

Trends in surface elevations of American Samoa mangroves

Eric Gilman · Joanna Ellison · Ierupaala Sauni Jr ·
Solialofi Tuaumu

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Abstract Rates of change in elevation of mangrove surfaces, determined from observations of changes in the height above the mangrove surface of stakes, generally inserted through the organic peat layer to reach consolidated substrate, were measured in one fringe and one basin mangrove wetland on Tutuila Island, American Samoa. Knowledge of trends in elevation change of coastal wetlands contributes to assessing vulnerability to projected relative sea level rise. The fringe and basin mangroves had rates of change in elevation of -0.6 mm yr^{-1} (± 2.0) and -2.2 mm yr^{-1} (± 5.6), where a negative result means lowering in elevation. These trends were not statistically significant ($P > 0.05$) and the error intervals around the point estimates of trends in change in elevation overlap zero for both study sites, meaning that it is not clear if the mangrove surfaces have been lowering, rising or not changing. Despite the large error intervals, likely due to short-term variability and cyclical patterns in sedimentation, results indicate

that the fringe mangrove has been experiencing a rise in sea level relative to the mangrove surface as the relative sea level rise rate ($+1.65$ to $+2.29 \text{ mm yr}^{-1}$) has been exceeding the rate of change in elevation of the mangrove surface (-2.6 to $+1.4 \text{ mm yr}^{-1}$). It is unclear if the basin mangrove has been experiencing a rise in sea level relative to the mangrove surface. If upper projections for accelerated relative sea level rise in American Samoa occur over coming decades, American Samoa mangroves will migrate landward, where unobstructed, as a natural response to relative sea level rise.

Keywords American Samoa · Mangrove · Elevation change · Sedimentation · Sea level rise

Introduction

Relative sea level¹ rise is a major factor contributing to recent losses and further projected future

E. Gilman · J. Ellison
School of Geography and Environmental Studies,
University of Tasmania, Hobart, Australia

I. Sauni Jr · S. Tuaumu
Department of Commerce, American Samoa Coastal
Management Program, American Samoa, USA

Present Address:

E. Gilman (✉)
2718 Napuaa Place, Honolulu, HI 96822, USA
e-mail: egilman@utas.edu.au

¹ 'Relative sea level change' is the change in sea level relative to the local land, as measured at a tide gauge relative to a fixed benchmark. Sea level measured at a tide gauge is a combination of the (i) change in 'global' ('absolute' or 'eustatic') sea level, the change in sea level relative to a fixed Earth coordinate system, which results from a change in the volume of water in the world oceans, which, over human time scales of decades, is due primarily to thermal expansion of seawater and the transfer of ice from glaciers, ice sheets and ice caps to water in the oceans; and (ii) local forces, such as vertical

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 (IUCN 1989; McLean et al. 2001; Gilman et al. 2006a, b). Global sea level rise is one of the more certain outcomes of global climate change, 12–22 cm occurred during the last century, and several climate models project accelerated rate of sea level rise over coming decades (Church et al. 2001, 2004; Cazenave and Nerem 2004; Holgate and Woodworth 2004; Thomas et al. 2004; Church and White 2006; IPCC 2007). Small island developing states and low-lying coastal areas of continents are particularly vulnerable to small increases in sea level (Gilman et al. 2006a, b). Accurate predictions of changes to coastal ecosystems, including mangroves, in response to projected relative sea level rise enable advance planning to minimize and offset anticipated ecosystem losses and reduce threats from coastal hazards (Hansen and Biringer 2003; Ellison 2004; Gilman et al. 2006a, b, 2007).

When relative sea level rise is the predominant factor 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, 2006; Berdin et al. 2003). Such predictions can be based on (i) the mean sea level change rate relative to the mangrove surface, (ii) 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 (iii) erosion or progradation rate of the mangrove seaward margin (Ellison and Stoddart 1991; Ellison 1993, 2000, 2001; Woodroffe 1995; Gilman et al. 2007). 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 (Semeniuk 1980; Ellison 1993, 2000, 2001; Woodroffe 1995; Gilman et al. 2007). 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 (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 mangrove tree species to colonize newly available habitat to keep 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 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 (Ellison and Stoddart 1991). The sediment composition of the upland habitat where the mangrove is migrating may also influence the migration rate and species composition (Semeniuk 1994). Other environmental conditions for recruitment and establishment of mangroves in new areas that become available with a rise in sea level include competition with non-mangrove plant species, soil suitability, and availability of waterborne seedlings.

Change in mangrove position will be variable over relatively small temporal and spatial scales (SCOR Working Group 1991; Woodroffe 1995; Gilman et al. 2007). 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 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; Gilman et al. 2007). Retreat of the

Footnote 1 continued

motion of the land from tectonic movement (e.g., earthquakes, slow mantle convection and sediment transport), the response of the Earth's crust to changes in the weight of overlying ice or water, coastal subsidence such as due to extraction of subsurface groundwater or oil, and sediment consolidation, as well as oceanographic processes such as El Nino phases and changes in offshore currents (Church et al. 2001; Hunter 2002). Relative sea-level changes as measured by tide gauges are therefore a result of the movement of the land on which the tide gauge is located and/or changes in absolute sea level.

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.

Mangrove boundary position will also be variable where other natural and anthropogenic factors exert a larger influence on mangrove margin position than changing sea level. Mangrove species each 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). While there is still incomplete understanding of what combination of factors control mangrove establishment and health, changes in any of these factors, whether resulting from natural variations, such as variability in coastal currents, or from anthropogenic development activities, can result in changes in the location of mangrove margins irrespective of any sea level rise (Donnelly and Bertness 2001; Saintilan and Wilton 2001).

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 also affect coastal systems, including mangroves (McKee 1993; Field 1995; Snedaker 1995; Ellison 2000, 2004; Gilman et al. 2005). For instance, rise in temperature and the direct effects of increased CO₂ levels are likely to increase mangrove productivity, change phenological patterns (such as the timing of flowering and fruiting), and expand the ranges of mangrove species into higher latitudes (McKee 1993; Field 1995; Snedaker 1995; Ellison 2000, 2004). Changes in precipitation and subsequent changes in aridity may affect the distribution of 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).

In this study, we use trends in elevation change of the surface of two mangrove wetlands in American

Samoa based on measurements of stakes to assess the vulnerability of the mangroves to projected sea level rise relative to the mangrove surfaces.

Stakes have been used extensively to observe rates of change in surface elevation of mangroves (Lee and Partridge 1983; Krauss et al. 2003), river and stream banks (Bradbury et al. 1995), estuaries, mud flats (Kirby et al. 1993), and salt marshes (Lee and Partridge 1983). The stakes are typically inserted into the sediment at intervals along transects positioned perpendicular to the coastline from low to high water across the coastal system (Lee and Partridge 1983; Kirby et al. 1993; Bradbury et al. 1995). The initial height of the top of the stakes above the sediment surface and changes in the height over time are recorded (Lee and Partridge 1983; Kirby et al. 1993; Bradbury et al. 1995). In high energy environments such as river and streambanks, mudflats, and estuaries, narrow steel rods 1–2 m long, 10 mm diameter, have been successfully used (Kirby et al. 1993; Bradbury et al. 1995).

The most precise method to measure the change in sea level relative to the mangrove surface would be to install a tide gauge within the mangrove site and survey from the tide gauge to a series of benchmarks throughout the site. This would be expensive, labor intensive to observe, and require a minimum of a 20-year local tide gauge record to obtain an accurate trend in relative sea level (Church et al. 2004). Alternatively, there are several methods that can be used to observe trends in mangrove surface elevation and sediment accretion and erosion. GPS technology may achieve mm precision and accuracy for vertical measurements over distances of a few kilometers, but unfortunately dense canopy cover resulting in changing satellite coverage (loss of lock and reduced availability) in mangroves tends to make current GPS technology unsuitable to monitor trends in the elevation of mangrove surfaces (personal communication, 6 October 2006, Richard Coleman, University of Tasmania). Horizon markers do not permit quantitative measurements of erosion rates, nor does this method measure the affect of subsurface processes on the change in elevation of the mangrove surface, but does provide accurate measurements of accretion. Measurement of ¹³⁷Cs and excess ²¹⁰Pb activity in shallow sediment cores may provide an accurate estimate of rates of change in mangrove surface elevation over recent decades (e.g., Lynch et al.

1989), which can then be compared to the relative sea level change rate as measured by the closest tide gauge. However, this is expensive, especially if multiple cores are taken in an attempt to characterize the entire 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 where a rod is inserted into the sediment to a depth where it reaches consolidated sediment, and is monitored over a sufficient time period, can provide accurate trends in elevation of the mangrove surface (surface elevation table—marker horizon technology, Cahoon et al. 2002; Cahoon and Hensel 2006). This requires that enough points are monitored to adequately characterize entire mangrove sites, which can be expensive, and that all of the rods are inserted to depths where they hit consolidated sediment, which can be time consuming in sites with deep mangrove peat and organic mud layers. A benefit of the surface elevation table method over employment of stakes in measuring changes in elevation of the mangrove surface is that in mangrove sites where the mangrove peat and organic mud layer is thick, all stakes may not be inserted until they hit consolidated sediment, while the rod inserted for each surface elevation table is typically long enough so that it will reach consolidated sediment (Cahoon et al. 2002; Cahoon and Hensel 2006). Also, because the surface elevation table rods are tied into a benchmark, and the benchmark can be converted to current mean sea level, this provides a reference point for the mangrove surface elevations. Furthermore, a benefit of employing the marker horizon method in combination with the surface elevation table method, or in combination with stakes that are consistently inserted until refusal, is that this enables distinguishing the contribution of surface sediment accretion and erosion from subsurface processes in causing the observed change in surface elevation, providing information useful for understanding fundamental mangrove processes.

A limitation in the use of both stakes and surface elevation tables to assess mangrove vulnerability to relative sea level rise is when mangrove study sites are located far from tide gauges, or where there is

<20 year tide gauge record. Many areas experience tectonic movements that result in substantial differences in local sea level relative to global eustatic 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 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 accurately it will reflect the actual sea level changes that are affecting the mangroves (Gilman et al. 2006a, b). 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 accurately calculated using the near global coverage of TOPEX/Poseidon satellite altimetry data combined with historical global tide gauge records (Church et al. 2004).

Methods

Study sites

Samoa is the eastern limit for indigenous mangroves in the Pacific (Ellison 1999). Two sites were selected for this study, which are the two largest mangrove areas of American Samoa, and located on Tutuila Island, a high volcanic island. One site, Nu'uuli (30.69 ha), the largest mangrove in American Samoa, is a fringing, tide-dominated mangrove, with an approximate center at 14 18.844' S, 170 42.766' W. Nu'uuli mangrove 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 (American Samoa Coastal Management Program 1992). Adjacent land uses include commercial and residential development, piggeries, and trash sites (Gilman et al. 2007).

The second site at 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, and is about 6.38 ha. It is the second largest mangrove of American Samoa, with an approximate center at 14 15.421' S, 170

38.048' W. Masefau mangrove receives drainage from a watershed contributing area of approximately 362 ha. Adjacent land uses include a freshwater marsh upslope along the southwestern boundary, residential development primarily along the eastern boundary, piggeries, and trash sites (Gilman et al. 2007).

The predominant soil type of American Samoa mangrove is Ngerungor Variant organic peat, a mixture of peat and basaltic and calcareous sand, comprised of 10–30% organic matter (U.S. Soil Conservation Service 1984; Ellison 2001). The color for moist soil from 0 cm to 10 cm is a very dark grayish brown (10YR 3/2) organic peat. The color for moist soil from 10 cm to 52.5 cm is a very dark brown (10YR2/2) peat (U.S. Soil Conservation Service 1984). In Nu'uuli mangrove the depth of peat and organic mud ranges from 0.01 m (mangrove trees growing on a hard rock base with pockets of organic mud and peat) to >1.5 m, with consolidated calcareous sand underlying the mangrove peat and mud horizon. A stratigraphic core from the seaward edge of mangroves between transects 4 and 5 at Nu'uuli (Fig. 1) showed 100 cm of mangrove mud above calcareous sand, and mud from 80 cm to 100 cm depth gave a radiocarbon date of 620 ± 70 year BP (Ellison 2001). Cores offshore of the seaward edge in the lagoon found mangrove mud underneath shallow calcareous lagoon sediment, indicating past dieback. In Masefau mangrove, the depth of mangrove peat and mud horizon ranges from 0.05 m to

>1.5 m, with consolidated basaltic sand underlying the mangrove peat and mud horizon. A stratigraphic core from the seaward edge of mangroves close to site 2a at Masefau (Fig. 2) showed 150 cm of mangrove mud above calcareous sand, and mud from 140 cm to 150 cm depth gave a radiocarbon date of 410 ± 60 year BP (Ellison 2001). Pollen analysis of this core demonstrated that the swamp had been dominated by *Bruguiera* through this period, as it is today. Tidal range is about 1.1 m. Mean annual rainfall is 312–563 cm. Mean annual temperature is 26.7°C (U.S. Soil Conservation Service 1984).

Elevation change

Changes in surface elevation were measured over 1.53 years, from 25 August 2004 until 6 March 2006, in Nu'uuli mangrove and over 1.30 years from 17 November 2004 until 8 March 2006 in Masefau mangrove using stakes. Figs. 1 and 2 identify the location of the 33 stations (each containing 10 stakes) containing a total of 330 stakes along 10 perpendicular seaward-landward transects located across the major mangrove embayments. The center of stake station locations were determined using Leica SR399 dual frequency and Garmin 72 GPS units, with horizontal accuracies on the order of centimeter and tens of meter, respectively. GPS units were not used to measure vertical position of individual stakes because canopy cover and intermittent satellite

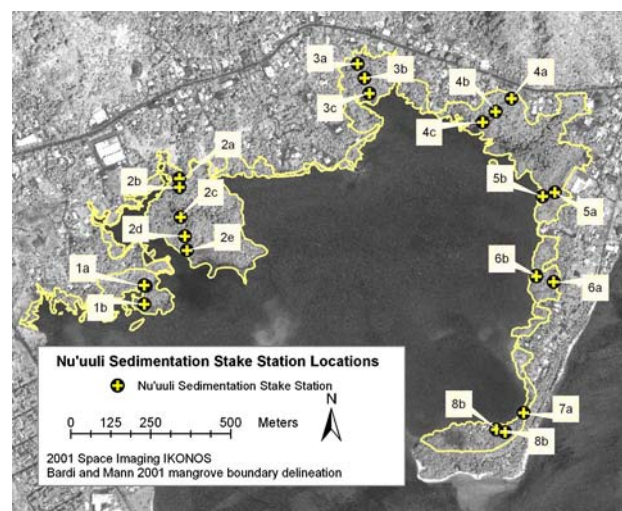


Fig. 1 Location of stations of stakes along transects in Nu'uuli mangrove

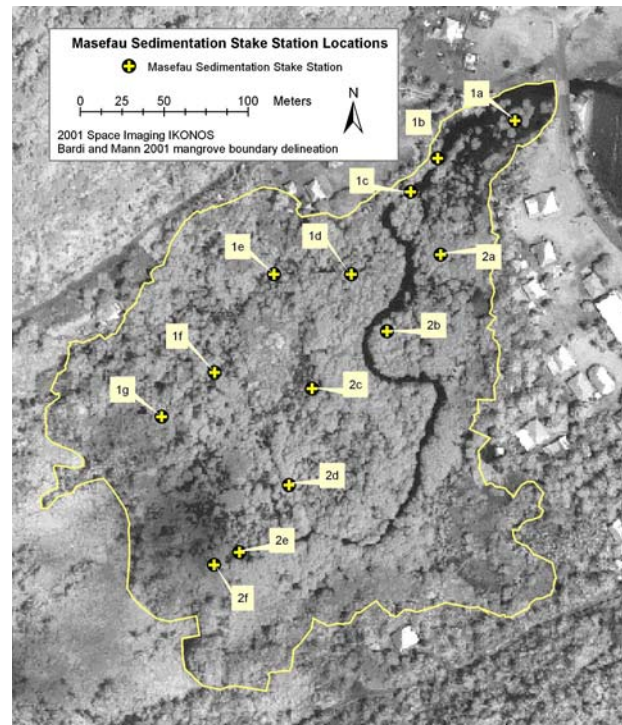


Fig. 2 Location of stations of stakes along transects in Masefau mangrove

coverage prevented achieving vertical error of better than ± 2 cm. Poly vinyl chloride (PVC) stakes were placed into the sediment leaving 15 cm of the stake protruding from the sediment surface, enough so that the stake is unlikely to become buried over coming years, but not so much as to make the stake overly visible to people who might disturb the stakes. Stakes were 1.5 and 2.0 cm in diameter, 1.5 m long, but were cut shorter in areas where the depth of consolidated substrate was shallower than 1.35 m and prevented inserting the full length of the stake. Researchers inserted 279 (85%) of the stakes until they reached consolidated substrate. The remaining 51 stakes did not penetrate the mangrove peat layer to reach hard substrate, but were inserted 1.35 m into the substrate, below mangrove roots. A length of 1.5 m was selected for the stakes to attempt to ensure that the stake is inserted sufficiently below the mangrove roots such that its vertical position is not substantially affected by any belowground biomass production and concomitant increase in elevation of the mangrove surface, as well as to record any other changes in elevation of the mangrove surface occurring within the upper 1.35 m of sediment, such as sediment

compaction, organic matter decomposition, fluctuations in sediment water storage and water table levels (Lynch et al. 1989; Donnelly and Bertness 2001; Krauss et al. 2003; Rogers et al. 2005). Stakes were located in stations of 10 replicates every 50 m along transects, with replicates of five stakes located on either side of the transect every 2 m perpendicular to the transect, with the central two stakes of the station each 2 m from the transect (4 m apart) to minimize disturbance from researchers walking along the transect. During the study period, 34 of the stakes were lost (29 from Nu'uuli and five from Masefau), likely a result of human disturbance. Transects in both study sites were located to cut across vegetation zones by being situated along the gradient from the high water line to lower elevations. Krauss et al. (2003) observed different sediment accretion rates and elevation change rates in different mangrove species stands, highlighting the need to measure accretion and elevation rates from representative locations across vegetation zones to provide results that are characteristic of the entire mangrove site. Nu'uuli transects were located in the center of major mangrove subsections to reduce edge effects and to

ensure that the sites were sufficiently sampled so the resulting data characterizes the entire system (Fig. 1). Transects in Masefau were located starting at the single seaward margin point, with one transect located through the center of the wetland generally along the lowest gradient, and one additional transect fanning out to the East and adjacent to the central transect (Fig. 2).

The initial heights of the top of the stakes above the sediment surface and changes in the heights over time were recorded. Measurements recorded as ± 1 mm from the top of the stake to the wetland surface were taken five times in Nu'uuli and four times in Masefau. The measurements of elevation from the top of the stakes to the wetland surface were made 10 cm from the stake, using a level to keep horizontal with the top of the stake, to avoid any distortion to the wetland surface caused by the presence of the stake, such as from scouring around the base of the stake. The elevations were measured 90° to the right of the stake when the researcher is facing the mangrove seaward margin along a transect that connects stations for stakes in Nu'uuli mangrove and facing the landward margin for stakes in Masefau mangrove, to minimize variance between measurements at the same stakes at different times resulting from variation in microtopography of the mangrove surface and to maximize consistency in measurements made by three researchers. Measurements were attempted to be made only at low tide to facilitate locating the stakes and to reduce error from identifying the mangrove surface when tidal water suspends the fine sediment from the mangrove surface.

Ten measurements of the elevation of a single stake were repeated at a single time by one researcher to provide an indication of the precision (uniformity) of the measurement method. A second researcher made 10 measurements of the elevation of the same stake at the same time to provide an indication of the replicability of the measurement method.

The rate of change in mangrove surface elevation was analyzed in five ways: (i) The mean change in mangrove surface elevation of the 10 stakes of each station versus date was plotted and a trend was calculated by fitting a linear regression model to the data series. (ii) The change in mangrove surface elevation versus date was plotted for each individual stake and a trend was calculated by fitting a linear

regression model to the data series. (iii) A linear regression model is fit to the data from each individual station. The trends in change in mangrove surface elevation and 95% CI are shown on an image of each study site to show the locations where positive and negative changes in elevation were observed. (iv) The mean of mean changes in elevation at each station was determined to estimate a rate of change in elevation for each study site and probable error, and (v) date versus the mean change in elevation for each station were plotted on the same graph to see if any seasonal trends are present.

Results

Ten measurements of the elevation of a single stake were made by two researchers to provide an indication of the precision and replicability of the measurement method. The difference between the two mean measurements was 1.1 mm and the standard deviations of the two means were 1.2 and 0.7 mm.

A linear regression model fit to the data series of the mean change in elevation of the mangrove surface of stakes in a station versus date shows there was a -0.7 mm yr^{-1} (± 2.8 95% CI, $N = 97$, $P = 0.6$) trend in elevation change in Nu'uuli mangrove over the observed 1.53 years (Fig. 3) and a -2.2 mm yr^{-1} (± 5.6 95% CI, $N = 52$, $P = 0.4$) trend in elevation change in Masefau mangrove over the observed 1.3 years (Fig. 4). A negative rate means lowering in elevation of the mangrove surface. These trends were not statistically significant ($P > 0.05$) and the error intervals around the point estimates of trends in change in elevation overlap zero for both study sites, meaning that results are inconclusive regarding whether the mangrove surfaces have been lowering, rising or not changing.

A linear regression model fit to the data series of the change in elevation of the mangrove surface at each individual stake versus date shows there was a -0.6 mm yr^{-1} (± 2.0 95% CI, $N = 902$, $P = 0.6$) trend in elevation change in Nu'uuli mangrove (Fig. 5) and a -2.4 mm yr^{-1} (± 6.2 95% CI, $N = 510$, $P = 0.4$) trend in elevation change in Masefau mangrove (Fig. 6). The point estimates of trends in change in elevation were very close when using the full data series versus the means of stakes in each station. Nu'uuli had a smaller error interval around the point

estimate for the full data series while Masefau had a smaller error interval for the averaged data series of the means of the stations.

Figures 7 and 8 show the location of trends in change in mangrove elevation for each individual station on a 2001 satellite image of the two study sites. In Nu'uuli mangrove, 12 stations had a mean rise in elevation and eight stations had a mean lowering in elevation (Fig. 7). The mean trend in change in elevation of Nu'uuli mangrove's surface was $+0.2 \text{ mm yr}^{-1}$ with a standard deviation of the mean of 1.1 mm yr^{-1} . Masefau had five stations with a mean rise in elevation and eight stations with a mean lowering in elevation (Fig. 8). The mean trend in change in elevation of Masefau mangrove's surface was -2.2 mm yr^{-1} with a standard deviation of the mean of 3.0 mm yr^{-1} .

Figures 9 and 10 show plots of the mean change in mangrove surface elevation for each of the 20 stations in Nu'uuli and 13 stations in Masefau for each date that measurements were made.

Discussion

Results indicate that the sampling method is relatively precise and replicable: if a researcher measured the elevations of 10 stakes at a station and repeated the measurements a second time, the two mean measurements would be within about 1.2 mm of each other. If two different researchers measured the elevations of the same 10 stakes, the two mean elevations would be within about 1.1 mm. The measures taken to maximize consistency in the location where measurements were

taken, by taking the elevation measurement at the same direction and distance from the stake and use of a level, likely contributed to maximizing the precision and replicability of the measurement method.

For both Nu'uuli and Masefau error intervals around the point estimates of trends in change in elevation are large and overlap zero, likely due to the high variability over the temporal and spatial scales observed, the temporal scale being 1.3–1.5 years and spatial scale being on the order of meters between individual stakes in a station. The large error intervals are likely due to the presence of cyclical forces that affect the mangrove surface elevation, and the occurrence of episodic forces that cause short-term pulses in sediment erosion and accretion (Lee and Partridge 1983; Kirby et al. 1993; Bradbury et al. 1995). Trends in elevation change would likely be more apparent, while signals from short-term, episodic, cyclical, and small-scale events would be less apparent over a longer time scale of several years and longer (SCOR Working Group 1991; Semeniuk 1994; List et al. 1997; Pethick 2001; Pilkey and Cooper 2004; Gilman et al. 2007). The potential existence of short-term pulses and cyclical sedimentation patterns in mangroves highlights the benefit of observing stake elevations over long time periods in order to determine accurate estimates of trends in change in surface elevation. The period of time over which stakes were observed in this study were likely too short to provide large confidence in the observed trends as seasonal sedimentation cycles and episodic events such as storms and heavy rain events might have prevented a clear understanding of the long-term trend.

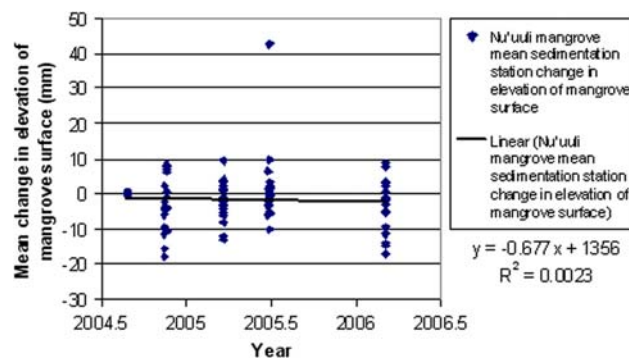


Fig. 3 Nu'uuli mangrove plot of mean change in mangrove surface elevation of stakes in each station versus date

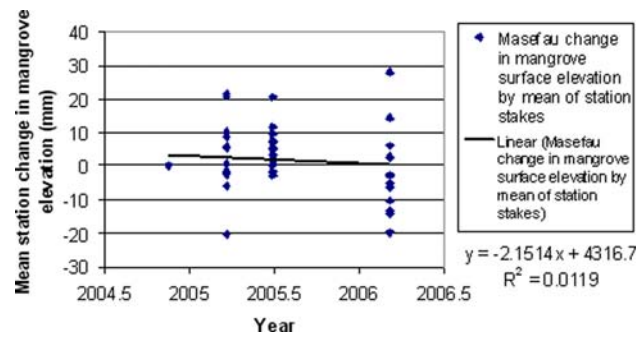


Fig. 4 Masefau mangrove plot of mean change in mangrove surface elevation of stakes in each station versus date.

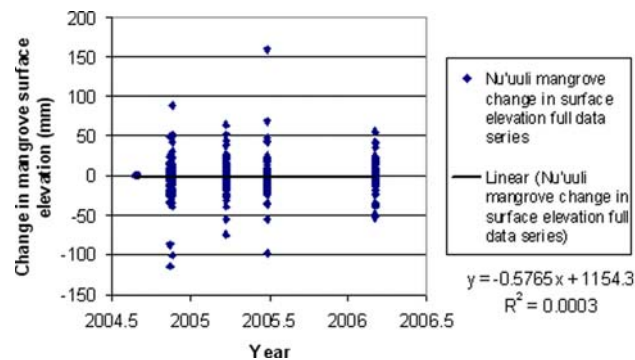


Fig. 5 Nu'uuli mangrove plot of change in mangrove surface elevation at each individual stake versus date

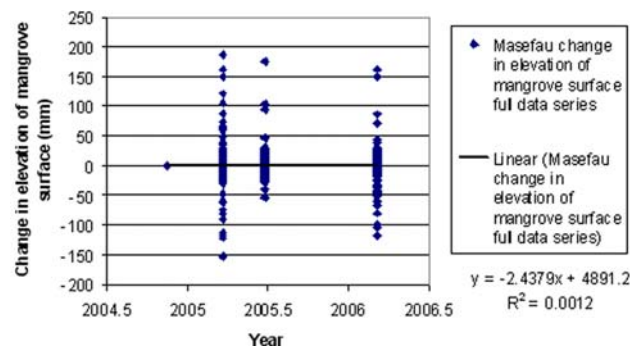


Fig. 6 Masefau mangrove plot of change in mangrove surface elevation at each individual stake versus date

Figures 7 and 8, which show the values for trends in change in mean mangrove surface elevation on a remotely sensed image of the two study sites, reveal no simple spatial patterns, such as a smaller change in elevation at the seaward margin and margins of tidal creeks relative to the landward portions of the mangroves, as would be expected with mangroves experiencing a rise in sea level relative to the mangrove surface (Gilman et al. 2006a, b, 2007).

Vanderzee (1988) models for salt marshes with sediment supply not quite sufficient to keep pace with sea level rise predict that the seaward margins will erode and be deposited in the mid and upper marsh to contribute to accretion. None of the Nu'uuli transects showed this pattern while only transect 2 at Masefau showed it but with some inconsistency. Additional analysis could be conducted to determine if more complex spatial patterns exist.

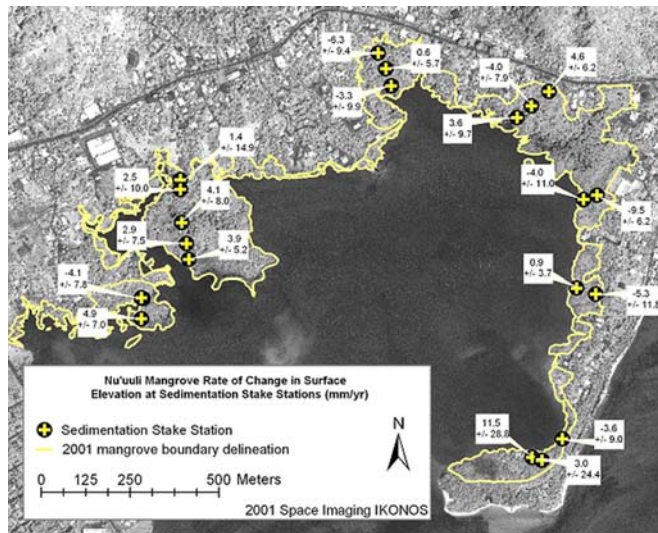


Fig. 7 Nu'uuli mangrove trends in change in surface elevation at individual stake stations and 95% CI. $N = 50$ for most stations

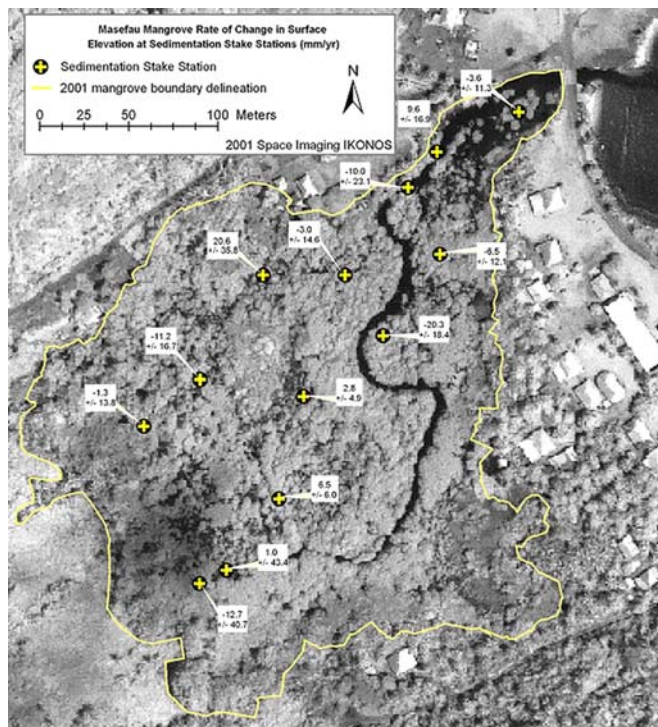


Fig. 8 Maséfau mangrove trends in change in surface elevation at individual stake stations and 95% CI. $N = 40$ for most stations

Figures 9 and 10 reveal no seasonal cycles in change in surface elevation. Some stations were experiencing positive changes in elevation while others were experiencing reductions in elevation at each date when measurements were made. We might

expect there to be large pulses of sediment accretion during the winter rainy season and during storm events, when surface runoff from the mangroves' watershed contributing areas carries terrigenous sediment into the mangroves, while there might be

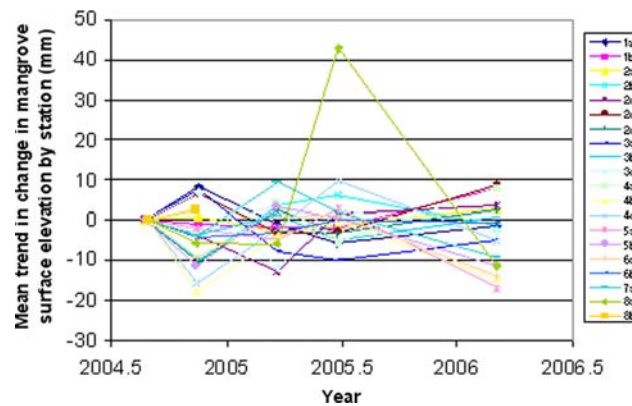


Fig. 9 Nu'uuli mangrove mean trend in change in mangrove surface elevation by station

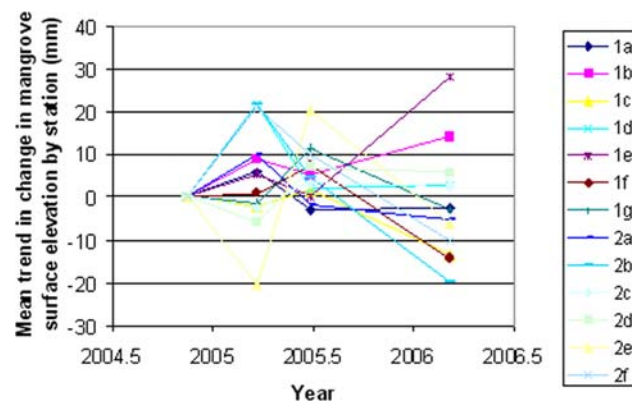


Fig. 10 Masefau mangrove mean trend in change in mangrove surface elevation by station

pulses of sediment erosion during extreme high water events (Gilman et al. 2005). For instance, Kirby et al. (1993) found a unidirectional trend of long-term accretion and erosion in portions of their study site in Northern Ireland, but also observed a seasonal cycle of winter and spring erosion and summer accretion, hypothesizing that wind-generated waves caused erosion in winter and spring, and summer accretion was enhanced by calmer weather and algal binding. Krauss et al. (2003) observed pulses in elevation increase over a 2.5-year study period in Pacific island mangroves, hypothesizing that the pulses are caused by episodic rainfall and bioturbation events.

Rates of change of the mangrove surface elevation reported by this study account for trends in sediment accretion and erosion as well as subsurface processes occurring down to the depth of the inserted stakes, where the majority of stakes were inserted to reach consolidated substrate and were a maximum of

1.35 m below the mangrove surface. In some wetlands, subsurface processes, such as organic matter decomposition, sediment compaction, fluctuations in sediment water storage and water table levels, and root production can alter the elevation of the wetland surface, which is why it is critical to insert the stakes until they reach consolidated sediment to obtain accurate observations of changes in mangrove surface elevations (Lynch et al. 1989; Donnelly and Bertness 2001; Krauss et al. 2003; Rogers et al. 2005). For instance, Krauss et al. (2003) found that, at three mangrove sites in the Federated States of Micronesia, shallow sediment subsidence was between 4.9 mm yr^{-1} and 11.2 mm yr^{-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 rods 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 mm yr⁻¹ to 16.0 mm yr⁻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. Subsurface processes may similarly be contributing to lowering in elevation of American Samoa mangrove surfaces.

Conclusions—mangrove vulnerability to relative sea level rise

The observed trend in relative sea level change for Pago Pago, American Samoa is 1.97 mm yr⁻¹ (± 0.32 mm 95% CI) based on a linear regression model fit to mean monthly relative sea levels from October 1948 through May 2004 from the Permanent Service for Mean Sea Level and University of Hawaii databases (Gilman et al. 2007). Nu'uuli mangrove has likely been experiencing a rise in sea level relative to the mangrove surface, as the relative sea level rise rate (1.65–2.29 mm yr⁻¹) has been exceeding the rate of change in elevation of the mangrove surface (-2.6 to $+1.4$ mm yr⁻¹), which would force the mangrove to retreat landward over past decades. This is consistent with the historical reconstruction results for this study sites by Gilman et al. (2007). It is unclear if Masefau mangrove has been experiencing a rise in sea level relative to the mangrove surface (the relative sea level rise rate error interval overlaps the Masefau rate of change in elevation error interval (-7.8 to $+3.4$ mm yr⁻¹)).

Several climate models project accelerated rate of sea level rise over coming decades (Church and White 2006; Church et al. 2001, 2004; Cazenave and Nerem 2004; Holgate and Woodworth 2004; Thomas et al. 2004). Projections for American Samoa range between 64 mm and 831 mm rise in relative sea level between 2004 and 2100 (Church et al. 2001; Gilman et al. 2007) while recent findings on global acceleration in sea level rise indicate that the upper projections of the Intergovernmental Panel on Climate Change are likely to occur (Church and White 2006). The range of projections for global sea-level rise from 1980 to 1999 to the end of the 21st century (2090–2099) is 0.18–0.59 m (IPCC 2007). Given the results reported here, if the upper projections occur,

American Samoa mangroves will be forced to migrate landward as a natural response to relative sea level rise.

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