Chapter 3: Global Climate Change and Sea-level Rise: Estimating the Potential for Submergence of Coastal Wetlands

by

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Abstract: The ability of coastal wetlands to keep pace with sea-level rise through vertical accretion and transgression onto adjacent upslope habitats was examined for the following coastal habitats in the southeastern United States: low salt marsh, high salt marsh, brackish marsh, and mangrove forests (fringe, basin, and overwash islands). The relationship between vertical accretion and soil elevation change was determined for these wetland types along gradients of marsh type, tidal range, and subsidence. Simultaneous measures of vertical accretion and soil elevation change were used to calculate each wetland's rate of shallow subsidence (accretion minus elevation change) and to evaluate the potential for submergence of each wetland given the local rate of sea-level rise. Significant rates of shallow subsidence were measured at 7 of 12 marsh-mangrove wetlands. Four of these seven sites experienced a significant elevation deficit (elevation minus relative sea-level rise), but none of the four sites experienced a significant accretion deficit (accretion minus relative sea-level rise), indicating how misleading accretion data can be when evaluating the potential for submergence of coastal wetlands. These findings also indicated that subsurface processes occurring in the top few meters of the soil were as or more important in determining marsh elevation than surface accretionary processes for some of the marshes. Subsurface processes that likely influenced elevation included compaction, plant growth, plant decomposition, and shrink-swell from water storage. Forces driving these processes apparently included seasonal changes in water levels and aperiodic occurrences of major storms. Hence, the potential for submergence of some coastal marshes is best determined by calculating elevation deficits rather than accretion deficits.

Rates of marsh transgression onto adjacent upland forests were determined at two high salt marshes located on Pamlico Sound, North Carolina, by radiocarbon dating of basal marsh peats along transects running from the marsh into the forest. The rate of movement of the marsh edge onto adjacent forest habitat was neither gradual nor constant, but was instead punctuated. The ages of the basal marsh sediments were grouped, indicating that transgression occurred as a series of events separated by longer periods of relatively little marsh-edge movement. It is unlikely that the transgression events were initiated directly by rapid, local relative sea-level rise because the events were not synchronous between the two sites. Rather, the transgression events were likely generated by disturbance of the upland vegetation, allowing the marsh to leap forward. A likely vector for disturbance would be major storms (e.g., hurricanes) or fires, although sea-level rise is still the driving force behind the transgression. Hence, short-term rates of marsh transgression may be meaningless and may not be useful tools to predict wetland habitat change, at least for some marshes.

The findings from this study indicate that predicting the vertical buildup and migration of coastal wetlands in response to sea-level rise requires site-specific information, and also that we need to understand more about the interactions among vegetation, soil, and hydrologic processes as they relate to soil elevation in marshes and mangrove forests if we are to properly manage these resources during future increases in sea level. Specifically, we need information on shallow subsidence from additional environmental settings, the critical processes controlling elevation in each environmental setting and site, the natural forces driving the processes controlling elevation, and the influence of management processes on shallow subsidence, marsh transgression, and the potential for marsh submergence.

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Introduction

In this chapter we present a summary of the technical results of a multiyear investigation into the relationships among accretionary processes, sea-level rise, and the potential for submergence of coastal wetlands during future rises in sea level. Technical explanations of the methodologies and experimental design used in this study are provided in Boumans and Day (1993), Cahoon et al. (1995a; 1995b; 1996a; 1996b), Reed and Cahoon (1992), and Reed et al. (1995).

Global mean sea level has risen approximately 1–2 mm/year during the past 100 years (Gornitz 1995). The Intergovernmental Panel on Climate Change predicts a 50-cm rise in average global eustatic sea level by 2100, between two and five times the rise in the past century (Watson et al. 1996). The low and high estimates of change range from 15 to 95 cm (Watson et al. 1996). Latest estimates by the U. S. Environmental Protection Agency (USEPA) similarly indicate that global warming will likely raise sea level 15 cm by the year 2050 and that the present rate of eustatic sea-level rise will increase by 4.2 mm/year (two- to fourfold) by the year 2100 (Titus and Narayanan 1995). These estimates do not include sea-level rise caused by factors other than global warming (e.g., land subsidence). Areas with high local rates of subsidence, such as the Mississippi River delta, are currently experiencing relative sea-level rise rates (i.e., eustatic sea-level rise plus land subsidence) up to 10 times the global mean sea-level rise rate (Penland and Ramsey 1990; Gornitz 1995). The potential for submergence of coastal wetlands, particularly deltas, will increase under a scenario of rising relative sea level (Gornitz 1991).

In order for marshes not to become submerged as sea level rises, vertical buildup of the marsh surface will have to equal or exceed the rate of relative sea-level rise. The question arises as to how an increase in sea level will affect marsh sediment deposition, vertical accretion processes, and ultimately elevation. An increase in sea level may increase or decrease the local tide range and may also result in a phase shift of the estuary from flood- to ebb-dominated (Dyer 1995). Such changes would directly affect patterns of water circulation, suspended sediment concentrations, and marsh flooding, as well as rates of vegetation growth and, ultimately, marsh accretionary processes (Dyer 1995; Reed 1995). Also, increased global warming may increase the frequency of hurricanes (Emanuel 1987), which could influence local sediment supplies and marsh accretionary processes as well as erosion caused by wind and waves. As sea level rises, marshes may migrate landward, provided there is no barrier to movement such as a fixed structure (e.g., a building or seawall). Subsidence can vary strongly among sites: for example, being high in deltas with thick Holocene deposits and low on stable geologic formations such as ancient shields. Hence, the potential for coastal marsh submergence is controlled more by the local environmental factors of relative sea-level rise, coastal geomorphology, sediment supply, and frequency of major storms than by the trend in eustatic mean sea level (Gornitz 1995). Therefore, predicting the potential for coastal marsh submergence caused by sea-level rise requires site-specific information and an improved understanding of the interactions among marsh vegetation, soil, and hydrological processes.

In this study, we investigated marsh accretion and elevation change in coastal marshes and mangroves selected along gradients of tidal range, subsidence, and marsh type in order to evaluate the processes controlling both vertical development of the marsh surface and transgression (horizontal movement) of the marsh surface onto adjacent uplands. The goal of this study was to improve our understanding of the relationships among marsh accretionary processes, marsh elevation changes, hydroperiod, relative sea-level rise, and the potential for coastal marsh submergence so that we could better evaluate the ability of marshes to keep pace with sea-level rise.

Vertical Buildup of the Marsh Surface

Traditionally, the potential for marsh submergence has been determined by calculating accretion deficits (Reed and Cahoon 1993). Measured rates of vertical accretion are compared directly to local rates of relative sea-level rise. If accretion is not keeping pace with sea-level rise then an accretion deficit is said to exist, and the potential for submergence of the coastal marsh is high. The accretion deficit concept assumes that surface accretion measures are a good indicator of marsh surface elevation change. We also know, however, that the marsh surface subsides because of autocompaction of the Holocene marsh deposits (Kaye and Barghoorn 1964), as reflected in the sharp decline in water content as well as consolidation over the top 1 m of the marsh substrate (Kearney and Ward 1986) and as inferred from slower accretion rates for historic (^{137}Cs and ^{210}Pb) and geologic (^{14}C) accretion methods (Reed and Cahoon 1993; Stevenson et al. 1986), and also that additional subsidence may occur through faulting and compaction of deep sediments, particularly in deltaic environments (Penland et al. 1989). Hence, the validity of the assumption that surface accretion equals elevation change should be questioned. If the increase in elevation is smaller than the vertical accretion gain because of soil subsidence, then the accretion deficit concept is underestimating the potential for coastal marsh submergence. Important questions for coastal managers include: What is the relationship between accretion and elevation change? How does this relationship vary over the range of coastal hydrogeomorphic settings? If elevation gain is slower than accretion gain, what are the important processes controlling elevation? What natural forces drive these processes? And, what are the implications for managing coastal wetlands during periods of rising sea level?

The objectives of this part of the study were to (1) measure accretion and elevation change in marshes along gradients of marsh type, subsidence, and hydroperiod; (2) evaluate the relationship between accretion and elevation change both within and between sites; (3) evaluate the role of hydroperiod in determining marsh response to sea-level rise; and (4) evaluate the relationship between elevation change and relative sea-level rise (i.e., calculate an elevation deficit).

Experimental Approach and Terminology

In order to meet these objectives and answer these questions, it was necessary to develop a new investigative approach that simultaneously quantified vertical accretion and surface-elevation change with a level of accuracy sufficient to distinquish between the influences of surface and subsurface processes on marsh elevation. Surface accretionary processes (e.g., sediment deposition and erosion) were determined from artificial marker horizon plots established on the marsh surface (Cahoon and Turner 1989). Marsh surface-elevation change was measured relative to a subsurface datum (usually 3–5 m deep) using a sedimentation-erosion table (SET) (Boumans and Day 1993). This method of measuring elevation integrates both surface processes (e.g., deposition, erosion) and subsurface processes (e.g., compaction, shrink-swell, plant growth, decomposition) occurring over the top several meters of the soil. The difference between the two simultaneous measures gives an estimate of the impact of subsurface processes on marsh surface elevation change and of the degree to which accretion measures alone underestimate the potential for coastal marsh submergence, if at all. The influence of subsurface processes on marsh elevation has been termed "shallow subsidence." These concepts and the relationship between the two methods are graphically presented in Fig. 3-1 and explained in detail in Cahoon et al. (1995a).

Study sites were selected along gradients of marsh type, subsidence, and tidal range, primarily in the southeastern United States (Fig. 3-2). Most sites were located in saline coastal habitats of low salt marsh (Old Oyster Bayou, Bayou Chitigue, and Tijuana Slough National Wildlife Refuge [NWR]), high salt marsh (St. Marks NWR and Cedar Island NWR), or mangrove (Rookery Bay) (Fig. 3-3a,b,c). Two sites were located in brackish marsh (McFaddin NWR and Three Bayous). At Rookery Bay, measurements were made in fringe, basin, and overwash island forests. The sites from the Mississippi River delta in Louisiana represent areas of high subsidence. Bayou Chitigue is a rapidly deteriorating low salt marsh, in contrast to Old Oyster Bayou, which is a stable, healthy marsh. All other sites represent low subsidence areas. All sites are microtidal, but the tidal range at St. Marks is five times greater than for Cedar Island. The tidal range at Tijuana Slough is three

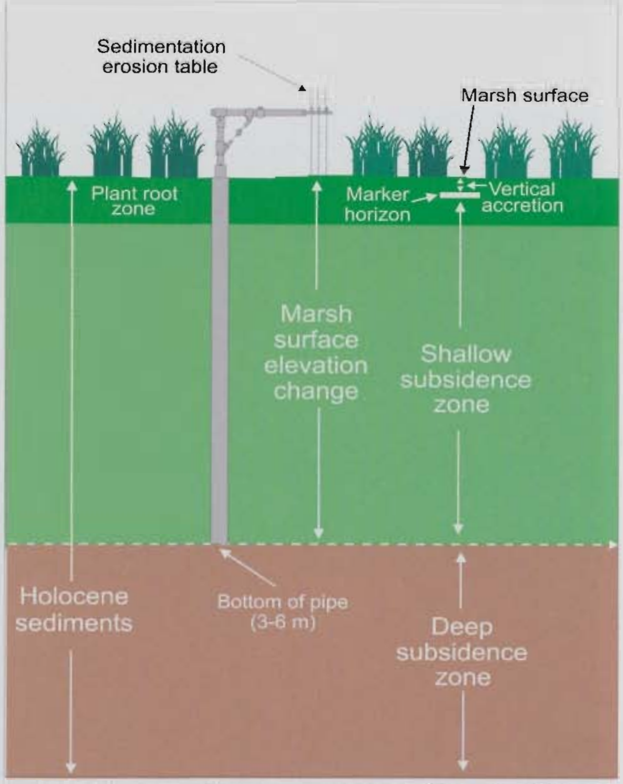

Figure 3-1. Conceptual diagram (not to scale) showing those portions of the soil profile being measured by the sedimentation-erosion table (SET) and marker horizon techniques. The boundary separating shallow and deep subsidence is defined operationally by the bottom of the SET pipe.

Figure 3-2. Location of study sites for estimating the potential for submergence of coastal wetlands.

times greater than the Louisiana marshes. Since both sediment distribution and plant growth are hydrologically mediated, hydroperiod (i.e., the frequency, depth, and duration of marsh surface flooding) was determined at each site from a local tide gauge and detailed levelling of the marsh

Fig. 3-3a. Low salt marsh dominated by *Spartina alterniflora*.

Fig. 3-3b. High salt marsh dominated by *Juncus roemerianus*.

Fig. 3-3c. Mangrove forest dominated by red mangrove, *Rhizophora mangle*.

surface (Reed and Cahoon 1992; Cahoon and Reed 1995; Cahoon et al. 1996a).

Shallow Subsidence

Comparison of annual means of vertical accretion and elevation change allowed us to calculate rates of shallow subsidence for each site (Table 3-1). Measurements were made approximately every 6 months over a 2- to 3.5-year period, and annual rates were determined from regression analyses. Vertical accretion rates at all 12 sites were significantly different from zero, with highest rates measured in low salt marsh, followed by brackish marsh, mangrove forests, and high salt marsh. In contrast, only 6 of 12 sites had rates of elevation change significantly different from zero with no apparent pattern related to wetland type. Significant shallow subsidence occurred at 7 of the 12 sites (Table 3-1), primarily in wetlands with highly organic or unstable soils.

Four of six low salt marsh and mangrove sites along the Gulf of Mexico had significant rates of shallow subsidence, ranging from 0.38 to 2.39 cm/year, with the highest rate measured at Bayou Chitigue. In contrast, Old Oyster Bayou, located near sediment-rich Atchafalaya Bay, and the basin mangrove forest at Rookery Bay had no significant shallow subsidence. The overwash islands and fringe mangrove forests at Rookery Bay, however, had significant rates of shallow subsidence of 0.38 and 0.58 mm/year. One of the islands had no significant elevation gain over the 2-year period despite significant vertical accretion.

In the southeastern United States, two high salt marshes dominated by black needlerush (*Juncus roemerianus*) had no significant elevation gain and a significant rate of shallow subsidence of nearly 3 mm/year. In contrast, two brackish marshes dominated by saltmeadow cordgrass (*Spartina patens*), one from the chenier plain and one from the delta plain along the north central Gulf of Mexico coast, had no measured shallow subsidence. In southern California, where sediment delivery to the marsh is related to erratic annual rainfall patterns and associated riverflows (Cahoon et al. 1996a), Tijuana Slough experienced a major sedimentation event associated with a major winter storm during our first sampling interval. In the low California cordgrass (*Spartina foliosa*) marsh, significant vertical accretion and elevation gain associated primarily with this event were measured, but no significant shallow subsidence occurred (Table 3-1). The high marsh, however, experienced a shallow subsidence rate of nearly 3 mm/year because of no significant gain in elevation over a 2-year period.

Significant rates of shallow subsidence indicate that, for some marshes, measures of total subsidence based on tide gauge records are underestimated by the amount of shallow subsidence occurring at depths between the tide gauge base and the marsh surface (Cahoon et al. 1995a). For example, at Bayou Chitigue, where the marsh is rapidly deteriorating, the actual rate of relative sea-level rise (RSLR) is likely greater than 3 cm/year (RSLR = 2.39 cm/year [shallow subsidence] + 1.38 cm/year [RSLR from tide gauge] = 3.77 cm/year).

Elevation Deficits

Significant rates of shallow subsidence also indicate that the potential for submergence of some coastal marshes is best determined by calculating elevation deficits rather than accretion deficits. Accretion and elevation deficits are

Table 3-1. Accretion, elevation, and shallow subsidence rates for selected coastal marshes in the United States.

Site	Dominant vegetation	Vertical accretion[a]	Change in elevation[a]	Shallow subsidence[b]	Length of record (year)
U. S. Southeastern coast					
Bayou Chitigue	*Spartina alterniflora*	2.67 ± 0.20**	0.28 ± 0.11	2.39**	3.0
Old Oyster Bayou	*Spartina alterniflora*	0.95 ± 0.19**	0.77 ± 0.24*	ns	3.0
Rookery Bay					
fringe forest	*Rhizophora mangle*	0.72 ± 0.02**	0.14 ± 0.05*	0.58**	2.5
basin forest	*Avicennia germinans*	0.60 ± 0.05**	0.37 ± 0.12*	ns	2.5
exposed island	*Rhizophora mangle*	0.63 ± 0.12**	0.25 ± 0.09*	0.38*	2.0
protected island	*Rhizophora mangle*	0.44 ± 0.03**	0.06 ± 0.11	0.38**	2.0
Cedar Island	*Juncus roemerianus*	0.37 ± 0.03**	0.08 ± 0.08	0.29**	3.5
St. Marks	*Juncus roemerianus*	0.46 ± 0.04**	0.19 ± 0.11	0.27*	3.0
McFaddin NWR	*Spartina patens*	1.11 ± 0.04**	1.26 ± 0.51	ns	2.0
Three Bayous	*Spartina patens*	0.78 ± 0.15**	1.49 ± 0.38*	ns	2.0
U. S. Pacific coast					
Tijuana Estuary					
low marsh	*Spartina foliosa*	1.31 ± 0.20**	1.96 ± 0.36**	ns	2.5
high marsh	*Salicornia subterminalis*	0.15 ± 0.01**	-0.13 ± 0.11	0.28*	2.0

[a] Vertical accretion and elevation change data are means ± 1 SE; units are cm/year. 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% = **).
ns Indicates no significant difference between the rates of vertical accretion and elevation change.

calculated by comparing accretion and elevation rates with sea-level rise (Fig. 3-4). For example, data from Bayou Chitigue show how misleading accretion measures can be when used as a measurement of elevation increase (Fig. 3-4a). The accretion data indicate there is no deficit relative to sea level; indeed, there is an accretion surplus. Yet a significant elevation deficit exists. In contrast, there is no accretion or elevation deficit at Old Oyster Bayou, where the marsh surface is in equilibrium with local relative sea-level rise; the marsh is not deteriorating, and the vegetation is healthy (Cahoon et al. 1995a).

A significant rate of shallow subsidence does not automatically mean that an elevation deficit exists relative to sea level. Both black needlerush high salt marsh sites (Cedar Island and St. Marks) were in equilibrium with current rates of rise in sea level, and these marshes can be considered stable (Fig. 3-4b), despite significant shallow subsidence. Similarly, in the mangroves of south Florida, where sea-level rise estimates range from 2–4 mm/year (Maul and Martin 1993; Wanless et al. 1994), three of the four sites were in equilibrium with the lower estimate of sea-level rise despite significantly smaller gains in elevation (compared to accretion) at three of the sites (Fig. 3-4c). Only the leeward island experienced an elevation deficit. Using the higher estimate of sea-level rise, both the leeward island and the fringe forest experienced a serious elevation deficit. Note, however, that none of the mangrove sites experienced an accretion deficit under the highest estimate of sea-level rise, again indicating how misleading accretion deficit data can be.

The infrequently flooded high marsh at Tijuana Slough, where there was significant shallow subsidence, experienced a significant elevation deficit (Fig. 3-4b). In the low marsh at Tijuana Slough, however, there was no accretion or elevation deficit (Fig. 3-4a) because a major winter storm in 1993 deposited about 32,000 metric tons of sediment, primarily in the low marsh (Cahoon et al. 1996a). This pulse of sediment ended nine years of drought, during which

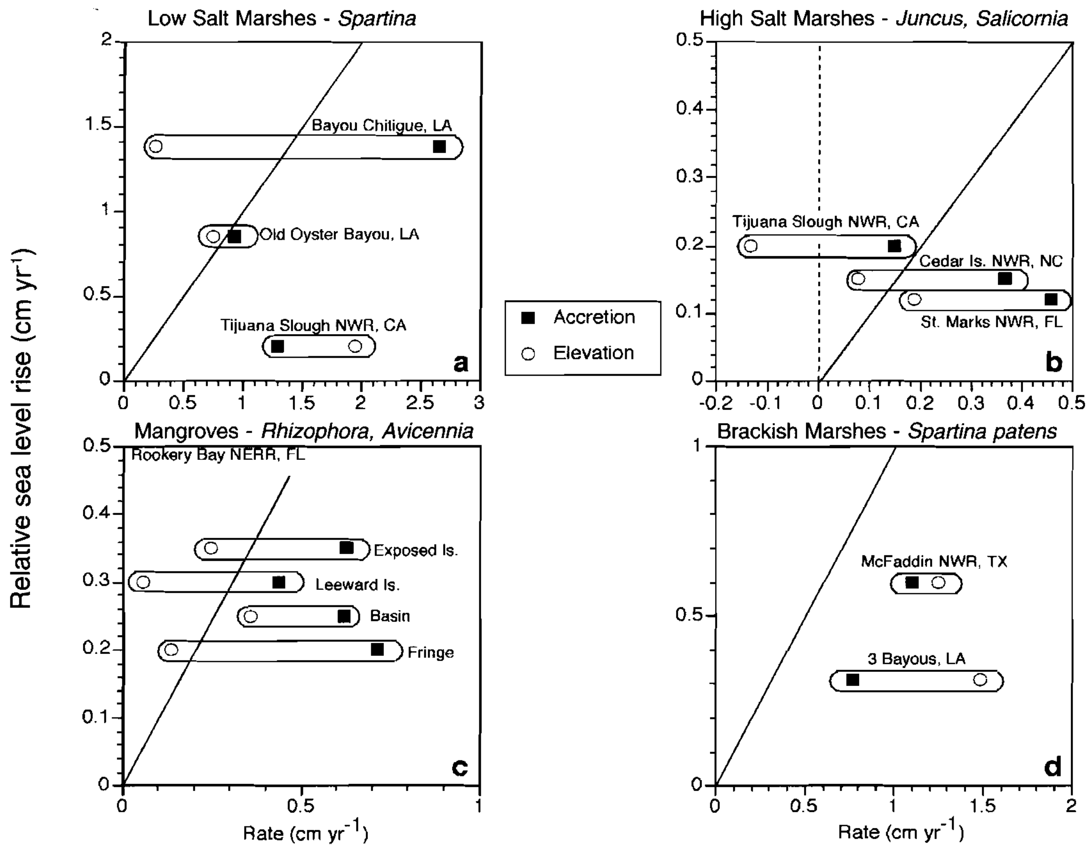

Figure 3-4. Relationship of vertical accretion and marsh surface elevation change with local relative sea-level rise for sites located in (a) low salt marsh, (b) high salt marsh, (c) mangrove forest, and (d) brackish marsh. Diagonal line indicates parity between accretion or elevation change and sea-level rise. Sea-level rise rates are from Stevenson et al. (1986) (North Carolina, northern Florida, and Texas), Baumann et al. (1984) (Old Oyster Bayou), Nyman et al. (1993) (Bayou Chitigue), Wanless et al. (1994) and Maul and Martin (1993) (southern Florida), and Roemmich (1992) (Tijuana Estuary).

time little or no sediment deposition occurred because of very limited river flow. There has been little sediment deposition since the storm. Finally, the brackish marshes on the northern Gulf of Mexico coast did not experience either shallow subsidence or an elevation deficit (Fig. 3-4d).

Processes Influencing Elevation Change

Significant rates of shallow subsidence indicate that subsurface processes can exert as strong, or stronger, an influence on marsh surface elevation as surficial processes of sediment deposition and erosion. Within-site comparisons of seasonal patterns (every 6 months) in vertical accretion and elevation change suggested that changes in marsh surface elevation are related to aperiodic soil compaction associated with hurricanes and to the changes in soil volume associated with (a) seasonal belowground plant production and decomposition cycles and (b) water storage as influenced by seasonal variations in local tide range and sea level. Hence, the controlling process is site specific and depends on the environmental setting and type of marsh substrate (e.g., organic vs. mineral soil). Marshes with highly organic or unstable substrates were most likely to exhibit shallow subsidence.

Shallow subsidence at two sites was apparently related to compaction of shallow sediments (<5 m) during passage of a major hurricane, with the degree of compaction related to stability of the substrate. For example, in 1992, Hurricane Andrew deposited 2–3 cm of material in the smooth cordgrass (*Spartina alterniflora*) salt marshes at Bayou Chitigue and Old Oyster Bayou in the Mississippi River delta in Louisiana (Cahoon et al. 1995b). Bayou Chitigue has a weak, deteriorating mineral soil caused by stress to the vegetation (Day et al. 1994). This marsh experienced a loss in elevation despite storm-related sediment accretion, apparently as a result of sediment overburden and/or storm surge impacts (Fig. 3-5a). The loss of elevation persisted over the next 2.5 years, suggesting it was caused by reduced soil porosity and compaction of organic matter. Old Oyster Bayou has a healthy, vigorous vegetative cover and

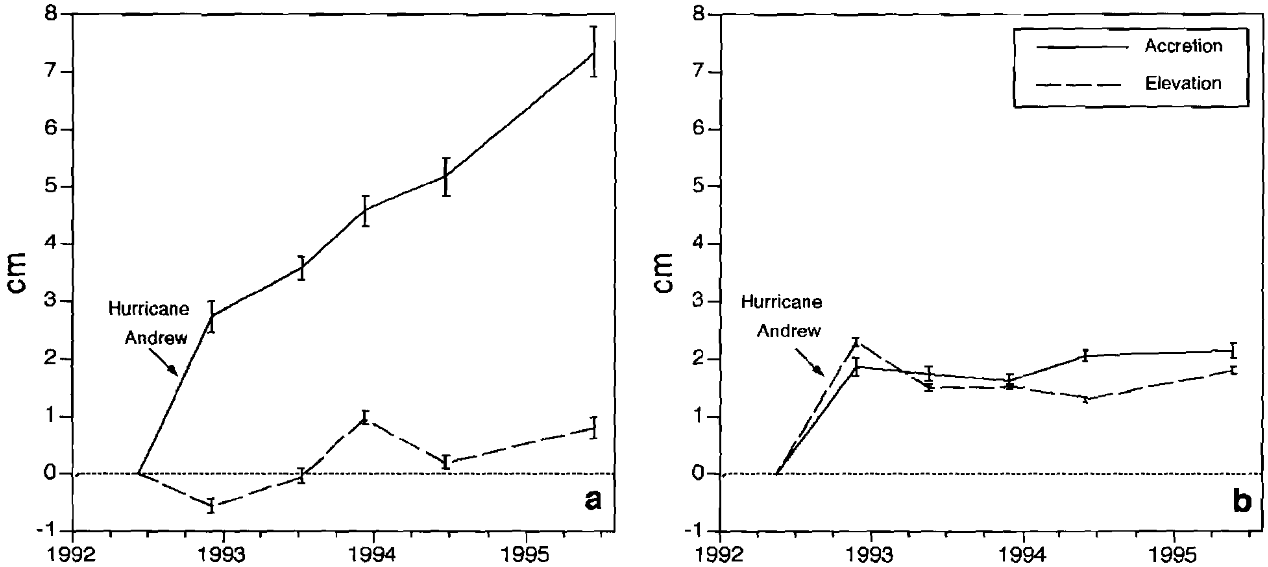

Figure 3-5. Marsh surface elevation change and vertical accretion at (a) Bayou Chitigue and (b) Old Oyster Bayou located in the delta plain of Louisiana. Separation between the two lines represents shallow subsidence.

stable soil substrate and experienced no loss of elevation (Fig. 3-5b). A similar loss of elevation related to passage of a hurricane was observed at the black needlerush marsh in North Carolina (Cedar Island NWR), which has a highly organic substrate (>60% by weight) (Fig. 3-6a). Three different hurricanes impacted this site, and each time there was a loss of elevation, even if sediment was deposited. The elevation loss was apparently related to compaction of organic matter and/or degassing of the substrate. After the second hurricane, the marsh surface apparently rebounded, only to be compressed again by the third storm. These results suggest that some marshes with highly organic substrates are being aperiodically compacted by major storms.

At the high salt marsh dominated by black needlerush in northern Florida (St. Marks NWR), there was no discernible relationship between the patterns of vertical accretion and surface elevation change (Fig. 3-6b), indicating

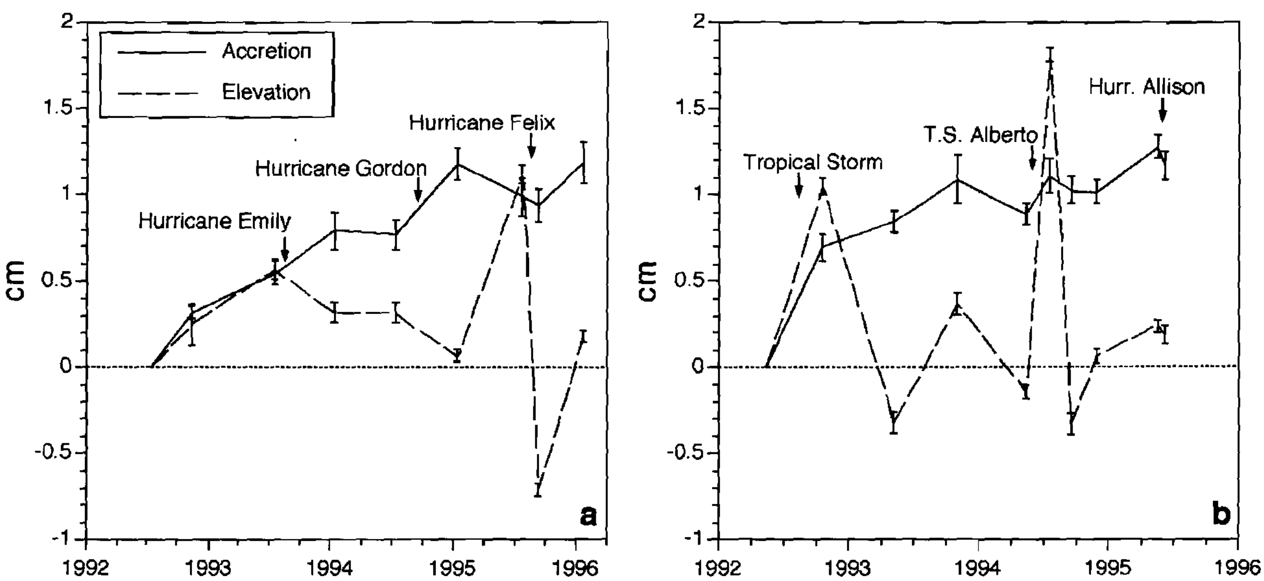

Figure 3-6. Marsh surface elevation change and vertical accretion at (a) Cedar Island on the southeast Atlantic coast and (b) St. Marks on the northern gulf coast of Florida.

that elevation is controlled by subsurface processes rather than the surficial processes which influence accretion. The changes in elevation were likely not related to daily tidal flooding and associated water storage, as has been reported for low salt marshes in New England (Nuttle et al. 1990), because surface elevation did not change over a single tidal cycle when the ground water level varied from greater than 33 cm below the soil surface to 6 cm above it (Cahoon et al. 1995a). Two possible explanations for this pattern are seasonal changes in soil water storage and changes in the volume of the root zone related to a seasonal pattern of plant production (summer) and decomposition (winter) (Cahoon et al. 1995a).

The seasonal trend in elevation could be caused by changes in water storage directly related to the seasonal variation in Gulf of Mexico mean water level and/or an increase in depth of water flooding the marsh at high tide. Mean water level in the northern Gulf of Mexico averages 25 cm higher in summer (Marmer 1954), and there was a 12-cm difference in mean daily tide range between summer (88.7 cm) and winter (76.4 cm) measured by a water level gauge at the site (Reed et al. 1995). Alternatively, the seasonal variations in water levels may influence plant production and belowground decomposition processes. Increased daily tidal range during the summer creates more oxidized substrate conditions which are well suited for plant production (Steever et al. 1976; Howes et al. 1986). In addition, evapotranspiration during periods of active photosynthesis in salt marsh plants can remove significant amounts of water from the soil (Dacey and Howes 1984; Morris and Whiting 1985). During the winter, aerobic plant decomposition processes are enhanced by lower mean water levels and plant senescence and death (Hackney and de la Cruz 1980). The combined influence of seasonal variations in both water level and plant production and decomposition may be responsible for the pattern of elevation change shown in Fig. 3-6b. In contrast, the seasonal trend was not observed in the black needlerush marsh at Cedar Island because there was no strong seasonal pattern in daily tidal range (16.8 cm in summer versus 24.1 cm in winter) and Cedar Island marsh is irregularly flooded, wind-dominated, and characterized by long, shallow flooding events (average flooding event is 47 h long and 13.7 cm deep [mean maximum depth] versus 3.5 h and 16.9 cm deep [mean maximum depth] at St. Marks; Reed et al. 1995). Finally, the data were inconclusive regarding the potential influence of major storms on elevation at St. Marks. Major storms may have increased elevation in October 1992 and July 1994 through water storage, but Hurricane Allison had no effect on elevation in June 1995.

In the mangroves of Rookery Bay, which occupy an ecological niche similar to the salt marshes at St. Marks, elevation change closely followed accretion in the basin forest (Fig. 3-7) but lagged behind accretion in the fringe (Fig. 3-7) and overwash island (Fig. 3-8) forests because of the influence of subsurface processes. The basin forest was located inland of the fringe forest and therefore was hydrologically remote. The soil of the basin forest was highly organic (58% organic content) since much of the vertical accretion was due to accumulation of leaf litter. In contrast, soils of the fringe forest were highly mineral (8% organic matter) and were exposed to continuous wave and tidal action. Consequently, the soil surface was a mosaic of small patches (<0.5 m^2) of mud and bare shell.

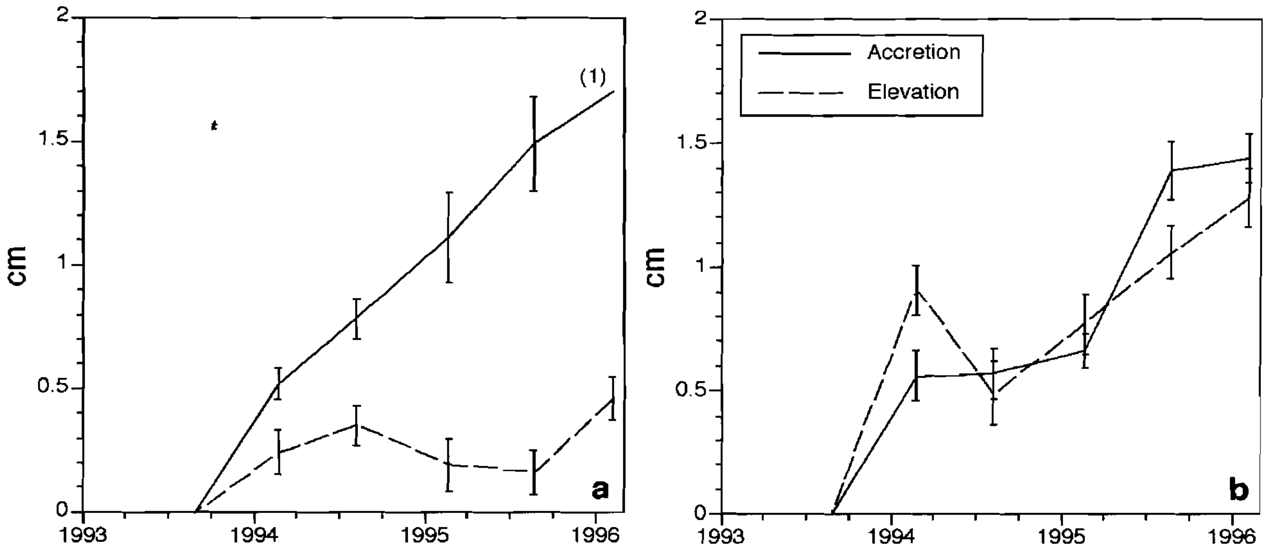

Figure 3-7. Marsh surface elevation change and vertical accretion at (a) the fringe mangrove forest and (b) the basin mangrove forest at Rookery Bay, Florida.

In the fringe forest, vertical accretion occurred wherever the loose, fine-grained mud was bound in place by filamentous algae. There were some bare shell patches where fine-grained mineral sediments did not accumulate because of wave action, although shells may continue to accumulate at this site. Since the marker horizon technique had an inherent bias toward measuring accreting surfaces to the exclusion of eroding surfaces (because those markers are lost), it likely overestimated accretion rates in the fringe forest. Erosion of the marker horizons occurred continuously over time, with only 50% of the markers remaining after 18 months and only 1 out of 21 remaining after 30 months. Hence, the slope of the accretion graph (Fig. 3-7) represents a maximum rate of accretion. On the other hand, the SET was equally likely to measure an eroding or an accreting surface and therefore provided a better estimate of overall surface elevation change. The difference between accretion and elevation (Fig. 3-7) was likely overestimated because of the bias of the accretion technique. The impact of erosion on elevation change was deduced by comparing the rate of shallow subsidence during the first 12 months, when erosion was low (Fig. 3-7), to the 2.5-year rate. The rate of shallow subsidence for the first year was 0.43 cm y^{-1}, indicating that erosion caused the remaining 1.5 cm y^{-1} loss in elevation (Table 3-1). Hence, most of the difference between accretion and elevation was apparently related to subsurface processes rather than erosion.

Two mangrove islands dominated by red mangrove (*Rhizophora mangle*), one exposed to wave fetch along most of the length of Rookery Bay and the other protected from wave action in the lee of a larger island, had substrates regularly washed by tides and firmly bound by fine roots (41% organic matter). The protected island had a very flat topography and had no significant gain in elevation despite continuous accretion (100% of the markers recovered). The vertical buildup of the soil was apparently counterbalanced by compaction and decomposition of organic matter (i.e., shallow subsidence; Fig. 3-8). The exposed island had a raised berm on its windward shore, and there was greater variation in the accretion data compared to the protected island. This greater variability, considered with the significant gain in elevation, suggests that there may be a closer relationship between accretion and elevation for this site than our calculated rate of shallow subsidence would indicate.

In the high marsh at Tijuana Estuary, the substrate consisted primarily of coarse-grained sediments (i.e., sand) with only shallow peat development (Cahoon et al. 1996a). This site received little influx of mineral sediments even during the major flood which occurred at the beginning of the study (Fig. 3-9a). There was a small but significant elevation gain during the sampling interval which included the storm, followed by a significant and steady decline. We hypothesize that two months of freshwater river flows reduced the salinity impacts of daily tides and temporarily improved growth conditions in this sandy soil (i.e., reduced high soil salinities related to nine years of drought), which resulted in a short-term increase in belowground plant growth (Zedler et al. 1986) and a gain in elevation. When drought conditions returned, production of belowground plant material declined because of salt stress (Zedler et al. 1986) which resulted in a loss of elevation. In contrast, there was no shallow subsidence in the low marsh at Tijuana Estuary.

The rates of vertical accretion and elevation change were the same in the two brackish marshes, yet the data from

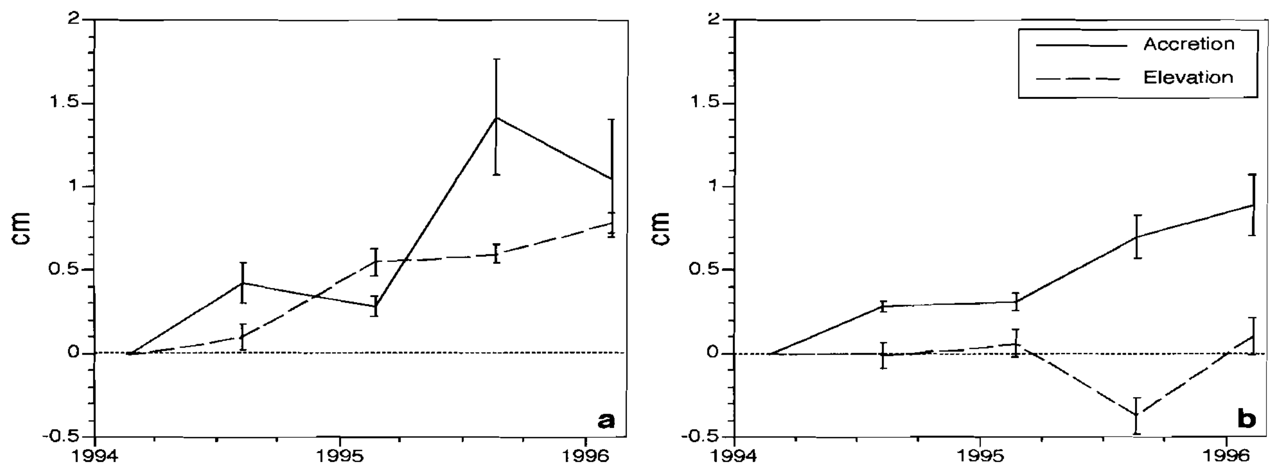

Figure 3-8. Marsh surface elevation change and vertical accretion at (a) the exposed island and (b) the protected island at Rookery Bay, Florida.

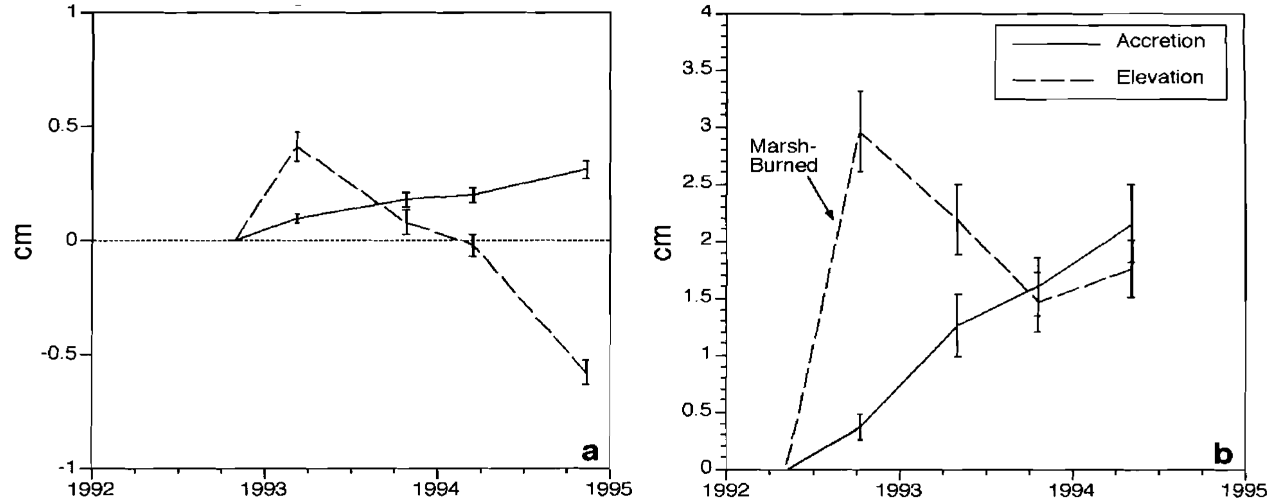

Figure 3-9. Marsh surface elevation change and vertical accretion for (a) the high marsh at Tijuana Estuary, California, and (b) the brackish *Spartina patens* marsh at McFaddin NWR on the upper Texas coast.

McFaddin NWR suggest that the management practice of burning the marsh may have influenced marsh elevation. A dramatic increase in elevation relative to accretion occurred during the first sampling interval, during which time the marsh had been burned (Fig. 3-9b). The rate of elevation change subsequently decreased until it was equal to the rate of accretion. The difference may have been related to a misinterpretation of the marsh surface because of accumulation of burned litter, or caused by an increase in soil volume associated with the rapid mineralization of nutrients and the resulting increase in growth of belowground plant parts.

Role of Hydroperiod in Vertical Accretion and Elevation Change

There was no significant relationship, either positive or negative, between vertical accretion and hydroperiod parameters (mean duration of flooding and mean maximum depth of flooding). Sites with higher duration of tidal flooding did not show increased vertical accretion, and the highest rates of accretion were at sites with relatively low duration of flooding. This pattern is in contrast to that reported by Cahoon and Reed (1995) for a single marsh in south Louisiana where there was an increase in accretion with increased flooding duration. The present analysis compares sites across the southeastern United States and across different marsh types. The sites with highest durations of flooding but only moderate levels of accretion were in brackish marshes (Three Bayous and McFaddin NWR) which are far from ready sources of sediment supply. Three Bayous is located in middle Barataria Basin, where there is no direct input of fluvial sediment. This marsh is also far from the bays in the southern part of the basin, a source of sediments remobilized by storms (Reed 1989). Supplies of sediment to McFaddin NWR are probably dominated by rainfall input within the Sabine-Neches system, and periods of high coastal water levels will not always coincide with periods of sediment supply. In contrast, the site with highest accretion, Bayou Chitigue, is located close to an open bay area where the same events which flood the marsh surface may also introduce sediments (Reed 1989). These ideas are confirmed by an examination of vertical accretion versus mean maximal depth of flooding. Bayou Chitigue had relatively deep flooding and was supplied with sediment, which raised accretion rates. However, events which resulted in deep flooding at the other sites did not necessarily introduce sediments, as reflected by moderate levels of accretion.

Like vertical accretion, there was no significant relationship between elevation change and any of the hydrologic variables. These hydrologic analyses provide further confirmation that site-specific factors such as geomorphology, marsh type, sediment supply, and storm frequency strongly influence vertical accretion and likely control elevation change through both surface and subsurface processes.

Landward Migration of the Marsh Surface

As sea level rises, marshes, like barrier islands and other coastal environments, move landward up the coastal plain. While this fact has been generally recognized, there has been little attempt to characterize, model, or document the landward movement of the boundary between upland and marsh. In order to thoroughly understand the system-wide response of coastal wetlands to rising sea levels, and in order to make reasonable predictions about the future of modern coastal wetlands, we must have a detailed understanding of the nature of marsh transgression, as well as of marsh accretion, erosion, and drowning.

The slope of the adjacent upland and the rates of sea-level rise and sedimentation are key factors in controlling coastal wetland transgression (migration of wetlands onto adjacent uplands). If horizontal migration of a coastal wetland is impeded by the steepness of the slope of adjacent uplands or by a barrier to marsh transgression (such as a sea wall or building), then the coastal wetland may become submerged. If the slope of the adjacent upland is gradual, then wetland expansion is possible. Although both responses of coastal marshes to sea-level rise have been observed, we know very little about the mechanism of marsh transgression. Are slope, the rate of sea-level rise, and accretion the only variables that need be considered for short-term prediction? To answer this question, a model for marsh transgression was developed based on a detailed, 2,000-year record of marsh edge movement from eastern North Carolina (Young 1995).

Experimental Approach

The investigative approach to studying past marsh transgression is straightforward. By identifying and dating the base of the modern marsh sediments in a core sample, we can determine the time at which marsh peat formation first began at the site where the core was taken. Thus, we can identify the time when the landward-moving boundary between the upland and the marsh reached the location of the particular core, although the marsh surface would have been at a slightly lower elevation. Therefore, in order to reconstruct the transgression of the marsh edge at a particular site, one can date the base of the marsh sediments in a transect of cores extending from the center of the marsh into the transition zone. By dating the base of the marsh in each core in the transect, the landward migration of the wetland margin can be observed, and the rate and nature of the marsh edge versus movement up the transgression surface (the basal unconformity) can be determined. Two marshes located on Pamlico Sound in coastal North Carolina, at Cedar Island NWR and Long Shoal River, were selected for study because (1) there was evidence of marsh transgression (i.e., dead trees standing in the marsh), and (2) there were no tidal creeks in the irregularly flooded, low energy marsh systems, hence interpretation of the cores would not be confounded by erosional unconformities caused by channel migration.

The Process of Marsh Transgression

An initial assumption in this study was that a rate for the gradual, landward movement of the upland/marsh boundary under a regime of rising sea level could be established for use in short-term marsh management. However, Fig. 3-10 illustrates that the marsh edge transgressions in both the Cedar Island and Long Shoal River sites were neither gradual nor constant. The ages of the base of the marsh sediments are grouped. Two or three consecutive cores along the transect have essentially the same basal peat age, followed by another set of cores with a much younger age. This pattern continues along the transect in both sites up to the modern upland/marsh boundary. If the basal peat dates indicate marsh initiation at each point along the transect, it is apparent that the marsh edge is moving landward in a series of relatively rapid jumps. These *transgression events* are separated by longer periods of relatively little marsh edge movement. Transgression events have occurred about every 300–350 years at both sites, and the magnitude of the jumps varies from two- to threefold.

A model of punctuated marsh transgression has been developed to explain these observations (Fig. 3-11). It is unlikely that the transgression events are initiated directly by rapid, local relative sea-level rise because the events are not synchronous between the two sites. Rather, the transgression events are likely generated by disturbance of the upland vegetation, such as by major storms (e.g., hurricanes or fires), which allows the marsh to leap forward. It is important to keep in mind that although disturbance of upland vegetation is the likely mechanism that allows transgression to occur in this model, sea-level rise is still the driving force behind the transgression. Based on this model, the process of marsh transgression can be described as follows: (a) upland vegetation delays the advance of the marsh margin, even as sea level continues to rise; (b) a disturbance impacts the upland vegetation, thus allowing the marsh margin to jump forward and strive for a new equilibrium position with the temporal position of sea level; and (c) following the transgression event, the marsh edge will move very little until the next disturbance.

Conclusions

Subsurface processes occurring in the top few meters of the soil were at least as important in determining marsh elevation than surface accretionary processes for some marshes. Elevation gain lagged behind vertical accretion at 7 of the 12 marshes we studied, indicating that subsurface processes occurring in the top few meters of the soil exerted more control over elevation than accretion. Four of these seven sites experienced a significant elevation deficit (elevation minus relative sea-level rise), but none of the four sites experienced a significant accretion deficit (accretion minus relative sea-level rise), indicating how misleading accretion data can be when evaluating the potential for submergence of coastal wetlands. Examples of subsurface processes that can influence elevation include compaction, plant growth and decomposition, and shrink-swell of the soil related to water storage. The term "shallow subsidence" is used to describe the collective effect of these processes on marsh surface elevation. Some of the

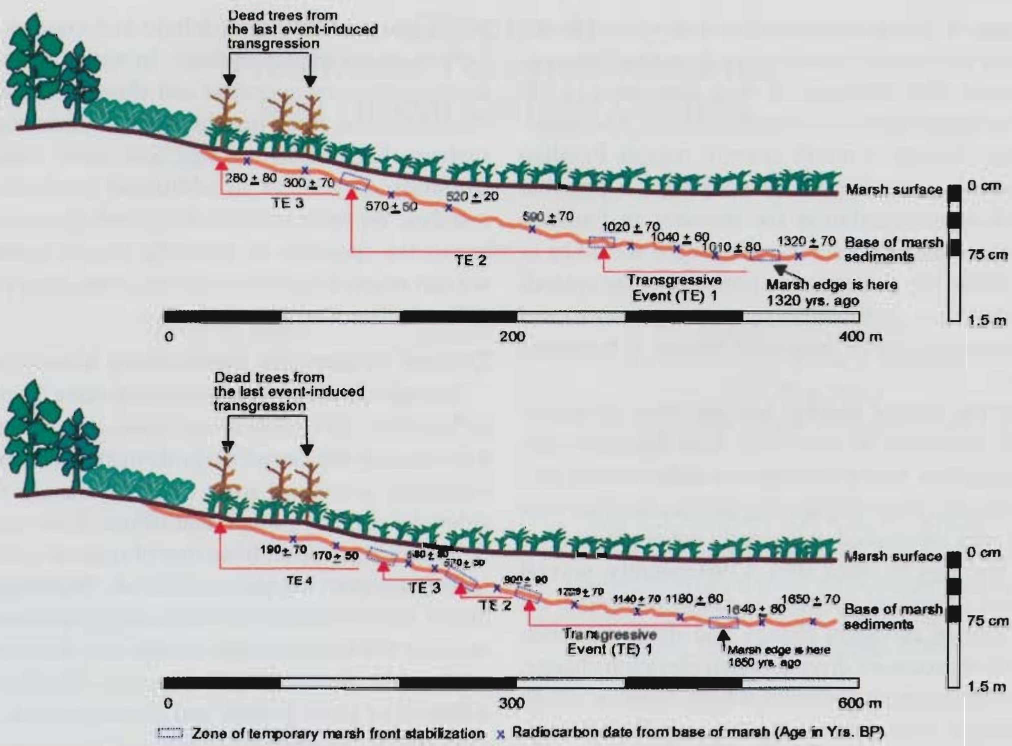

Figure 3-10. Diagram of punctuated marsh transgression event at Long Shoal River (top) and Cedar Island (bottom), North Carolina.

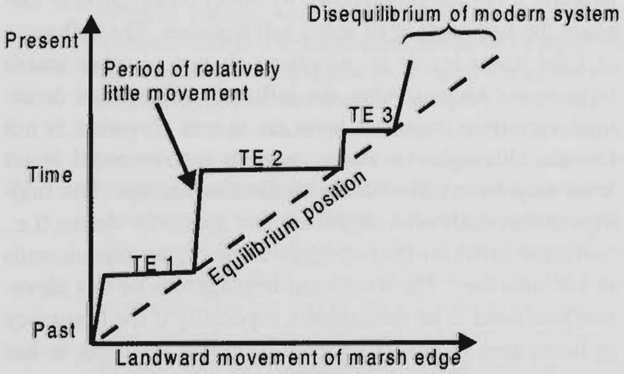

Figure 3-11. Diagram of the conceptual model for punctuated marsh transgression. TE = transgression event.

forces driving shallow subsidence apparently included seasonal changes in water levels and aperiodic occurrences of major storms. Hence, the controlling process for marsh elevation was site specific and depended on the environmental setting. Marshes with highly organic or unstable substrates were most likely to exhibit shallow subsidence.

Marsh transgression was an episodic process that was driven not only by sea-level rise but also local environmental conditions. Transgression of two marshes on Pamlico Sound, North Carolina, appears to have occurred through a process of punctuated events which were controlled by the biologic system (i.e., the biologic system influences geologic change), and therefore landward migration of the marsh was only indirectly linked to the rate of sea-level rise. The apparent trigger for a transgression event was a disturbance of the upland vegetation, such as a major storm event.

Management Implications

The potential for submergence of some coastal marshes is best determined by calculating elevation deficits rather than accretion deficits. The possible occurrence of shallow subsidence in a marsh system means that marsh managers should be calculating elevation deficits rather than accretion deficits when determining the potential for submergence of a marsh. The implication of these findings is that the potential for coastal marsh submergence is being underestimated for some marshes, especially in the Mississippi delta.

Measures of total subsidence based on tide gauge records are underestimated by the amount of shallow subsidence.

Short-term rates of marsh transgression may be meaningless and may not be useful tools to predict wetland habitat change. If marsh transgression is an episodic process driven by infrequent events rather than a continuous, gradual process, then estimates of short-term rates (<100 years) may be meaningless as a predictive tool. The applicability of this finding to marsh systems outside Pamlico Sound, however, is not known. Nevertheless, a possible management recommendation for marshes in Pamlico Sound which are about to become submerged would be to artificially release the transgression potential at the upland/marsh boundary (i.e., artificially create a disturbance) and allow the marsh to move landward before it becomes submerged.

Predicting the vertical buildup and migration of coastal wetlands in response to sea-level rise requires site-specific information. Given the apparent differences in processes and driving forces influencing marsh elevation over the range of sites we studied, it is clearly not appropriate to extrapolate findings to other sites. Consequently, several issues become of critical concern to marsh managers, including the rate of elevation change and shallow subsidence, the critical processes driving marsh elevation change, and current management practices which enhance marsh elevation change. Managers must also consider how current management practices influence the potential for submergence of a marsh; whether transgression of the marsh is occurring, and if so, if it occurs through a series of punctuated events or a gradual process; and how he/she can facilitate marsh transgression. We recommend that marsh managers employ management techniques that will enhance marsh elevation and minimize the potential for marsh submergence.

Future Research

The findings from this study indicate that we need to understand more about the interactions among vegetation, soil, and hydrologic processes as they relate to soil elevation in marshes and mangrove forests. Specifically, we need information on (1) shallow subsidence at additional environmental settings, (2) the critical processes controlling elevation in each environmental setting and site, (3) the natural forces driving those processes, and (4) the influence of management processes on shallow subsidence, marsh transgression, and the potential for marsh submergence.

Additional Environmental Settings

The site-specific nature of the relationship between accretion and elevation change, and the driving forces affecting that relationship, indicate that it is not appropriate to extrapolate findings of our study to other sites. The 12 sites we investigated represent a limited range of marsh types (tidal salt and brackish marsh, mangrove forest) and physiographic settings (deltaic and coastal fringe), all located in microtidal settings. Investigations of the relationship between accretion and elevation need to be conducted in tidal fresh marshes, river-dominated mangrove systems, backbarrier settings, and meso- and macrotidal wetlands, as well as in additional brackish and saline marshes. We must establish long-term elevation data bases across the spectrum of federally owned wetlands so that we can assess their vulnerability to sea-level rise and provide advance warning of change.

Critical Processes Controlling Elevation

Numerous subsurface processes have been suggested or identified as causes of elevation change, but few have been directly measured. Organic matter content of the soil, especially growth of roots and rhizomes, is widely considered a primary component of marsh elevation change. Separating its impact from that of mineral sediment deposition, however, has proven difficult. Shrinking and swelling of the soil related to water storage has been shown to displace the marsh surface in some salt marshes. Soil compaction also decreases soil elevation. But the relative contribution of plant growth and decomposition, water storage, and compaction to marsh soil elevation change has not been determined.

Natural Driving Forces

Hydrologic events on daily, seasonal, or annual time scales can influence marsh soil elevation. Tidal variation in water level has been shown by direct observation to displace the soil surface of some salt marshes. The influence of tidal water levels on elevation change in other marsh types is not known. Also, the influence of seasonal or annual variations in water level on marsh elevation is not known, although our study suggests that seasonal water level may have influenced elevation at one site. The findings of this study also suggested that aperiodic storms (i.e., hurricane storm surges) compacted the highly organic soils of two marshes. The long-term implications of this elevation loss need to be determined, especially if the frequency of hurricanes increases because of global warming as has been predicted (Emanuel 1987).

Influence of Management Practices

Common wetland management and restoration practices include burning, hydrologic manipulations, sediment introduction (including dredged material disposal), and controlled and uncontrolled river diversions. A considerable portion of the several million acres of federally owned wetlands has been managed by at least one of these methods. There are few data available, however, on the impact of these management practices on wetland soil elevation. In addition, research is needed to evaluate the feasibility of artificially inducing a marsh transgression event.