Vertical accretion and shallow subsidence in a mangrove forest of southwestern Florida, U.S.A

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Abstract

Simultaneous measurements of vertical accretion from artificial soil marker horizons and soil elevation change from sedimentation-erosion table (SET) plots were used to evaluate the processes related to soil building in fringe, basin, and overwash mangrove forests located in a low-energy lagoon which receives minor inputs of terrigenous sediments. Vertical accretion measures reflect the contribution of surficial sedimentation (sediment deposition and surface root growth). Measures of elevation change reflect not only the contributions of vertical accretion but also those of subsurface processes such as compaction, decomposition and shrink-swell. The two measures were used to calculate amounts of shallow subsidence (accretion minus elevation change) in each mangrove forest. The three forest types represent different accretionary environments. The basin forest was located behind a natural berm. Hydroperiod here was controlled primarily by rainfall rather than tidal exchange, although the basin flooded during extreme tidal events. Soil accretion here occurred primarily by autochthonous organic matter inputs, and elevation was controlled by accretion and shrink-swell of the substrate apparently related to cycles of flooding-drying and/or root growth-decomposition. This hydrologically-restricted forest did not experience an accretion or elevation deficit relative to sea-level rise. The tidally dominated fringe and overwash island forests accreted through mineral sediment inputs bound in place by plant roots. Filamentous turf algae played an important role in stabilizing loose muds in the fringe forest where erosion was prevalent. Elevation in these high-energy environments was controlled not only by accretion but also by erosion and/or shallow subsidence. The rate of shallow subsidence was consistently 3–4 mm y^{-1} in the fringe and overwash island forests but was negligible in the basin forest. Hence, the vertical development of mangrove soils was influenced by both surface and subsurface processes and the processes controlling soil elevation differed among forest types.

The mangrove ecosystem at Rookery Bay has remained stable as sea level has risen during the past 70 years. Yet, lead-210 accretion data suggest a substantial accretion deficit has occurred in the past century (accretion was 10–20 cm < sea-level rise from 1930 to 1990) in the fringe and island forests at Rookery Bay. In contrast, our measures of elevation change mostly equalled the estimates of sea-level rise and our short term estimates of vertial accretion exceeded the estimates by the amount of shallow subsidence. These data suggest that (1) vertical accretion in this system is driven by local sea-level rise and shallow subsidence, and (2) the mangrove forests are mostly keeping pace with sea-level rise. Thus, the vulnerability of this mangrove ecosystem to sea-level rise is best described in terms of an elevation deficit (elevation change minus sea-level rise) based on annual measures rather than an accretion deficit (accretion minus sea-level rise) based on decadal measures.

Introduction

Mangroves, like other wetlands, are considered highly vulnerable to submergence under a scenario of rising sea-level (Gornitz, 1991). Global mean sea level has risen approximately 1–2 mm y^{-1} during the past 100 years (Gornitz, 1995) and this rate of rise is predicted to increase 2–5 fold by the year 2100 (Titus and Narayanan, 1995; Biljsma, 1996). Sea level is also enhanced on a local scale relative to the land surface by subsidence. The combined effect of eustatic sea-level rise and land subsidence is referred to as relative sea-level rise. In order for mangroves not to become submerged, vertical buildup of soil surfaces will have to equal or exceed the local rate of relative sea-level rise. In muddy coastal environments, mangroves are considered excellent landbuilders (Augustinus, 1995) because of the soil-binding capacity of mangrove roots (Scoffin, 1970; Spenceley, 1977). Hence, surface accretionary processes play an important role in maintaining soil elevation in muddy environments. In carbonate settings where there is little mineral sediment input, such as south Florida, subsurface production of mangrove peat is considered the primary soil-building mechanism (Snedaker, 1993; Parkinson et al., 1994). This conclusion is supported by observations in south Florida of rapid soil subsidence following the death of red mangrove trees after Hurricane Andrew (Wanless et al., 1995). Parkinson et al. (1994) suggested that artificial marker horizons laid on the soil surface may not become buried because, they argued, peat production is the primary contributor to soil elevation in carbonate settings. Yet, there have been few studies of vertical accretion in any mangrove setting (Parkinson et al., 1994) from which to discern the relative contributions of surface and subsurface processes (e.g., sediment deposition vs. peat production) to soil building.

Measuring the short-term (< 10 years) rate of mud sedimentation beneath mangroves has proven difficult (Woodroffe, 1992). The use of marker horizons and pins to measure vertical accretion in mangroves has met with only limited success (Woodroffe, 1992) as indicated by the small number of published reports during the past 40 years (Table 1). Chapman and Ronaldson (1958) and Bird (1971), using marker horizons of iron filings and brick dust, reported vertical accretion rates of 2–16 mm y^{-1} in mangroves along the muddy coasts of New Zealand and Australia. However, no estimates of seasonal or annual variability in accretion were reported. Measurements from pins or stakes inserted into mangrove muds have exhibited a high degree of variability in accretion and were often difficult to interpret because of the confounding effects of erosion and near-surface subsidence (Bird, 1981; Bird and Barson, 1977; Spencely, 1982; and Anthony, in press; Table 1). Hence, our understanding of short-term, seasonal to annual patterns of vertical accretion in mangroves is very limited.

Our ability to determine the potential for submergence of mangroves is further limited by a lack of knowledge of shallow subsidence (compaction) of mangrove soils.

Traditionally, the potential for submergence of coastal wetlands is determined by comparing measured rates of vertical accretion directly to local rates of relative sea-level rise. If vertical accretion is not keeping pace with sea-level rise then an 'accretion deficit' is said to exist (Reed and Cahoon, 1993; Stevenson et al., 1986). The accretion deficit concept assumes that surface accretion measures are equivalent to soil surface elevation change. However, Cahoon et al. (1995) used simultaneous measurements of vertical accretion from marker horizons and soil elevation from an elevation table to demonstrate that vertical accretion was not equal to surface elevation change for some salt marshes in the southeastern United States. Accretion often overestimated elevation change because of subsurface processes such as compaction (i.e., autocompaction of marsh peat (Kaye and Barghoorn, 1964)). Cahoon et al. (1995) referred to these subsurface processes (e.g., compaction, decomposition, dewatering) collectively as shallow subsidence and argued that the vulnerability of these marshes to sea-level rise is better expressed in terms of an 'elevation deficit' (i.e., direct comparison of elevation change to sea-level rise) rather than an accretion deficit.

In this study, we made simultaneous measurements of vertical accretion and soil elevation in fringe, basin, and overwash island mangrove forests located in the low-energy, emergent carbonate platform of southwestern Florida. The measurements were made with a level of accuracy sufficient to distinguish between the influence of surface and subsurface processes on soil elevation. Our objectives were three-fold: (1) determine the contribution of sediment deposition to soil building, (2) estimate rates of shallow subsidence and the influence of subsurface soil processes on soil elevation, and (3) determine the potential for submergence of each mangrove setting based on calculated accretion deficits and elevation deficits. Shallow subsidence was calculated for each forest type as the difference between accretion and elevation change. Semi-annual measurements were made to examine the processes controlling vertical accretion and soil elevation. No seasonal or annual patterns of accretion in mangroves have been reported for the Wider Caribbean Region and no evaluations of the relationship between vertical accretion and soil elevation (i.e., shallow subsidence) have been reported for any mangrove system. The data were used to evaluate the processes controlling vertical development of mangrove soils so as to improve our

Table 1. Short-term rates (<10 years) of vertical accretion and soil elevation change in mangrove forests.

Method	Site	Rate (mm y^{-1})	Reference
Marker horizon	Auckland, NZ		Chapman and Ronaldson, 1958
	Pollen Island	1.7	
	Kaitaia	1.7	
	Yaringa, AUS		Bird, 1971, 1980
	seaward	1.0–16	
	center	8.0 (maximum)	
	landward	2.3 (maximum)	
	Rookery Bay, FL		This study
	fringe	7.2	
	basin	6.0	
	islands	4.4–6.3	
Pins	Yaringa, AUS	8.0 (maximum)	Bird and Barson, 1977
	Cairns Bay, AUS	5–10	Bird and Barson, 1977
	Magnetic Is., AUS	–6.5 to 0.1	Spencely, 1982
	Sierra Leone	–0.5 to 1.0	Anthony, in press
Elevation table	Rookery Bay, FL		This study
	fringe	1.4	
	basin	3.7	
	islands	0.6–2.5	

understanding of the relationships among mangrove accretionary processes, soil subsurface processes, geomorphic setting, and relative sea-level rise.

Methods

Study site

This study was conducted at Rookery Bay National Estuarine Research Reserve located in southwestern Florida adjacent to the Gulf of Mexico (Figure 1). Field plots were established in fringe, basin, and two overwash island forests which were typical of the forest types around Rookery Bay and which represented a range of hydrodynamic settings. The fringe forest site, located on the sloping shore of Rookery Bay and exposed to northwesterly fetch and wave action, was dominated by *Rhizophora mangle*. A stationary shell berm approximately 0.6 m high separated the fringe and basin forests (Figure 2). Fringe soils consisted of approximately 30 cm of mangrove peat and carbonaceous mud overlying an oyster shell reef (S. Fournet, unpublished data). The basin forest, located immediately landward of the fringe forest and berm, included a mixed association of *Avicennia germinans* (L.) L., *Rhizophora mangle* L., and *Laguncularia racemosa* (L.) Gaertn.f. Tidal exchange between the basin and the bay was restricted and occurred only through a few low areas in the berm. Unlike the fringe forest, the basin soil surface was not sloping (Figure 2). Basin soils consisted of approximately 1 m of mangrove peat overlying clean, well-sorted, quartz sand (S. Fournet, unpublished data). The basin forest was the site of earlier investigations of mangrove productivity (Twilley et al., 1986) and vertical accretion using the ^{210}Pb method (Lynch et al., 1989). The overwash islands were 50 m in diameter and were vegetated with monospecific stands of *R. mangle*. One island was exposed to wave action while the other was sheltered behind a larger island (Figure 1). Island soils consisted of approximately 1 m of mangrove peat overlying an oyster shell reef (S. Fournet, unpublished data). The exposed island had a shell berm approximately 0.6 m high on its windward (northwestern) edge while the sheltered island had no berm and the soil surface exhibited small topographic relief (Figure 2).

Lynch et al. (1989) summarized the climate and hydrologic setting of Rookery Bay. The area has a warm temperate to subtropical climate with an average annual precipitation of 1,346 mm. Rainfall varies throughout the year with the region experiencing a

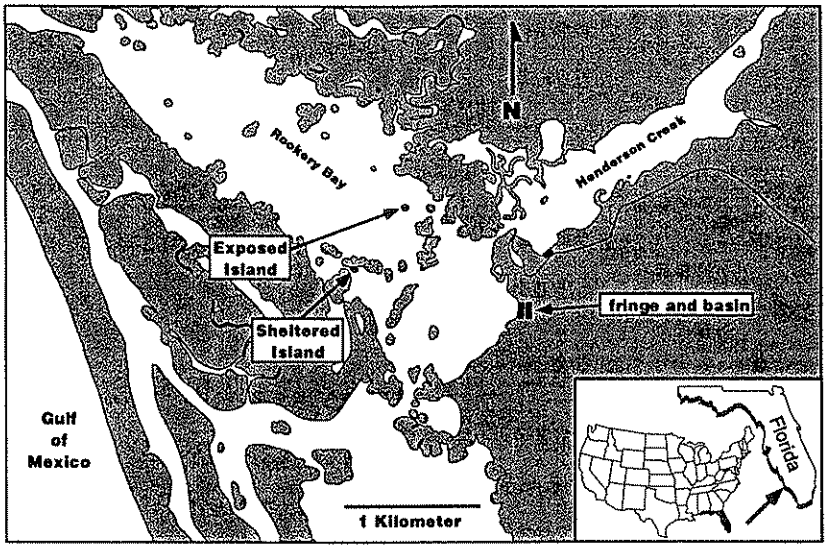

Figure 1. Site map of Rookery Bay National Estuarine Research Reserve.

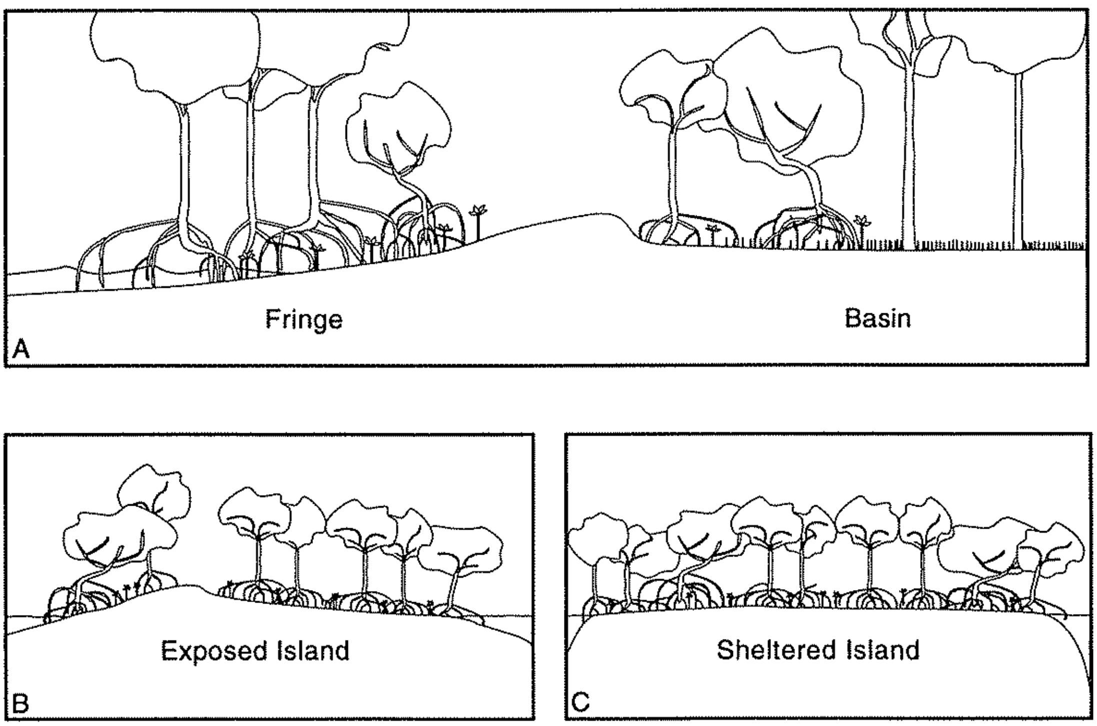

Figure 2. Conceptual diagram (not to scale) illustrating the geomorphic setting of each of the four study sites.

six-month dry season (November through April) and a six-month wet season (May through October) (Davis, 1943). Approximately 60–65% of the annual precipitation falls between June 1 and September 1 (Twilley, 1982). Sea level in the Gulf of Mexico in the south Florida area varies 15–20 cm thoughout the year (Marmer, 1954; Provost, 1974). Sea level is low in the first half of the year (January–July) and high in the autumn, peaking in October at 10–15 cm above the annual mean. Rookery Bay is a shallow (2 m average depth), nonstratified, mesohaline estuary with semidiurnal tides (annual mean range of 0.6 m). The primary source of freshwater input to the Bay is Henderson Creek (Figure 1; average annual discharge of 0.68 m^3 s^{-1}) which provides minor inputs of terrigenous sediments (Figure 1). Estimates of sea level rise in south Florida over the past 70 years range from 2.3 mm y^{-1} (Maul and Martin, 1993) to 3 to 4 mm y^{-1} (Wanless et al., 1994).

Sampling schedules and techniques

Accretion and elevation data were collected every six months (August and February) beginning in August, 1993 and continuing until February, 1996. The August-February sampling interval coincides with the peak in sea level in the Gulf of Mexico (Marmer, 1954; Provost, 1974) and includes approximately 25–30% of the annual rainfall (Twilley, 1982). The February-August sampling interval coincides with the low stand in sea level in the Gulf of Mexico (Marmer, 1954; Provost, 1974) and includes approximately 70–75% of the annual rainfall (Twilley, 1982). For the purpose of describing flooding patterns (i.e., hydroperiod) on the mangrove forest floor, August–February will be referred to throughout the remainder of the paper as the high flood interval and February–August as the low flood interval.

Permanent sampling plots were established in the basin and fringe forests in August 1993 and in the two overwash islands in February 1994; a total of 4 sampling sites. At the fringe and basin sites, seven small sampling platforms were constructed to allow access to the soil surface while minimizing disturbance. The platforms were randomly located between the bay and the berm in the fringe forest and within 20 m of the berm in the basin forest. Only 2 permanent sampling plots were established at the island sites, one in the center and one on the edge, because of the small size of the islands. Construction of platforms was not feasible on the islands because of the high density of prop roots. Disturbance to the soil was minimal, however, because the plots were accessed by walking mostly on the prop roots.

Vertical accretion was measured as the rate of accumulation above feldspar marker horizons laid upon the soil surface at the start of the study in 1993 and 1994 (Cahoon and Turner, 1989). Soil accumulation above the marker horizon occurs not only through the deposition of mineral matter and organic debris but also the growth of plant roots (Reed and Cahoon, 1993; Cahoon and Lynch *personal observation*). Three feldspar marker horizons were laid at each platform in the fringe and basin sites ($n = 21$). On the exposed and sheltered islands, 2 and 3 feldspar marker horizons were laid at each sampling plot, respectively ($n = 4$, exposed; $n = 6$, sheltered). A single cryogenic core (Cahoon et al., 1996) was taken through each marker horizon twice yearly, in August and February, and the depth of the marker horizon below the surface was measured to the nearest millimeter at 1–4 locations around the core. The four core measurements were averaged into a single datum for each feldspar plot during each sampling. Cryogenic cores were collected until the marker was recovered or at least 3 cores had been taken. An additional soil core was collected adjacent to each permanent plot during each 6-month sampling by using a 10-cm diameter piston-corer with a razor blade cutting edge (Hargis and Twilley, 1994). These cores were analyzed for organic matter content and dry bulk density. Organic matter content was determined by loss-on-ignition at 375°C for 16 h (Hesse, 1971).

Elevation change was measured with a sedimentation-erosion table (SET; Boumans and Day, 1993). The SET is a portable levelling device designed to attach to a benchmark pipe that has been driven into the soil surface (Figure 3). The SET pipes were vibracored into the soil until they would no longer move, a depth of approximately 3 m in all forest types. The pipe was assumed to be a stable datum for the period of study (Childers et al., 1993; Cahoon et al., 1995). Levelling of the pipes to each other by standard survey methods (laser level) in 1994, 1995, and one year after completion of the study in 1997 revealed no movement of the pipes relative to each other (differences in elevation were smaller than the error of the survey technique (i.e., < 1 mm/y)). The SET was attached to the benchmark pipe only during sampling and then was removed. Nine pins located at the end of an accurately levelled horizontal arm were lowered to the soil surface to measure elevation with an accuracy of $\pm$ 1.5 mm. Pin readings were taken at 4 fixed positions of the arm at each pipe (n = 36/pipe). SET stations were established at 3 randomly-selected platforms in the fringe and basin forests, and at each of the permanent plots on the overwash islands (total $n = 108$ for fringe and basin, $n = 72$ for the islands). The reference datum for the measure of elevation change was the bottom of the SET pipe. SET readings were taken when the marker horizons were laid and at each accretion sampling interval. Shallow subsidence was calculated as the difference between vertical accretion and surface elevation change and is therefore defined as the subsidence occurring between the marker horizon and the bottom of the pipe (Figure 3). For the purpose of distinguishing between the influence of surface and subsurface processes on soil elevation, the influence of soil processes which occurred above the marker horizon (e.g., subsidence and the contribution of root growth to accretion over a soil depth of ~1–2 cm) was assumed to be negligible compared to the influence of soil processes which occurred between the marker horizon and the bottom of the pipe (e.g., compaction, decomposition, root growth, dewatering over a soil depth of ~0.01 to 3 m). Note that the reference datum for a pin inserted into mangrove soils, as used by previous researchers (e.g., Table 1), would also be the bottom of the pin (Figure 3). Hence, pins would measure not only accretion-erosion but also subsurface processes contributing to elevation change. Thus, the pin data in Table 1 is more analagous to elevation table data than marker horizon measures.

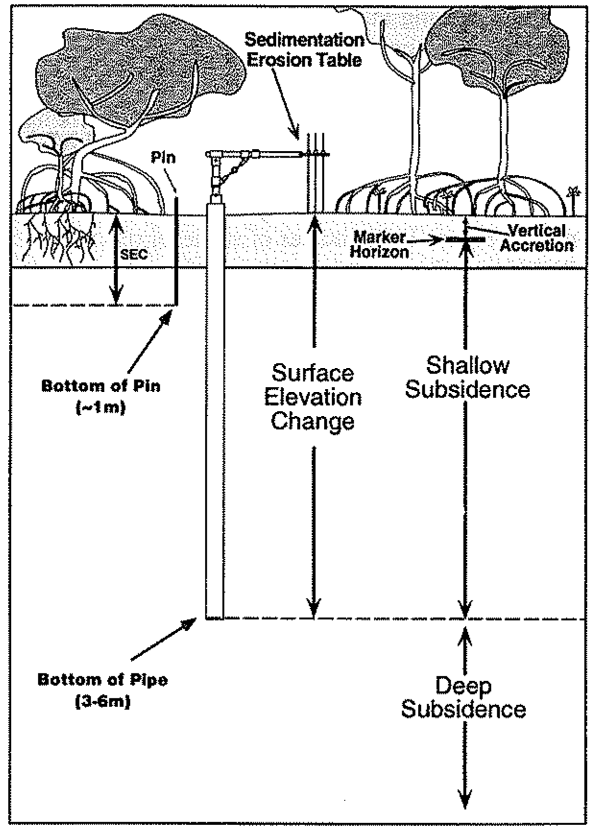

Figure 3. Conceptual diagram (not to scale) showing those portions of the soil profile being measured by the Sedimentation-Erosion Table (SET) and marker horizon techniques. The boundary separating the shallow and deep subsidence zones is defined operationally by the bottom of the SET pipe. The portion of the soil profile measured by pins is also indicated.

Beginning in February 1994, water level was measured hourly in both the fringe and basin forests with float gauges connected to a continously recording datalogger and solar panel (Dataloggers Inc., P.O. Box 361, Logan, Utah 84323-0361, 801-753-8311). Soil elevation measures at all sites were conducted using a laser level and standard surveying methods. The average relative surface elevation of each forest type was determined from 66 survey readings in both the fringe and basin forests, and 32 and 28 readings in the sheltered and exposed island forests, respectively. Due to the distance of the islands from any survey benchmarks, a hypsometric analysis was used to tie the island elevations into the fringe and basin forests. Hydroperiod calculations (e.g., frequency, duration, and depth of flooding) were based on waterlevel data corrected for elevation differences between each site. Although the hypsometric approach assumes the water surface was flat and therefore may result in errors when carried over a distance of a km, we believe any potential errors were minimal because of the small tidal range and lack of wind at the time of measurement.

All statistical analyses were conducted using SAS (1991) and comparisons were tested at the alpha = 0.05 level. A one-tailed 2-sample *t*-test was used to test if accretion was greater than elevation for each sampling interval (PROC TTEST, p. 1633–1640). Differences between forest types in vertical accretion were tested using ANOVA (PROC GLM, p. 891–996). Differences in bulk density and organic matter content among forest types and in depth and duration of flooding among forest types and time were tested using MANOVA because the errors of these two pairs of variables were correlated (PROC GLM, p. 891–996). The bulk density, organic matter content, and accumulation data were log-transformed to meet the requirements for normalcy but the untransformed data are presented for clarity. Annual rates of accretion and elevation were calculated from linear regression analysis and regression lines were compared for calculations of shallow subsidence (PROC REG, p. 1351–1456). Simple correlation coefficients were calculated using PROC CORR (SAS, 1991).

Results and discussion

Forest elevations and hydroperiod

The relative mean elevations of the 4 sites were as follows: the basin was 16.46 cm higher than the sheltered island, which was 1.83 cm higher than the fringe, which was 3.96 cm higher than the exposed island; for a total range in mean elevation among sites of 22.25 cm. Hydroperiod (frequency, duration, and depth of flooding) differed significantly among sites (Table 2). The fringe and overwash island forests exhibited similar hydroperiods although the exposed island flooded slightly more frequently and for greater duration and depth because of its lower elevation. These sites flooded an average of 1.5–2.0 times a day as a result of tidal action. The basin forest hydrologic setting was completely different from the other sites. It was characterized by comparatively few long, shallow flooding events, each event lasting 2–10 days on average.

There were important differences in hydroperiod between high and low flood intervals (Table 2). The frequency, duration, and depth of flooding increased in the tidally-dominated fringe and overwash island forests during high flood intervals. In contrast, the frequency of flooding declined in the basin forest during high flood intervals because precipitation and flood waters that entered the basin were slow to drain. Duration of each flooding event increased 2–4-fold (from 2 to 10 days) during high flood intervals. Hydroperiod was atypically high in the low flood interval of 1995, with values similar to the high flood intervals, because of unusually high rainfall amounts.

Accretionary processes

A total of 52 marker horizons were established in the 4 forest sites. All but one of the marker horizons were buried (one marker in the fringe eroded) before the first sampling (6 month interval) and burial continued throughout the study at all sites if the soil did not erode (Figure 4). The burial of the marker horizons indicated that surface deposition processes combined with root growth at the soil surface contributed to the vertical development of the mangrove soils. This finding contradicts the suggestion of Parkinson et al. (1994) that sediment accretion is controlled primarily by below ground peat production in carbonate settings and hence the markers may not become buried. The rates of vertical accretion in the three forest types at Rookery Bay were within the range of those reported for Yaringa, Australia by Bird (1971) and exceeded those reported for New Zealand by Chapman and Ronaldson (1958) (Table 1). Three distinct accretionary environments were identified among the four Rookery Bay sites based on hydroperiod (Table 2) and soil properties (Table 3): regularly-flooded mineral soils (fringe forest), irregularly-flooded organic soils (basin forest), and regularly-flooded mixed mineral-organic soils (overwash island forests).

In the fringe forest, the soil surface was a mosaic of accretional and erosional surfaces characterized by patches of mud and bare shell. Litter accumulation was low because of tidal action. Mineral sediment was the primary building material and these soils had the highest bulk density of the 4 sites (Table 3). Vertical accretion was associated with the presence of filamentous turf algae (e.g., *Cladophora gracilis* (Griffiths *ex* Harvey) Kutzing, and *Boodleopsis pusilla* (Collins) Taylor, Joly, et Bernatowicz; algae identified by C. J. Dawes, personal communication) which apparently helped to bind the soil in place (Dawes, 1967). If these mud patches were not eroded away (i.e., did not become patches of bare shell) they eventually became anchored in place by the dense root mat of the red mangrove trees (Scoffin, 1970). Filamentous turf algae were absent from the patches of bare shell and mineral sediments did not accumulate in these areas because of wave action.

It should be noted that the marker horizon technique has an inherent bias toward measuring accreting surfaces to the exclusion of eroding surfaces (since those markers are lost), and hence can overestimate average accretion rates on partially eroding surfaces. Erosion of marker horizons occurred continuously in the fringe forest with only 50% of the markers remaining after 18 months and 1 out of 21 remaining after 30 months. Hence, the slope of the accretion graph (Figure 4) represents a maximum rate of accretion for the fringe forest as a whole. Consequently, accumulation estimates were calculated using only the first 12 months of accretion data (Table 3) when 86% of the marker plots were recovered. Estimates of accumulation over the entire 2.5 years of study were not included because of the confounding effects of erosion. The fringe forest had a significantly higher rate of total accumulation of matter than the other 3 sites because of a high rate of mineral accumulation (Table 3).

All 21 marker horizons in the tidally-restricted basin forest were recovered and showed no sign of deterioration or erosion after 2.5 y. The soil was 60% organic matter by weight, composed primarily of plant

Table 2. Hydroperiod summary for mangrove forests at Rookery Bay, Florida, February 1994–February 1996.

		Forest type			
Accretion-elevation sampling interval	Hydrologic parameter	Basin	Fringe	Exposed island	Sheltered island
2-year record	No. flooding events	88	1,188	1,229	1,136
(February 24, 1994 to February 8, 1996)	Total hours of flooding	10,182	5,891	6,821	5,452
	Maximum duration (h)	1,780	47	49	47
	Mean duration (h)	116 (25)[a]	5.0 (0.08)[b]	5.6 (0.09)[c]	4.8 (0.08)[b]
	Maximum depth (cm)	56.5	74.0	77.8	72.2
	Mean depth (cm)	3.3 (0.2)[a]	12.4 (0.2)[b]	14.1 (0.2)[c]	11.9 (0.2)[b]
First interval – high flood	No data[1]	No data	No data	No data	No data
(August 23, 1993 to February 24, 1994)					
Second interval – low flood	No. flooding events	31	274	295	258
(February 24, 1994 to August 10, 1994)	Total hours of flooding	1,534	1,103	1,330	996
	Maximum duration (h)	218	10	10	10
	Mean duration (h)	49.5 (9.2)	4.0 (0.1)	4.5 (0.1)	3.9 (0.1)
	Maximum depth (cm)	32.5	50.3	54.1	48.5
	Mean depth (cm)	2.8 (0.3)	9.8 (0.4)	11.5 (0.4)	9.2 (0.4)
Third interval – high flood	No. flooding events	15	325	337	313
(August 10, 1994 to February 22, 1995)	Total hours of flooding	3,325	1,582	1,842	1,448
	Maximum duration (h)	1,048	20	21	20
	Mean duration (h)	221.7 (67)	4.9 (0.1)	5.5 (0.1)	4.6 (0.1)
	Maximum depth (cm)	30.8	48.2	46.4	50.8
	Mean depth (cm)	4.0 (0.4)	12.2 (0.4)	13.9 (0.4)	11.7 (0.4)
Fourth interval – low flood	No. flooding events	26	320	322	305
(February 22, 1995 to August 23, 1995)	Total hours of flooding	2,659	1,561	1,808	1,445
	Maximum duration (h)	708	20	20	17
	Mean duration (h)	102.3 (33)	4.9 (0.1)	5.6 (0.2)	4.7 (0.1)
	Maximum depth (cm)	37.0	54.9	58.8	53.1
	Mean depth (cm)	3.0 (0.4)	12.3 (0.4)	14.1 (0.4)	11.7 (0.4)
Fifth interval – high flood	No. flooding events	16	269	275	260
(August 23, 1995 to February 8, 1996)	Total hours of flooding	2,664	1,644	1,841	1,563
	Maximum duration (h)	1,780	47	49	47
	Mean duration (h)	167 (108)	6.1 (0.3)	6.7 (0.3)	6.0 (0.3)
	Maximum depth (cm)	56.5	74.0	77.8	72.2
	Mean depth (cm)	4.0 (0.6)	15.4 (0.5)	17.1 (0.5)	14.9 (0.5)

[a]Data are means with 1 SE presented in parentheses. Means within a row followed by a different letter are statistically significantly different at the 1% level.
[1]Collection of hydroperiod data did not commence until February 1994.

litter and root material. This irregularly-flooded site apparently received few allochthonous inputs of matter since it had the lowest rate of mineral accumulation (Table 3). As a result of the lack of flushing, a dense layer of plant litter (mostly leaves) accumulated on the soil surface. Visual examination of the accretion cores revealed that this litter contributed substantially to soil accumulation above the marker horizon. Hence, the accretion rate in the basin was comparable to that of the tidally dominated fringe and overwash island sites despite the low mineral inputs (Table 3) in part because litter export was low. The similarity in organic matter accumulation rates and difference in litter flux rates between the basin and fringe forests (Table 3) suggests that root production contributed a roughly equal portion to the organic content of the soil at each site. Differences between the sites in the accumulation of litter could explain the higher value for organic accumulation in the basin.

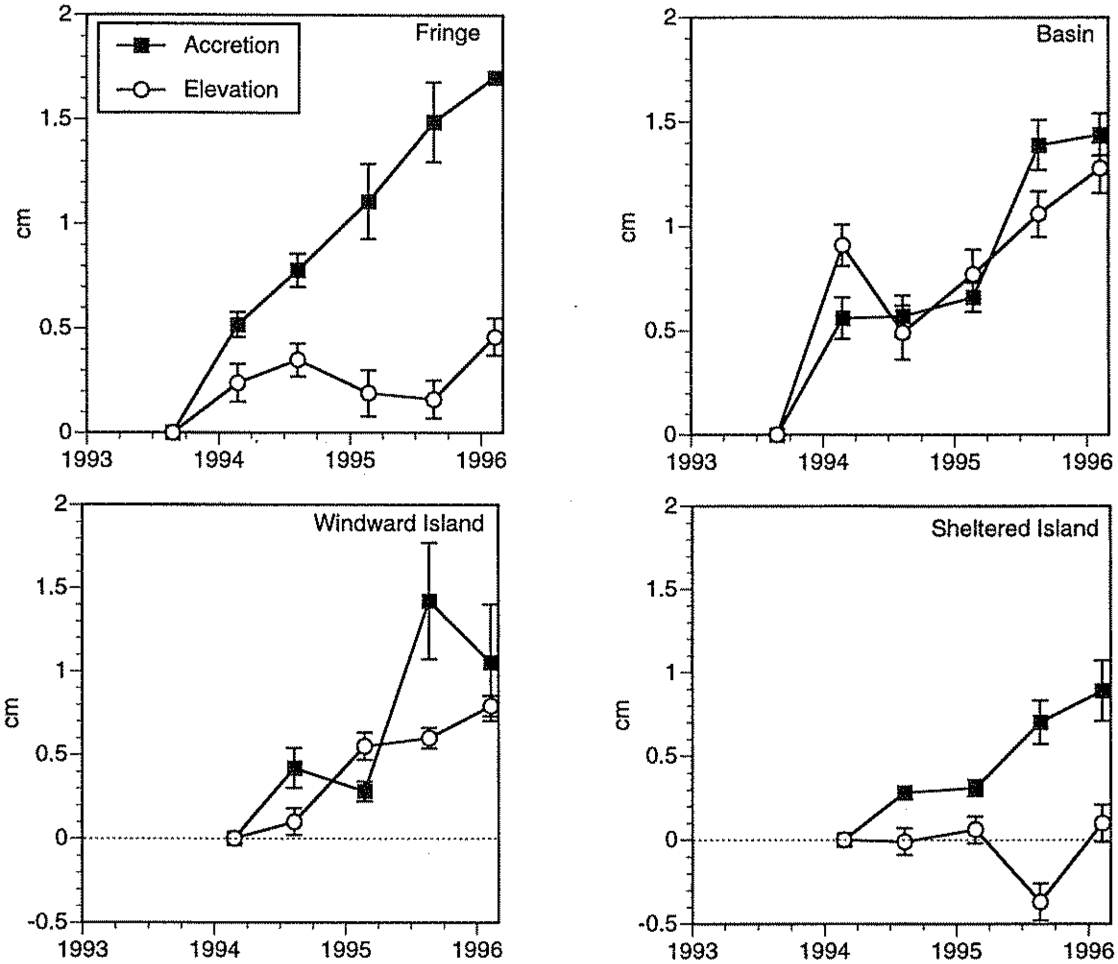

Figure 4. Soil surface elevation change and vertical accretion in four mangrove forest sites at Rookery Bay NERR. Open circles = elevation change, solid squares = vertical accretion. Separation between the two lines represents shallow subsidence. The flood potential for each sampling interval, in order from August 1993, can be characterized as high, low, high, low, high.

Table 3. Accumulation of organic and mineral matter in mangrove soils.

Site	Record length (y)	*n*	Vertical* accretion (cm y^{-1})	Bulk density (g cm^{-3})	Organic: Mineral (%)	Accumulation Total	Organic (g m^{-2} y^{-1})	Mineral
Fringe	1.0	18	0.78 (0.08)[a]	0.51 (0.03)[a]	12:88 (0.5)[a]	4017 (509)[a]	456 (52)[ab]	3561 (461)[a]
Basin	2.5	21	0.59 (0.04)[ab]	0.19 (0.004)[b]	60:40 (0.7)[b]	1094 (66)[b]	656 (40)[a]	438 (27)[b]
Exposed island	2.0**	4	0.65 (0.14)[ab]	0.23 (0.004)[b]	39:61 (0.2)[c]	1482 (301)[b]	582 (120)[ab]	900 (181)[c]
Sheltered island	2.0**	6	0.46 (0.08)[b]	0.21 (0.006)[b]	40:60 (0.5)[c]	948 (163)[b]	382 (67)[b]	566 (96)[c]

*Data for vertical accretion, elevation, bulk density, organic matter content, and accumulation are means with one standard error presented in parentheses. Means within a column followed by a different letter are statistically significantly different at the 1% level. All data except for vertical accretion were log transformed prior to statistical analyses being conducted but untransformed data are presented in the table.

**The record length for two plots on the exposed island and one plot on the protected island was 1.5 years because no marker horizon was recovered during the last sampling.

In the overwash island forests, accretion occurred through both allochthonous inputs of mineral sediment and autochthonous inputs of plant root matter. The islands were overwashed daily and the soil surface was washed clean of litter by tidal action. Macroparticulate leaf and stem material were not observed in soil cores. The possible role of soil algae in binding sediments on overwash islands in southwest Florida has not been studied to our knowledge. The filamentous turf algae found in the fringe forest typically occurs only in the upper intertidal zone of mangrove systems (C.J. Dawes, personal communication). Hence, turf algae likely were not present on the sheltered island where there was little topographic relief but may have been present on the higher elevations of the exposed island behind the berm (Figure 2). Consequently, plant roots likely played a primary role in binding mineral sediments on the sheltered island. The probable lack of turf algae could explain why the accretion rate was slower on the sheltered island compared to the fringe and exposed island forests (Figure 4 and Table 4). Accretion in the exposed island forest was more variable than in the sheltered island forest (Figure 4), probably because of the greater hydrodynamic energy at that site. Two marker horizons on the exposed island and one on the sheltered island were not recovered during the last sampling interval. The remaining markers on both islands were recovered at the end of the 2 y study. The basin and overwash islands were similar in vertical accretion and bulk density but the island soils contained less organic matter by weight (Table 3). Total accumulation of matter was similar among the basin and overwash island sites, but both islands accumulated more mineral matter and the sheltered island accumulated less organic matter.

Importantly, there was no significant correlation between the total hours of flooding and the rate of accretion in any of the 3 forest types (using data from each sampling interval, $n = 4$). Given the different hydrodynamic settings of the basin, fringe, and overwash island forests, and the similarity in accumulation between the basin and island forests, this lack of correlation suggests that different processes controlled accretion in each of the forest types. In the basin, the lack of correlation between flooding and accretion was due to the fact that the accreting material came primarily from within the basin as indicated by the low mineral accumulation rate and buildup of a dense litter layer. In the fringe and overwash islands, the high wave energy removed more litter than in the basin (Twilley et al., 1986) which, combined with the differential effectiveness of filamentous turf algae and plant roots to bind mineral sediments in these environments, limited accretion.

Soil elevation change and shallow subsidence

All of the sites except for the sheltered island showed a significant gain in elevation (based on SET measurements) during the 2 to 2.5 y study (Figure 4, Table 4). In the fringe and 2 overwash island sites, the rate of elevation change was significantly lower than the rate of vertical accretion indicating that shallow subsidence had occurred (calculated as accretion minus elevation) and that elevation was controlled by both surface (accretionary) and subsurface (shallow subsidence) processes. Three distinct elevational environments were identified among the four sites where, in addition to accretion, elevation was influenced by (1) a combination of erosion and subsidence, (2) subsidence, and (3) seasonal shrink-swell related to water storage and/or root growth-decomposition, and perhaps subsidence (decomposition and compaction).

In the fringe forest, the rate of soil elevation change was controlled by both accretion-erosion and shallow subsidence. Shallow subsidence over the full 2.5 year period (based on the overestimate of accretion) was 0.58 cm y^{-1} (Table 4). The impact of erosion on elevation change can be deduced by comparing the rate of shallow subsidence during the first 12 months when erosion of the marker horizons was low (Figure 4) to the 2.5 year rate. The rate of shallow subsidence for the first year was 0.43 cm y^{-1} (Table 4), suggesting that erosion caused the remaining 0.15 cm y^{-1} loss in elevation.

In the organic soils of the basin forest, there was no significant difference in the rate of vertical accretion and elevation change. Yet, elevation change exhibited a semi-annual pattern which was significantly correlated with the total hours of flooding ($r = 0.94$, $p = 0.057$, $n = 4$). Since accretion occurred primarily through autochthonous processes (i.e., there was no correlation between flooding and accretion), this pattern implied that elevation change was related to subsurface processes occurring below the marker horizons. Possible explanations for this pattern include: (1) shrink-swell of the highly organic soils related to semi-annual patterns of soil water storage; and (2) cycles of root growth and belowground organic matter decomposition.

A strong argument can be made that shrink-swell of the highly organic soils controlled elevation in the

Table 4. Accretion, elevation, and shallow subsidence rates for selected mangrove forest types, Rookery Bay, Fl.

Forest type	Dominant vegetation	Vertical Accretion[a]	Change in Elevation	Shallow Subsidence[b]	Length of Record (y)
Fringe	*Rhizophora mangle*	$0.72 \pm 0.02^{**}$	$0.14 \pm 0.05^{*}$	0.58^{**}	2.5
		$0.78 \pm 0.08^{**}$	$0.35 \pm 0.08^{*}$	0.43^{**}	1.0[c]
Basin	*Avicennia germinans/R. mangle*	$0.60 \pm 0.05^{**}$	$0.37 \pm 0.12^{*}$	n.s.	2.5
Exposed island	*Rhizophora mangle*	$0.63 \pm 0.12^{**}$	$0.25 \pm 0.09^{*}$	0.38^{*}	2.0
Sheltered island	*Rhizophora mangle*	$0.44 \pm 0.03^{**}$	0.06 ± 0.11	0.38^{**}	2.0

[a]Vertical accretion and elevation change data are means $\pm$ 1 SE; units are cm y^{-1}. Means were calculated from regression analysis and those rates which are significantly different from zero are indicated by an asterisk (5% = *; 1% = **).
[b]Shallow subsidence = (vertical accretion - elevation change). Shallow subsidence was calculated only for those sites where the mean vertical accretion and elevation change rates were significantly different (5% = *; 1% = **).
[c]Data are from the first 12 months of sampling, as shown in Figure 4.
n.s. Indicates no statistically significant difference between the rates of vertical accretion and elevation change.

basin. During the first sampling interval (high flood), elevation change was greater than vertical accretion (Figure 4), implying that subsurface storage of water in the organic soil exerted a greater influence on elevation than surface accretion. During the subsequent low flood interval, elevation decreased even though there was no erosion of the surface (i.e., the marker horizon was not buried less deep than before). Elevation increased during the following high flood interval. Elevation increased again during the subsequent low flood interval in part because this interval had the highest rainfall total during the 2 y study; 42.2 cm more rainfall (112.1 vs. 69.9 cm), with 1,100 more h of flooding and each flooding event twice as long on average (102 vs 49.5 h) than the previous low flood interval. Hydroperiod characteristics for this low flood interval were comparable to those of the high flood intervals (Table 2). It can also be argued that cycles of root production and organic matter decomposition influenced soil elevation, particularly aerobic decomposition during the low flood intervals which could contribute to elevation loss. Yet, the increase in elevation during the atypically wet low flood interval suggests that shrink-swell of the soil had a greater influence on elevation than growth-decomposition processes. Both shrink-swell and growth-decomposition processes likely contributed to elevation change but there was no way to separate the influence of drainage from decomposition. Studies of belowground decomposition are needed in this system. Soil compaction likely occurred in the basin forest, but its effect was probably masked by the strong semi-annual influence of water storage and/or growth-decomposition on soil elevation.

In the overwash island forests, shallow subsidence exerted a strong influence on elevation change. Despite an annual accretion rate of 0.44 cm y^{-1}, the annual rate of elevation change on the sheltered island was essentially zero (Table 4). This difference was not caused by erosion because all markers were recovered at the end of the study except for one which disappeared during the last sampling interval. Hence, soil elevation was controlled by accretion and subsidence related to compaction and/or decomposition. In the exposed island forest, soil elevation increased significantly throughout the study, but at a significantly slower rate than vertical accretion. Erosion apparently partially contributed to this difference during the second (0.14 cm) and final (0.37 cm) sampling intervals (Figure 4) although all markers were recovered until the last sampling when 2 horizons were not recovered. Therefore, soil elevation was controlled by accretion-erosion and subsidence related to compaction and/or decomposition. Unfortunately, it was not possible to separate the influence of erosion from subsidence, although subsidence was probably the primary controlling factor since shallow subsidence during the first, third, and fourth sampling intervals was 0.3, 0.8, and 0.3 cm, respectively (Figure 4).

The rate of shallow subsidence was similar among the tidally dominated fringe and island red mangrove forests, approximately 0.3–0.4 cm y^{-1} (Table 4). These consistent estimates of shallow subsidence for red mangrove forests in southwestern Florida imply that estimates of total subsidence and relative sea-level rise determined from tide gauges may be underestimated by 0.3–0.4 cm y^{-1} because shallow subsidence occurs at depths between the tide gauge base (similar to the SET base (Figure 3)) and the mangrove soil surface (Cahoon et al., 1995).

Accretion deficits vs. elevation deficits

A significant rate of shallow subsidence does not mean that an elevation deficit exists for that site. Existence of an accretion or elevation deficit can only be determined from direct comparisons with rates of sea-level rise. Accretion and elevation deficits were calculated by comparing both historical accretion rates (lead-210) and short-term rates of accretion and elevation to regional estimates of sea-level rise (Figure 5).

The size of the elevation deficit varied among the 4 sites. The nontidal basin forest, which did not experience any shallow subsidence, also did not experience an accretion or elevation deficit at the highest regional estimate of sea-level rise. In contrast, the tidally-dominated fringe and island sites experienced an accretion deficit based on analysis of lead-210 accretion data. The historical accretion rates (lead-210) lagged behind sea-level rise 0.9 to 3.2 mm y^{-1} (Figure 5). Summed over the 60–70 y sea level record, the minimum lead-210 accretion deficit was 6.3 to 10.5 cm and the maximum was 15.6 to 19.2 cm. A close investigation of historical aerial photography of Rookery Bay, however, revealed little to no net change in the cover, distribution, and location of mangroves on the two islands and the fringe forest between 1928 and 1993 (M. Shirley, Rookery Bay NERR, personal communication). These observations are in line with those of Ross et al. (1991) and Meeder et al. (1993) who reported that the area of mangroves expanded on several islands in the Florida Keys during the past several decades (see review in Snedaker et al., 1994). The stability of the mangrove habitats during the past several decades suggests that the lead-210 accretion deficits are misleading. When comparing average rates of sea-level and land-level change over several decades one must remember that sea-level varies on daily, weekly, monthly, seasonal, and annual cycles (Marmer, 1954; Provost, 1974). It is these short term water-level cycles to which wetland plants respond (Reed, 1995). Our short-term (2–3 y) data suggest that it is more appropriate to examine the relationship among vertical accretion, elevation, and sea-level rise on an annual or semi-annual time scale than a decadal time scale (e.g., lead-210) in this system.

Comparison of our short-term accretion data with the regional sea-level rise estimates revealed that the fringe and island sites did not experience an accretion deficit even at the highest rate of relative sea-level rise (Figure 5). In addition, the exposed island and the accreting patches in the fringe gained elevation at a rate equal to or greater than the lowest estimate of regional sea-level rise. The sheltered island and fringe forests (2.5 y data), however, apparently experienced a small elevation deficit (Figure 5) at the lowest estimate of regional sea-level rise (2.3 mm y^{-1}), although the error bars were close to the line. At the highest rate of sea-level rise, all fringe and island sites experienced an elevation deficit except for the accreting patches in the fringe forest during the first 12 months. Hence, the mangrove forests are accreting fast enough in the near term to maintain present soil elevation relative to the lowest regional sea-level rise estimate, with the possible exception of the sheltered island. It should be noted that the rates of short-term vertical accretion were comparable to the regional rates of sea-level rise adjusted for local shallow subsidence (0.53–0.83 cm y^{-1}, Figure 5), indicating that sea-level rise and shallow subsidence were driving vertical accretion.

For a healthy mangrove ecosystem in south Florida, the relationships shown in Figure 5 indicate that historic lead-210 accretion measures underestimated while short term surface marker horizon measures overestimated the relationship of soil elevation to sea-level. The best estimate of the relationship between land and sea levels was provided by short term measures of elevation change. Our approach suggests a mechanism for determining the potential for submergence of mangrove systems during a scenario of rising sea level. Our findings are consistent with those of other researchers in the Caribbean region (Snedaker et al., 1994; Bacon, 1994) who report that many areas of mangroves are keeping pace or expanding under rates of sea-level rise (2.3 to 4.0 mm/y) which Ellison and Stoddart (1991) predicted would result in the collapse of mangroves in southwest Florida. What is not known is the rate of sea-level rise at which elevation deficits will begin to develop in the south Florida mangrove systems if predicted increases in the rate of sea-level rise are accurate. The ability of mangrove systems to keep pace with increased sea-level rise rates will most likely vary among sites and depend on the availability of sediment and the local geomorphic setting.

Conclusions

In the sediment-poor, carbonate setting of southwestern Florida, the process of soil building in the mangrove forests at Rookery Bay was complex and differed among forest types. Surface accretionary processes contributed importantly to soil elevation with three

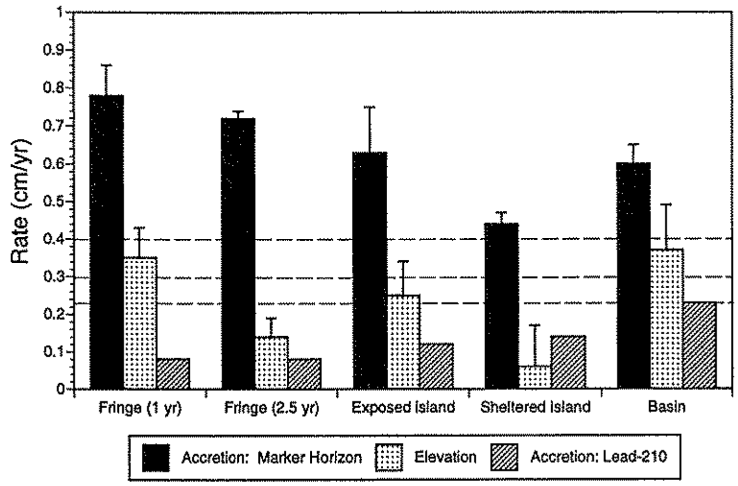

Figure 5. Rates of accretion (artificial marker horizon: black columns; lead-210 analysis: diagonal columns), elevation change (stippled columns), and sea-level rise (dashed lines) in four mangrove forest sites at Rookery Bay NERR. The lead-210 accretion data are from Lynch et al. (1989) for the basin forest while the remaining lead-210 data are from Cahoon and Lynch (unpublished manuscript). The lower estimate of sea-level rise is from Maul and Martin (1993), the middle and upper sea-level rise estimates are from Wanless et al. (1994). The vertical accretion and elevation data are means with 1 standard error bar.

accretionary environments identified: mineral soils (fringe), organic soils (basin), and a combination of mineral and organic soils (overwash islands). Deposition of allochthonous mineral matter was an important process contributing to soil elevation in the tidally dominated fringe and overwash island forests. Turf algae and the fine roots of the red mangrove apparently played an important role in binding the soil in place in these forests, although turf algae may not have affected soil accumulation on the sheltered mangrove island. The accumulation of autochthonous matter was the primary soil building mechanism in the hydrologically isolated basin forest. Soil elevation was controlled not only by surface accretionary processes, but also by subsurface soil processes including: subsidence combined with erosion (fringe and exposed island), subsidence (sheltered island), and shrink-swell of the soil (related to water storage and/or growth-decomposition) and subsidence (basin). Shallow subsidence was consistently 0.3–0.4 cm y^{-1} in the tidally dominated red mangrove forests, indicating that relative sea-level rise estimates from tide gauges for southwestern Florida mangroves are underestimated by this amount. Accretion measures from marker horizons overestimated while accretion measures from lead-210 underestimated the relationship of soil elevation to sea level. The potential for submergence of these mangrove systems during sea-level rise is best estimated by elevation deficits calculated from short-term measures of elevation change.

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