intergovernmental Panel on Climate Change's upper projection for global sea-level rise through the year 2100.

Shoreline development and coastal ecosystems are particularly vulnerable to small increases in sea-level and other climate change effects in the Pacific islands region. Many of the low islands do not exceed 4 m above current mean sea-level, and even on high islands, most development is located on narrow coastal plains. Small island states have limited capacity to adapt to relative sea-level rise, including accommodating landward migration of mangroves and other coastal ecosystems. This is a result of their small land mass, high population densities and population growth rates, limited funds, poorly developed infrastructure, and susceptibility to damage from natural disasters (Nurse et al., 2001). It may not be physically or economically feasible for many small island state communities to retreat from a landward-migrating mangrove and other coastal habitats, or to establish zoning setbacks from coastal habitats for new development.

Pacific island governments have recognized the value of mangroves and the need to augment conservation efforts (e.g. South Pacific Regional Environment Programme, 1999a). The Pacific islands contain roughly 3% of global mangrove area, a small area in global terms, but each island group has a unique mangrove community structure (Ellison, 2000) and mangroves provide site-specific functions and values (e.g., Gilman, 1998; Lewis, 1992). Reduced mangrove area and health will increase the threat to human safety and shoreline development from coastal hazards such as erosion, flooding, and storm waves and surges. Mangrove loss will also reduce coastal water quality, reduce biodiversity, eliminate fish and crustacean nursery habitat, adversely affect adjacent coastal habitats, and eliminate a major resource for human communities that traditionally rely on mangroves for numerous products and services (Ewel, 1997; Ewel et al., 1998; Mumby et al., 2004; Victor et al., 2004). Mangrove destruction can release large quantities of stored carbon and exacerbate global warming trends (Kauppi et al., 2001; Ramsar Secretariat, 2001; Chmura et al., 2003).

Land-use planners can obtain information from assessments predicting shoreline responses to projected relative sea-level rise and other climate change effects over coming decades to mitigate anticipated losses of coastal habitats and avoid and minimize damage to coastal development. We assess the capacity of Pacific Island Countries and territories to determine vulnerability and adapt to mangrove responses to climate change effects. Results highlight priority technical and institutional capacity-building needs nationally and regionally.

1.1. National, regional and international initiatives

Due to anticipated effects of climate change in the Pacific islands region, several international and regional initiatives discuss the severity of this threat and provide general guidelines for planning. However, there have been few site-based vulnerability assessments or identification of alternatives for site-based management of mangroves' and other coastal ecosystems' responses to sea-level and other climate change effects.

There have been several national or island-scale vulnerability assessments in Pacific Island Countries and territories that provide qualitative assessments to describe the anticipated responses of coastal systems to projected sea-level and other climate change effects and concomitant threats to developed portions of the coastal zone. For example, Phillips (2000) describes the vulnerability of Vanuatu's coastal villages to sea-level rise, referencing global sea-level rise models produced by the Intergovernmental Panel on Climate Change and other projected global climate change parameters (temperature and precipitation), as a basis for hypothesizing possible environmental, social, and economic effects. Other vulnerability assessments have established the locations and elevations of coastal habitats and development and use global or relative sea-level change projections to make rough predictions of the sections of coastline that will be affected. For example, Solomon et al. (1997) create a GIS of a developed stretch of the coastline of Viti Levu, Fiji using topographic maps to identify the locations and elevations of coastal development, including sea walls, revetments, and other shoreline protection structures. They then use this GIS to assess the vulnerability of the coastline to inundation from four sea-level rise scenarios (a rise of 0 m, 0.25 m, 0.5 m, and 1 m) and storm surges. This approach to conducting a vulnerability assessment does not incorporate natural coastal ecosystem response to changes in relative sea-level and other climate change effects.

All twelve Pacific Island Countries with indigenous mangroves are Parties to United Nations Framework Convention on Climate Change (UNFCCC). Of these, eleven countries (Kiribati, Marshall Islands, Federated States of Micronesia, Nauru, Palau, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu, and Vanuatu) have submitted an initial National Communication to the UNFCCC. Fiji has not yet submitted a National Communication. The eleven initial National Communications discuss general considerations and guidelines related to coastal ecosystem vulnerability and adaptation to future sea-level and climate change (Federated States of Micronesia, 1997; Government of Samoa, 1999; Government of Tuvalu, 1999; Kiribati Government, 1999; Republic of Nauru, 1999; Republic of Vanuatu, 1999; Papua New Guinea Government, 2000; Republic of the Marshall Islands Environmental Protection Authority, 2000; Republic of Palau Office of Environmental Response and Coordination, 2002; Solomon Islands Government, 2004; Kingdom of Tonga, 2005). A review of these reports highlights that there is a gap in information on anticipated site-specific responses of mangroves and other coastal ecosystems to climate change effects and site-specific strategies for adaptation. Examples of some of the general adaptation strategies to manage mangrove and other coastal ecosystem responses to climate change effects identified in several of these National Communication reports include (i) establishing zoning rules for setbacks of new development from mangroves; (ii) retreating to higher ground or off-island for appropriate sections of coastline as a last resort option; (iii) identifying sections of coastal areas vulnerable to flooding and inundation to guide future development; and (iv) fortifying relevant sections of developed coastline (Federated States of Micronesia, 1997; Government of Samoa, 1999; Republic of Vanuatu, 1999; Kiribati Government, 1999; Papua New Guinea Government, 2000; Republic of the Marshall Islands Environmental Protection Authority, 2000; Republic of Palau Office of Environmental Response and Coordination, 2002; Solomon Islands Government, 2004). These examples are representative of the level of specificity in the National Communication reports to assess the vulnerability of and adapt to coastal ecosystem response to sea-level and other climate change effects.

The “South Pacific Sea-level and Climate Monitoring Project” was initiated in 1991 to establish stations in eleven Pacific Island Countries to measure the relative motions of land and sea at each station (South Pacific Sea-level and Climate Monitoring Project, 2001). The project is managed by the National Tidal Facility of Flinders University of South Australia. These data will assist in long-term calibration of satellite altimetry and radio astronomy and provide a measure of regional vertical control.

The Secretariat of the Pacific Regional Environment Programme’s (SPREP’s) Pacific Islands Climate Change Assistance Programme was implemented from 1997-2000 to assist ten Pacific Island countries that signed and ratified UNFCCC with their reporting, training and capacity-building responsibilities under the convention, including assessing their vulnerability to climate change. Participants from 12 countries (Papua New Guinea was the one participating country with indigenous mangroves) received training on assessing climate change vulnerability and adaptation requirements during a six-month training course in 1998. Under this program, SPREP produced a document, *Adapting to Climate Change: Incorporating Climate Change Adaptation into Development Activities in Pacific Island Countries: A Set of Guidelines for Policymakers and Development Planners* (South Pacific Regional Environment Programme, 2000). The document presents general guidelines for Pacific island governments to incorporate considerations of sea-level and climate change into new development planning.

The *Regional Wetlands Action Plan for the Pacific Islands* (South Pacific Regional Environment Programme, 1999a) specifies regional actions to monitor mangroves. Action 3.3.1 calls for the development of a regional monitoring program to assess the status of mangroves in the region, evaluate the success of management and conservation actions and develop more effective management practices. Furthermore, Action 3.3.5 identifies that mangrove swamps, particularly those of low islands, are likely to be sensitive to rise in sea-level. It promotes the development of a mangrove monitoring network for identification of changes, which has yet to be established.

SPREP implemented, “Capacity Building for the Development of Adaptation Measures in Pacific Island Countries,” in the Cook Islands, Fiji, Samoa, and Vanuatu from 2002-2005. The project’s aim was to build capacity of communities of these four countries to adapt to climate change, including incorporation of climate change adaptation considerations into national and local planning and budgeting. The project focused on socioeconomic effects and policy development, and did not address coastal ecosystem response to sea-level and climate change forces. For instance, SPREP conducted seminars for senior government officials from the four participating countries and produced and distributed briefing papers and educational materials to raise awareness of climate change effects and adaptation (Secretariat of the Pacific Regional Environment Programme, 2003).

The South Pacific Applied Geoscience Commission (SOPAC) has developed an environmental vulnerability index for application at national scales to provide a quick and inexpensive method to characterize the vulnerability of natural systems at large scales. It is not designed for site-based vulnerability assessments (South Pacific Applied Geoscience Commission, 2003). SOPAC produced a report, *Towards Managing Environmental Vulnerability in Small Island Developing States (SIDS)* (Kaly et al., 2002), which includes a general discussion of possible hazards to small island developing states resulting from sea-level and climate change.

2. Capacity-Building Priorities to Address Mangrove Responses to Climate Change Effects

We collected information from 10 of the 16 Pacific Island Countries and territories with indigenous mangroves to identify capacity-building priorities to address mangrove responses to climate change effects (Fig. 1): American Samoa - USA, Republic of the Fiji Islands, Republic of Kiribati, Republic of the Marshall Islands, Federated States of Micronesia, Commonwealth of the Northern Mariana Islands - USA, Republic of Palau, Independent State of Papua New Guinea, Kingdom of Tonga, and Republic of Vanuatu. These ten countries and territories contain 84% of the area of the region’s indigenous mangroves (Gilman et al., In Press). Table 1 provides a synthesis of the case study results. This section describes (i) the technical resources needed for the best possible prediction of how a mangrove wetland will respond to projected relative sea-level rise and climate change over coming decades, (ii) the institutional resources needed to manage and adapt to these mangrove responses to climate change effects, and (iii) the technical and institutional areas that are in urgent need of strengthening in the Pacific Islands Region.

Table 1. Summary of technical and institutional capacity of ten Pacific Island Countries and territories with indigenous mangroves to assess vulnerability and adapt to mangrove responses to relative sea-level and climate change.

Technical and Institutional Capacity Attribute	**Country or Territory**									
	American Samoa	**Fiji**	**Kiribati**	**Marshall Islands**	**Federated States of Micronesia**	**Northern Mariana Islands**	**Palau**	**Papua New Guinea**	**Tonga**	**Vanuatu**
Length of tide gauge record through Dec. 2005 (years)[a]	56.2	31.2	11.0	58.5	47.7	23.1	33.8	39.7	13.4	10.9
Largest distance between tide gauge and mangrove (km)	6.5	800	Not known	Not known	563	10	700	500	17	Not known
Percent of mangrove boundaries delineated and mapped	100	80	22	0	21	100	99	Not known	90	0
Year of most current mangrove boundary survey [b]	2002	1993	1998	NA	2002	1989	1971	1993	2000	NA
Percent of mangrove islands with topographic map coverage	100	100	22	0	100	100	87.5	86	0	100
Percent of mangrove islands with maps showing buildings, roads, and other development	100	100	25	20	100	100	0	0	33	100
Year of most current map showing location of development [b]	2001	1993	1998	2004	2004	1999	NA	NA	1998	Not known
Date of earliest imagery showing mangrove	1961	1954	1960	2004	1944	1940	1946	1971	1995	1980

margin (aerial photos, satellite imagery, maps) [b]										
Have mangrove sediment erosion/ accretion rates been measured?	Y	N	N	N	Y	N	N	N	N	N
Is there a mangrove monitoring program	Y	Y	N	N	Y	N	N	N	Y	N
Is there in-country staff with skills to conduct mangrove surveys and inventories?	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
Have mangroves been successfully rehabilitated? [c]	N	Not known	Y	N	N	Y	Y	N	Y	N
Is there a permit or zoning program for coastal development?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Has there been site-specific mangrove vulnerability assessments?	Y	N	N	N	N	N	N	N	N	N
Is there a plan for adaptation to coastal ecosystem responses to climate change effects?	N	N	N	N	N	N	N	N	N	N

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[a] Tide gauge record lengths based on the time span from the earliest and most current sea-level records through December 2005 possessed by the Permanent Service for Mean Sea-level and University of Hawaii Sea-level Center Joint Archive for Sea-level and GLOSS/CLIVAR Research Quality Data Set databases. Does not account for gaps in data records. Tide gauge record lengths may be longer than reported for sites where tide gauges are active, as there is a lag in updating the two data repositories.

[b] Mangrove boundary surveys, maps showing roads and development, and historical imagery may have incomplete coverage of mangroves.

[c] Successful mangrove rehabilitation is defined as one where ≥ 25% of the project area was successfully restored, enhanced or created.

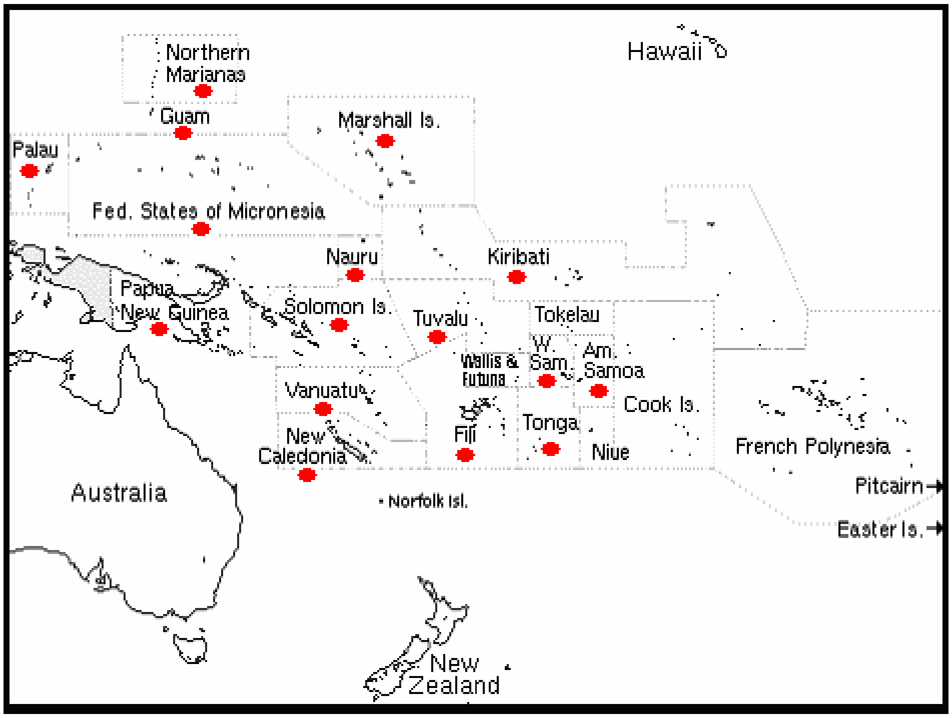

Fig. 1. The Pacific Islands region and location of the twelve Pacific Island Countries and four territories with indigenous mangroves, identified by a red oval below the country/territory name.

Hawaii and Tahiti, where mangroves are human introductions (Allen 1998; Ellison, 1999), are not included in the assessment because management authorities in these areas may actively control the alien invasive species (e.g., Smith, 2005). While mangrove wetlands have been reported from Niue (Ellison, 1999), a Niue government focal point reported that there are no mangrove wetlands in Niue (personal communication, 10 June 2005, Fiafia Rex, Fisheries Division, Niue Department of Agriculture Forestry and Fisheries). While one true mangrove species *Excoecaria agallocha* is documented to be present in Niue (Yuncker, 1943; Tomlinson, 1986; Whistler, 1992), in Niue, this species is only found in dry littoral forest.

2.1. Analysis of tide gauge data for trends in mean sea-level and extreme high water events

A minimum of a 20-year local tide gauge record is required to obtain an accurate trend in relative sea-level (Hunter, 2002, Church et al., 2004a). Many Pacific islands are located in tectonic settings that cause differences in local relative sea-level from the global eustatic sea-level trends. In addition to vertical land-level changes from tectonics, change in relative mean sea-level over time as measured by a tide gauge can result from glacial rebound, subsidence from extraction of subsurface groundwater or oil, oceanographic processes such as El Niño phases and changes in offshore currents, long-term changes in regional temperature, sediment consolidation, as well as from global sea-level change (Komar, 1998; Church et al., 2001). The closer the tide gauge is to the mangrove site, the more likely these forces causing the change in mean sea-level as measured by the tide gauge will be the same strength for the mangrove and the observed trend in relative mean sea-level as measured by the tide gauge will apply to that mangrove site. However, for sites with a local tide gauge record of < 20 years or that are located far from the nearest tide gauge, sea-level trends can be calculated from the near global coverage of TOPEX/Poseidon satellite altimetry data combined with historical global tide gauge records employing a method by Church et al. (2004a). Pacific Island Countries and territories also need the technical capacity to analyze available tide gauge data to determine projected trends in mean sea-level and extreme high water events, and incorporate this information into land-use planning.

Most (7 of 10) countries and territories have sufficiently long tide gauge records (≥20 years) to determine accurate trends in men sea-level and extreme high water events (Fig. 2). However, tide gauges of four of the seven countries and territories with the long (≥ 20 years) tide gauge records are located several hundred kilometers from at least one mangrove site in that country. Three countries with tide gauge records < 20 years require assistance to determine reconstructed sea-level trends from satellite altimetry data combined with historical global tide gauge records (Church et al., 2004a). Agencies managing coastal land use and coastal ecosystems of Pacific Island Countries and territories require assistance to determine trends in relative mean sea-level and trends in the frequency and elevations of extreme high water events (Church et al., 2001; Woodworth and Blackman, 2002, 2004; Gilman et al., In Press, 2005a), and assistance to interpret and incorporate this information into land-use planning processes.

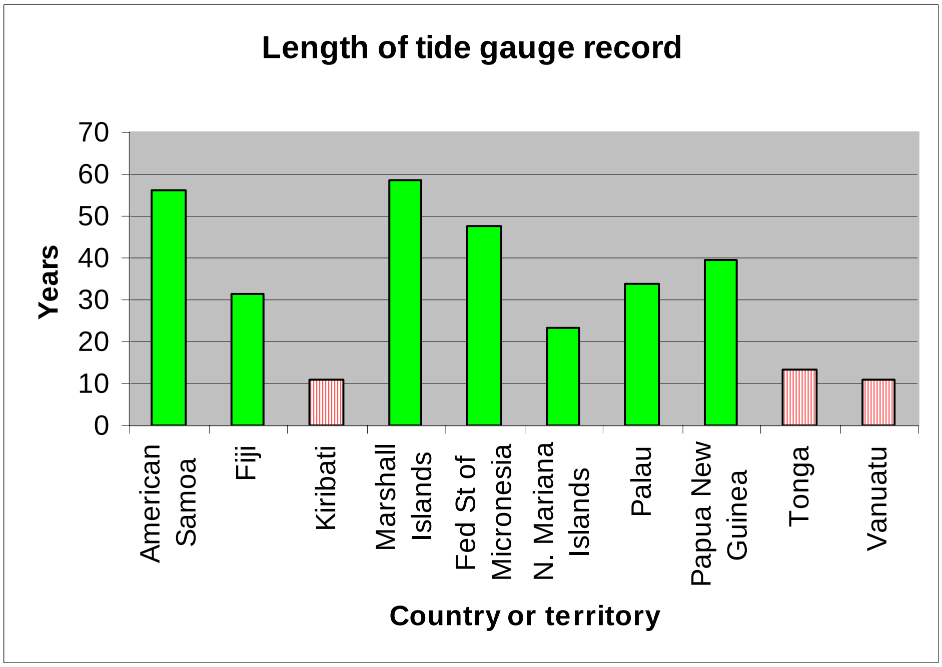

Fig. 2. Length of tide gauge records of ten Pacific Island Countries and territories with indigenous mangroves. Bars with vertical lines have a tide gauge record < 20 years.

2.2. Information on change in sea-level relative to mangrove surfaces

Information on trends in change in the elevation of the mangrove surface over recent decades by installing tide gauges in individual mangroves, using a Surface Elevation Table (Cahoon et al., 2002a,b), or otherwise by measuring sedimentation accretion and erosion rates is needed to determine how sea-level has been changing in recent decades relative to the mangrove surface. Sedimentation rates can be determined by measuring ^{137}Cs or excess ^{210}Pb activity in shallow sediment cores, observing sedimentation stakes, using soil horizon markers, or conducting precision surveying (e.g., DeLaune et al., 1978; Lee and Partridge, 1983; Lynch et al., 1989; Krauss et al., 2003; Gilman et al., In Press).

American Samoa and the Federated States of Micronesia have some information on mangrove sedimentation rates, obtained from monitoring the change in distance of the mangrove surface from the top of sedimentation stakes and from determining ^{137}Cs and Excess ^{210}Pb activity depth profiles from shallow sediment cores (Krauss et al., 2003; Gilman et al, In Press). This contributes to understanding how sea-level has been changing in recent decades relative to the mangrove surface. Otherwise, regionally there is a lack of information on how sea-level is changing relative to mangrove surfaces. The mangrove surface can change in elevation from sediment accretion or erosion and from subsurface processes, such as organic matter decomposition, sediment compaction, fluctuations in sediment water storage and water table levels, and root production (Lynch et al., 1989; Donnelly and Bertness, 2001; Krauss et al., 2003; Gilman et al., In Press; Rogers et al., 2005). Information on trends in change in the elevation of the mangrove surface over recent decades is needed.

2.3. Analysis of historical imagery to observe changes in mangrove margin positions

Analysis of a time series of recent historical remotely sensed imagery such as aerial photographs and satellite imagery, which show the positions of mangrove seaward margins, can be used to observe trends in movement of the mangrove margins (erosion or seaward progression). This information can then be used to determine if the movement has been correlated with the observed trend in relative mean sea-level, and predict the future position of the seaward margin. Extrapolation from observations of historical shoreline movement will be more accurate the longer the time period covered by the available imagery. The extrapolation assumes that no new large forces, such as from future human alterations to the coastline's sediment budget, will substantially change the trend from the recent observations.

Eight countries and territories have historical imagery ≥ 25 years old (Fig. 3). Only American Samoa has analyzed available historical imagery to observe historical trends in changes in position of mangrove margins (Gilman et al., In Press). An effort to identify additional historical aerial photographs, provide IKONOS and QuickBird space imaging to in-country GIS practitioners, and provide assistance to co-register available historical imagery to the georeferenced satellite imagery is needed. Some countries and territories may need assistance to establish or augment capacity of a GIS program.

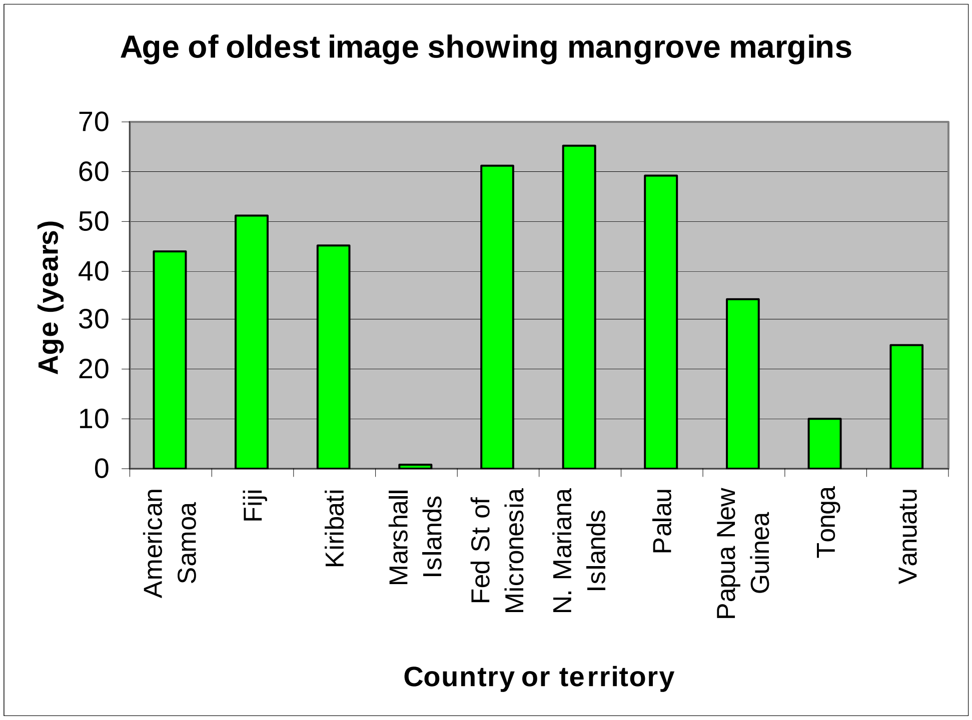

Fig. 3. Age of oldest known historical imagery showing the location of mangrove margins, for ten Pacific Island Countries and territories with indigenous mangroves.

2.4. Mangrove boundary delineation

Periodic delineation of the mangrove landward margin using GPS or traditional survey techniques is needed to observe any movement of the boundary, providing fundamental information needed to determine trends in mangrove area. Interpretation of remotely sensed imagery (aerial photos and space imaging) generally can be used to delineate the mangrove seaward margin (e.g., Gilman et al., In Press), otherwise, delineation with GPS and survey equipment is needed.

Five of nine countries and territories have delineated 80% or more of their mangrove boundaries (Fig. 4). Two countries have no mangrove boundary delineations. While Papua New Guinea has delineated mangrove boundaries, the percent that has been delineated is not known, and is not included in Fig. 4. Four of the ten countries and territories have delineated mangrove boundaries within the last ten years. This highlights the need by some countries and territories to delineate mangrove boundaries at regular intervals.

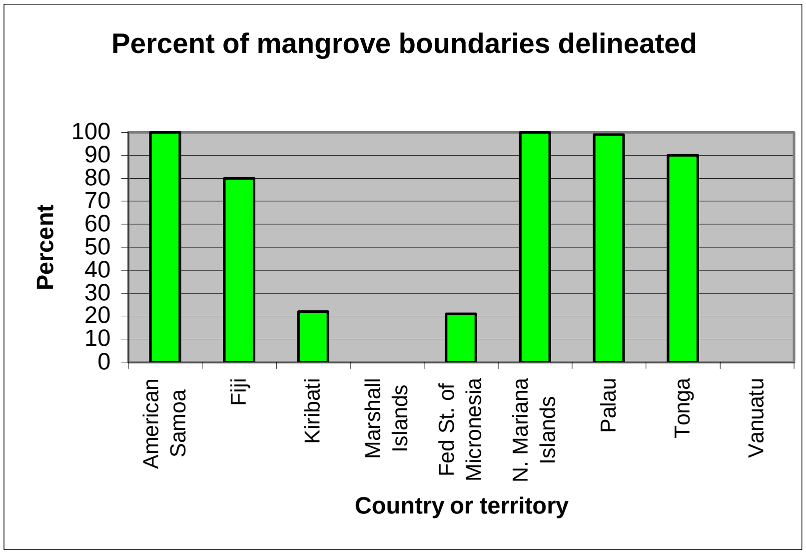

Fig. 4. Percent of total mangrove area with boundaries delineated of nine Pacific Island Countries and territories with indigenous mangroves.

2.5. Map products

Topographic information is needed to determine the mean slope of the land immediately adjacent to the landward mangrove margins to calculate estimated rates of landward mangrove migration. This requires a recent delineation of the landward mangrove margin. Alternative scenarios for projected change in sea-level relative to the mangrove surface can then be used to estimate the distance that the landward mangrove margin will move.

If sea-level is rising relative to the mangrove surface, then information on the current location of any obstacles to the landward migration of mangroves, such as seawalls, buildings, and roads, and the distance that these structures are from the current landward mangrove margin, is needed to determine how these structures may obstruct future landward mangrove migration.

Some countries identified a need for topographic maps and maps showing the location of roads and development in the vicinity of mangroves. Support for in-country GIS programs may be needed to produce these map products. Seven of the countries and territories have > 85% topographic map coverage of their mangrove islands (Fig. 5). Two lack any topographic map coverage of their mangrove islands. Five countries and territories have maps showing locations of development and roads in the vicinity of all mangroves (Fig. 6). Two countries lack maps showing development and roads next to any of their mangroves.

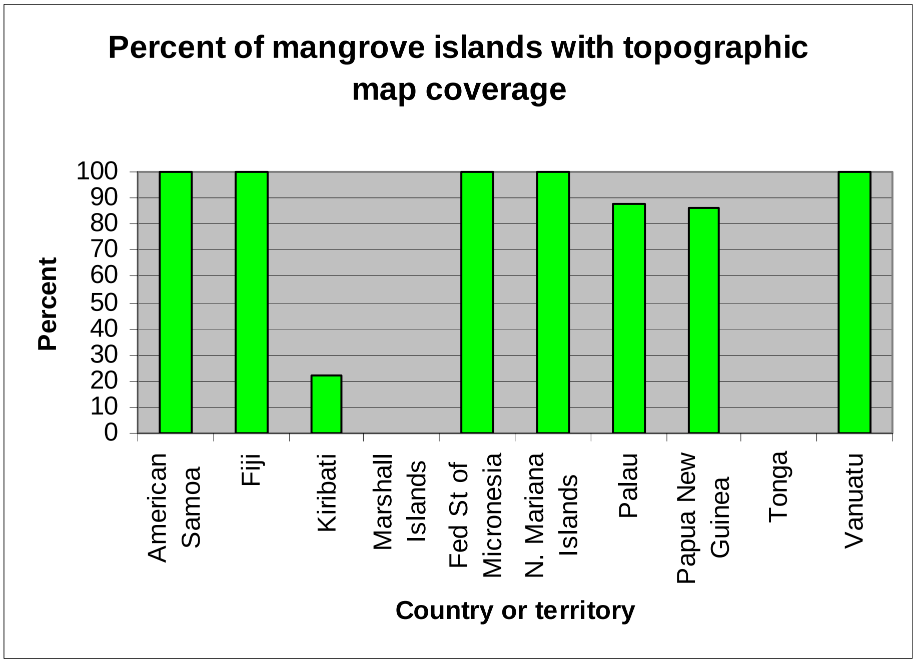

Fig. 5. Percent of the islands with mangroves that also have topographic map coverage, for ten Pacific Island Countries and territories with indigenous mangroves.

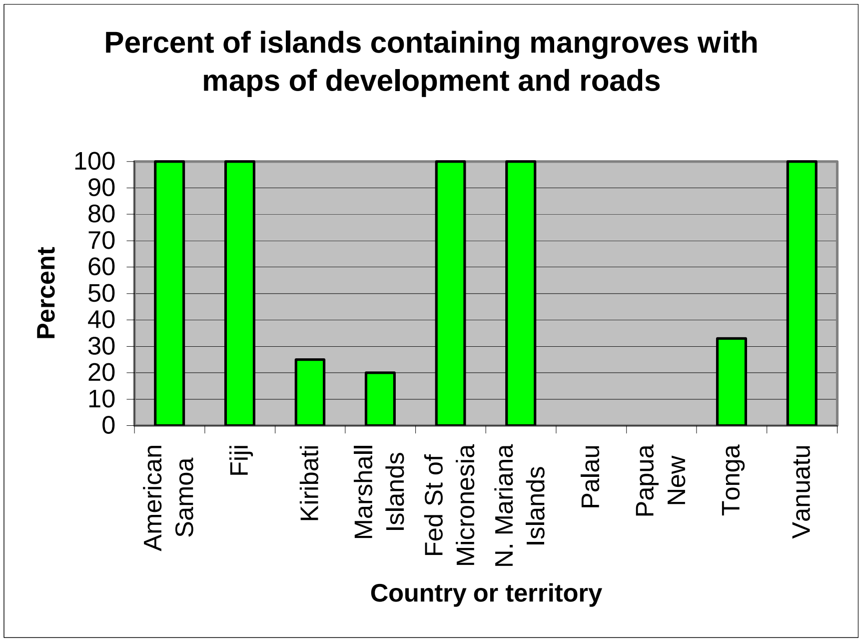

Fig. 6. Percent of islands containing mangroves for which maps showing the location of development and roads are available, for ten Pacific Island Countries and territories with indigenous mangroves.

2.6. Mangrove monitoring and assessment for adaptive management and regional mangrove monitoring network

Given uncertainties about future climate change and responses of mangroves and other coastal ecosystems, we need to manage adaptively and proactively. In-country staff with training, experience, and motivation is required to conduct monitoring and assessment of relevant mangrove parameters, in part, to facilitate adaptive management. Sea-level and climate changes are expected to alter mangrove position, area, structure, species composition, and health. Linking national mangrove monitoring efforts through a regional network using standardized techniques would enable the separation of site-based influences from global changes to provide a better understanding of mangrove responses to global climate and sea-level change and alternatives for mitigating adverse effects (Ellison, 2000; Nurse et al., 2001).

Four countries and territories identify a strong need for training and capacity-building of in-country personnel in mangrove assessment and monitoring: Vanuatu, Kiribati, Northern Mariana Islands, and Palau. Other countries (American Samoa, Tonga, Fiji, Marshall Islands, Papua New Guinea, and the Federated States of Micronesia) have some in-country capacity already, but identify information gaps. Fiji, Federated States of Micronesia and American Samoa conduct some monitoring of mangrove tree girth (diameter at breast height or DBH), which allows quantitative assessment of mangrove ecosystem change in community structure and growth rates. Palau and Tonga have more limited monitoring, such as of birds or human impacts.

There has also been no coordination between the limited mangrove monitoring work that has been done. The countries and territories with a mangrove monitoring program do not employ standardized techniques to enable a meaningful comparison of results from the different programs. Other countries have no monitoring. There is no Pacific Islands regional mangrove monitoring program in place. All countries indicate that they would be interested in participating in a regional network to monitor mangroves and assess mangrove response to sea-level rise and climate change, if such a network were established.

Projections are available over coming decades for rising sea-level and changes in climate and weather (Church et al., 2001; Houghton et al., 2001). These changes are expected to alter the position, area, structure, species composition, and health of most coastal communities, including mangroves. Establishing mangrove baselines and monitoring gradual changes through regional networks using standardized techniques will enable the separation of site-based influences from global changes to provide a better understanding of mangrove responses to sea-level and global climate change, and alternatives for mitigating adverse effects (Ellison, 2000; Nurse et al., 2001). The monitoring system, while designed to distinguish climate change effects on mangroves, would also therefore show local effects, providing coastal managers with information to abate these sources of degradation.

Establishing a regional wetland monitoring network for the Pacific Islands region has been proposed in the *Action Strategy for Nature Conservation in the Pacific Islands Region* (South Pacific Regional Environment Programme, 1999a), and the *Regional Wetlands Action Plan for the Pacific Islands* (South Pacific Regional Environment Programme, 1999b). This has not been implemented to date.

2.7. Strengthen management frameworks

Governments need the institutional capacity to manage a land-use permit or zoning program to ensure coastal earthmoving and development activities are sustainable, including accounting for effects on mangroves, and to plan for any landward mangrove migration.

While existence of a coastal permit and zoning program does not necessarily mean that current legal and management frameworks and political will are adequately preventing mangrove degradation, it indicates that the institution capacity needed to sustainably manage activities in mangroves and other sensitive coastal ecosystems exists. Given an existing coastal development permit or zoning program, if the political will exists, it could be possible to establish zoning setbacks for new coastal development adjacent to mangroves in certain sections of coastline, adopt rules on where hard versus soft engineering erosion control structures can and cannot be constructed, and determine which sections of coastline would undergo managed retreat versus fortification.

All ten participating countries and territories report having some form of coastal permitting or zoning program that regulates coastal activities such as earthmoving and development activities. The existence of a framework to manage coastal activities is part of the requisite institutional capacity to sustainably manage activities in mangroves and other sensitive coastal ecosystems. However, this does not necessarily mean that current legal and management frameworks and political will are adequately preventing mangrove degradation. There is a need to assess the efficacy of national management frameworks at preventing mangrove degradation to determine if this is an area in need of attention. For instance, despite the existence of a permit program for coastal development activities, the wetlands management framework in the U.S. Commonwealth of the Northern Mariana Islands has not been preventing site-specific, island-wide, or cumulative losses of wetland functional performance or wetland area (Gilman, 1998 and 1999a). And Palau's state Public Land Authorities have been leasing and allowing the development of property containing mangroves (Republic of Palau Office of Environmental Response and Coordination, 2002).

Only American Samoa has assessed the site-specific vulnerability of mangroves to sea-level and climate change (Gilman et al., In Press). Information from the case studies and a review of National Communication Reports to the United Nations Framework Convention on Climate Change reveal that none of the ten countries and territories have developed a plan for adaptation to mangrove or other coastal ecosystem responses to climate change effects. Technical assistance is needed to support conducting site-specific vulnerability assessments and to incorporate this information into land-use and master planning.

2.8. Mangrove rehabilitation

Capacity to rehabilitate (restore, enhance and create) mangroves will compliment adaptation to mangrove response to sea-level and climate change. Restoring areas where mangrove habitat previously existed, enhancing degraded mangroves by removing stresses that caused their decline, and creating new mangrove habitat will help to offset anticipated reductions in mangrove area and increase resilience to climate change effects (Hansen and Biringer, 2003; Ellison, 2004). If successful mangrove rehabilitation has been achieved in the past, this indicates that it may be possible to replicate this success at other sites. However, failure to provide adequate training to coastal managers in the basics of successful mangrove rehabilitation leads to project failures or projects that only partially achieve stated goals (Lewis, 2005).

There has been limited activity in the region in rehabilitation of mangroves, with small-scale successful projects only recorded from Kiribati, Northern Mariana Islands, Palau, and Tonga and two failed mangrove rehabilitation efforts in American Samoa and Papua New Guinea. The results of two additional rehabilitation efforts in Palau and Fiji are not known. This highlights the need for improved staff training, capacity building and information sharing.

3. Considerations for Developing a Coastal Site Planning and Adaptation Strategy

Management authorities, especially of small island countries and territories, are encouraged to assess site-specific mangrove vulnerability to climate change effects now and not wait for problems to become apparent when options for adaptation will be restricted. Managers can then incorporate the results of these vulnerability assessments into coastal land-use policies to provide adequate lead-time to minimize social disruption and cost, minimize losses of valued coastal habitats, and maximize available options. The policy adopted to manage site-based shoreline response to rising sea-level will be made as part a broader coastal planning analysis. This analysis requires balancing multiple and often conflicting objectives of allowing managers and stakeholders to sustain the provision of ecological, economic, and cultural values; address priority threats to natural ecosystem functioning; maintain ecological processes and biodiversity; achieve sustainable development; and fulfill institutional, policy, and legal needs (Gilman, 2002).

Site planning for some sections of shoreline containing mangroves that are not highly developed may call for abandonment and adaptation to manage long-term retreat with relative sea-level rise (Dixon and Sherman, 1990; Mullane and Suzuki, 1997; Ramsar Bureau, 1998; Gilman, 2002). "Managed retreat" involves implementing land-use planning mechanisms before the effects of rising sea-level become apparent, which can be planned carefully with sufficient lead time to enable economically viable, socially acceptable, and environmentally sound management measures.

Coastal development can remain in use until the eroding coastline becomes a safety hazard or begins to prevent landward migration of mangroves, at which time the development can be abandoned or moved inland. Adoption of legal tools, such as rolling easements, can help make such eventual coastal abandonment more acceptable to coastal communities (Titus, 1991). Zoning rules for building setbacks and land use for new development can be used to reserve zones behind current mangroves for future mangrove habitat. Managers can determine adequate setbacks by assessing site-specific rates for landward migration of the mangrove landward margin (Gilman et al., In Press). Construction codes can be instituted to account for relative sea-level rise rate projections to allow for the natural inland migration of mangroves based on a desired lifetime for the coastal development (Mullane and Suzuki, 1997). Any new construction of minor coastal development structures, such as sidewalks and boardwalks, should be required to be expendable with a lifetime based on the assessed sites' erosion rate and selected setback. Otherwise, the structure should be portable. Rules could prohibit landowners of parcels along these coasts from constructing coastal engineering structures to prevent coastal erosion and the natural inland migration of mangroves. This managed coastal retreat will allow mangroves to migrate and retain their natural functional processes, including protecting the coastline from wind and wave energy.

Employing shoreline erosion control measures, such as surge breakers, dune fencing, and detached breakwaters, can help reduce the rate of coastal erosion (Mullane and Suzuki, 1997). Use of hard engineering technology, including groins, seawalls, revetments, and bulkheads, a traditional response to coastal erosion and flooding in small island states and worldwide, can increase coastal vulnerability (Tait and Griggs, 1990; Fletcher et al., 1997; Mullane and Suzuki, 1997; Mimura and Nunn, 1998; Nurse et al., 2001). These coastal engineering structures usually can effectively halt erosion as relative sea-level rises, but often lead to the loss of the coastal system located in front of and immediately downstream in the direction of longshore sediment transport from the structure, converting the seaward coastal system into deepwater habitat (Tait and Griggs, 1990; Fletcher et al., 1997; Mullane and Suzuki, 1997). For some sites, it may be less expensive to avoid hard solutions to relative sea-level rise and instead allow coastal ecosystems to migrate inland. These ecosystems provide natural coastal protection that may be more expensive to replace with artificial structures (Mimura and Nunn, 1998; Ramsar Bureau, 1998). However, results of site planning may justify use of hard engineering technology and shoreline erosion control measures to prevent erosion for some sections of highly developed coastline adjacent to mangroves. As a result, the mangroves' natural landward migration will be prevented and the mangrove fronting the development will eventually be lost, along with its valued function of buffering the developed coastline from wave and wind energy.

Most cost-benefit analyses included in site planning only examine costs and benefits as measured by market prices, ignoring mangrove and other coastal system values not described by established monetary indicators (Dixon and Sherman, 1990; Ramsar Bureau, 1998). Site planning and cost-benefit analyses employed to determine if a section of coastline abutting a mangrove should be fortified or undergo managed retreat should account for the benefits of allowing mangroves to undergo natural landward migration under a rise in relative sea-level. These benefits include the continued provision of valued services and products, including consumptive benefits, education and research, aesthetic and cultural benefits, and future values such as a mangroves future potential for tourism (Dixon and Sherman, 1990; Ramsar Bureau, 1998).

Customary management systems, although weakened, still continue to function at some level throughout the Pacific islands region (Johannes, 1982; Huber and McGregor, 2001; Gilman, 2002). Community-based approaches, which capitalize on traditional knowledge and management systems, and catalyze stakeholder support for requisite conservation measures, are suitable in some regions. Stakeholders will be more likely to comply with restrictions on their traditional resource use activities if they understand and support the rules, which can be accomplished through direct community participation in monitoring, planning, and management decision-making. The rural conditions, including relatively small population size, high dependence of local communities on coastal and marine resources, social cohesion, customary tenure and traditional use of coastal and marine areas and resources, existence of strong and intact traditional authority, and low conventional government management capacity, of some sites make local community-based management through collaboration between local government and the local community (e.g. clans or individual villages) appropriate (White et al., 1994; Whyte, 2001). In more urban areas, the larger and more heterogeneous the local community, more complicated and numerous the multiple resource uses and users are, more numerous external threats to the coastal and marine environment, less recognition of customary tenure and traditional governance, and generally the more complex the site is, there will be a larger need for central government management, where community-based management would be less effective (Huber and McGregor, 2001). The optimal approach to manage adaptation to mangrove responses to climate change effects will depend on the local context.

4. Conclusions and Next Steps

To assess mangrove vulnerability to sea-level rise and other climate change effects and to plan for adaptation, Pacific Island Countries and territories need to build their technical and institutional capacity to:

- Determine trends in relative mean sea-level and trends in the frequency and elevations of extreme high water events, and incorporate this information into land-use planning processes.
- Measure trends in the change in mangrove surface elevation to determine how sea-level is changing relative to the mangrove surface.
- Acquire and analyze historical remotely sensed imagery to observe historical trends in changes in position of mangrove margins.
- Produce topographic maps and maps of locations of development and roads for land parcels adjacent to and containing mangroves, and establish or augment GIS programs. The World Bank-funded Infrastructure Asset Management Project in progress in Samoa might serve as a suitable model.
- Develop standardized mangrove monitoring programs as part of a regional mangrove-monitoring network. Provide training opportunities for in-country personnel to manage the mangrove-monitoring program, coordinate with a regional hub, and conduct monitoring techniques. Monitoring methods would include periodic delineation of mangrove margins.
- Assess efficacy of mangrove management frameworks and provide assistance to manage coastal activities to prevent unsustainable effects on mangroves and other coastal habitats, in part, to increase resilience to climate change effects, and plan for any landward mangrove migration in response to relative sea-level rise.
- Augment regional capacity to rehabilitate mangroves.

Establishing a regional mangrove monitoring network may enable many of the identified capacity-building priorities to be fulfilled, and is one of the highest regional priorities. Participating countries and territories could share technical and financial resources to maximize monitoring and conservation benefits through economy of scale.

Assessing the efficacy of management frameworks to avoid and minimize adverse affects on mangroves and other valuable coastal ecosystems and plan for any landward mangrove migration is also critical. Ensuring that management frameworks are capable of eliminating and minimizing stresses that degrade mangroves is necessary to provide for mangrove resilience to anticipated stresses from sea-level and other climate change effects. And managers will need the institutional capacity to plan for site-specific mangrove response to climate change effects, such as instituting setbacks from mangroves for new development for appropriate sections of coastline. However, management frameworks will only be effective if local communities and management authorities recognize the value of mangrove conservation. It is therefore also a priority to continually develop and augment a mangrove conservation ethic.

The value of wetlands conservation is often underestimated, especially in less developed countries with high population growth and substantial development pressure, where short-term economic gains that result from activities that adversely affect wetlands are often preferred over the less-tangible long-term benefits that accrue from sustainably using wetlands. The status of mangrove wetlands as one of the most threatened natural communities worldwide, of which roughly 50% of the global area has been lost since 1900 (Ramsar Secretariat, 1999), supports this observation. Stresses associated with relative sea-level rise and other effects from climate change present one set of threats to mangroves and other coastal ecosystems. Mangroves experiencing stress from other anthropogenic activities such as clearing trees and dumping of pollutants will be less resilient to these additional climate-related stresses. Local communities and leaders must recognize the long-term benefits of mangrove conservation to reverse historical trends in loss of mangrove area, maximize mangrove resilience to climate change, and where sea-level is projected to rise relative to mangrove surfaces, enable unobstructed natural landward migration wherever possible. Education and outreach programs are an investment to bring about changes in behavior and attitudes by having a better-informed community of the value of mangroves and other ecosystems. This increase in public knowledge of the importance of mangroves can provide the local community with information to make informed decisions about the use of their mangrove resources, and can result in grassroots support and increased political will for measures to conserve and sustainably manage mangroves.

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