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ORIGINAL ARTICLE

Assessment of mangrove response to projected relative sea-level rise and recent historical reconstruction of shoreline position

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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. A 12% reduction in mangrove area by the year 2100 is possible in the Pacific islands region.

Keywords American Samoa · Coastal · Erosion · Mangrove · Sea-level rise · Wetland

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

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decades (Church *et al.*, 2001, 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 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):

- *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, displacing other coastal habitats, 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

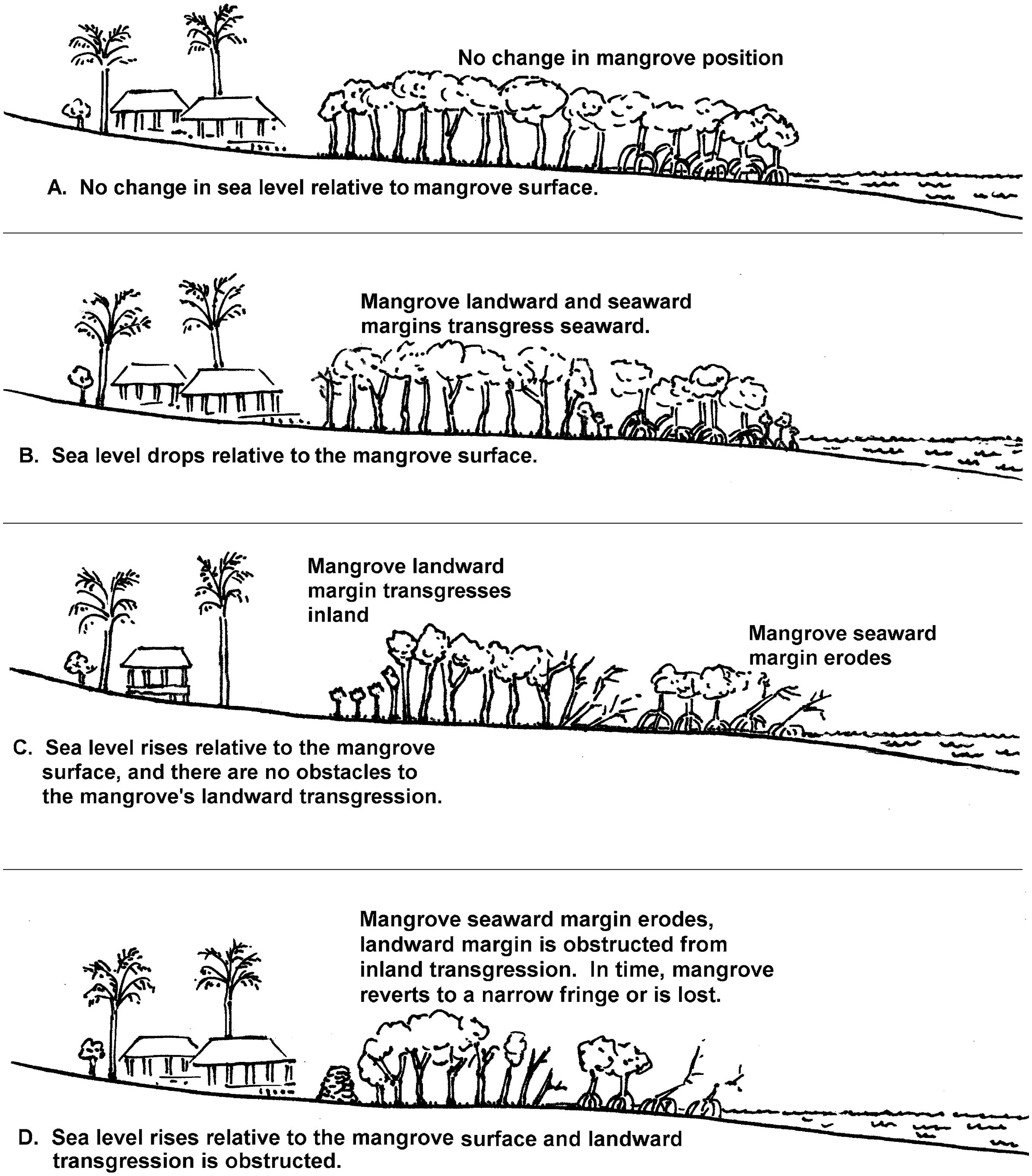

Fig. 1 Four scenarios for generalized mangrove response to relative sea-level rise

(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, 1990; Wakushima *et al.*, 1994a, b). 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,b; 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 sulphate and reduced salinity (McKee, 1993; Ellison, 2000, 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 mangrove losses continue (Amerson *et al.*, 1982; American Samoa Coastal Management Program 1992; Bardi and Mann, 2004).

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

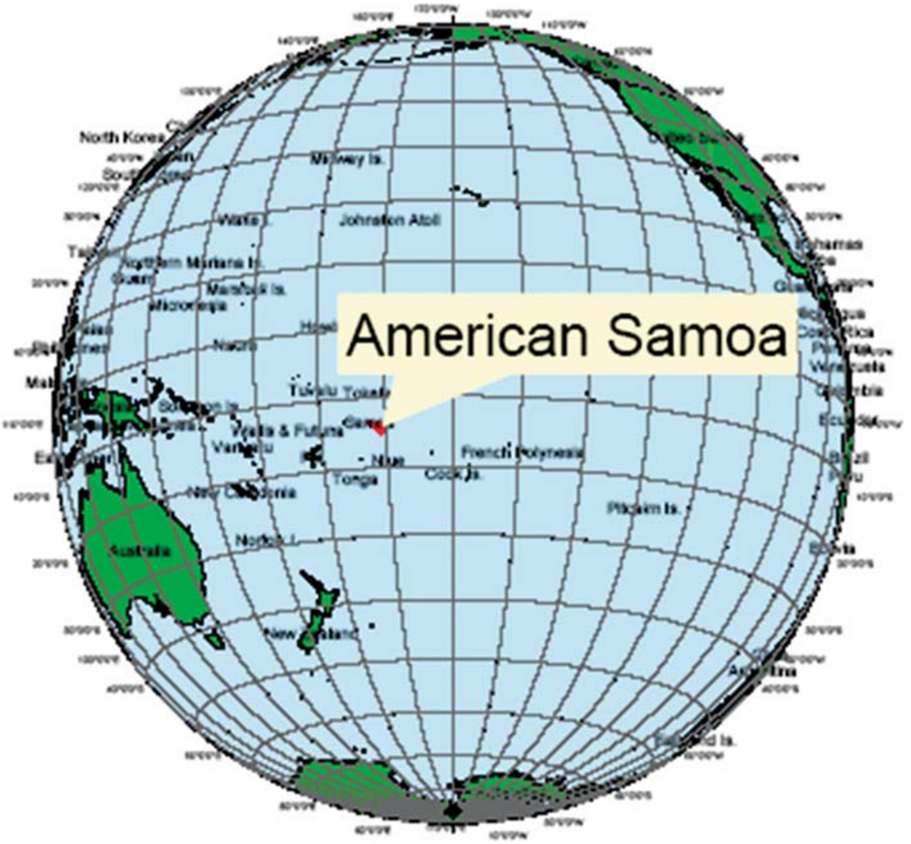

Fig. 2 Location of American Samoa, the Eastern portion of the Samoa archipelago, located between 168 and 173 W longitude and 13 and 15 S latitude

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 to 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

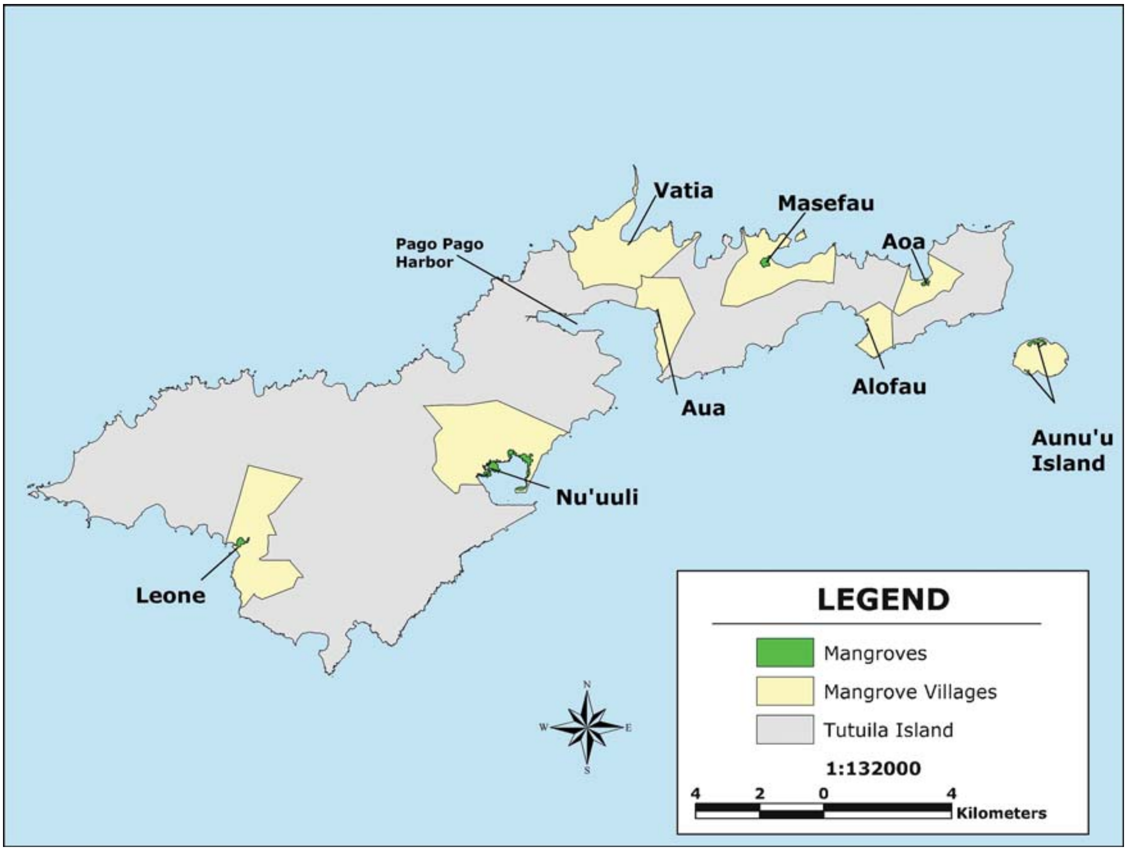

Fig. 3 Location of American Samoa's nine mangroves, including the three study sites, Leone, Nu'uuli, and Masefau mangroves, on Tutuila and Aunu'u Islands

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 2.5, Table 2.5.1, 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 $1.5 \pm 0.5\,\mathrm{mm\,a^{-1}}$ (Church *et al.*, 2001; Cazenave and Nerem, 2004), while Church *et al.* (2004a) provide an estimate of $1.8 \pm 0.3\,\mathrm{mm\,a^{-1}}$ from 1950–2000. The observed American Samoa rate of relative sea-level change during the 20th century (October 1948 through December 2000) of $1.77\,\mathrm{mm\,a^{-1}}$ (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:

$$\frac{25{,}000\ \mathrm{m}^2\ \text{observed change mangrove area 16 Sept 1961—15 Dec. 2003}}{0.083\ \mathrm{m}\ \text{change relative sea—level 16 Sept. 1961—15 Dec. 2003}} = \frac{X\ \mathrm{m}^2\ \text{change mangrove area 15 Dec. 2003—15 June 2100}}{0.82\ \mathrm{m}\ \text{projected change relative sea—level 15 Dec. 2003—15 June 2100}}$$

where $X = 246{,}988\,\mathrm{m}^2$, 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 $1.97\,\mathrm{mm\,a^{-1}}$, 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

Figure 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. 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.

3.2 Time series analysis of mangrove seaward margins

Figures 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.

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}.

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

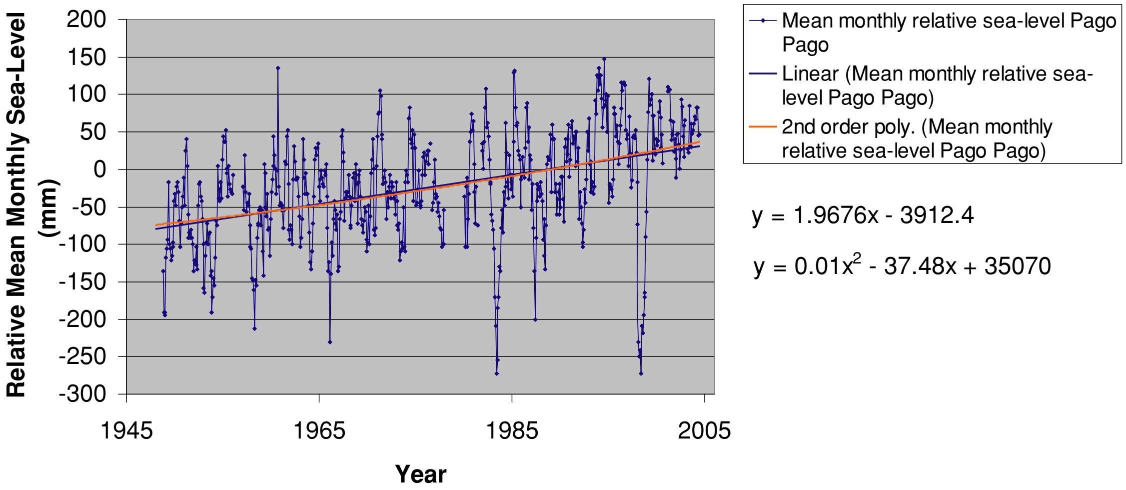

Fig. 4 Mean monthly relative sea-level from a tide gauge located in Pago Pago harbor, American Samoa, from October 1948 – May 2004. Gaps appear in the data plots where there were not enough data to produce a reliable monthly mean. Linear and second order polynomial regression models are fit to the data.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

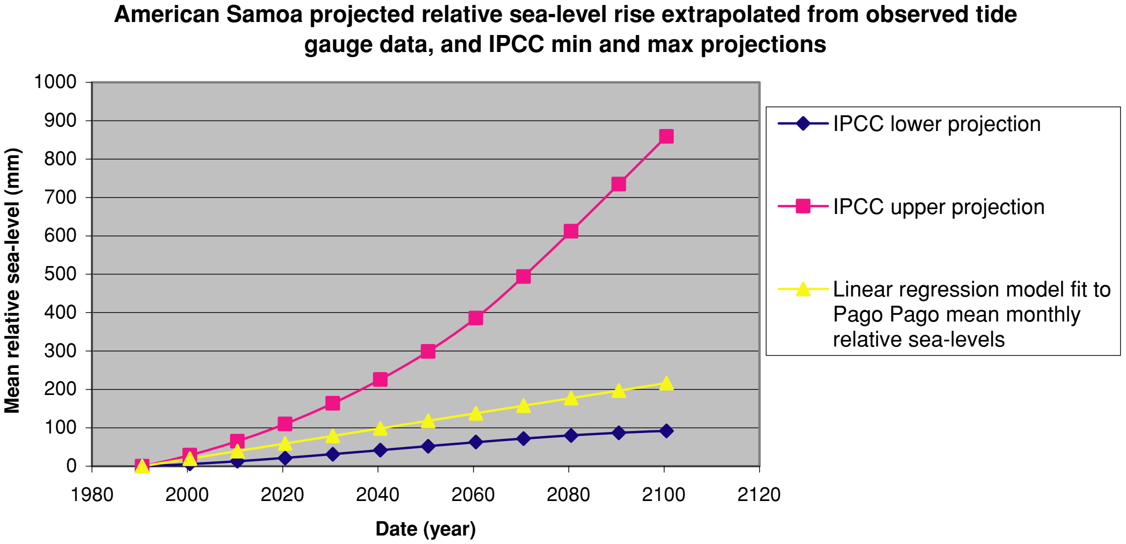

Fig. 5 Plot of a linear regression model fit to the mean monthly relative sea-level tide gauge data for Pago Pago, American Samoa from 1948 – 2004 ($y = 1.97(x) - 3921.3$) plotted from the middle of 1990 through the middle of 2100, where the relative sea-level 0 mm benchmark is set to the middle of 1990, 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)

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

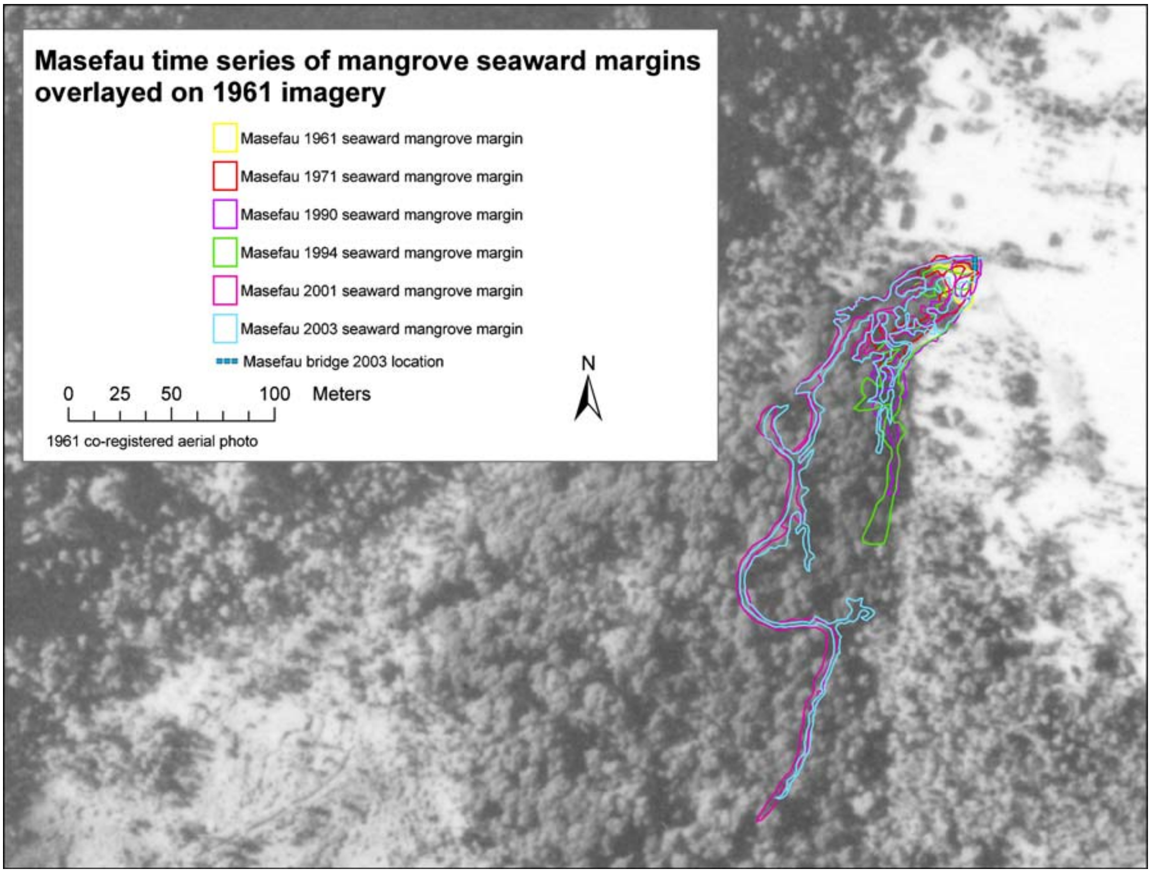

Fig. 6 Time series of Masefau mangrove seaward margin at six points in time from 1961–2003 overlayed on a 1961 co-registered aerial photo and 2003 QuickBird space imaging *(Continued on next page)*

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 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.

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 and 47,996 m^2,

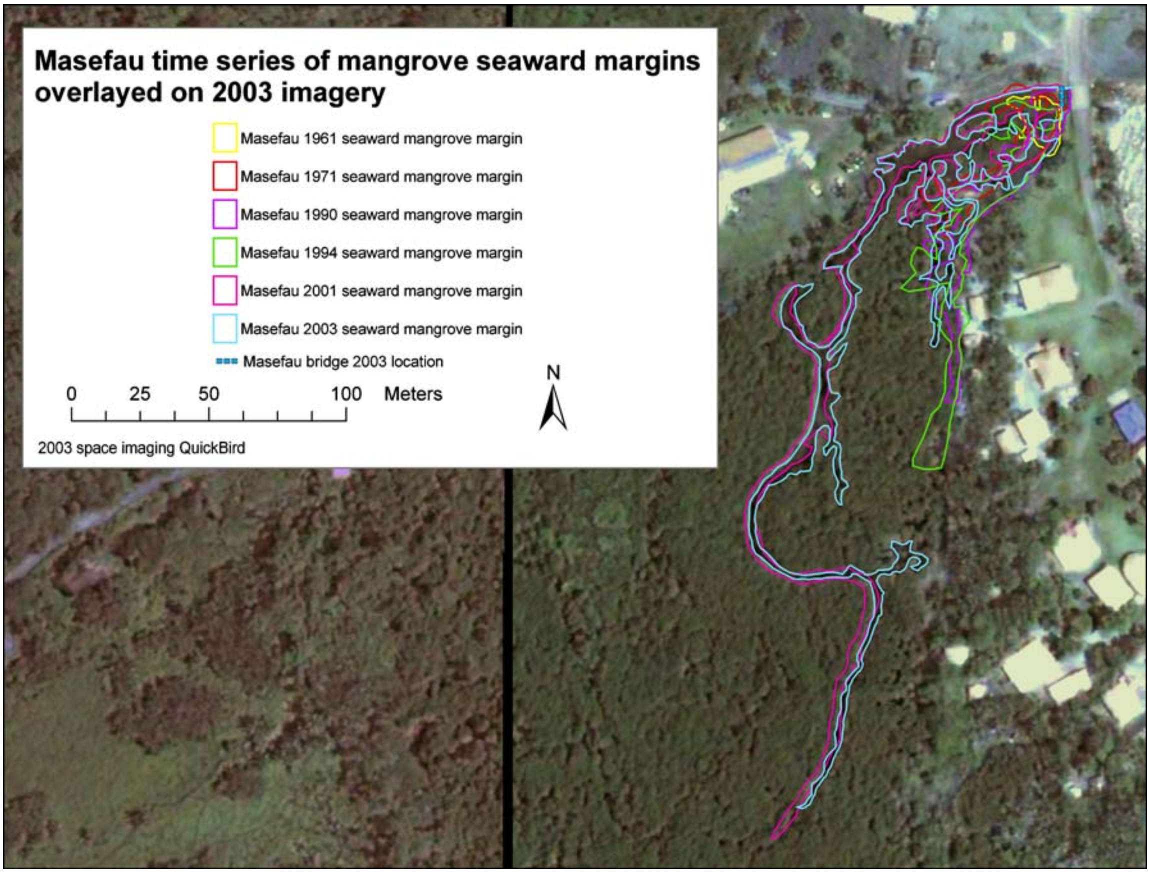

Fig. 6 *(Continued)*

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 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

4.1 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,

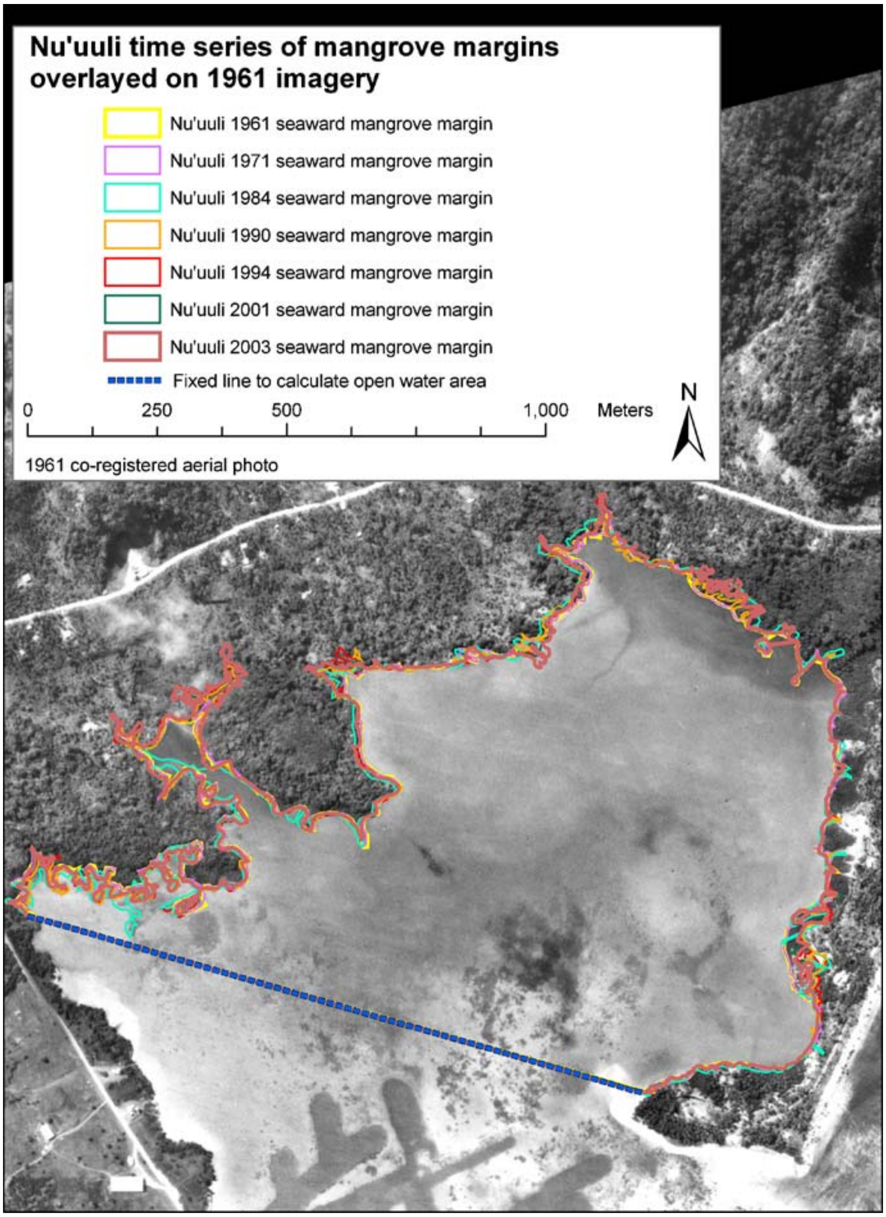

Fig. 7 Time series of Nu'uuli mangrove seaward margin at seven points in time from 1961–2003 overlayed on a 1961 co-registered aerial photo and 2003 QuickBird space imaging

(Continued on next page)

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

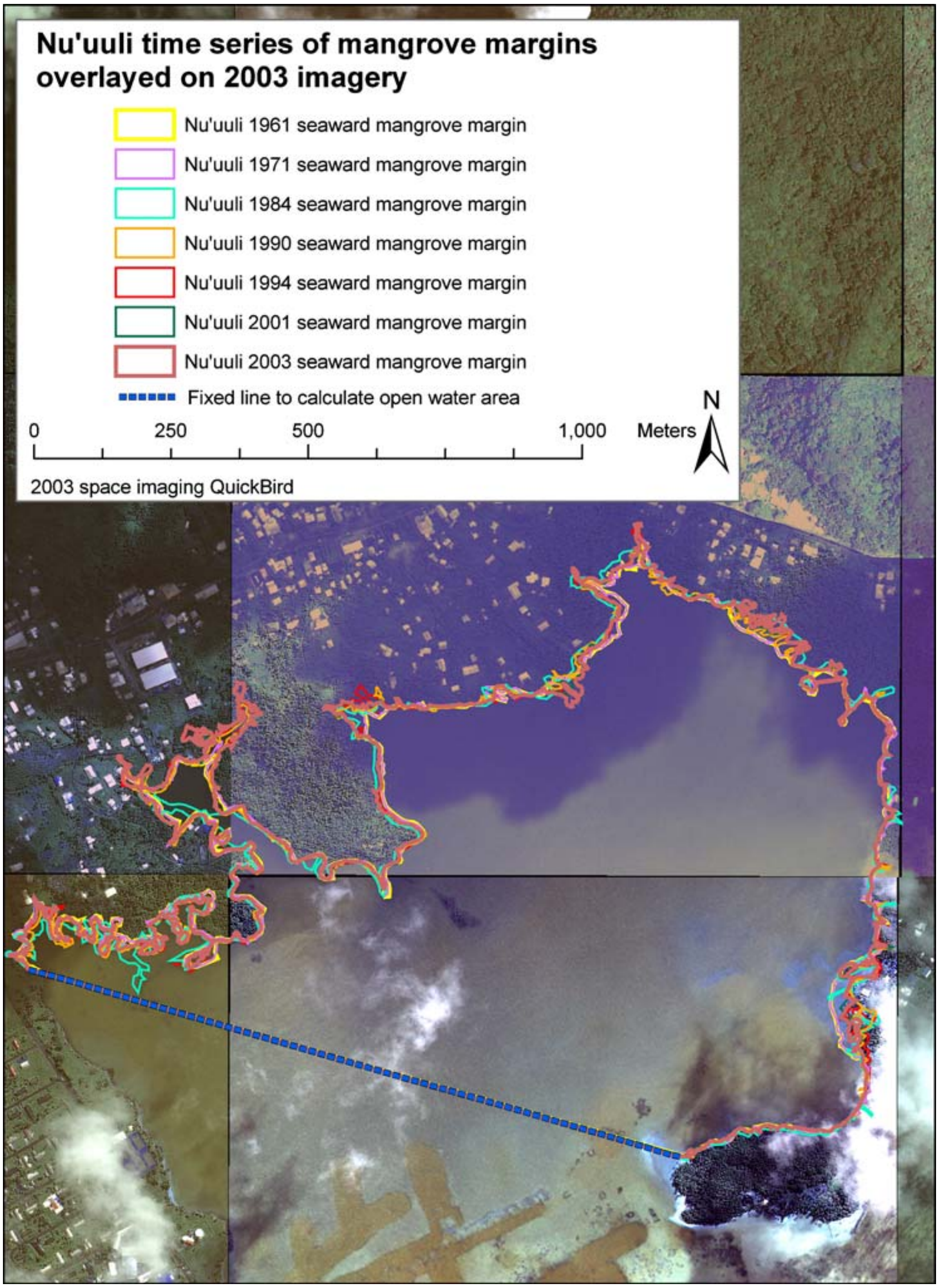

Fig. 7 *(Continued)*

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.

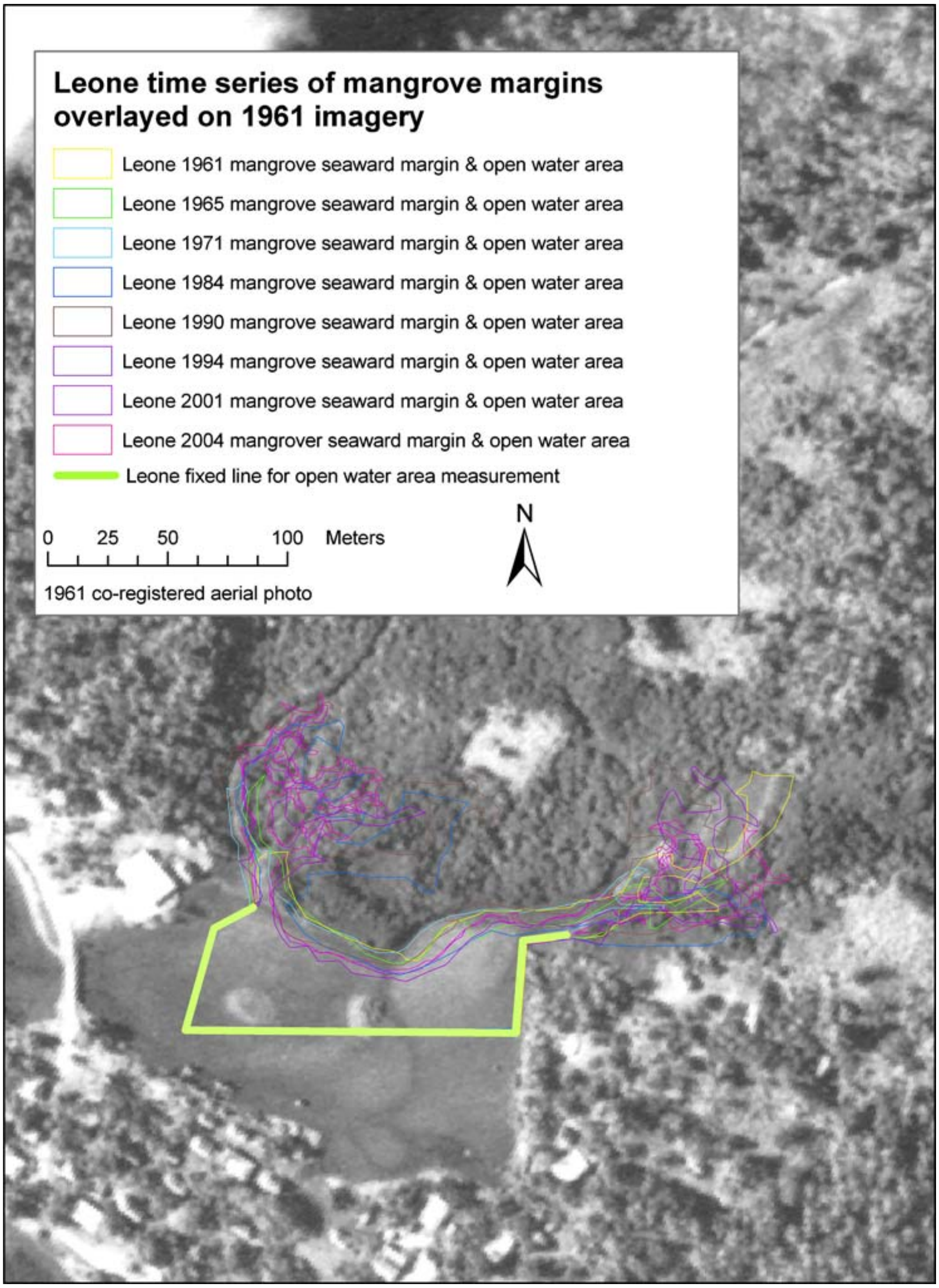

Fig. 8 Time series of Leone mangrove seaward margin at eight points in time from 1961–2004 overlayed on a 1961 co-registered aerial photo and 2004 QuickBird space imaging

(Continued on next page)

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

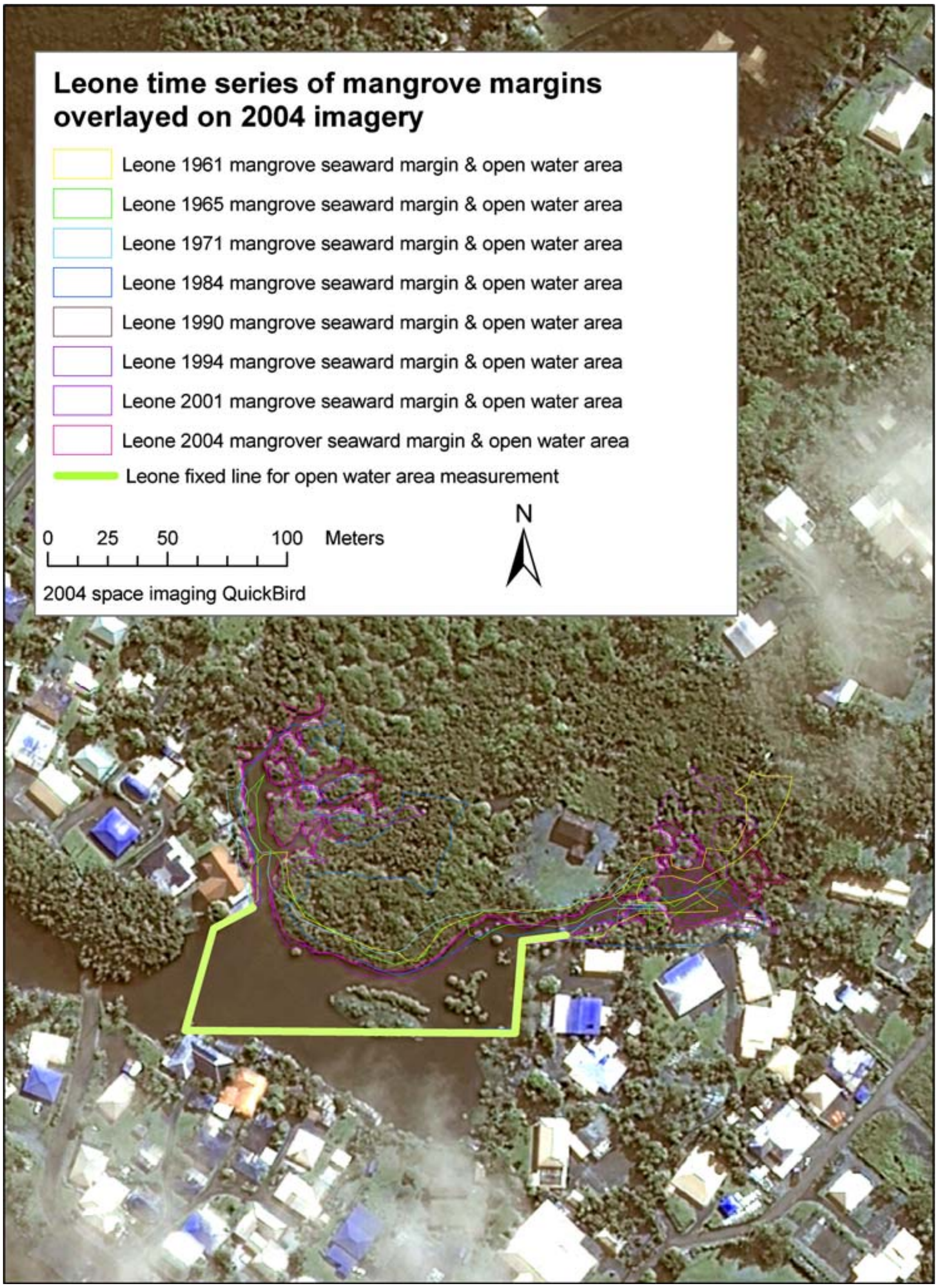

Fig. 8 *(Continued)*

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

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

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.

4.2 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

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 seaward mangrove area ($m^2\ a^{-1}$)	Rate of landward migration of 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	47	34
Extrapolate using observed trend in relative sea-level from American Samoa tide gauge	6,451	67	48
Upper projection IPCC	21,663	224	161
Nu'uuli[d]			
Lower projection IPCC	23,160	240	30
Extrapolate observed historical erosion rate	46,729	484	64
Extrapolate using observed trend in relative sea-level from American Samoa tide gauge	53,073	550	70
Upper projection IPCC	228,812	2,370	310

[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 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

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,

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	32.1	32.9
Upper projection IPCC	13,291	138.3	141.8
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}

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

Table 4 Rough estimate of mangrove response to relative sea-level change for the 16 Pacific Island countries and territories where mangroves are indigenous

Country/territory[a]	Current mangrove area (ha)	Relative sea-level change rate (mm a^{-1})[b]	Rate of change in mangrove surface elevation (mm a^{-1})	Year 2100 mangrove area extrapolating applying historic relative sea-level trends (ha)[c]	Year 2100 mangrove area IPCC upper projection (ha)[c]
American Samoa	52[d]	1.97	4.5[e]	52	38
Northern Mariana Islands	5[f]	0.9	1.2[e]	5	3
Federated States of Micronesia	8,564[g]	1.8	1.3[h]	8,299	4,616
Fiji	41,000[i]	6.7	4.5[e]	35,383	17,343
Guam	70[j]	−0.6	1.2[e]	70	48
Kiribati	258[k]	−0.4	1.2[e]	258	175
Marshall Islands	4[l]	2.8	1.2[e]	3.6	1.8
Nauru	1[j]	−1.94	1.2[e]	1	0.8
New Caledonia	20,250[m]	0.2	4.5[e]	20,250	17,314
Palau	4,500[n]	1.0	4.5[e]	4,500	3,609
Papua New Guinea	372,770[j]	−0.73	4.5[e]	372,770	341,457
Samoa	700[o]	−5.0	4.5[e]	700	700
Solomon Islands	64,200[p]	−7.0	4.5[e]	64,200	64,200
Tonga	1,305[q]	1.3	1.2[e]	1,297	737
Tuvalu	40[j]	2.3	1.2[e]	37	20
Vanuatu	2,750[j]	1.0	4.5[e]	2,750	2,206

[a] Hawaii and Tahiti, where mangrove were introduced (Ellison, 1999; Allen 1998), 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) and one true mangrove species *Excoecaria agallocha* is documented from Niue (Tomlinson, 1986), this species is also found in non-wetland habitat such as littoral forest, and a national government contact reported that there are no mangrove wetlands in Niue (personal communication, 10 June 2005, Fiafia Rex, Fisheries Division, Niue Department of Agriculture Forestry & Fisheries)

[b] Calculated from fitting a simple linear regression model to mean monthly relative sea-levels from historical tide gauge records with tidal constituents removed for Pohnpei, Federated States of Micronesia; Suva, Fiji; Guam, USA; Kanton Island, Republic of Kiribati; Majuro, Republic of the Marshall Islands; Noumea, New Caledonia, France; Malakal, Palau; Honiara, Solomon Islands; and Funafuti, Tuvalu. Calculated from fitting a simple linear regression model to mean monthly relative sea-levels for Pago Pago, American Samoa; Nauru; and Port Moresby, Papua New Guinea. For Saipan, Commonwealth of the Northern Mariana Islands, USA; Apia, Samoa; Nuku'alofa, Tonga; and Port Vila, Vanuatu, sites with a local tide gauge record of <20 years, relative sea-level change trends are calculated from TOPEX/Poseidon satellite altimetry data combined with historical global tide gauge records over the period 1950-2001 employing the method by Church *et al.* (2004a). Papua New Guinea has less than 20-year tide gauge record but results from reconstructed analysis was not available

[c] For countries and territories where sea-level is rising relative to the mangrove surface, we assume that the ratio of 1.97 mm a^{-1} mangrove relative sea-level rise rate to 12.3% reduced mangrove area by year 2100 assessed for American Samoa applies for mangroves in other areas when extrapolating from observed relative sea-level rise rates to project relative sea-level through the year 2100. A ratio of 7.59 mm a^{-1} mangrove relative sea-level rise rate to 50.0% reduced mangrove area is used when employing the IPCC's upper projection for global sea-level rise through the year 2100. For this scenario, the global mean sea-level was estimated to have risen 1.5 mm a^{-1} during the twentieth century, and is projected to rise at 8.0 mm a^{-1} from 1990–2100 (Church *et al.*, 2001), which is a mean increase of 6.5 mm a^{-1} sea-level rise (this interprets the IPCC projection to be a linear rise instead of a variable slope, and ignores the acceleration term, which introduces some error into this analysis). For sites where either relative sea-level is not rising or the estimated rate of change in elevation of the mangrove surface exceeds the projected rate of change in relative sea-level, we assume there is no net change in mangrove area. These calculations assume that the slope of the land adjacent to the mangrove, seaward margin erosion rate, presence of obstacles to landward migration of mangroves, proportion of the total mangrove area that has a seaward and landward margin, and other factors are similar at these sites as was observed at the three American Samoa mangrove sites. Also, relative sea-level trends may be based on analysis of data from a tide gauge located far from the mangrove sites and may not reflect the relative sea-level trend at the mangrove locations (Gilman *et al.*, 2005)

[d] Bardi and Mann (2004)

[e] Based on a generalization from Ellison and Stoddart (1991). Does not account for subsurface processes such as root production, decomposition, compaction, and dewatering, which change the elevation of the mangrove surface and hence affect the sea-level change rate relative to the mangrove surface (Lynch *et al.*, 1989; Donnelly and Bertness, 2001; Krauss *et al.*, 2003)

[f] Gilman (1998, 1999b)

[g] MacLean *et al.* (1998), compilation of previous assessments interpreting aerial photography from 1976 combined with 1983 fieldwork

(Continued on next page)

Table 4 *(Continued)*

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[h] Average of observed sedimentation rates from plots in *Rhizophora spp.*, *Sonneratia alba*, and *Bruguiera gymnorrhiza* mangrove stands in the Enipoas River basin, Pohnpei, Federated States of Micronesia measured using stakes driven to a depth of 70 cm observed over 2.5 years (Krauss *et al.*, 2003). Does not account for subsurface processes occurring below 70 cm, which can change the elevation of the mangrove surface (Lynch *et al.*, 1989; Donnelly and Bertness, 2001; Krauss *et al.*, 2003)

[i] Watling (1985)

[j] Scott (1993). For Papua New Guinea, estimate is between 353,770 and 391,770 ha. For Vanuatu, estimate is between 2,500 and 3,000 ha

[k] Nenenteiti Teariki-Ruatu, personal communication, February 2005, Republic of Kiribati Ministry of Environment, Lands, and Agricultural Development

[l] John Bungitak, personal communication, August 2005, Environmental Protection Agency, Republic of the Marshall Islands

[m] Thollot (1987)

[n] Maragos (1994); Metz (2000)

[o] Pearsall and Whistler (1991)

[p] Hansell and Wall (1976)

[q] Wiser *et al.* (1999)

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).

4.3 Comment on Bruun rule model assumptions applicability to mangroves and use for small temporal and spatial scales

Calculation of the mangrove seaward margin erosion rate using a predictive model of beach erosion called the Bruun rule (Bruun, 1962, 1988), or a modified Bruun rule, was not relied on for this study as mangroves are not expected to respond in accordance with Bruun rule assumptions and because, the Bruun rule, as with other general predictive models of coastal erosion, is not suitable for small-scale, site-specific estimates (Bruun, 1988; List *et al.*, 1997; Komar, 1998; Pilkey and Cooper, 2004). The Bruun rule and modifications of the model have been used broadly to estimate erosion of various coastal types despite a large body of evidence that this largely results in inaccurate estimates of both past erosion rates and future erosion estimates at specific locations and over short time periods (SCOR Working Group, 1991; List *et al.*, 1997; El-Raey *et al.*, 1999; Pilkey and Cooper, 2004).

Bruun (1962, 1988) provides a simplistic model of change to beach profile with sea-level rise, and assumes a closed material balance system so that the migrating beach has no net loss of sand volume, and that there is a uniform sandy shoreface with no outcrops or other obstacles that could cause non-uniform retreat rates to sea-level rise spatially and temporally (Bruun, 1988; Komar, 1998; Pilkey and Cooper, 2004). The Bruun (1962, 1988) model assumes that with increased sea-level, the equilibrium beach profile and shallow offshore migrates upward and landward, the upper beach is eroded due to the landward translation of the profile, the material eroded from the upper beach is deposited immediately offshore, and the rise in nearshore bottom equals the rise in sea-level.

The results from this study observed erosion rates of the mangrove seaward margin of 12.4, 32.4, and 36.7 times the rate of relative sea-level rise for Leone, Masefau, and Nu'uuli mangrove study sites, respectively. Assuming an average slope of many coastlines of 0.01–0.02, according to the Bruun model, the landward recession rate will be between 50 to 100 times the rate of relative sea-level rise (Bruun, 1962, 1988; SCOR Working Group, 1991; Komar, 1998). The slopes of the three mangrove study sites are estimated to be 0.007 (range 0.002–0.025) based on the local tidal range ($\sim$1 m), mean width of the three mangrove study sites of about 75 m (range 2–300 m), and that mangroves are generally located between the level of mean high water spring tides (just above the high tide line) and mean sea level (Ellison, 2001, 2004), the upper half of the tidal range, in this case being 0–0.5 m above msl. In this case, the Bruun model predicts an erosion rate of about 143 times the relative sea-level rise rate, which is inconsistent with observations.

Because mangroves have different sediment budget processes than beaches, mangroves are not expected to respond in accordance with Bruun rule assumptions. For instance, mangrove sediment is generally finer grained than that of beaches, and wave energy dissipates as waves progress through mangroves. Furthermore, the Bruun Rule produces inaccurate erosion estimates because other factors can be considerably larger forces causing shoreline changes than relative sea-level rise, especially over relatively small temporal and spatial scales (Bruun, 1988; List *et al.*, 1997; Komar, 1998; Nunn, 2000; Donnelly and Bertness, 2001; Pilkey and Cooper, 2004).

5 Conclusions – regional implications

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.

Table 4 projects change in mangrove area through the year 2100, based on observations from American Samoa and several large assumptions, for countries and territories of the Pacific Islands region where mangroves are indigenous. Based on extrapolating relative sea-level trends through the year 2100, the current estimated 516,469 ha of indigenous mangroves in the Pacific islands region would be reduced by only 1.1%. However, using IPCC's upper projection for global sea-level rise through the year 2100, Pacific island mangrove area could be reduced by 12.4%.

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.*, 2005). 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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