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Surface Elevation Change and Susceptibility of Different Mangrove Zones to Sea-Level Rise on Pacific High Islands of Micronesia

Ken W. Krauss,[1,3]* Donald R. Cahoon,[2] James A. Allen,[1,4] Katherine C. Ewel,[1,5] James C. Lynch,[2] and Nicole Cormier[1,3]

[1]USDA Forest Service, Institute of Pacific Islands Forestry, 60 Nowelo Street, Hilo, Hawaii 96720, USA; [2]U.S. Geological Survey, Patuxent Wildlife Research Center, 10300 Baltimore Avenue, BARC-EAST Building #308, Beltsville, Maryland 20705, USA; [3]U.S. Geological Survey, National Wetlands Research Center, 700 Cajundome Blvd., Lafayette, Louisiana 70506, USA; [4]School of Forestry, Northern Arizona University, P.O. Box 15018, Flagstaff, Arizona 86011, USA; [5]School of Forest Resources and Conservation, University of Florida, Gainesville, Florida 32611, USA

Abstract

Mangroves on Pacific high islands offer a number of important ecosystem services to both natural ecological communities and human societies. High islands are subjected to constant erosion over geologic time, which establishes an important source of terrigeneous sediment for nearby marine communities. Many of these sediments are deposited in mangrove forests and offer mangroves a potentially important means for adjusting surface elevation with rising sea level. In this study, we investigated sedimentation and elevation dynamics of mangrove forests in three hydrogeomorphic settings on the islands of Kosrae and Pohnpei, Federated States of Micronesia (FSM). Surface accretion rates ranged from 2.9 to 20.8 mm y^{-1}, and are high for naturally occurring mangroves. Although mangrove forests in Micronesian high islands appear to have a strong capacity to offset elevation losses by way of sedimentation, elevation change over 6½ years ranged from −3.2 to 4.1 mm y^{-1}, depending on the location. Mangrove surface elevation change also varied by hydrogeomorphic setting and river, and suggested differential, and not uniformly bleak, susceptibilities among Pacific high island mangroves to sea-level rise. Fringe, riverine, and interior settings registered elevation changes of −1.30, 0.46, and 1.56 mm y^{-1}, respectively, with the greatest elevation deficit (−3.2 mm y^{-1}) from a fringe zone on Pohnpei and the highest rate of elevation gain (4.1 mm y^{-1}) from an interior zone on Kosrae. Relative to sea-level rise estimates for FSM (0.8–1.8 mm y^{-1}) and assuming a consistent linear trend in these estimates, soil elevations in mangroves on Kosrae and Pohnpei are experiencing between an annual deficit of 4.95 mm and an annual surplus of 3.28 mm. Although natural disturbances are important in mediating elevation gain in some situations, constant allochthonous sediment deposition probably matters most on these Pacific high islands, and is especially helpful in certain hydrogeomorphic zones. Fringe mangrove forests are most susceptible to sea-level rise, such that protection of these outer zones from anthropogenic disturbances (for example, harvesting) may slow the rate at which these zones convert to open water.

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Corresponding author; e-mail: kkrauss@usgs.gov

Key words: disturbance; hydrogeomorphic zone; sea-level rise; subsidence; surface-elevation table; vertical accretion; wetlands; Federated States of Micronesia.

Introduction

Understanding coastal sedimentation processes that affect mangrove forests is important because of the value of these ecosystems not only in supporting both subsistence and commercial economies of tropical peoples around the world, but also in protecting villages, agricultural plots, and other infrastructure (Ewel and others 1998a). Natural sedimentation processes may result in either seaward transgression or loss of mangroves, with mineral sedimentation and belowground organic matter production affecting both rate and direction of mangrove movement significantly (Davis 1938; Furakawa and Wolanski 1996). Because sedimentation interacts with both flora and fauna in a mangrove forest, understanding what affects sedimentation may help tropical resource managers to make informed decisions about a variety of land-use activities. Such information will be particularly useful for tropical islands that support human populations and are lined by mangrove forests, as mangroves can occupy a significant proportion of an island's total land area (Woodroffe 1987).

Mangrove forests in oceanic settings are often assumed to have small sediment loads from terrigenous sources (Woodroffe 1987), with peaty soils that develop as a stand ages (Kikuchi and others 1999). Recent studies have shown considerably more complexity, converging on at least three important aspects. First, mangroves often surround islands and serve as critical transition zones in mediating water flows, accumulating sediment and building elevation, and in facilitating important nutrient transformations (Ewel and others 2001; Ellison 2009). Second, root production can dominate belowground organic matter accumulation in some settings (Middleton and McKee 2001; Gleason and Ewel 2002), and can mediate an important balance with relative sea level change (Cahoon and others 2006; McKee and others 2007). Third, species assemblage and associated root type matter locally in influencing the variability in sedimentation (Scoffin 1970; Spenceley 1977; Furakawa and others 1997; Gleason and Ewel 2002; Krauss and others 2003).

Hydrogeomorphic settings vary widely among mangrove forests in Pacific high islands and elsewhere (Woodroffe 1987; Fujimoto and others 1996), and soils in different settings may be characterized by different disturbances, including rates of sea-level rise. For example, basin mangroves in south Florida accrete comparable amounts of sediment as small overwash islands or mainland fringes but are influenced less by shallow subsidence (Cahoon and Lynch 1997). In this study, we used surface-elevation tables (SET) and marker horizons to determine how mangroves in fringe, riverine, and interior hydrogeomorphic zones differ in susceptibility to sea-level rise in four river basins on two high islands in the Federated States of Micronesia (FSM). Although it was not possible to control for disturbance in this study, considering the effects of such phenomena as drought, typhoons, development in the watershed, and tree harvesting can sometimes help explain variation in data. Our study was initiated during a major El Niño/Southern Oscillation (ENSO) event in late 1997 and early 1998, which also led to widespread but short-term drought at all of our study sites.

Materials and Methods

Study Sites

Research was conducted on the islands of Kosrae (5°19′ N; 163°00′ E) and Pohnpei (6°51′ N; 158°19′ E), the easternmost island states in the FSM (Figure 1). Both are volcanic high islands where coastal mangroves occupy approximately 14% of the total land area. Kosrae has an estimated 1600 ha of mangrove wetlands, whereas Pohnpei contains approximately 5300 ha (MacLean and others 1998). Although development on neither island is as intensive as in many other tropical coastal environments, roads, homesites, and perennial agriculture are common upslope from mangrove forests on both islands.

Mangrove forests on Kosrae and Pohnpei have been divided into broad hydrogeomorphic zones based upon the degree of tidal inundation, substrate, and proximity to rivers. For the main part of this study, all river basins were divided into fringe, riverine, and interior hydrogeomorphic zones (Ewel and others 1998b). We selected two river basins on each island (Figure 1). On Kosrae, the Yela River, is located on the northwest coast, and its fringe zone is exposed to frequent wave energy, and the Utwe River, which has more wave protection, is located on

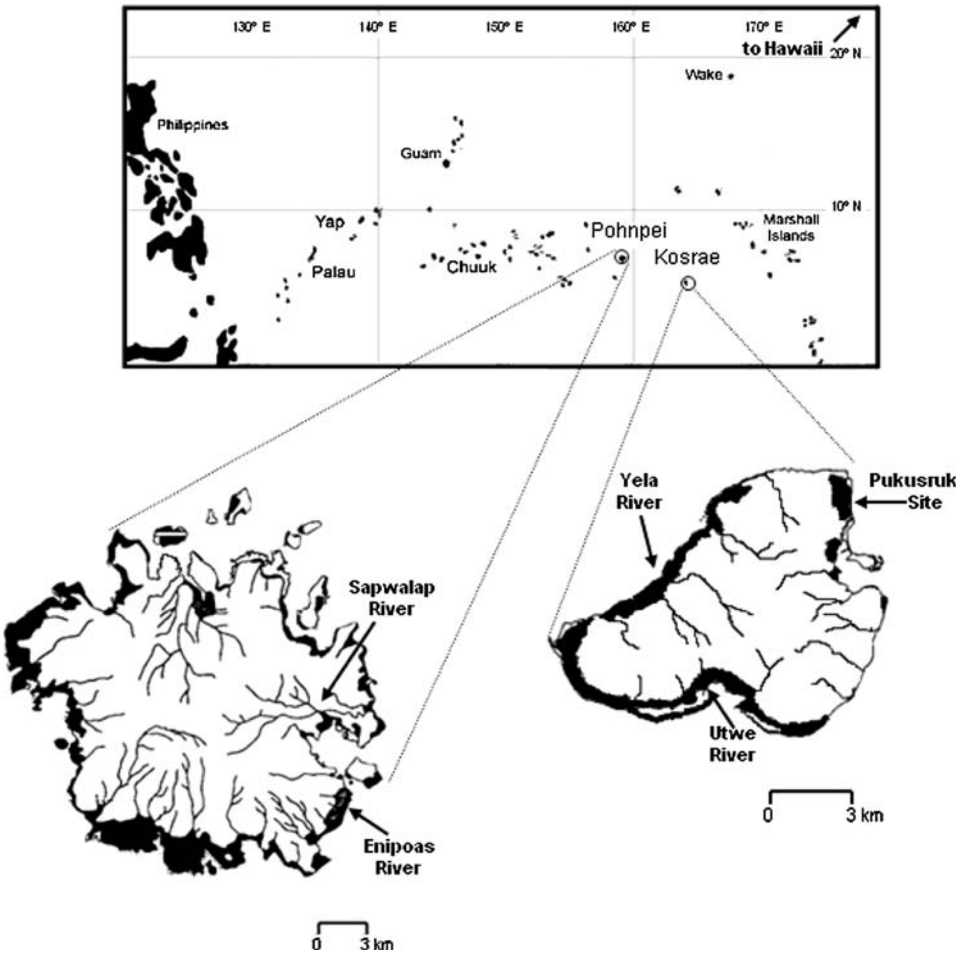

Figure 1. Location of study sites on Kosrae and Pohnpei, Federated States of Micronesia. Shaded areas along the coast depict approximate mangrove coverage on each island, whereas approximate locations of major rivers are represented by lines.

the southern coast. On Pohnpei, both the Enipoas and Sapwalap Rivers are located in the southeastern corner of the island; however, the Enipoas River discharges directly into a lagoon and is subjected to greater wave activity. The Sapwalap River discharges into a bay, and all zones are protected from oceanic waves. Furthermore, the Yela, Utwe, and Enipoas Rivers are small rivers of similar size; the Sapwalap River is much larger. On Kosrae, the Yela River is protected from upstream development, whereas the Utwe River is lined by agroforests in which taro (*Cyrtosperma chamissonis*) and perennial crops such as banana (*Musa* spp.) and sugar cane (*Saccharum* spp.) are actively farmed. The Enipoas River is slightly less disturbed by development (for example, rural villages and agriculture plots) than the Sapwalap River on Pohnpei.

A site not directly affected by a river was also selected on Kosrae. Pukusruk is located on Kosrae's northeast coast and is isolated from direct wave energy by a fringing reef and beach ridge (Figure 1). Tides freely ebb and flow into this site but through backwater routes only. Fujimoto and others (1996) classified Pukusruk as a backmarsh/lagoon mangrove; it would be classified as interior by Ewel and others (1998b) and is equivalent to the interior zone in the hydrogeomorphic classification scheme of Lugo and Snedaker (1974). Pukusruk is surrounded by homes, and agroforests are common in the watershed.

Forest structure and/or growth characteristics at these sites have been described in previous articles (Fujimoto and others 1995; Ewel and others 1998b, 2003; Kikuchi and others 1999; Krauss and others 2007). All stands have similar species composition, with *Sonneratia alba* J. Smith, *Bruguiera gymnorrhiza* (L.) Lamk., and *Rhizophora apiculata* Bl. dominating. Average stand heights range approximately from 15 to 27 m, with trees in interior and riverine zones generally being taller than trees in fringe zones (Ewel and others 1998b, 2003).

Annual rainfall along the coast of both islands is variable, but high (4.1–4.8 m: Krauss and others 2007), and few major tropical storms disturb this region of the Pacific (Allen and others 2001). However, two tropical storms did affect Pohnpei in 2003. Super Typhoon Kujira formed near Pohnpei in April, toppled trees, and caused several deaths due to wind, flooding, and rough seas (Schneider 2003). Super Typhoon Lupit caused heavy rainfall on both Kosrae and Pohnpei in November (Colasacco and others 2004). Both typhoons were tropical depressions when they struck Pohnpei, but at least one (probably Kujira) left litter and small branches on the mangrove soil surface on both the Enipoas and Sapwalap sites.

Soil Surface Elevation

We used surface-elevation tables (SET) as described by Cahoon and Lynch (1997) to track vertical changes in the mangrove soil surface (Figure 2). The SET, originally termed sedimentation-erosion table (Boumans and Day 1993), was developed to quantify elevation dynamics of wetland ground surfaces relative to a vertical, stable datum (Childers and others 1993; Cahoon and others 1995).

Aluminum pipes (7.6 cm in diameter) were driven into the soil until refusal and backfilled with

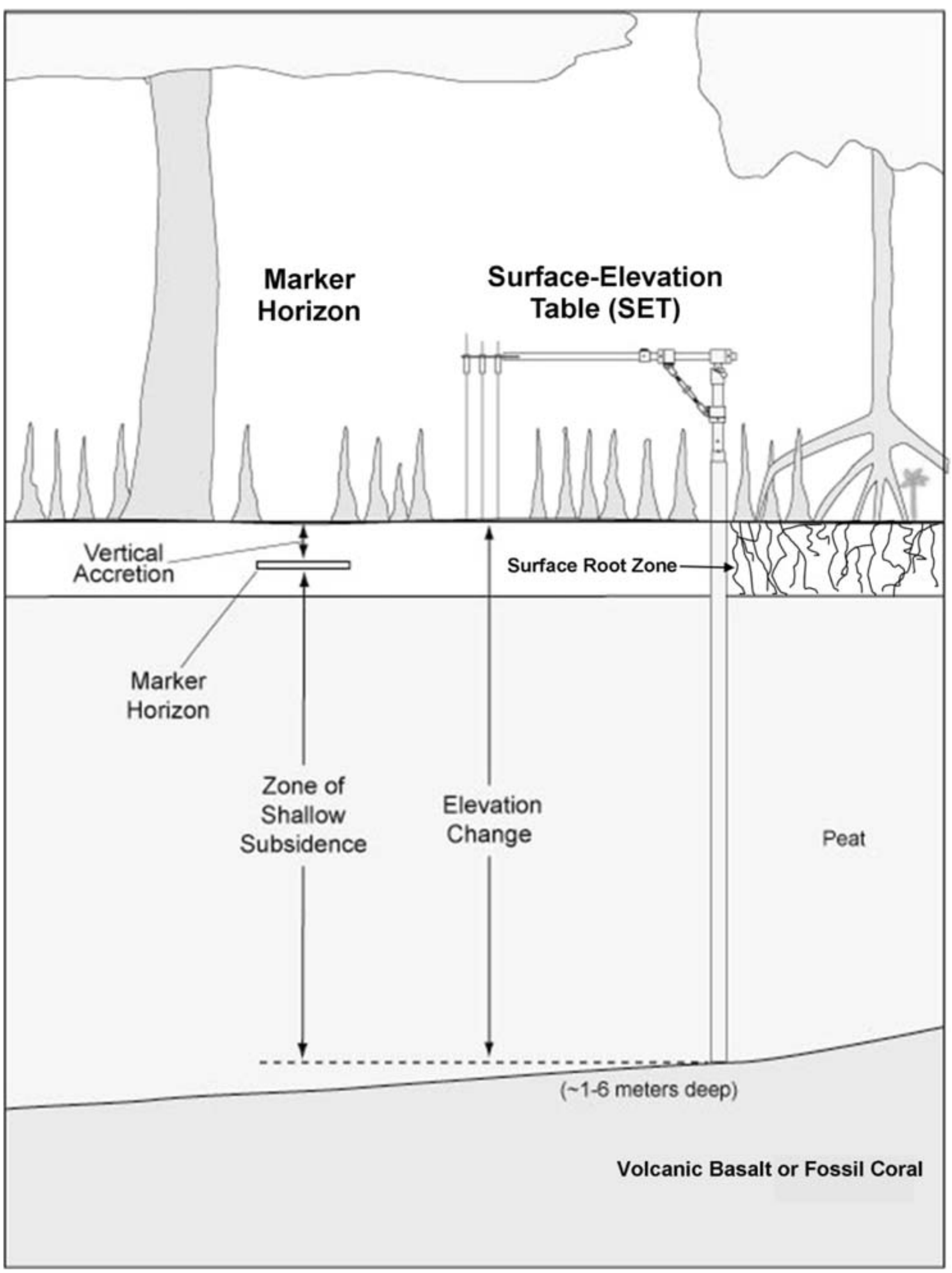

Figure 2. Surface-Elevation Table (SET) design demonstrating how different components of change in the soil profile were measured (after Cahoon and Lynch 1997). The vertical datum for all SETs was the bottom of the pipe at the interface between soil and volcanic basalt or fossil coral, 1.5–5.4 m deep.

cement, and the top of each pipe was affixed with a notched insert tube. A portable SET was attached to the insert tube on each pipe for each measurement period. The table has nine holes for brass rods to slide through to the soil surface. When leveled, the table provides a stable reference for repetitive elevation measurements. Tables were located at four separate directions per SET pipe, so a total of 36 measurements were made at each pipe during each measurement period. Changes in the resultant elevation of the pins relative to an initial starting point reflect the interaction of erosion, vertical accretion, soil expansion, and shallow subsidence (Cahoon and others 1995, 1999). On Kosrae and Pohnpei, all SET pipes were driven to a firm volcanic basalt or dense fossil coral substrate at a depth of 1.5–5.4 m (benchmark) (Figure 2).

We established three SET pipes in each fringe, riverine, and interior zone along the Yela River and Utwe River on Kosrae in July and September 1997, respectively. We repeated this design for the Enipoas and Sapwalap Rivers on Pohnpei in September 1998 and added three SET pipes at Pukusruk that same month. In all, we established 39 SET pipes on Kosrae and Pohnpei and measured them for 5–7 years. SET pipes were sampled quarterly during 1998 on Kosrae, then all pipes were sampled bi-annually through 2000. Subsequent readings were made once annually in 2002, 2003, and 2004. Data were reported as short- and long-term trends, with short-term trends corresponding to surface accretion intervals (described below), and long-term trends extending to 2004 on all sites.

Surface Accretion

We used marker horizons to determine surface accretion (including mineral and organic matter deposition) around each SET pipe. Initially, surface accretion was determined by soil accumulation above a pure feldspar layer deposited at the time of SET installation (Cahoon and Turner 1989). Thirteen of the 27 pure feldspar marker horizons initially laid on Kosrae were recoverable but not interpretable within 9–15 months, indicating that they were not necessarily eroding away but becoming diffuse within the soil over time. Mixing feldspar at an approximate 50:50 ratio with coralline sand was only slightly more effective (20 of 27 were interpretable after approximately 530 days), making it necessary to reapply marker horizons several times on some sites on Kosrae. Feldspar was applied only once on Pukusruk (Kosrae) and Pohnpei. Hence, we sampled surface accretion over short time intervals only, with all surface accretion measurements ending in June 2000, after the following start dates: Yela River, July 1997; Utwe River, September 1997; Pukusruk, Enipoas, and Sapwalap, January 1999.

On Kosrae, we established three marker horizons as close to each SET pipe as possible, for a total of nine marker horizons per river and zone, including Pukusruk. On Pohnpei, we established two marker horizons near each SET pipe. In all, we established 99 marker horizons. A small, cubic core sample was taken from each marker horizon ($N = 2$–3 per SET), and vertical accretion was measured with a ruler as the average depth of the sediment layer atop the marker horizon from the sides of each sample. Values were not recorded for cores with non-interpretable layers, thereby providing potentially slight bias to overall rates of vertical accretion (similar to that reported in Cahoon and Lynch 1997). Surface accretion data should be viewed conservatively as maximum rates were measured.

Sub-Surface Change

Sub-surface change, as estimated from the bottom of the SET pipe to the soil surface (Figure 2), was calculated as the difference between elevation change and surface accretion for a given time interval (Cahoon and others 1995; Cahoon and Lynch 1997). We estimated sub-surface change in Micronesian mangroves over short time intervals, or for those periods of time when we had data for both elevation change (SET) and surface accretion (feldspar plots). Because SET pipes were driven to basaltic rock or fossil coral, subsurface processes occurring below the zone we measured would be geologic.

Sea-Level Rise Trends for FSM

Sea-level rise has been measured for several high islands in FSM, including Yap, Chuuk (Moen Island), and Pohnpei (Church and others 2006). Tide gauge trends dating as far back as 1952 (for Chuuk) indicate that sea-level rise ranges from 0.8 to 1.8 mm y^{-1}, and has been estimated as 1.8 mm y^{-1} for Pohnpei (Church and others 2004, 2006). There are no published data for Kosrae, so we use FSM-wide trends. An important caveat is that tide gauge records from the equatorial Pacific have become more and more variable since 1970, with recent glacial isostatic and ''inverse barometer'' adjustments suggesting sea-level rise may be approximately 0.5 mm y^{-1} higher for these islands (Church and others 2006).

Data Analysis

The experimental unit for the SET was the benchmark for each pipe, which is the secure vertical position of each pipe relative to the elevation of the soil surface. Each pipe provided four subsamples (that is, SET directions) and nine sub-subsamples (that is, individual pins in each direction) for each of three sample replicates (that is, pipes) per site. Pseudoreplication was avoided by pooling the four subsamples per benchmark into an average reading. Feldspar plots were treated similarly, except that individual cores represented subsamples of each feldspar plot.

Elevation and surface accretion data were tested for significant linear trends using standard regression analysis, and we established the null hypothesis that the linear trend did not differ from 0 at $\alpha = 0.05$. Where either elevation change or vertical accretion differed significantly from 0, sub-surface change data were also tested for significance.

Elevation and vertical accretion trends (slopes) were analyzed with a general linear model (Type I error, for regression models with categorical variables) for all sites combined (Yela, Utwe, Enipoas, and Sapwalap Rivers) and zone (fringe, riverine, interior). Pukusruk was removed from the general linear model to avoid unbalanced statistical treatment. In addition, we used a step-wise, general linear model analysis (PROC GLMSELECT: SAS Institute 2007) to determine which specific process influenced actual surface elevation change greater by zone, and used their respective estimates to test for strength of the relationship if significant. Data that were not normal with homoscedastic variance were log transformed. All analyses were conducted using SAS (Version 9.1: SAS Institute 2007).

Results

Surface Elevation Change

Soil elevation data were evaluated across two time periods: a short-term record to measure surface accretion and a long-term record for comparison with sea-level rise. The short-term record allowed us to discriminate among soil elevation change, surface accretion, and sub-surface processes.

Short-Term Trends

Short-term changes in mangrove soil surface elevation varied from −5.8 to 6.3 mm y^{-1} (Table 1); all but four elevation trends by site and zone differed significantly from zero. Many sites and zones experienced an increase in relative elevation during the short-term period after SETs were installed, followed by a gradual loss of elevation thereafter. There were three notable exceptions. First, riverine and interior zones along the Utwe River (Kosrae) and the interior zone along the Yela River (Kosrae) built elevation throughout the 6½ year record, and showed the greatest short-term positive elevation gains (Table 1; Figure 3). Second, locations along the Yela River (Kosrae) registered a 5–8 mm elevation decrease for all zones in early 1998 coincident with a major ENSO-related drought; this immediate decrease in elevation held the overall short-term elevation trends for the Yela River to −3.0 to 1.3 mm y^{-1}. Finally, with the exception of the interior zone along the Sapwalap River (Pohnpei), where elevation increase was 0.9 mm y^{-1}, all locations on Pohnpei lost elevation consistently through the short-term period (−0.6 to −5.8 mm y^{-1}: Table 1). Site by zone interactions were significant for all processes (Table 1); however, elevations at fringe mangrove forests consistently decreased at all but the Utwe River site. Riverine zones demonstrated the greatest variability in short-term elevation change from −2.7 to 6.3 mm y^{-1}. Overall, short-term elevation changes at fringe, riverine, and interior mangrove forests in FSM were −1.13, 1.87, and 0.78 mm y^{-1}, respectively.

Long-Term Trends

Over 6½ years, changes in mangrove soil surface elevation at all zones on all sites on both islands ranged from −3.2 to 4.1 mm y^{-1}. For many of the zones in the four river basins, long-term rates of elevation change were either less positive or more negative than short-term rates from the same location (Table 1). Long-term trajectories were much more revealing because they incorporated a couple of fairly major sedimentation events that otherwise would have been missed. Two locations were of particular interest. First, soil elevation at Pukusruk increased slightly until early 2002, when it decreased by approximately 21 mm following the harvest of nearby overstory trees (Figure 3). Second, a long period of elevation loss at the fringe mangrove forest along the Enipoas River ended with a rapid elevation increase (Figure 4). In fact, all sites and zones on Pohnpei experienced a 6.1–21.8 mm increase in elevation from 2003 to 2004 (Figure 4). Among the four river basins, fringe mangrove forests continued short-term trends by losing elevation at an overall rate of 1.30 mm y^{-1}, whereas riverine and interior zones gained elevation at rates of 0.46 and 1.56 mm y^{-1}, respectively.

Table 1. Measured Rates of Surface Elevation Change from Two Time Intervals, Surface Accretion, and Estimated Rates of Shallow Sub-Surface Change (±1 SE) for Mangrove Sites in Kosrae and Pohnpei, Federated States of Micronesia

	Short-term trend							Long-term trend		
	Surface elevation change			Surface accretion		Sub-surface change		Surface elevation change		
	Record duration (years)	mm y^{-1}	$P > F$[1]	mm y^{-1}	$P > F$	mm y^{-1}	$P > F$	Record duration (years)	mm y^{-1}	$P > F$[1]
Yela River (Kosrae)										
Fringe	3.0	−3.0 ± 0.8	**	11.6 ± 1.3[3]	***	−14.6 ± 1.5	***	6.6	−1.84 ± 0.3	***
Riverine	3.0	−2.7 ± 0.6	**	12.9 ± 2.1[3]	***	−15.6 ± 1.1	***	6.6	−1.13 ± 0.3	**
Interior	3.0	1.3 ± 0.7	*	12.0 ± 1.2[3]	***	−10.7 ± 1.0	***	6.6	0.91 ± 0.3	**
Utwe River (Kosrae)										
Fringe	3.0	1.2 ± 0.3	**	11.9 ± 1.7[3]	***	−10.7 ± 0.7	***	6.4	−0.25 ± 0.3	ns
Riverine	3.0	6.3 ± 0.5	***	18.7 ± 2.2[3]	***	−12.4 ± 0.7	***	6.4	3.29 ± 0.6	***
Interior	3.0	1.3 ± 0.2	*	12.9 ± 4.3[3]	*	−11.6 ± 1.9	*	6.4	4.08 ± 0.5	***
Enipoas River (Pohnpei)										
Fringe	1.4	−5.8 ± 0.9	**	6.6 ± 3.1	ns	−12.4 ± 2.3	**	5.0	−0.61 ± 1.1	ns
Riverine	1.4	−1.4 ± 2.2	ns	6.3 ± 0.9	**	−7.7 ± 1.2	*	5.0	−0.48 ± 0.9	ns
Interior	1.4	−2.8 ± 0.4	**	2.9 ± 1.4	ns	−5.7 ± 0.1	***	5.0	−1.44 ± 0.8	ns
Sapwalap River (Pohnpei)										
Fringe	1.4	−2.3 ± 0.6	*	4.1 ± 1.5	*	−6.4 ± 1.3	*	5.0	−3.15 ± 0.8	**
Riverine	1.4	−0.6 ± 0.8	ns	14.1 ± 1.7	***	−14.7 ± 0.9	***	5.0	−1.51 ± 0.4	*
Interior	1.4	0.9 ± 0.5	ns	8.2 ± 1.2	***	−7.3 ± 0.7	**	5.0	0.33 ± 0.4	ns
Pukusruk (Kosrae)										
Backswamp	1.4	0.9 ± 0.4	ns	20.8 ± 2.4	***	−19.9 ± 1.8	*	5.0	−1.84 ± 0.7	*
ANOVA[2]		*F* Value	$P > F$	*F* Value	$P > F$	F Value	$P > F$		*F* Value	$P > F$
Site		34.76	***	6.39	***	9.83	***		26.63	***
Zone		26.26	***	2.31	ns	9.2	***		21.91	***
Site × zone		2.94	*	3.05	*	2.43	*		2.98	*

[1] *ns: regressions not significantly different from 0 at the 0.05 level.*
[2] *ANOVA model excluded Pukusruk because it created an unbalanced statistical design.*
[3] *Data on surface accretion were established using three separate sets of marker horizons relaid over time (benchmarks).*
** Significant at 0.01–0.05 level; ** significant at 0.01–0.001 level; *** significant at <0.001 level.*

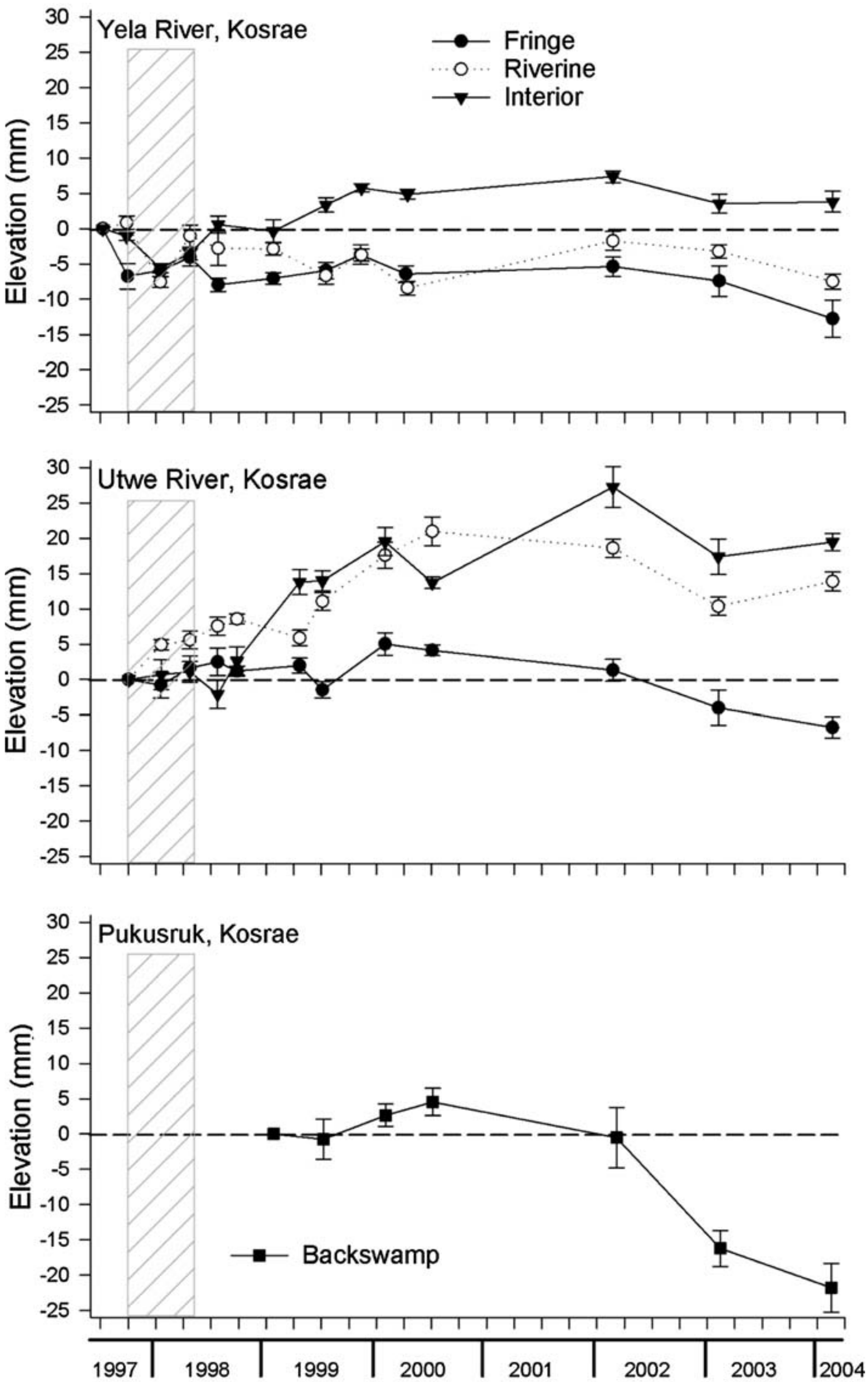

Figure 3. Mangrove soil surface elevation change over 6½ years for fringe, riverine, and interior hydrogeomorphic zones along the Yela River and Utwe River, as well as in a backswamp location (Pukusruk), on the Island of Kosrae, Federated States of Micronesia. The *dashed line* represents soil surface elevation at the beginning of the study period, whereas the *hatched bar* represents the approximate period of the 1997/1998 ENSO drought.

Surface Accretion

Some feldspar marker horizons had to be reestablished several times throughout the study as a consequence of burrowing activity of small crabs (Grapsidae), surface activity of mud skippers (Gobiidae), sub-surface water movement, and natural diffusion of the layer. Vertical surface accretion rates ranged from 2.9 mm y^{-1} for an interior zone along the Enipoas River to 20.8 mm y^{-1} for the backswamp zone at Pukusruk (Table 1). Sediment deposition contributed significantly to vertical accretion for all sites and zones, but rates did not

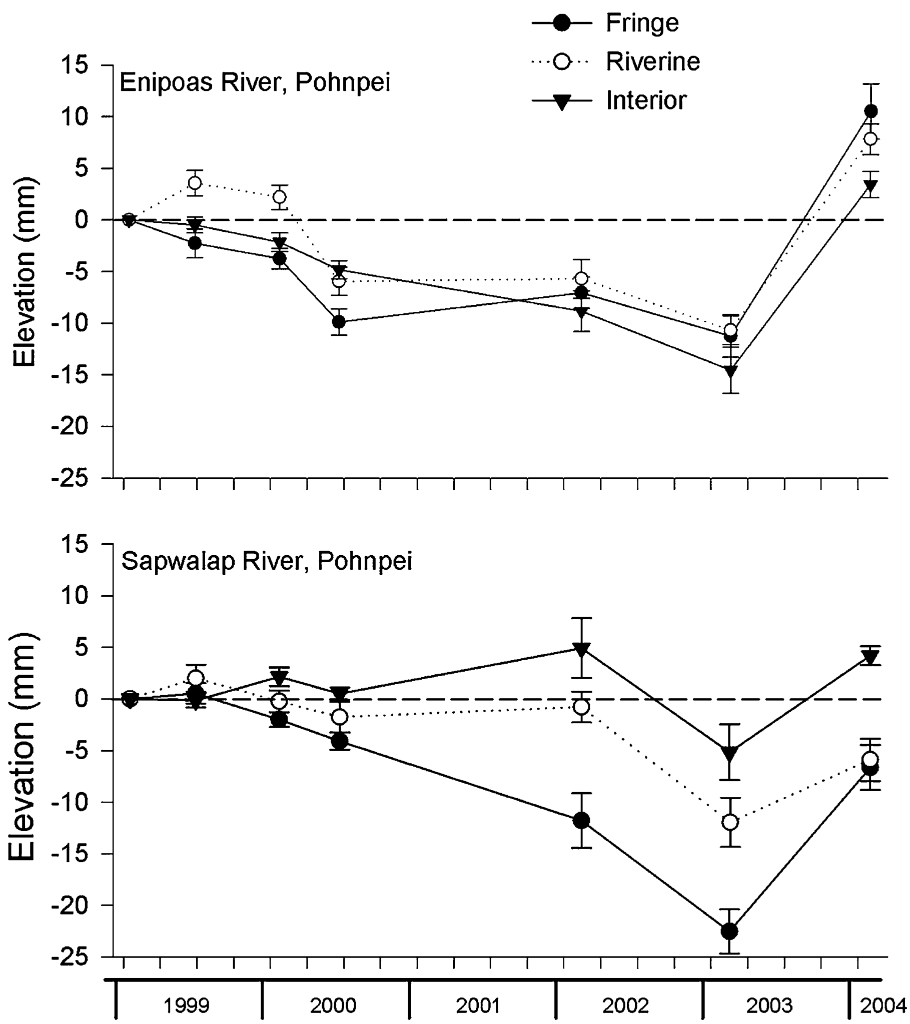

Figure 4. Mangrove soil surface elevation change over 5 years for fringe, riverine, and interior hydrogeomorphic zones along the Enipoas River and Sapwalap River on the Island of Pohnpei, Federated States of Micronesia. The *dashed line* represents soil surface elevation at the beginning of the study period.

differ significantly among zones (Table 1). Sapwalap Riverine, Utwe Riverine, Utwe Interior, and Pukusruk had obvious signs of recent sediment deposition upon every visit. Deposition for these four site and zone combinations ranged from 12.9 to 20.8 mm y^{-1}.

Sub-Surface Change

At each site and zone, sub-surface change was negative, implying shallow subsidence. Subsidence rates were very high for many site and zone combinations, ranging from −5.7 to −19.9 mm y^{-1}, and all subsidence rates differed significantly from zero (Table 1). A high rate of subsidence (−14.7 mm y^{-1}) at the riverine zone along the Sapwalap River, where surface accretion and sub-surface change both differed significantly from zero, did not influence elevation initially, but subsidence did decrease elevation significantly in five of 13 mangrove study site by zone combinations in FSM.

Even for riverine zones along the Sapwalap River, long-term elevation change was eventually detected (Table 1).

Processes Influencing Surface Elevation Change in Different Zones

Overall, surface elevation change was influenced significantly by surface accretion ($F_{3,68} = 7.46$; $P < 0.001$). However, the GLM estimates for individual zones indicated that surface accretion affected surface elevation only in riverine zones (t-ratio = 4.28; $P < 0.001$) where the highest rates of surface accretion were consistently recorded (Table 1: excluding Pukusruk). On the other hand, sub-surface change did not influence elevation change in the overall statistical model ($F_{3,68} = 2.32$; $P = 0.083$), even though there was a significant regression between sub-surface change and surface elevation change among all fringe zones (t-ratio = 2.08; $P = 0.041$).

Discussion

General Patterns of Mangrove Soil Surface Elevation Change

Mangrove forests on Kosrae and Pohnpei, as well as other Pacific high islands, will decrease in area over the coming centuries as a consequence of natural geologic subsidence; an entire island eventually subsides and erodes to become an atoll. Even over the short period of time occupied by this study, rates of elevation change in mangroves were generally negative, despite high rates of surface accretion (2.9–20.8 mm y^{-1}: Table 1). Whereas surface accretion and shallow elevation change in mangroves have been reported before (compare Bird 1971; Bird and Barson 1977; Spenceley 1977; Young and Harvey 1996; Krauss and others 2003), only a few have considered the influence of deeper soil horizons on overall elevation change in mangroves (Cahoon and Lynch 1997; Cahoon and others 2003; Whelan and others 2005; McKee and others 2007). Soil elevation change on Kosrae and Pohnpei ranged from −3.2 to 4.1 mm y^{-1} (Table 1). Krauss and others (2003) found that elevation varied from only −0.2 to 3.4 mm y^{-1} from a shallower vertical datum (0.7 m) and shorter time frame (2.5 years) from some of the same Pacific island mangrove stands. This comparison highlights the importance of considering deeper influences on surface elevation; elevation change is often explained by processes occurring well below a depth of 0.35 m (Whelan and others 2005).

Mangrove soil surface elevation change in our study was similar in magnitude to other locations (Table 2). Surface elevation in mangroves ranged from 0.6 to 3.7 mm y^{-1} in Rookery Bay, Florida, USA (Cahoon and Lynch 1997), from −0.6 to −2.2 mm y^{-1} in American Samoa (Gilman and others 2007b), from 0.9 to 5.6 mm y^{-1} in Everglades National Park, Florida, USA (Whelan and others 2005, 2009), and from −3.7 to 4.1 mm y^{-1} on peat-based, carbonate islands in Belize (McKee and others 2007). However, surface elevation increase of 7.2 mm y^{-1} in one Australian mangrove stand (Rogers and others 2005a) was greater than what we report for FSM (Table 2). In general, net soil elevation change in FSM was similar to changes in other mangrove stands around the world in spite of the high rates of surface accretion we recorded.

The higher rates of surface accretion in FSM (average of 11.0 mm y^{-1}; maximum of 20.8 mm y^{-1}) were comparable only to natural mangrove forests elsewhere that were subjected to high sediment influx during disturbance, for example, 14 mm y^{-1} in Honduras after the passage of Hurricane Mitch (Cahoon and others 2003), and 11.5 mm y^{-1} in a southwest Florida mangrove forest after Hurricane Wilma (Whelan and others 2009). The importance of shallow subsidence in counteracting accretion was also demonstrated at our FSM study sites; subsidence was high and ranged from −5.7 to −19.9 mm y^{-1} (Table 2). Notwithstanding potentially positive biases created by missing marker horizons on some sites, Micronesian high islands appear to have the strongest capacity thus far recorded in the literature to offset elevation losses by way of natural sedimentation to mangrove communities. Surface accretion was especially important in influencing elevation change in riverine zones in FSM; soil surface accretion in mangrove forests developing on point bars along riverine zones on the Pacific coast of Costa Rica appears to be even higher (29.8 mm y^{-1}: P. Delgado and P. Hensel, pers. comm.). In contrast, mangrove forests developing in areas with large environmental impacts can experience large amounts of surface accretion. For example, mangroves along a heavily urbanized estuary in China received as much as 13–60 mm y^{-1} in vertical sediment deposition (Alongi and others 2005; Alongi 2009).

Susceptibility to Sea-Level Rise

The trends we measured suggest that high-island mangroves on Kosrae and Pohnpei are experiencing changes in average soil elevation that range from a deficit of 4.95 mm y^{-1} to a surplus of 3.28 mm y^{-1} relative to sea-level rise estimates for FSM (0.8–1.8 mm y^{-1}). Responses by different hydrogeomorphic zones help explain site-to-site variability (Figure 5). Fringe and riverine zones appear at least moderately susceptible to long-term sea-level rise; however, fringe zones may be most susceptible despite the high rates of surface accretion on fringe zones along the Yela and Utwe Rivers.

In contrast to the FSM sites, greater elevation gains were recorded in peat-based fringe environments on carbonate settings in Belize, where root accumulation was higher than in interior locations (McKee and others 2007). Root growth can be an important process dictating soil surface elevation gain in Caribbean island mangroves where mineral sedimentation rates are low (Middleton and McKee 2001; Cahoon and others 2006; McKee and others 2007), and it is likely that root growth influences soil elevation in Micronesian high island mangrove forests as well, primarily by helping to retain sediments on site. In fact, although fine root

Table 2. Summary of Published Studies Using Surface-Elevation Tables (SET) to Track Soil Elevation Change in Mangrove Ecosystems

Site	Duration of record (years)	Surface elevation change (mm y^{-1})	Surface accretion (mm y^{-1})	Sub-surface change (mm y^{-1})	Reference
Rookery Bay, Florida, USA					
Fringe	1.0	1.4–3.5	7.2–7.8	−4.3–(−5.8)	Cahoon and Lynch (1997)
Basin	2.5	3.7	6.0	n.s.	
Exposed overwash island	2.0	2.5	6.3	−3.8	
Sheltered overwash island	2.0	0.6	4.4	−3.8	
Guanaja and Roatan, Honduras					
Island fringe—high impact	1.3[1]	9.9	14.0	−4.1	Cahoon and others (2003)
Island fringe—medium impact	1.3	4.8	2.0	2.8	
Island fringe—low impact	1.3	4.8	2.0	2.8	
Island basin—high impact	1.3[1]	−9.5	2.0	−11.0	
Island basin—medium impact	1.3	−9.2	2.0	−11.0	
Island basin—low impact	1.3	4.8	2.0	2.8	
Shark River, Everglades National Park, Florida, USA					
Riverine—(4 m datum)	1.0	0.9	6.6	−5.7	Whelan and others (2005)
Riverine—(4 m datum)	3.3	5.6	6.5	−0.9	Whelan and others (2009)
Riverine—(4 m datum)	4.6[1]	11.3	11.5	−0.2	
Riverine—(6 m datum)	1.0	3.6	6.6	−3.0	Whelan and others (2005)
Riverine—(6 m datum)	3.3	1.4	6.5	−5.1	Whelan and others (2009)
Riverine—(6 m datum)	4.6[1]	6.2	11.5	−5.2	
Twin Cays, Belize					
Fringe—peat-based island	3.0	4.1	1.6	2.4	McKee and others (2007)
Transition—peat-based island	3.0	−1.1	2.0	−3.1	
Interior—peat-based island	3.0	−3.7	0.7	−4.4	
Sydney Harbour, New South Wales, Australia					
Control forest	3.5	7.2	17.6	−10.4	Rogers and others (2005a)
Southeast Australia					
Ukerebagh Island	3.0	2.4	2.2	0.2	Rogers and others (2006)
Kooragang Island	1.8	2.0	4.7	−2.7	
Homebush Bay[2]	3.7	5.6	4.6	1.1	
Minnamurra River	2.0	0.6	6.6	−6.1	
Cararma Inlet	2.0	−0.8	3.0	−3.8	
Currambene Creek	3.0	0.3	0.7	−0.4	
French Island	3.0	−2.1	9.5	−11.6	
Kooweerup	3.0	0.0	7.2	−7.2	
Quail Island	3.0	−2.6	6.8	−9.4	
Rhyll	3.0	0.9	5.1	−4.2	
Kosrae and Pohnpei, Federated States of Micronesia					
Island fringe	1.4–3.0	−1.1	8.6	−9.7	Current study
Island fringe	5.0–6.6	−1.3	n/a	n/a	
Island riverine	1.4–6.6	1.8	13.0	−11.2	
Island riverine	5.0–6.6	0.5	n/a	n/a	
Island interior	1.4–6.6	0.8	9.0	−8.2	
Island interior	5.0–6.6	1.6	n/a	n/a	
Island backswamp	1.4	0.9	20.8	−19.9	
Island backswamp	5.0	−1.8	n/a	n/a	

[1] *Measurements taken after large sediment deposits from a hurricane.*
[2] *Measurements were made from the same sites as Rogers and others (2005a), but over a slightly longer duration.*

productivity (measured as 46–119 g m^{-2} y^{-1} for roots ≤ 2 mm: Cormier 2003) did not differ significantly among zones along the Yela and Sapwalap Rivers, the capacity for fine root turnover was lowest in the Yela fringe and highest in the Sapwalap riverine forest (Cormier 2003).

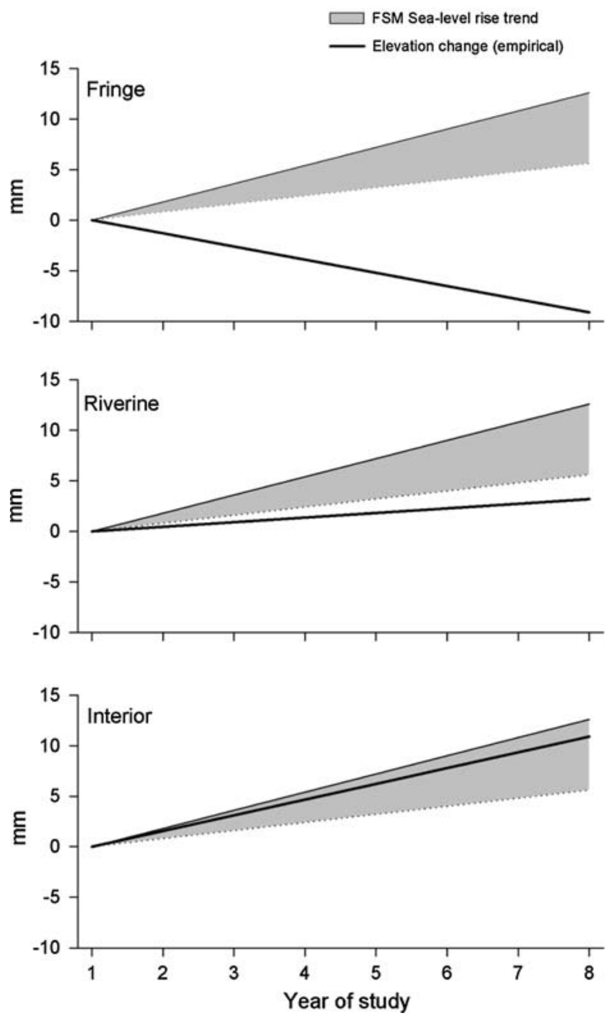

Figure 5. Mean rates of mangrove soil surface elevation change for fringe, riverine, and interior hydrogeomorphic zones in four river basins on Kosrae and Pohnpei (data from Table 1) compared with minimum and maximum linear averages for sea-level rise in the Federated States of Micronesia (0.8–1.8 mm y^{-1}: Church and others 2006).

Background rates of fine root growth ranged from 43 to 197 g m^{-2} y^{-1} on Belizean islands (McKee and others 2007). It is likely that the high rates of natural surface accretion measured in FSM mangroves are more influential in maintaining net mangrove surface elevation than belowground root growth per se (see Table 2); however, the specific role of roots in affecting mangrove elevation dynamics remains untested on Pacific high islands.

The margins of island ecosystems are especially prone to shifts in boundaries, with sea-level rise, slope and physiographic setting, and erosion all interacting (Ellison and Stoddart 1991; Woodroffe 1995). For example, mangroves in American Samoa are expected to migrate landward 12–37 times faster than would be predicted by sea-level rise alone, owing to episodic erosive losses and chronic flood stress on mangrove trees in fringing locations (Gilman and others 2007a). Mangroves in fringe zones grow slower than in riverine and interior zones on Kosrae (Krauss and others 2007), and we suggest here that fringe mangrove settings in FSM may be most susceptible to sea-level rise due in part to physiological stress on trees imposed by prolonged flooding (Figure 5). Surface elevation losses in fringe zones also appear to be driven by subsurface processes. This agrees with reports by Gilman and others (2007b) who found that fringe mangrove forests in American Samoa are experiencing an elevation deficit of 1.7–2.3 mm y^{-1}, whereas trends from interior zones in the same study were less clear. However, sea-level rise does vary considerably from year-to-year (compare Church and others 2006), suggesting that making long-term predictions based on linear extrapolation may itself lead to uncertainty.

Disturbance

We found little indication that the modest watershed development along the Utwe/Sapwalap Rivers affected soil surface elevation dynamics more than background conditions at the Yela/Enipoas Rivers. However, selective removal of mangrove trees from Pukusruk in mid-2002 for construction and fuel wood was accompanied by the loss of 21 mm of mangrove soil surface elevation over a 2-year period (Figure 3). Similarly, Whelan (2005) found that lightning-induced mortality of mangroves was accompanied by soil surface elevation losses of 8.5–60.9 mm in south Florida over a similar 2-year period; however, damage gaps in Florida mangroves eventually recovered the elevation of adjacent, intact forests. Total peat collapse can occur if tree mortality is extensive (Cahoon and others 2003), but recovery of elevation within the Pukusruk backswamp setting on Kosrae following partial harvesting seems likely.

The trend in soil surface elevation at Pukusruk before harvesting suggests that this backswamp area (sensu Fujimoto and others 1996) may behave similarly to the interior zone at our other study sites. Certainly, standing forest structure and tree species composition on backswamp and interior zones on Kosrae were similar (Ewel and others 2003). It is very likely, however, that soils in fringe mangrove forests would respond similarly to harvesting but without the eventual return to predisturbance elevations; current tree growth and root turnover in fringe settings are probably insufficient to counter erosion and subsidence following harvesting.

Soil elevation data collected along the Yela River suggested that ENSO events may also affect elevation dynamics in FSM, at least in the short term. After the onset of an ENSO event toward the end of 1997, the elevation of all three zones decreased by nearly 7 mm over 190 days (Figure 3). ENSO reduced monthly rainfall depths from 250 to 400 mm $month^{-1}$ to nearly 0 for the first few months of 1998, eliminated groundwater flow to the mangrove forests at the Yela site from a freshwater forested wetland just upslope, and reduced mangrove tree growth and concentrated soil pore water salinities on some sites around the island (Drexler and Ewel 2001; Krauss and others 2007). All three zones were affected, but elevation in both the interior and riverine locations recovered rapidly after the event, perhaps reflecting a greater reliance on subsurface water accumulation. Full recovery was not seen in the fringe zone, suggesting that the effects on the fringe could be longer term. It is possible that increases in saltwater intrusion and soil aeration to the fringe during ENSO may have caused an increase in subsoil decomposition. Similarly, marsh surface elevation in Australia decreased during an ENSO drought in 2002 and 2003, indicating that water accumulation plays an important role in the maintenance of soil surface elevation in those wetlands (Rogers and others 2005b). Dewatering events during drought may be an especially important driver in the loss of mangrove soil surface elevation on high-rainfall Pacific islands.

Major pulses of elevation gain on Pohnpei recorded in early 2004 coincided with two tropical storms in 2003. Both Super Typhoon Kujira and Super Typhoon Lupit brought high winds and flooding, and the former caused the greatest amount of flooding recorded on Pohnpei in over 60 years (Schneider 2003). Increases in mangrove surface elevation on Pohnpei may have been caused by storm-related fallen wood from the canopy (Allen and others 2000; Krauss and others 2005), accelerated propagule fall (N. Cormier, pers. obs.), swelling of soil substrates (Cahoon and others 2006), or higher rates of sediment deposition (compare Reed 1989). High rates of year-round rainfall on Pohnpei gives rise to continual sediment inputs to the estuary (Victor and others 2006), which is in contrast to the large, seasonal sediment pulses observed on other Micronesian high islands such as Palau where a distinct rainy season occurs (Victor and others 2004). Our data from SET investigations (reported here) and sediment pin studies (Krauss and others 2003) support the observation that sediment accretes consistently from month-to-month over an annual cycle on both Kosrae and Pohnpei, and this accretion rate is high (Table 1). Periodic sediment pulses from major storm events clearly help to offset elevation losses on Pacific island mangroves.

Conclusions

Mangrove forests around the world tend to lose surface elevation relative to sea-level rise despite nearly universally positive increments in surface accretion over a range of mangrove settings (Cahoon and others 2006). This finding is of special concern on Pacific high islands of Micronesia because of the importance of mangroves to the local economy (Ewel and others 1998a; Naylor and Drew 1998) and the long-term concern for island susceptibility to the effects of climate change (Woodward and others 1998; Gilman and others 2007a; Yamano and others 2007; Ellison 2009). However, our results indicate that mangrove surface elevation change also varied by hydrogeomorphic setting and river, and suggested differential, and not uniformly bleak, susceptibilities among Pacific high island mangroves to sea-level rise. Fringe, riverine, and interior settings registered elevation changes of −1.30, 0.46, and 1.56 mm y^{-1}, respectively, over a period of 6½ years. Although natural disturbance is important in mediating elevation gain in some situations, continual allochthonous sediment deposition is perhaps most important on these islands. Because fringe mangrove forests are most susceptible to sea-level rise, protecting this outer zone from such anthropogenic disturbances as harvesting may slow the rate at which soil is lost and more landward forests become fringe forests themselves.

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