Journal of Coastal Research	13	1	181–191	Fort Lauderdale, Florida	Winter 1997

Sediment Accretion Rates from Four Coastal Wetlands Along the Gulf of Mexico

J.C. Callaway,[1] R.D. DeLaune and W.H. Patrick, Jr.

Wetland Biogeochemistry Institute
Louisiana State University
Baton Rouge, LA 70803-7511

ABSTRACT

CALLAWAY, J.C.; DeLAUNE, R.D., and PATRICK, W.H., JR., 1997. Sediment accretion rates from four coastal wetlands along the Gulf of Mexico. *Journal of Coastal Research,* 13(1), 181–191. Fort Lauderdale (Florida), ISSN 0749-0208.

Our study of sediment accretion rates from four low tidal-range sites along the Gulf of Mexico does not support previous hypotheses concerning the relationship between tidal range and vertical accretion rates. The addition of our data to an earlier data set decreased the correlation between these variables, and all but one of our low-tidal range sites had positive accretion rates, contradicting previous studies which have predicted that low tidal-range sites would have negative net accretion rates. Additionally, in transects across the marsh, accretion rates decreased from low- to high-marsh stations; however, this appeared to be caused by changes in rates of organic matter accumulation, not mineral matter accumulation, as has been proposed in previous studies. Vertical accretion rates were more strongly correlated with organic matter accumulation rates than mineral matter accumulation rates, confirming previous studies which indicated the important role of sediment organic matter in determining sediment structure. These results do not imply that mineral matter is unimportant in maintaining the elevation of the marsh; mineral matter input affects organic matter production and sediment bulk density. There was little correlation between mineral and organic matter accumulation rates, with average organic matter accumulation rates for each site having little variation compared to the variation in mineral matter accumulation rates. This result supports a previous hypothesis that there may be a limit to annual rates of organic matter accumulation. Finally, the study indicates that the negative net accretion rates documented in Louisiana are not typical of other Gulf coast wetlands.

ADDITIONAL INDEX WORDS: *Sea-level rise, subsidence, salt marshes, mangroves.*

INTRODUCTION

Extensive data have been collected over the last decade concerning sediment accretion rates in coastal wetlands because of the potential impacts of increases in sea-level rise on these habitats. Recent estimates of future eustatic sea-level rise vary from 20 to 115 cm by the year 2100 (Woodroffe, 1993), although more conservative estimates range from 35–50 cm over that time period (Wigley and Raper, 1992). Most coastal wetlands studied to determine sediment accretion rates are keeping pace with current rates of sea-level rise (Griffin and Rabenhorst, 1989; Patrick and DeLaune, 1990; Anderson *et al.,* 1992; Thom, 1992; Craft *et al.,* 1993); however, some are experiencing submergence (DeLaune *et al.,* 1983; Baumann *et al.,* 1984; Stevenson *et al.,* 1985). If future rates of sea-level rise increase, it is unclear how large an increase coastal wetlands will be able to withstand (Orson *et al.,* 1985). Potential impacts to coastal wetlands include the conversion of vegetated wetlands to intertidal mudflats if the inundation tolerances of vegetation are exceeded (Salinas *et al.,* 1986) and the conversion of high marsh to low marsh (Warren and Niering, 1993). Despite the growing number of studies of wetland sedimentation rates, there are still many unknowns concerning the relationship of accretion rate, sea-level rise, subsidence, and other variables.

The maintenance of the relative elevation of an intertidal wetland is a complex process, and many factors, including variables on a variety of scales, may be involved. Some of the key factors that have been proposed to affect accretion rates include: relative elevation (Letzsch and Frey, 1980; Pethick, 1981), tidal range (Harrison and Bloom, 1977), proximity of the sediment source and creek system (Stoddart *et al.,* 1989), plant community and density of vegetation (Richard, 1978; Gleason *et al.,* 1979; Stumpf, 1983), and local rates of subsidence (Redfield, 1972). In a review of accretion processes and sea-level rise, Stevenson *et al.* (1986) showed a positive linear relationship between tidal range and net accretion rate. However, all of the low-tidal range sites which they studied were experiencing relatively high rates of subsidence and, as a result, had very low rates of net accretion (in fact all were negative). This lead to the question, "Are low net accretion rates really characteristic of low tidal-range sites?"

The Gulf coast is an ideal place to study accretion rates under a low tidal regime. There are an abundance of coastal wetlands and the entire coast has a low tidal regime. Many studies of accretion rates in Louisiana coastal wetlands have

94182 received 9 September 1994; accepted in revision 25 November 1994.

[2] Current address: Pacific Estuarine Research Laboratory, Department of Biology, San Diego State University, San Diego, CA 92182, U.S.A.

been completed (DELAUNE *et al.,* 1978; HATTON *et al.,* 1983; KNAUS and VAN GENT, 1989; NYMAN *et al.,* 1990). These areas have low tidal ranges but are also characterized by extremely high rates of subsidence and hence relative sea-level rise. Very few wetland accretion studies have been completed on the Gulf coast outside of Louisiana (LYNCH *et al.,* 1989). In order to evaluate sediment accretion processes in low tidal-range wetlands, accretion rates from four different coastal wetlands in the Gulf of Mexico were measured. Sites include three tidal salt marshes from Aransas National Wildlife Refuge (NWR), TX; San Bernard NWR, TX; and Biloxi Bay, MS; and a group of tidal mangrove wetlands in the Florida Keys (Figure 1).

In addition to addressing the correlation of tidal range and accretion rates, this data set allowed evaluation of additional questions concerning wetland accretion processes, including some relationships proposed by other researchers and enumerated above. This study specifically targets the relationships between vertical accretion, organic matter accumulation, and mineral matter accumulation rates. Correlations between these variables are used to help interpret the roles of organic and mineral matter in coastal wetlands (BRICKER-URSO *et al.,* 1989; NYMAN *et al.,* 1993). This approach was used to determine if similar trends could be found from sites across the Gulf of Mexico. Finally, vertical accretion data from these coastal wetlands identify areas which may be vulnerable to increases in global sea level.

METHODS

Site Locations

At each of the four sites described below, six cores were collected. Sites were chosen in order to obtain samples from areas ranging broadly across the Gulf coast and with a wide range in rates of relative sea-level rise. At the first three sites, cores were collected along two transects, with sampling stations in the low, mid and high marsh. Throughout the paper, the term "site" is used to refer to the four sampling areas described below and the term "station" to designate a sampling location within a given site. The low-marsh station was situated approximately 10 m from the creek bank to avoid abnormally high rates that have been found in "streamside" habitats (HATTON *et al.,* 1983). The mid- and high-marsh stations were each located 20 m farther into the marsh. In the Keys, we were not interested in evaluating changes along transects through the wetland; focus was placed on areas dominated by red mangroves (*Rhizophora mangle*) and black mangroves (*Avicennia germinans*). Because of this, we collected three samples from different areas dominated by each of these species. Our four study sites (Figure 1) were:

(a) Aransas National Wildlife Refuge, TX (Figure 1A)—This old barrier island marsh is located near Austwell, TX. Both transects were collected from the seaward side of Mustang Lake, just north of False Live Oak Point. The low-marsh stations here were dominated by *Spartina alterniflora,* with very little *Grindelia* sp., and *Batis maritima.* Mid- and high-marsh stations consisted of *S. alterniflora, Salicornia virginica,* and *Grindelia* sp.

(b) San Bernard National Wildlife Refuge, TX (Figure 1B)—Samples were collected from the backside of the barrier peninsula, southwest of Raccoon Point (transect #1), and from the edge of the mainland, near the Cedar Lakes Backwater on the western edge of the refuge (transect #2). The vegetation at the low-marsh stations on both transects consisted mostly of *S. alterniflora,* with some *B. maritima.* The mid- and high-marsh stations were *Distichlis spicata, S. alterniflora,* and *B. maritima.*

(c) Biloxi Bay, MS (Figure 1C)—Samples were collected from Davis Bayou, near the mouth of Biloxi Bay (transect #1), and from upper Biloxi Bay (transect #2). As is typical in marshes from this area of the gulf (ELEUTERIUS, 1972), *Juncus roemerianus* and *S. alterniflora* were found in the low marsh, and *Spartina patens* and *S. alterniflora* in the mid and high marsh. This was the only marsh that we sampled that had extensive amounts of *J. roemerianus.*

(d) Florida Keys, FL (Figure 1D)—Samples were collected from Lignumvitae Key, Plantation Key, and North Key Largo. At each Key, one sample was collected approximately 10 m from the open water/mangrove interface, in areas dominated by red mangroves. A second core was taken in the same vicinity, but in areas dominated by black mangroves.

In 4 of the 24 cores, ^{137}Cs profiles did not yield a distinct peak, and rates of accretion could not be calculated. Cores that were not dated came from: 1) low-marsh station from transect #2 at Aransas NWR; 2) mid-marsh station from transect #2 at Aransas NWR; 3) low-marsh station from transect #1 at Biloxi Bay; and 4) red mangrove station at Lignumvitae Key. Because of these omissions, two of six transects were incomplete. These transects have been dropped from the calculation of averages for each site and from the analysis of changes along the transects; however, the remaining samples from these sites were included in the correlation analyses of sediment characteristics and sedimentation rates.

Collection Methods and Sample Analyses

Cores were collected in 15 cm diameter aluminum cylinders to a depth of 30–50 cm. Compaction was minimized by using sharpened, thin-walled coring tubes. Sediment compaction was estimated by measuring the elevation of the marsh inside and outside of the core and was less than 1 cm in all cores that we analyzed. Additionally, compaction due to core extraction was estimated by measuring the length of the sediment column before and after extraction. Corrections for compaction were made in estimating sediment depth, and compaction was assumed to be uniform throughout the sediment column.

Cores were sectioned every 2 cm, and individual sections were dried at 80 °C, weighed and crushed with a mortar and pestle. ^{137}Cs activity of the bulk sediment was counted with a Lithium Drifted Geranium detector and multi-channel analyzer. ^{137}Cs is a product of nuclear weapons testing and does not occur naturally. Significant levels of this isotope first appeared in the atmosphere in the early 1950's with the peak quantities detected in 1963/64 (RITCHIE and MCHENRY, 1990). Sediment profiles are dated based on the 1963 peak in ^{137}Cs, giving an average vertical accretion rate for the period from 1963 to the present (DELAUNE *et al.,* 1978).

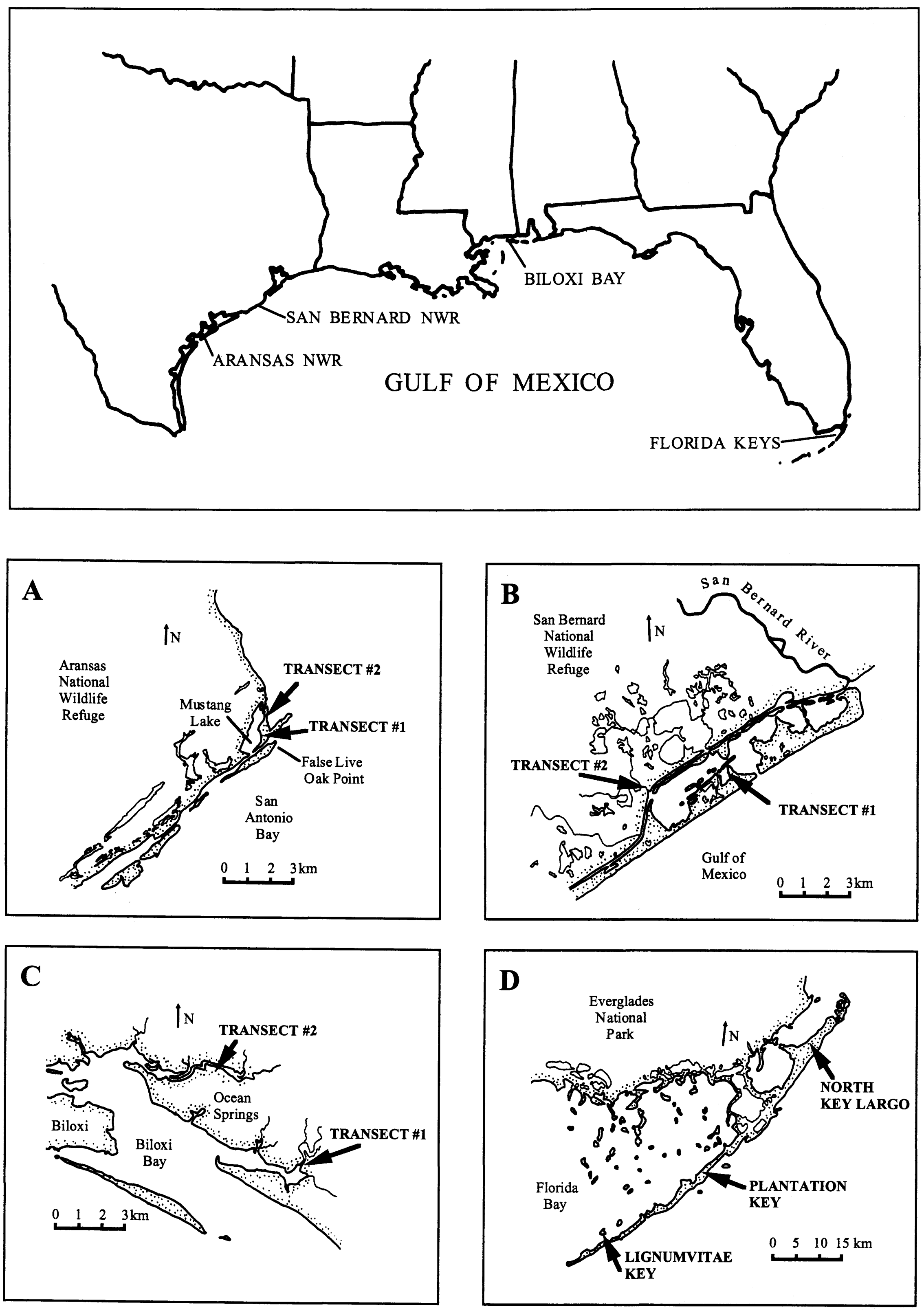

Figure 1. Location of sampling sites along the Gulf of Mexico, including Aransas NWR (A), San Bernard NWR (B), Biloxi Bay (C), and the Florida Keys (D).

Table 1. *Sediment characteristics for cores from transects from three salt marshes and from mangrove areas in the Florida Keys. Values given are for the top 10 cm of the core. Standard deviations are given in parentheses.*

Site	Bulk Density (g/cm³)	Organic Content (percent)
Aransas NWR	0.70 (0.226)	14.4 (5.20)
San Bernard NWR	0.90 (0.165)	9.1 (1.84)
Biloxi Bay	0.28 (0.039)	24.3 (3.98)
Florida Keys		
Red Mangroves	0.16 (0.013)	55.5 (10.01)
Black Mangroves	0.15 (0.024)	61.3 (8.86)

In addition to the ^{137}Cs analysis, 5 g subsamples were taken from each section for combustion at 400 °C in order to determine organic matter content by loss-on-ignition (BALL, 1964; CRAFT *et al.,* 1991). Using the organic/mineral content of the sediment and the bulk density, vertical accretion rates were converted to mass-based rates and divided into organic and mineral components in order to evaluate the importance of these components to the accretion process. Profiles of organic content and sediment bulk density were constructed in order to evaluate changes in these parameters with depth. These profiles were also converted to volume distribution profiles, using specific gravity conversions for organic matter and mineral matter of 1.14 and 2.61 g/cm³ respectively (SMITH, 1943; DELAUNE *et al.,* 1983).

Many different terms have been used in studies of sedimentation rates and clear definitions of these terms are necessary in order to ensure understanding. Vertical accretion rates are gross linear rates of sediment accumulation averaged over a particular time period. Dating with ^{137}Cs gives average rates from 1963 until the present, while other methods may give averages for shorter or longer periods. The term "accumulation rate" is used to refer to mass-based sedimentation, either organic or mineral. Net accretion rates or accretion balance equals the gross vertical accretion rate minus relative sea-level rise for a given site. This is equal to the change in the relative elevation of the wetland sediment surface over a given period and indicates whether or not the wetland is keeping pace with sea-level rise or is undergoing submergence.

Statistical analyses were performed using PC SAS (SAS, 1988). We used a two-way ANOVA without replication in testing for differences between different stations along the transects. The Tukey Test for non-additivity was used to determine the significance of the interaction term. Since it was not significant, the interaction term was used as the error term for the two-way ANOVA without replication (SOKAL and ROHLF, 1981). Treatment comparisons were made using Duncan's Multiple Range Test which is a procedure for obtaining all pairwise comparisons among sample means.

RESULTS

Sediment Characteristics and Profiles

Large differences were found in sediment characteristics between the different sites (Table 1). Cores from mangroves in Florida had the lowest bulk densities and the highest organic content. The sediments from the coastal salt marshes in Aransas and San Bernard both had very high bulk densities; whereas Biloxi Bay sediments were mid range. Organic content was negatively correlated with bulk density (Figure 2); although the relationship between these two variables was very different for mangrove sediments than for the salt marsh sediments from Aransas, San Bernard and Biloxi Bay. Previous studies of soil bulk density and organic content have shown similar relationships for sediments from Louisiana coastal marshes (GOSSELINK and HATTON, 1984). There were no consistent trends in organic content or bulk density across the marsh transects.

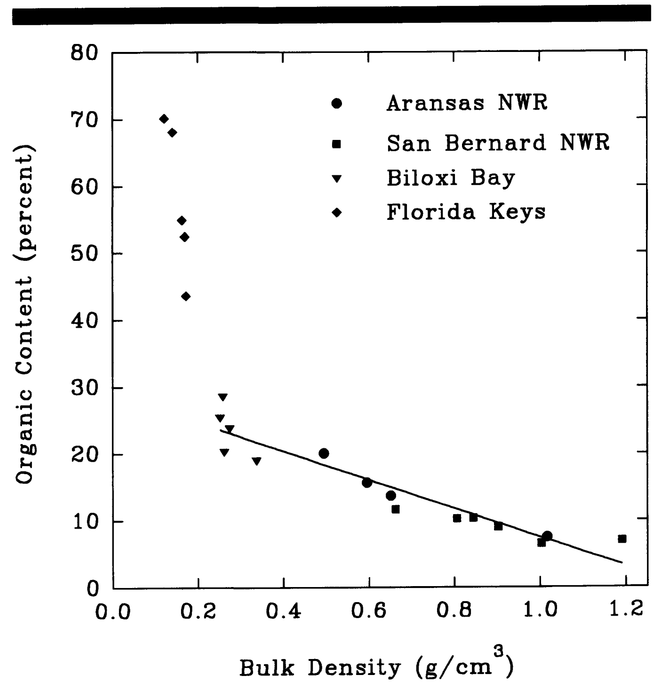

Figure 2. Organic content and sediment bulk density for the top 10 cm of cores collected from all sites. Solid line indicates correlation for salt marsh sites only (r^2 = 0.87).

Most cores exhibited decreases in organic content and increases in bulk density with depth (Figures 3a and 3b). These changes were paralleled in the volume distribution profiles, with relatively less space occupied by organic matter and pore space and more space being occupied by mineral matter as the depth increases. These changes in sediment characteristics with depth are due to below-ground organic matter production, decomposition and compaction throughout the sediment profile. RAE and ALLEN (1993) have documented similar trends, although it is difficult to separate the relative importance of the three factors above because all are occurring simultaneously. In order to evaluate these processes, a computer model was developed. The model simulated sediment processes over both depth and time using data taken from one of the cores from the high-marsh station at Biloxi Bay (CALLAWAY *et al.,* in press). The model was calibrated with profiles of organic matter and bulk density, as well as ^{137}Cs-based accretion rates and simulated processes such as

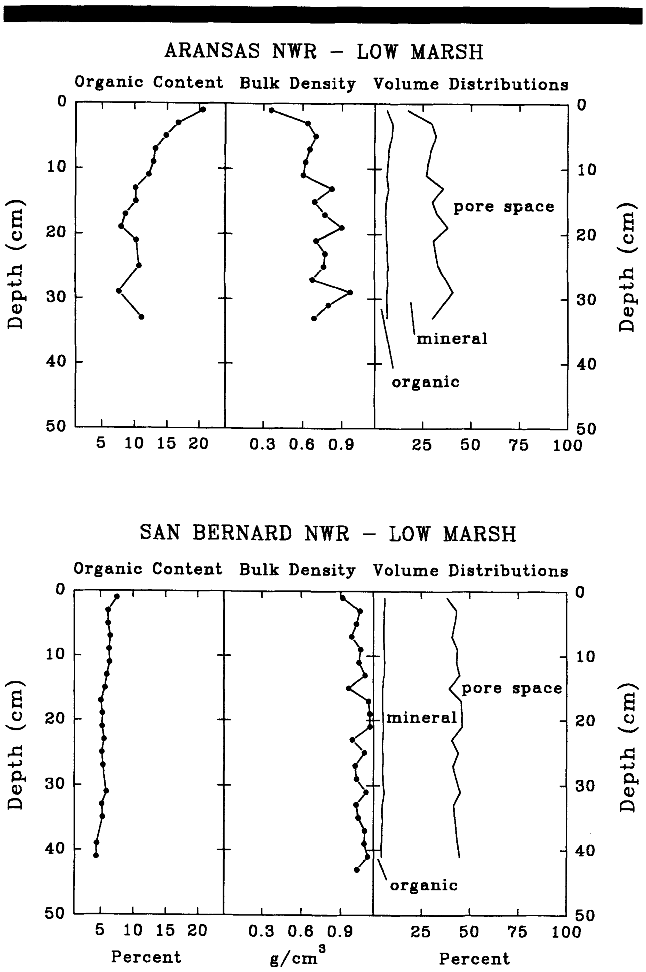

Figure 3a. Profiles of organic content, bulk density, and sediment volume distributions for cores from the low marsh at Aransas NWR (top) and San Bernard NWR (bottom).

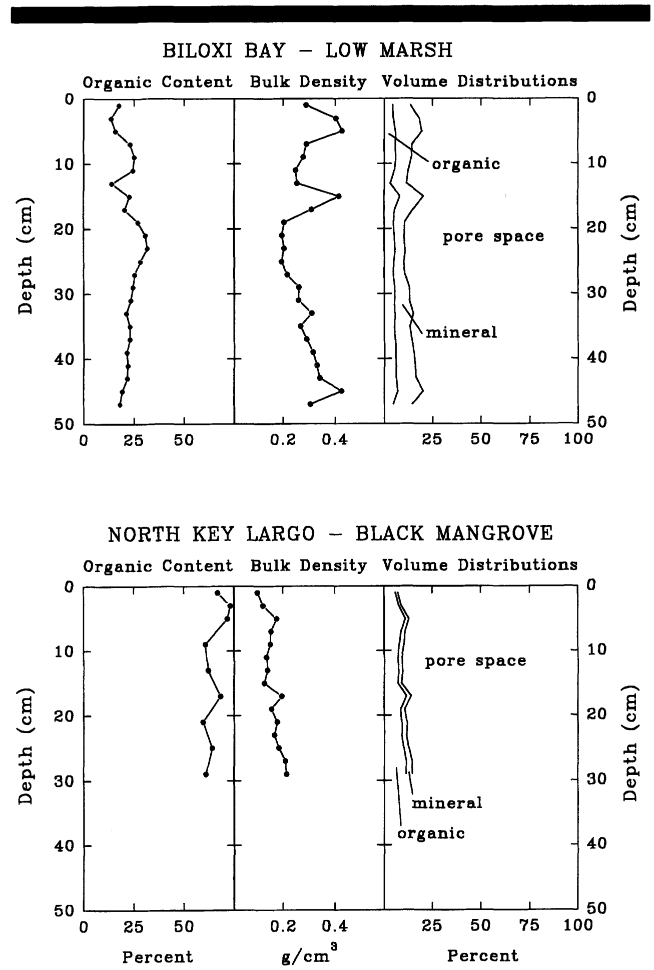

Figure 3b. Profiles of organic content, bulk density, and sediment volume distributions for cores from the low marsh at Biloxi Bay (top) and from the black mangrove station at North Key Largo (bottom).

compaction, decomposition and organic matter production, and changes in the relative elevation of the marsh over time.

Vertical Accretion Rates

Based on ^{137}Cs peaks (Figure 4), rates of vertical accretion from the individual cores ranged from 0.18 to 0.89 cm/yr. At all of the three sites where samples were collected on a transect through the marsh (Aransas NWR, San Bernard NWR, and Biloxi Bay), accretion rates decreased from the low to high station (Figure 5). There were significant differences between high, mid, and low marshes ($p = 0.001$; Duncan's Multiple Range Test for differences between stations, $p = 0.05$). Using average rates from the transects only, rates of vertical accretion were highest at Biloxi Bay and lowest at Aransas NWR (Table 2).

Vertical accretion rates from the incomplete transects that are not included in Figure 5 and individual rates for cores from the mangrove sites are given in Table 3. The three samples from the incomplete transects were similar to those found along the complete transects, with the exception of the high rates found at the high station on Biloxi Bay transect #1. This was probably due to the fact that this sample, although being at the upper end of the marsh, was also very near to an adjacent tidal creek that may have delivered material and drained this area, causing it to function similarly to a low-marsh station. This exception indicates some of the variability that is typical across any wetland and makes assessing rates for a given area very difficult.

A similar evaluation of rates across the wetland was not possible for the mangrove samples, since samples were not collected along transects; however, average rates were higher for the red mangrove stations (0.40 cm/yr *vs.* 0.27 cm/yr for black mangrove stations). This agrees with the trend found along the salt marsh transects, because red mangroves grow along the lowest edge of the wetland, with black mangroves in the interior of the mangrove swamp (ODUM *et al.,* 1982). These rates of vertical accretion are higher than have been shown previously for other mangroves swamps in Florida (LYNCH *et al.,* 1989).

Gross vertical accretion rates were compared to rates of relative sea-level rise for each site. Data for relative sea-level

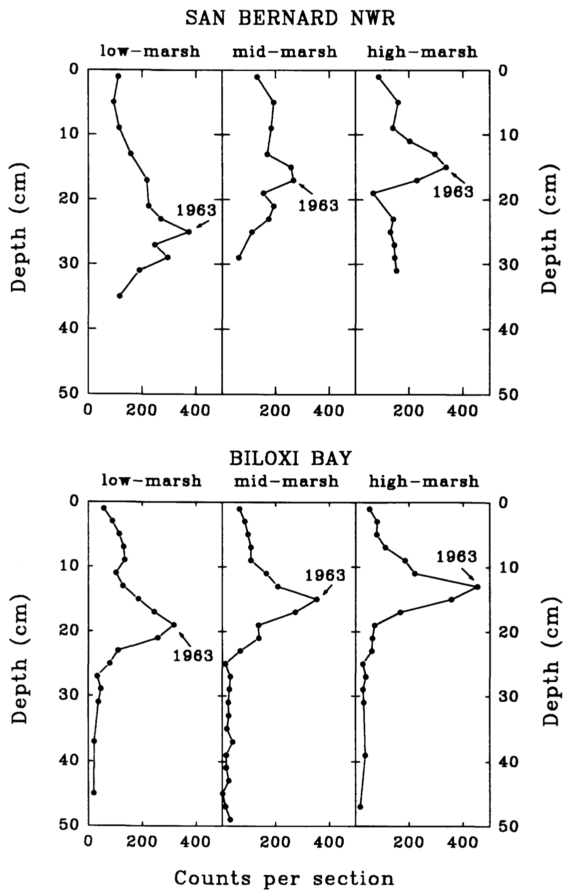

Figure 4. Profiles of ^{137}Cs activity for high, mid and low-marsh cores from San Bernard NWR (top) and Biloxi Bay (bottom). Peaks in ^{137}Cs activity correspond to 1963.

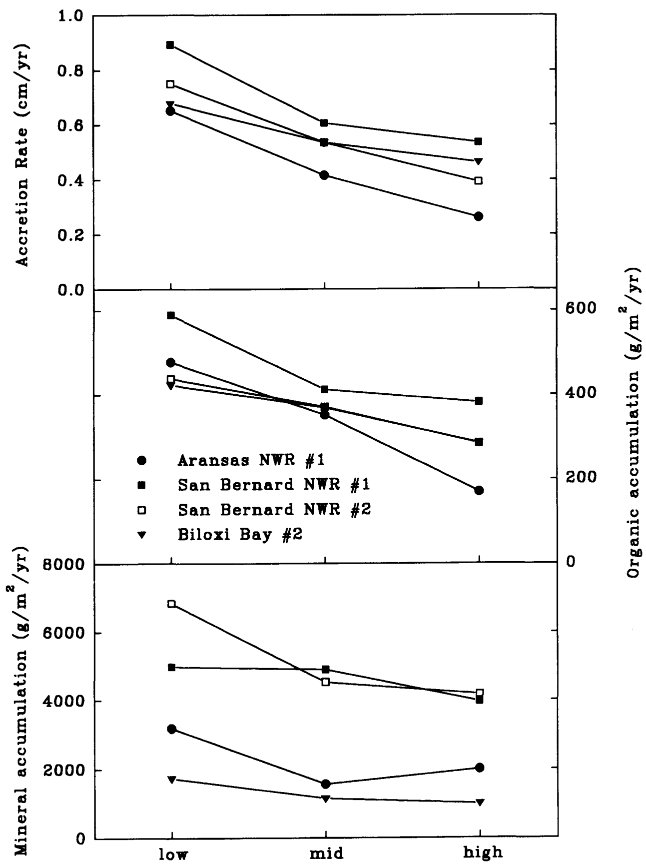

Figure 5. Rates of vertical accretion (top), organic accumulation (middle), and mineral accumulation (bottom) from transects across the marsh. Data are for complete transects from salt marsh sites only.

rise are from tide-gauge analysis by PENLAND and RAMSEY (1990). Three of the four sites had vertical accretion rates greater than recent rates of relative sea-level rise (Table 2). San Bernard NWR was the only site with a negative accretion balance. In fact, the rate of relative sea-level rise that was used for this site may be too large, because the only nearby tide-gauge station that was available was from Galveston, where rates of subsidence are relatively high and are probably higher than at San Bernard NWR.

Mass-Based Accumulation Rates

Organic matter accumulation declined consistently across the marsh ($p = 0.0027$), with significant differences between all stations based on Duncan's Multiple Range Test with $p = 0.05$ (Figure 5). Mineral matter accumulation rates also declined across the marsh ($p = 0.032$); however, significant differences were found only between the low-marsh station and the other stations using the same Duncan's Test (Figure 5).

Average organic accumulation rates at the four sites ranged from 210 to 380 g/m^2/yr, with a much larger variation in average rates of mineral matter accumulation (Table 4). San Bernard NWR and Aransas NWR had the highest rates of mineral matter accumulation; whereas rates from the mangroves in the Florida Keys were extremely low (Table 4). The rates of mineral matter accumulation from San Bernard NWR and Aransas NWR are much greater than other published values for most coastal salt marshes (BRICKER-URSO *et al.*, 1989).

Table 2. *Average vertical rates of accretion. Standard deviations are given in parentheses. Rates of relative sea-level rise are from tide-gauge data from Penland and Ramsey (1990).*

Site	Vertical Accretion (cm/yr)	Relative Sea-Level Rise (cm/yr)	Net Accretion (cm/yr)
Aransas NWR	0.44 (0.16)	0.31	0.13
San Bernard NWR	0.62 (0.15)	0.63	−0.01
Biloxi Bay	0.56 (0.09)	0.15	0.41
Florida Keys			
Red Mangroves	0.40 (0.01)	0.22	0.18
Black Mangroves	0.27 (0.11)	0.22	0.05

Table 3. *Vertical accretion, organic accumulation and mineral accumulation rates for cores from incomplete transects and for mangrove cores from the Florida Keys.*

Site and Core Location	Vertical Accretion (cm/yr)	Organic Accumulation ($g/m^2/yr$)	Mineral Accumulation ($g/m^2/yr$)
Aransas NWR #2 high	0.48	368.4	2,626.3
Biloxi Bay #1 mid	0.32	205.4	669.5
Biloxi Bay #1 high	0.61	350.3	1,304.3
Florida Keys—red mangroves			
Core #3	0.42	331.6	143.5
Core #6	0.39	304.4	171.5
Florida Keys—black mangroves			
Core #2	0.42	361.0	303.7
Core #4	0.19	115.4	123.3
Core #5	0.19	156.3	64.9

DISCUSSION

Differences along the Transects

Previous authors have reported decreases in accretion rates with increasing elevation within the marsh or with increasing distance from a tidal channel (RICHARD, 1978; PETHICK, 1981; OENEMA and DELAUNE, 1988). PETHICK (1981) stated that the frequency and duration of inundation were most important in affecting rates of accretion across the marsh. LETZSCH (1983) used marker horizons in a seven year study of six different stations in a Georgia marsh and found consistently lower accretion rates in the upper part of the marsh. STODDART *et al.* (1989) evaluated changes with distance from tidal channels at a macrotidal site along the Norfolk coast in Britain. It was assumed that the channels were the main source of mineral matter for the marsh, and they found lower accretion rates with increasing distance from the channel.

Our data with ^{137}Cs dating confirm these trends over a 30-year time scale. However, the results of the mineral matter accumulation estimates indicate that the cause may not be simply a decrease in the delivery of mineral sediments to the upper marsh, due to the shorter duration of flooding at higher elevation as had been proposed previously. If this were the case, we would expect a sharp decrease in mineral matter accumulation rates across the marsh. However, our results showed that vertical accretion rates across the marsh decreased significantly, but mineral matter accumulation rates were only significantly greater at the low station (Figure 5). It appears that the decrease in vertical accretion rates was due to decreases in organic accumulation rates, which also were significantly different across all three stations, not the delivery of mineral matter to the marsh surface (Figure 5).

A tidal subsidy is still possible at these sites, even if it is not in the form of mineral matter delivery. Increased drainage combined with above- and below-ground plant production at the low end of the marsh may have been the cause for increased rates of organic matter accumulation in these lower stations. WIEGERT *et al.* (1983) have shown a significant increase in above-ground production with increased drainage and soil water movement. Other studies have also documented trends in production across the marsh (DELAUNE *et al.,* 1979). The differences in organic matter accumulation could also be due to differences in below-ground decomposition rates across the marsh, although most evidence indicates that decomposition rates would be higher where drainage is better because of increased aerobic decomposition rates (HEMMINGA *et al.,* 1988). Further study of production and decomposition rates across the marsh are needed to confirm these hypotheses.

Table 4. *Average rates of organic and mineral accumulation. Standard deviations are given in parentheses.*

Site	Organic Accumulation Rate ($g/m^2/yr$)	Mineral Accumulation Rate ($g/m^2/yr$)
Aransas NWR	333.4 (125.67)	2,248.4 (686.97)
San Bernard NWR	413.0 (91.71)	4,895.2 (937.84)
Biloxi Bay	359.6 (56.17)	1,288.1 (318.86)
Florida Keys		
Red Mangrove	318.0 (13.62)	157.5 (13.97)
Black Mangrove	210.9 (107.46)	164.0 (101.64)

Tidal Range Versus Net Accretion Rates

On a scale larger than a single marsh, tidal range has been correlated with accretion rates (HARRISON and BLOOM, 1977; STEVENSON *et al.,* 1986). Previous studies have indicated a positive relationship between tidal range and accretion rates. In a study of five high marsh sites along the Connecticut coast in Long Island Sound, HARRISON and BLOOM (1977) found that gross accretion rates along the sound increased with increases in mean tidal range. HARRISON and BLOOM (1977) provided several explanations for this and indicated that the most probable was the increased input of mineral material with increases in tidal range and not organic matter or the availability of mineral matter at different sites.

STEVENSON *et al.* (1986) also proposed a positive relationship between tidal range and accretion rates in their review of accretion processes; however, this was for net accretion rates rather than gross vertical accretion rates. They found a significant positive correlation between net accretion rate and tidal range for 13 wetland sites. However, the only low tidal-range sites that had been measured at that time were sites with high rates of local subsidence (Louisiana and Chesapeake Bay). Furthermore, STEVENSON *et al.* (1986) pointed out that additional data from low tidal-range sites were necessary in order to confirm their findings. Data from this study indicate that this trend is probably not as simple as has been shown in the past (Figure 6). The four data points that we added to Stevenson *et al.*'s study decreased the r^2 of the regression from 0.73 to 0.42, although the regression remained significant ($p = 0.0037$). In addition, our samples indicate that low-tidal range sites do not necessarily have negative accretion balances, as had been proposed (STEVENSON *et al.,* 1986).

Recent studies from two areas on the Atlantic coast also does not support the relationship between tidal range and

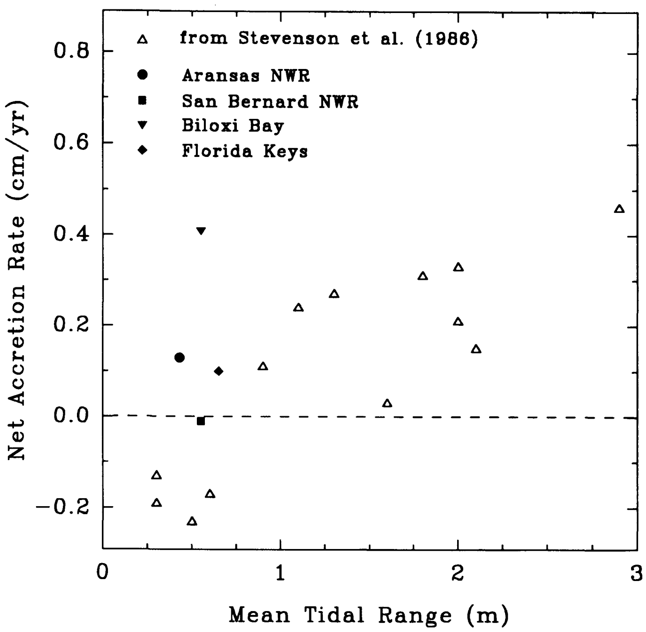

Figure 6. Relationship of mean tidal range and net accretion rate for data from the sites sampled and from other coastal wetlands (additional data from STEVENSON *et al.*, 1986). Tidal-range values for Gulf coast sites are from NOAA (1993).

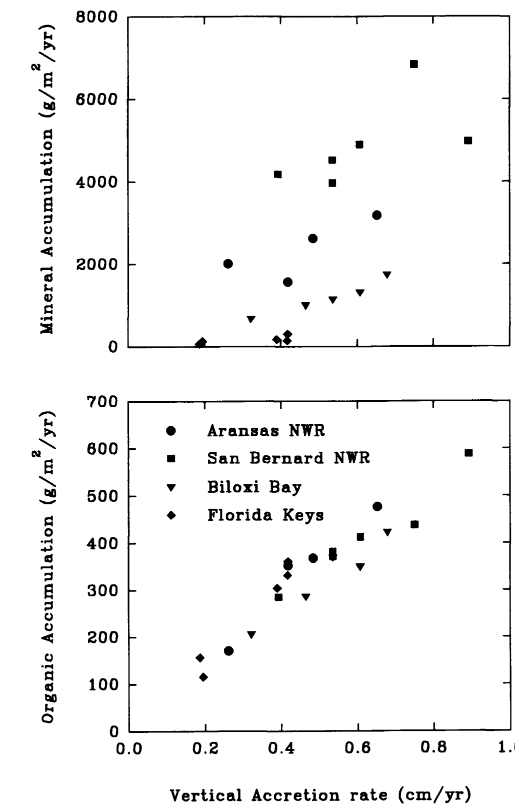

Figure 7. Correlation of vertical accretion rates with mineral accumulation rates (top) and organic accumulation rates (bottom) for all cores.

accretion rates, nor the fact that wetlands with low tidal ranges are likely to have negative accretion balances. WOOD *et al.* (1989) studied short term accretion rates at 26 sites in Maine, with tidal ranges varying from 2.5 to 5.5 m, and found no relationship between mean tidal range and accretion balance for these sites (see Figure 8 from WOOD *et al.*, 1989). Additionally, CRAFT *et al.* (1993) found positive accretion balances for three of the four microtidal sites that they studied on the North Carolina coast. They measured rates in regularly and irregularly flooded marshes and found a deficit of 0.1 cm/yr in the regularly flooded backmarsh site, while all other areas had positive accretion balances, ranging from 0.05 to 0.17 cm/yr (CRAFT *et al.*, 1993). Our data together with these additional studies do not imply that there is no relationship between tidal range and accretion rates; however, they do indicate that tidal range alone cannot predict the accretion balance of a particular site. Many more local variables affect the average accretion rate and accretion balance for a given wetland, such as organic matter production, below-ground decomposition, mineral inputs, and other factors.

Correlations of Vertical Accretion, Organic and Mineral Accumulation Rates

Given the fact that there appears to be more involved in the vertical accretion rates at these sites than just the delivery of mineral matter, the question arises, "What is controlling the accumulation of sediment in coastal wetlands along the Gulf of Mexico?" Using data from all of our 20 cores, rather than just the transect data, we evaluated the correlation between vertical accretion, mineral accumulation and organic accumulation rates. As other authors (NYMAN *et al.*, 1993) have pointed out, vertical accretion rates are used in the calculation of the mass-based accumulation rates, so it is to be expected that these rates are correlated. However, the evaluation of these trends can still assist in the understanding of accretion processes in coastal wetlands.

For the wetlands that we evaluated, vertical accretion was more highly correlated with organic accumulation rates than mineral accretion rates (Figure 7). The r^2 value for vertical accretion and organic accumulation rates was 0.895; whereas, it was 0.458 for vertical accretion and mineral accumulation rates. This reinforces the trends that we found along the transects and is to be expected since we used some of the same data in this analysis. The correlation that we found for vertical accretion and organic accumulation rates is very similar to the relationship that NYMAN *et al.* (1993), found from coastal wetlands in Louisiana, and indicates that there may be a similar relationship for organic matter accumulation and vertical accretion across the Gulf coast region. Other researchers have also looked at the relationship of organic matter and mineral matter accumulation rates in hopes of interpreting sedimentation processes in some areas (MCCAFFREY and THOMSON, 1980; BRICKER-URSO *et al.*, 1989). Our data adds further support to the hypothesis that organic matter is

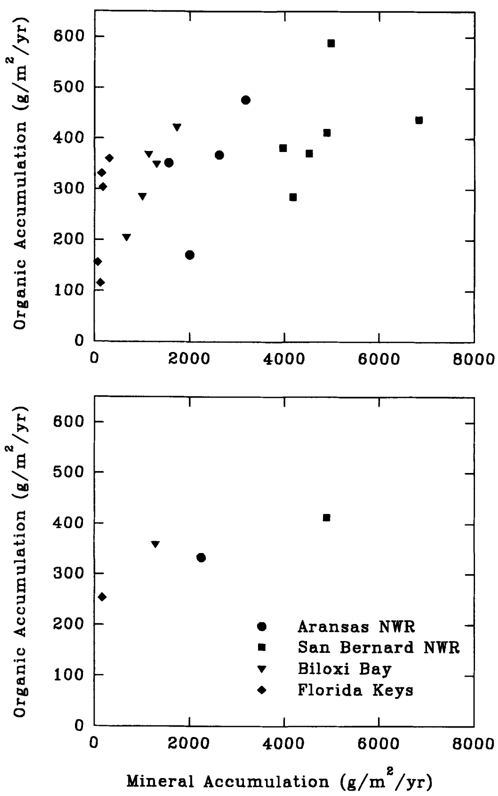

Figure 8. Correlation of mineral and organic accumulation rates for all cores (top) and using average values for each site (bottom).

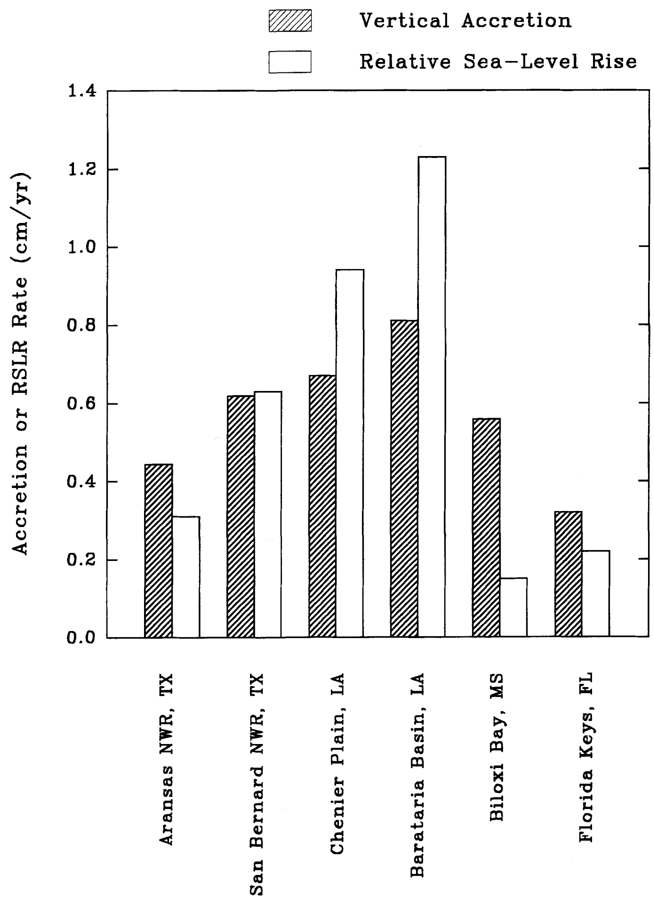

Figure 9. Vertical accretion rates and rates of local sea-level rise (from PENLAND and RAMSEY, 1990) for our sites from the Gulf of Mexico, as well as two sites in Louisiana (data from DELAUNE *et al.,* 1983 and HATTON *et al.,* 1983).

the key to the development of marsh sediment (MCCAFFREY and THOMSON, 1980; NYMAN *et al.,* 1993).

In order to interpret processes on a regional scale, it is instructive to evaluate the relationship between organic and mineral matter accumulation rates, using data from individual cores as well as average values for each site (Figure 8). The difficulties in assigning an average value for a given site have been discussed above; however, the researchers in this study feel that the transect approach is the best method for obtaining an average value. Most of the variability in the rates of organic matter accumulation was due to changes across the transects or within a given mangrove area, and when data were averaged for individual sites, average organic accumulation rates from all of the sites were very similar (Table 4). BRICKER-URSO *et al.* (1989) have suggested that there may be a limit to the organic accumulation rates in marshes along the Atlantic and Gulf coasts (see their Figure 12). The average data from our sites showed little increase in organic matter accumulation despite large increases in mineral matter accumulation rates. Average mineral matter accumulation rates at our sites varied from approximately 160 to 5,000 g/m²/yr, while organic matter accumulation rates varied from approximately 200 to 400 g/m²/yr. The small range of organic matter accumulation rates indicates that there may be a limit to organic matter accumulation as BRICKER-URSO *et al.* (1989) have suggested. If in fact there were a limit to the maximum rates of organic matter accumulation, this could have important consequences for the ability of marshes to compensate for future increases in sea-level rise.

POSSIBLE EFFECTS OF SEA-LEVEL RISE AND CONCLUSIONS

There was not a significant relationship between subsidence rates (relative sea-level rise rates) and accretion rates based on data from our 4 sites. The r^2 value for these 2 variables including data from all 20 cores was 0.19 ($p = 0.055$). Although it has been suggested that there is a positive relationship between relative sea-level rise and accretion (REDFIELD, 1972), the lack of a statistical relationship has been shown by other researchers (STEVENSON *et al.,* 1986; WOOD *et al.,* 1989).

Vertical accretion rates at the coastal wetlands that we studied were large enough to compensate for rates of local sea-level rise, and these wetlands are not likely to be flooded in the near future (Figure 9). The one site that may experience flooding is San Bernard NWR. Interestingly this site had the highest rates of mineral matter accumulation. Also, the estimate of the subsidence rate for this site may be too high, as discussed earlier. These Gulf sites are functioning very differently than sites that have been studied in Louisiana (Figure 9). Several studies (DELAUNE *et al.,* 1983; BAUMANN *et al.,* 1984; SALINAS *et al.,* 1986) have documented the relationship between negative accretion balances and the loss of coastal marsh acreage in coastal Louisiana. However, the four sites from the Gulf of Mexico that we studied do not have negative accretion balances and are not experiencing major losses of coastal wetlands. There is a Gulf wide trend in subsidence rates with higher rates near the influence of the Mississippi River Delta (PENLAND and RAMSEY, 1990), but sites away from this delta are currently not likely to experience submergence.

There are potential problems with using tide-gauge data sets for estimating rates of relative sea-level rise for marsh accretion studies. TURNER (1991) concluded that in order to minimize the effect of short-term trends in the tide-gauge signal on estimates of relative sea-level rise, the longest available data set should be used. In addition, rates of subsidence are probably not the same in tidal channels, where tide gauges are usually installed as they are in coastal wetlands (TURNER, 1991). Because of the processes, such as organic matter production, decomposition, and compaction which occur within the sediment column in coastal wetlands, it is likely that rates of sea-level rise would be different in the wetland. If this is the case, positive values for accretion balance may not necessarily mean that the relative elevation of the marsh is increasing. Rather, if the differences between processes at the tide gauge and within the wetland (decomposition and compaction) are also considered, slightly positive values of accretion balance may indicate that the wetland is simply keeping pace with measured increases in relative sea-level rise.

Besides actual land loss, one potential impact of an increase in sea-level rise that could be very important is the conversion of high marsh to low marsh. High marsh areas are likely to be converted to low-marsh habitats because of the lower vertical accretion rates in the high marsh (Figure 5). This type of a change in vegetation communities has been documented in New England tidal marshes over the past 50 years and through peat core analysis (WARREN and NIERING, 1993). There could be a similar change in coastal wetland plant communities along the Gulf coast, and this conversion of upper marsh habitat could have important consequences for wildlife and other marsh functions, even though there would not be a net loss of wetland habitat.

ACKNOWLEDGEMENTS

This work was supported in part by the United States Geological Survey, Grant No. 14-08-0001-23320. We would like to thank Jack Meeder for collecting cores from the Florida Keys, John Rybczyk for assisting with core collection at the sites in Texas, and personnel from both Aransas NWR and San Bernard NWR for help and accommodations during our sampling trip. We thank Andy Nyman for helpful suggestions and insight, and D.F. Belknap and R.W. Parkinson for thoughtful suggestions on an earlier version of this manuscript.

LITERATURE CITED

ANDERSON, R.S.; BORNS, H.W., JR.; SMITH, D.C., and RACE, C., 1992. Implications of rapid sediment accumulation in a small New England salt marsh. *Canadian Journal of Earth Science,* 29, 2013–2017.

BALL, D.F., 1964. Loss-on-ignition as an estimate of organic matter and organic carbon in non-calcareous soils. *Journal of Soil Science,* 15, 84–92.

BAUMANN, R.H.; DAY, J.W., JR., and MILLER, C.A., 1984. Mississippi deltaic wetland survival: Sedimentation versus coastal submergence. *Science,* 224, 1093–1095.

BRICKER-URSO, S.; NIXON, S.W.; COCHRAN, J.K.; HIRSCHBERG, D.J., and HUNT, C., 1989. Accretion rates and sediment accumulation in Rhode Island salt marshes. *Estuaries,* 12, 300–317.

CALLAWAY, J.C.; NYMAN, J.A., and DELAUNE, R.D., In Press. Sediment accretion in coastal wetlands: A review and a simulation model of processes. *Current Topics in Wetland Biogeochemistry.*

CRAFT, C.B.; SENECA, E.D., and BROOME, S.W., 1991. Loss on ignition and Kjeldahl digestion for estimating organic carbon and total nitrogen in estuarine marsh soils: Calibration with dry combustion. *Estuaries,* 14, 175–179.

CRAFT, C.B.; SENECA, E.D., and BROOME, S.W., 1993. Vertical accretion in microtidal regularly and irregularly flooded estuarine marshes. *Estuarine, Coastal and Shelf Science,* 37, 371–386.

DELAUNE, R.D.; BAUMANN, R.H., and GOSSELINK, J.G., 1983. Relationship among vertical accretion, coastal submergence, and erosion in a Louisiana Gulf Coast marsh. *Journal of Sedimentary Petrology,* 53, 147–157.

DELAUNE, R.D.; BURESH, R.J., and PATRICK, W.H., JR., 1978. Sedimentation rates determined by ^{137}Cs dating in a rapidly accreting salt marsh. *Nature,* 275, 532–533.

DELAUNE, R.D.; BURESH, R.J., and PATRICK, W.H., JR., 1979. Relationship of soil properties to standing crop biomass of *Spartina alterniflora* in a Louisiana marsh. *Estuarine and Coastal Marine Science,* 8, 477–487.

ELEUTERIUS, L.N., 1972. The marshes of Mississippi. *Castanea,* 37, 153–168.

GLEASON, M.L.; ELMER, D.A.; PIEN, N.C., and FISHER, J.S., 1979. Effects of stem density upon sediment retention by salt marsh cord grass *Spartina alterniflora* Loisel. *Estuaries,* 2, 271–273.

GOSSELINK, J.G. and HATTON, R., 1984. Relationship of organic carbon and mineral content to bulk density in Louisiana marsh soils. *Soil Science,* 137, 177–180.

GRIFFIN, T.M. and RABENHORST, M.C., 1989. Processes and rates of pedogenesis in some Maryland tidal marsh soils. *Soil Science Society of America Journal,* 53, 862–870.

HARRISON, E.Z. and BLOOM, A.L., 1977. Sedimentation rates on tidal salt marshes in Connecticut. *Journal of Sedimentary Petrology,* 47, 1484–1490.

HATTON, R.S.; DELAUNE, R.D., and PATRICK, W.H., JR., 1983. Sedimentation, accretion and subsidence in marshes of Barataria Basin Louisiana. *Limnology and Oceanography,* 28, 494–502.

HEMMINGA, M.A.; KOK, C.J., and DE MUNCK, W., 1988. Decomposition of *Spartina anglica* roots and rhizomes in a salt marsh of the Westerschelde Estuary. *Marine Ecology Progress Series,* 48, 175–184.

KNAUS, R.M. and VAN GENT, D.L., 1989. Accretion and canal impacts in a rapidly subsiding wetland. III. A new soil horizon marker method for measuring recent accretion. *Estuaries,* 12, 269–283.

LETZSCH, W.S., 1983. Seven year's measurement of deposition and erosion. Holocene salt marsh, Sapelo Island, Georgia. *Senckenbergiana Maritima,* 15, 157–165.

LETZSCH, W.S. and FREY, R.W., 1980. Deposition and erosion in a Holocene salt marsh, Sapelo Island, Georgia. *Journal of Sedimentary Petrology,* 50, 529–542.

LYNCH, J.C.; MERIWETHER, J.R.; MCKEE, B.A.; VERA-HERRERA, F., and TWILLEY, R.R., 1989. Recent accretion in mangrove ecosystems based on ^{137}Cs and ^{210} Pb. *Estuaries,* 12, 284–299.

MCCAFFREY, R.J. and THOMSON, J., 1980. A record of the accumulation of sediment and trace metals in a Connecticut salt marsh. *Advances in Geophysics,* 22, 165–236.

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, 1993. *Tide Tables 1994: high and low water predictions: East Coast of North and South America.* Washington, D.C.: NOAA.

NYMAN, J.A.; DELAUNE, R.D., and PATRICK, W.H., JR., 1990. Wetland soil formation in the rapidly subsiding Mississippi River Deltaic Plain: Mineral and organic matter relationships. *Estuarine, Coastal and Shelf Science,* 31, 57–69.

NYMAN, J.A.; DELAUNE, R.D.; ROBERTS, H.H., and PATRICK, W.H., JR., 1993. Relationship between vegetation and soil formation in a rapidly submerging coastal marsh. *Marine Ecology Progress Series,* 96, 269–279.

ODUM, W.E.; MCIVOR, C.C., and SMITH, T.J., III, 1982. The ecology of the mangroves of South Florida: A community-profile. *FWS/OBS-81/24.* U.S. Fish and Wildlife Service, Office of Biological Services, Washington, D.C., 144p.

OENEMA, O. and DELAUNE, R.D., 1988. Accretion rates in salt marshes in Eastern Scheldt, south-west Netherlands. *Estuarine, Coastal and Shelf Science,* 26, 379–394.

ORSON, R.; PANAGEOTOU, W., and LEATHERMAN, S.P., 1985. Response of tidal salt marshes of the U.S. Atlantic and Gulf Coasts to rising sea level. *Journal of Coastal Research,* 1, 29–37.

PATRICK, W.H., JR. and DELAUNE, R.D., 1990. Subsidence, accretion and sea level rise in south San Francisco Bay marshes. *Limnology Oceanography,* 35, 1389–1395.

PENLAND, S. and RAMSEY, K.E., 1990. Relative sea-level rise in Louisiana and the Gulf of Mexico: 1908–1988. *Journal of Coastal Research,* 6, 323–342.

PETHICK, J.S., 1981. Long-term accretion rates on tidal salt marshes. *Journal of Sedimentary Petrology,* 51, 571–577.

RAE, J.E. and ALLEN, J.R.L., 1993. The significance of organic matter degradation in the interpretation of historical pollution trends in depth profiles of estuarine sediment. *Estuaries,* 16, 678–682.

REDFIELD, A.C., 1972. Development of a New England salt marsh. *Ecological Monographs,* 42, 201–237.

RICHARD, G.A., 1978. Seasonal and environmental variations in sediment accretion in a Long Island salt marsh. *Estuaries,* 1, 29–35.

RITCHIE, J.C. and MCHENRY, J.R., 1990. Application of radioactive fallout Cesium-137 for measuring soil erosion and sediment accumulation rates and patterns: A review. *Journal of Environmental Quality,* 19, 215–233.

SALINAS, L.M.; DELAUNE, R.D., and PATRICK, W.H., JR., 1986. Changes occurring along a rapidly subsiding coastal area: Louisiana, USA. *Journal of Coastal Research,* 2, 269–284.

SAS, 1988. *SAS/STAT User's Guide.* Release 6.03 edition. Cary, North Carolina: SAS Institute.

SMITH, W.O., 1943. Density of soil solids and their genetic relations. *Soil Science,* 56, 263–272.

SOKAL, R.R. and ROHLF, F.J., 1981. *Biometry.* New York: Freeman, 859p.

STEVENSON, J.C.; KEARNEY, M.S., and PENDLETON, E.C., 1985. Sedimentation and erosion in a Chesapeake Bay brackish marsh system. *Marine Geology,* 67, 213–235.

STEVENSON, J.C.; WARD, L.G., and KEARNEY, M.S., 1986. Vertical accretion in marshes with varying rates of sea level rise. *In:* WOLF, D. (ed.), *Estuarine Variability.* New York: Academic, pp. 241–260.

STODDART, D.R.; REED, D.J., and FRENCH, J.R., 1989. Understanding salt-marsh accretion, Scolt Head Island, Norfolk, England. *Estuaries,* 12, 228–236.

STUMPF, R.P. 1983. The process of sedimentation on the surface of a salt marsh. *Estuarine, Coastal and Shelf Science*, 17, 495–508.

THOM, R.M., 1992. Accretion rates of low intertidal salt marshes in the Pacific Northwest. *Wetlands,* 12, 147–156.

TURNER, R.E., 1991. Tide gauge records, water level rise, and subsidence in the northern Gulf of Mexico. *Estuaries,* 14, 139–147.

WARREN, R.S. and NIERING, W.A., 1993. Vegetation change on a northeast tidal marsh: Interaction of sea-level rise and marsh accretion. *Ecology,* 74, 96–103.

WIEGERT, R.G.; CHALMERS, A.G., and RANDERSON, P.F., 1983. Productivity gradients in salt marshes: The response of *Spartina alterniflora* to experimentally manipulated soil water movement. *Oikos,* 41, 1–6.

WIGLEY, T.M.L. and RAPER, S.C.B., 1992. Implications for climate and sea level of revised IPCC emissions scenarios. *Nature,* 357, 293–300.

WOODROFFE, C., 1993. Sea level. *Progress in Phyical Geography,* 17, 359–368.

WOOD, M.E.; KELLEY, J.T., and BELKNAP, D.F., 1989. Patterns of sediment accumulation in the tidal marshes of Maine. *Estuaries,* 12, 237–246.