Roles and Patterns of Hurricane Sedimentation in an Estuarine Marsh Landscape

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The passage of hurricane Andrew across the Louisiana coastal zone in 1992 was used to study the effects of hurricane sedimentation on estuarine marshes. (1) The thickness and nutrient content of hurricane sediments, (2) the composition of hurricane sediments relative to pre-existing sediments, and (3) the relationship between hurricane sedimentation and small-scale heterogeneity in the emergent plant community were investigated. Vertical accretion resulting from the hurricane was 4–11 times greater than the long-term (30 year) annual rate. The hurricane sediments will be within the root zone of emergent vegetation for 35–50 years, depending on the local marsh vertical accretion rate. Element concentration, organic matter content, and texture of hurricane sediments varied over a wide area, which suggested that hurricane sediments did not originate from a common sediment pool. The concentration of most elements analysed did not differ between hurricane sediments and pre-existing sediments, which suggested that hurricane sediments originated primarily from the same local bays and lakes that provide material for other sedimentation events. Hurricane sediments were thicker in *Juncus roemerianus* stands than in surrounding *Spartina alterniflora* stands. Greater hurricane sedimentation in *J. roemerianus* stands was attributed to greater stem density there and may help maintain plant community heterogeneity if *J. roemerianus* is less flood-tolerant than *S. alterniflora*, as previous work suggests. Previous studies have noted the effect of environmental gradients on plant species distribution, but our data indicate that plant species can also generate different environmental conditions associated with their distribution.

Introduction

Sedimentation is an important process controlling the structure and function of estuarine marshes. Sediments provide plant nutrients such as nitrogen and phosphorus (DeLaune *et al.*, 1981) and contribute to marsh vertical accretion (Mitsch & Gosselink, 1984). Accretion is required to counter regional subsidence and the current gradual rise in global sea level (Mitsch & Gosselink, 1984). Otherwise, marsh flooding increases over

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time, which increases flooding stress on vegetation that may cause marsh loss (e.g. DeLaune *et al.*, 1983). Winter storm-induced sedimentation seems more important than tidally-induced sedimentation in some New England and Gulf of Mexico marshes (Harrison & Bloom, 1977; Reed, 1989), perhaps because tidal flooding is not energetic enough to suspend bay bottom sediments. However, the relative importance of winter storms and more energetic, but less frequent summer hurricanes, is unclear.

We have been sampling vegetation and soils in several Louisiana marshes since 1989 as part of a detailed study of marsh soil process (Nyman *et al.*, 1993, 1994; DeLaune *et al.*, unpubl. data). A new blanket of mineral sediments appeared on these peat soils at some study sites following hurricane Andrew, which made landfall in Louisiana on 26 August 1992. One objective of this study was to quantify the role of hurricane sediments in nutrient budgets and marsh vertical accretion. We were also interested in large-scale patterns of deposition. Was the same amount of sedime.. deposited throughout the area? Were these sediments carried inland from the Gulf of Mexico or did they originate from the same island bays and lakes that are mined by winter storm events? Thus, a second objective of this study was to compare the texture and chemical composition of hurricane sediments deposited tens of kilometres apart, and to compare the new sediments at each site with pre-existing, non-hurricane sediments. Furthermore, we investigated the relationship between small-scale structure in the marsh plant community and sediment deposition. Louisiana salt marshes lack strong environmental gradients and generally contain monospecific stands of *Spartina alterniflora* Loisel but are often interspersed with denser patches of *Juncus roemerianus* Scheele. Thus, a third objective of this study was to determine if this small-scale heterogeneity in plant community structure influenced sediment capture on the landscape.

Materials and methods

Study area

The Mississippi River built extensive marshes during the last several thousand years as it filled the shallow margins of the Gulf of Mexico. Louisiana's microtidal coastal marshes do not exhibit high marsh/low marsh characteristics typical of many other tidal marshes (e.g. Daiber, 1986). Instead, environmental gradients are broad and salt marsh gradually gives way to brackish marsh over several kilometres with an imperceptible slope. Saltmarsh elevations average approximately 4 cm below mean water levels and brackish-marsh elevations average about 2 cm above mean water levels (Sasser, 1977). In Louisiana, brackish marsh typically floods 43% of the time (120 times per year) whereas salt marsh typically floods 55% of the time (190 times per year; Sasser, 1977). These marshes periodically received sediments and freshwater from the Mississippi River until the early 1900s, but most are now isolated from overbank flooding by an extensive levee system (Frazier, 1967). Any new sediments to these marshes may therefore be critical in maintaining marsh elevations relative to rising sea level. We sampled 12 sites spanning 200 km of these marshes adjacent to the path of hurricane Andrew (Figure 1). All but our most western site lay east of the track of the eye.

The eastern end of our study area is in the advanced stages of the Delta Lobe Cycle (Coleman, 1988). During this stage of the Delta Lobe Cycle, sediment starvation and consolidation of underlying sediments causes marshes to gradually drown and convert to shallow bays. The western end of our study area is relatively sediment-rich because the

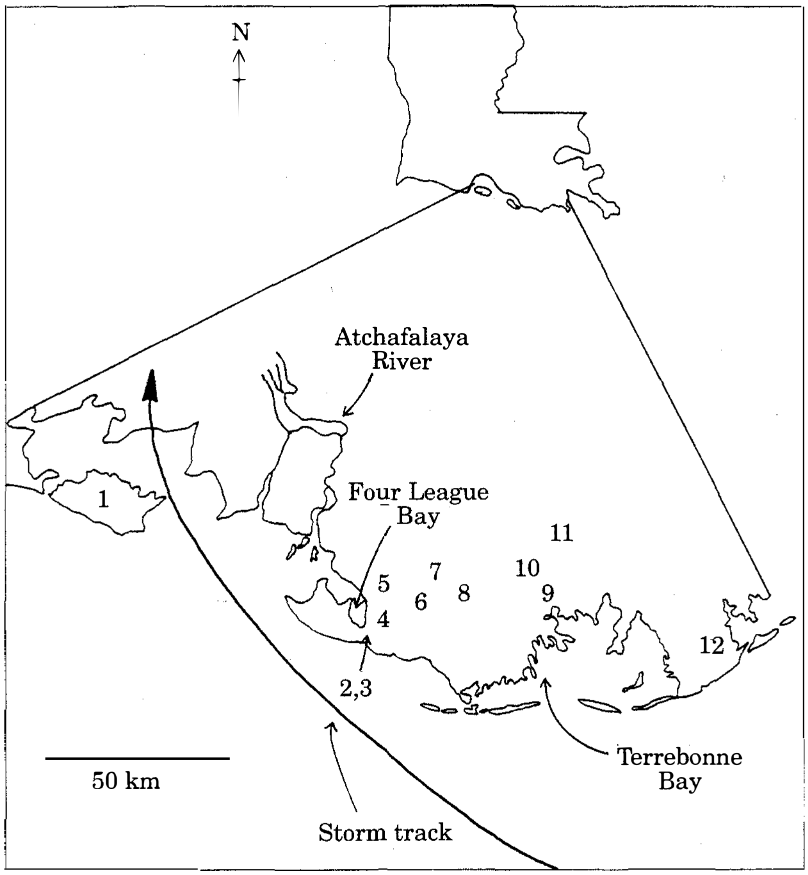

Figure 1. South-eastern Louisiana showing the track of the eye of hurricane Andrew and the 12 sites where we sampled hurricane sediments. The study area is bounded by 90°W, 92°W, 30°N, and 29°N.

Atchafalaya River, which is actually a distributary of the Mississippi River, empties into adjacent shallow bays.

Stone *et al.* (1993) provided a detailed description of hurricane Andrew. The storm travelled parallel to nearly 150 km of coastline during the 6 h prior to landfall (Figure 1). Increased water levels and wind speed were noted over 24 h prior to landfall when the eye of the storm was more than 240 km offshore. Water levels continued to increase for 19 h and peaked at 0·9–2·0 m above normal, and remained above normal for 20–40 h. Peak water levels coincided with peak wind speeds. Peak sustained wind speeds of 72 $km\ h^{-1}$ occurred and wind speeds remained over 47 $km\ h^{-1}$ for more than 12 h at stations over 95 km east of the storm's eye. Hurricane force winds ($>119\ km\ h^{-1}$) extended outward 113 km north-east of the eye and 48 km in other directions (Stone *et al.*, 1993). Our most eastern site was furthest, roughly 90 km from the track of the storm's eye. Our most western site was the closest to the eye's track, roughly 15 km. Thus, although the sites experienced different levels of storm energy, hurricane force winds occurred at all sites.

Sample collection

Pre-hurricane sediments were collected from August 1989 to August 1992 as part of completed and continuing field studies (Nyman *et al.*, 1993, 1994; DeLaune *et al.*, unpubl. data). Those methods are described in Nyman *et al.* (1993), which also contains vertical accretion rates, sediment accumulation rates, and organic matter accumulation rates from sites at the eastern end of the study area. Laboratory assays were conducted on soil collected 9–12 cm below the marsh surface. We did not use the surface of those pre-hurricane soils, 0–3 cm, because surface irregularities decrease the accuracy of soil bulk density estimates of the surface layer. We chose the 9–12 cm depth because we assumed this was representative of the living root zone of marsh vegetation and because we assume that these sediments are non-hurricane sediments. We based this latter assumption on the low soil bulk density, which is less than 0·50 g cm^{-3} (Nyman *et al.*, 1993; DeLaune, unpubl. data).

A blanket of mineral sediments that had not been present before the storm was noted on the marsh surface following hurricane Andrew. Such hurricane sediments were sampled at 12 sites from 15 October 1992 to 8 March 1993, although all soil samples were collected by 30 December 1992. *Spartina alterniflora* was the dominant vegetation at all sites except 1, 5, 10 and 11, which were brackish marsh where *S. patens* dominated. Pre-existing sediments contained an extensive root network, whereas the hurricane sediments lacked a root network (Figure 2). Hurricane sediments at some sites also appeared to have a higher sand content than pre-existing sediments (e.g. Figure 2), but this was not consistent.

Large-scale patterns in hurricane sedimentation were examined by determining the thickness of hurricane sediments at several places in the inland marsh at each site. Three methods of measuring sediment thickness were used. Thin rulers were sometimes inserted directly through the hurricane sediments until they reached the pre-existing marsh surface, which the ruler could not penetrate. This method could not be used where dense vegetation prevented us from getting at eye-ball level with the marsh surface. Alternatively, a plug of soil could be removed from the marsh, and the thickness of hurricane sediments could be measured at several places around the plug. Generally, however, a shovel was used to dig a small hole and the thickness of hurricane sediments was measured at several positions around the edge of the hole. Thickness was recorded to the nearest millimetre. All methods yielded similar estimates during preliminary trials.

Hurricane sediments were collected from six sites for element analyses. Triplicate cores were collected at site 2 so that variability within a site could be evaluated. These cores were separated in the field into hurricane sediments and pre-existing sediments. Grab samples consisting only of hurricane sediments (roughly 10 cm × 10 cm) were collected elsewhere. All samples were collected from inland marsh, that is, greater than 5 m from streamside.

Small-scale variability in the amount of hurricane sedimentation was also examined. The thickness of hurricane sediments was measured on transects at site 2 (one transect), site 6 (one transect) and site 7 (two transects). Transects originated at the streamside, and extended 60 m inland. Sediment thickness was measured in *S. alterniflora* stands and in adjacent *J. roemerianus* stands at seven equally spaced stations on the transects. These marshes are primarily *S. alterniflora*, but scattered throughout are irregular shaped stands of *J. roemerianus* occurring in 3–10-m-wide bands and polygons. If the two species did not occur adjacent to each other at a particular station, the station was offset laterally so that both species were present. Stem density of each species was measured at the 20, 30, 50 and 60 m stations in 0·1-m^2 circular plots on transects at sites 6 and 7.

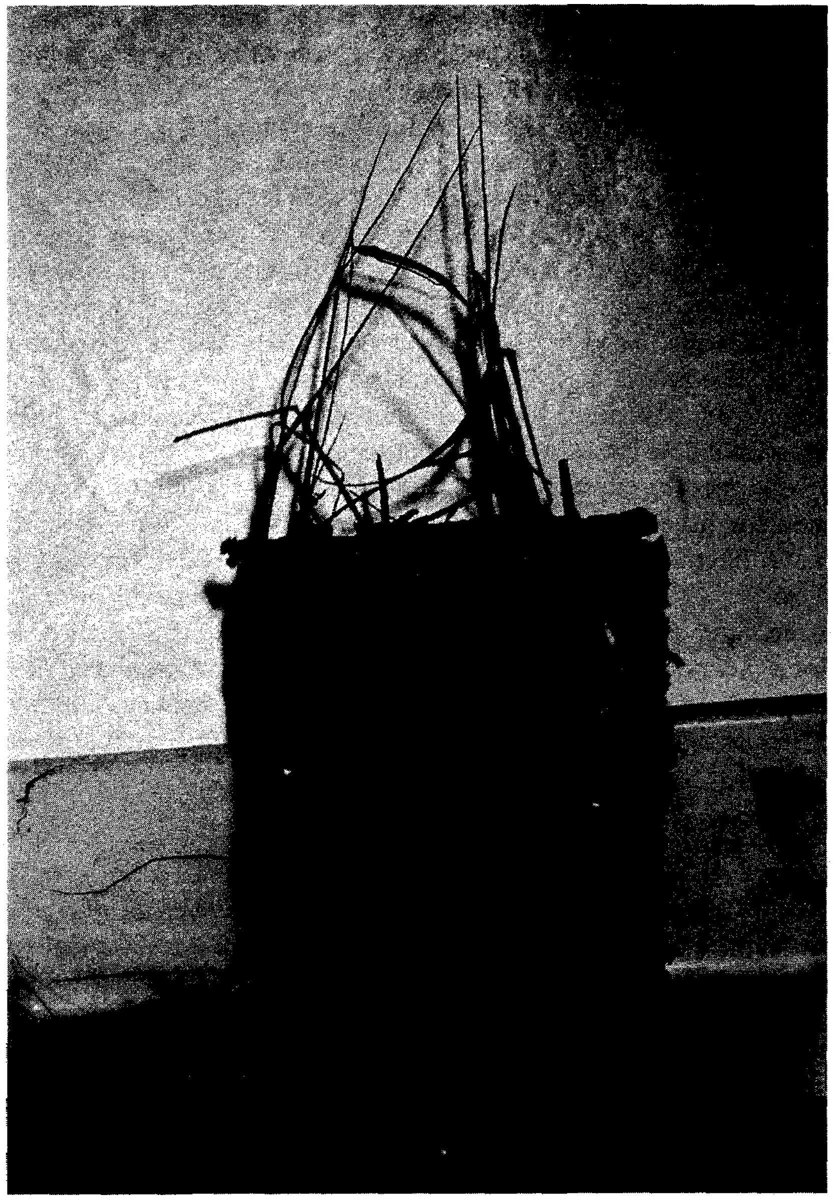

Figure 2. Side view of a vertically sliced 15-cm-diameter core collected from site 2 showing the layer of mineral sediments produced by hurricane Andrew, which overly the pre-existing root-dominated soil. The vertical structure filled with hurricane sediments is probably a fiddler crab burrow. The core was allowed to dry for several days to maximize contrast between hurricane and pre-existing sediments before this photograph was taken.

Laboratory assays

Total core wet and air-dried weight were used to calculate bulk density of the hurricane sediments from site 2. Bulk density was estimated from organic matter content for the other sites (Hatton *et al.*, 1983). Subsamples from all sites were air-dried and ground to pass a 2-mm sieve. Percent organic matter was determined by combustion at 400 °C (Davies, 1974). Particle size distribution of sediments was measured according to Gee and Bauder (1986) except that the concentration of the dispersant (sodium hexametaphosphate) was tripled to counter soil salinity, which causes clays to flocculate. Particle size distribution could not be determined in pre-existing soils because boiling with H_2O_2, which is the standard method for removing soil organic matter for particle size distribution analysis (Gee & Bauder, 1986), did not completely oxidize these peats.

Total nitrogen was determined in the three samples from site 2 using the Kjeldahl method. Ammonium in digests was determined by steam distillation into H_3BO_3, followed by titration with dilute HCl (Bremner & Mulvaney, 1982).

Concentrations of Ca, Mn, Na, S, P, Al, Fe, K and Mg in hurricane sediments and pre-existing soils were measured from HNO_3 digests using an inductively coupled argon plasma emission spectrophotometer (ICP). These elements were quantified because they were identified as limiting nutrients or as stress factors in previous studies of marsh vegetation (Broome *et al.*, 1975; DeLaune *et al.*, 1979; King *et al.*, 1982; DeLaune & Pezeshki, 1988). Element input to the marshes was calculated from the sediment thickness, bulk density, and element concentration.

Soil bulk density profiles from the sediment-rich and sediment-poor areas were examined for mineral lenses buried in the marsh that might be products of previous hurricanes. Methods used to collect and process those cores, and to estimate soil bulk density and ^{137}Cs activity are described in detail elsewhere (Nyman *et al.*, 1993). Briefly, 15-cm-diameter cores were collected to a depth of 50 cm. The cores were sectioned into 3-cm increments, dried, weighed, and ^{137}Cs activity was measured. Soil bulk density was calculated from the weight of the dried sediment and the wet volume of each increment. Peak ^{137}Cs activity indicated the location of the 1963 marsh surface (DeLaune *et al.*, 1978).

Statistical analyses

Thickness of hurricane sediments was compared between *S. alterniflora* and *J. roemerianus* stands with Wilcoxon's signed-rank test, which is a test for paired observations that does not require normally distributed data (Steele & Torrie, 1980). Data from each transect were analysed separately, pairing on distance. Too few stem density data were collected to analyse those data separately for each transect, thus those data were pooled and a single Wilcoxon's signed-rank test was used to compare stem density between the plant species. Wilcoxon's signed-rank test was also used to compare element concentration between hurricane sediments and pre-existing sediments. Data were paired by site for that analyses. An alpha level of 0·05 was used for all analyses and critical values of $T^{+/-}$ were obtained from Siegel and Castellan (1988).

Results

No hurricane sediments were noted at either the most eastern site (site 1) or the most western site (site 12; Table 1). Other sites, except for site 11, had a fresh blanket of hurricane sediments however. The thickness of the hurricane deposits was large relative to annual vertical accretion rates, but varied considerably between sites (Table 1). The sediment blanket appeared thicker in the western, sediment-rich area than in the eastern, sediment-poor area. For example, 9 cm were deposited in the brackish marsh at site 5 whereas no sediments were found in the brackish marsh at site 11. The particle size distribution of hurricane sediments also varied between sites (Table 1). Bulk density at site 2 averaged 0·78 g cm^{-3}. Organic matter content was less than 10% except at the two brackish sites that received sediments (Table 1).

TABLE 1. Sediment characteristics of hurricane Andrew deposits in some Louisiana *Spartina alterniflora* and *Spartina patens* marshes

Site (west to east)	Thickness (cm)	Ratio of thickness to annual accretion	Organic (%)	Sand (%)	Clay (%)
1 Marsh Island[a]	0	—	—	—	—
2 Upstream Hard Bayou	3·2	5·0	2·7	60	25
3 Downstream Hard Bayou	3·5	6·5	2·5	78	11
4 Old Oyster Bayou	3·5	7·3	6·0	42	16
5 Blue Hammock Bayou[a]	9·0	10·7	10·7	8	43
6 Bayou DuLarge	3·3	n.d.	n.d.	n.d.	n.d.
7 King Lake	3·6	n.d.	n.d.	n.d.	n.d.
8 Grand Pass	6·5	n.d.	n.d.	n.d.	n.d.
9 Bayou Chitigue	3·0	3·8	9·2	42	22
10 Madison Bay[a]	4·0	4·9	29·9	n.d.	n.d.
11 Billy Goat Bay[a]	0	—	—	—	—
12 Leeville	0	—	—	—	—

[a]*Spartina patens* marsh. All others are *Spartina alterniflora* marsh.
n.d., Not detected.

TABLE 2. Element concentration of hurricane Andrew deposits in some Louisiana marshes

Site no.	Concentration ($g\ kg^{-1}$)							
	P	Fe	K	Mg	Ca	Mn	Na	S
2	0·4	10·4	2·4	10·2	7·1	0·2	3·8	2·8
3	0·3	8·0	1·7	4·4	6·4	0·2	2·9	1·2
4	0·4	13·4	3·2	6·0	6·6	0·2	4·9	6·2
5	0·4	22·2	5·5	8·5	4·6	0·3	8·0	9·6
9	0·4	17·3	4·5	7·8	3·1	0·2	1·3	5·6
10	0·4	14·4	3·6	6·3	3·7	0·2	6·6	14·4
Mean concentration	0·4	14·3	3·4	7·2	5·2	0·2	6·2	6·6
SE	0·02	2·0	0·5	0·8	0·7	0·03	1·2	1·9
Coefficient of variability (%)	15	35	40	28	32	33	49	72

Element concentration of hurricane sediments varied erratically over the area (Table 2). Potassium, Mg, S, and Na varied up to 10-fold among sites, but statistical comparisons between sites were not possibly because only composite samples were collected. Element concentration of pre-existing sediments also varied over the area, but the coefficient of variability was lower than in hurricane sediments for all elements analysed except P (Tables 2 and 3).

Statistical comparisons indicated that hurricane sediments differed from pre-existing sediments in concentrations of three elements. Hurricane sediments contained more Ca ($P > T^{+} = 0{\cdot}0039$), more Mn ($P > T^{+} = 0{\cdot}0039$), and less Na ($P > T^{-} = 0{\cdot}0195$) than pre-existing sediments. No differences were detected between hurricane and pre-existing sediments for the other six elements analysed.

Element inputs resulting from the hurricane varied greatly (Table 4) because of differences in amounts of sediments deposited among sites, and because of differences in the element concentration among sites. Inputs were greatest at Blue Hammock Bayou

TABLE 3. Element concentration of marsh soil predating hurricane Andrew deposits in some Louisiana marshes

	Concentration ($g\,kg^{-1}$)							
Site no.	P	Fe	K	Mg	Ca	Mn	Na	S
2	0 3	16·7	5·5	7·6	2·8	0·01	12·5	9·6
–3	0·3	13·1	4·8	6·5	1·8	0·07	10·7	6·6
4	0·2	12·2	4·2	5·6	1·9	0·06	10·0	9·4
5	0·4	13·3	4·7	6·5	1·9	0·06	12·0	6·2
9	0·3	14·0	3·9	5·7	1·9	0·09	8·6	10·3
10	0·6	8·7	3·8	6·0	3·1	0·04	10·1	10·5
Mean concentration	0·3	13·0	4·5	6·3	2·2	0·07	10·7	8·8
SE	0·01	1·1	0·3	0·3	0·2	0·008	0·6	0·8
Coefficient of variability (%)	39	20	15	12	26	28	13	22

TABLE 4. Estimated input of elements to some Louisiana marshes resulting from hurricane Andrew deposits

	Input ($g\,m^{-2}$)							
Site no.	P	Fe	K	Mg	Ca	Mn	Na	S
2	9·7	258·1	59·6	252·8	176·8	4·6	94·3	70·6
3	7·7	219·7	46·6	120·7	174·8	4·2	80·0	33·7
4	9·5	350·6	82·7	157·5	174·4	5·6	129·2	161·8
5	28·6	1665·3	409·2	639·6	341·3	26·1	597·9	717·5
9	8·7	363·7	95·5	164·7	65·6	5·0	237·5	118·6
10	9·0	288·8	71·2	126·8	73·3	3·2	131·4	287·6
Mean input	12·2	524·4	127·5	243·7	167·7	8·1	211·7	231·6
SE	3·3	229·3	56·7	81·5	40·7	3·6	80·4	103·6
Coefficient of variability (%)	66	107	109	82	59	109	93	110

(site 5) partly because of the thickness of the sediment deposits. Nitrogen concentration of hurricane sediments at site 2, which was the only site where N content was measured, averaged 0·58 $mg\,g^{-1}$. This resulted in 16 $mg\,N\,m^{-2}$ of new N to the marsh there.

Mineral matter lenses, as indicated by soil bulk density, were found buried in brackish marsh in the sediment-rich, western area (site 5), but not from brackish marsh in the sediment-poor, eastern area (site 11; Figure 3). One lens was slightly below the 1963 marsh surface (DeLaune, unpubl. data). The other was at the very bottom of the core. There is no way to determine if these resulted from hurricanes, but hurricane Audrey (1957) is a possibility for the shallower lens. Mineral matter content of pre-existing brackish soil ranged from 48 to 64% in cores from the sediment-poor area, but from 52 to 83% in cores from the sediment-rich area, which reflected long-term differences in sediment availability and the movement of those sediments by the ubiquitous winter storms. Mineral lenses were not apparent in saltmarsh cores from either site probably because of the higher mineral matter content in salt marsh.

Hurricane sediments averaged 3·9 cm thick (n=27, SD=1·5) in *S. alterniflora* stands but 6·6 cm thick (n=27, SD=2·1) in adjacent *J. roemerianus* stands on the four transects sampled. Sediments were significantly (P<0·05) thicker in *J. roemerianus* stands than in

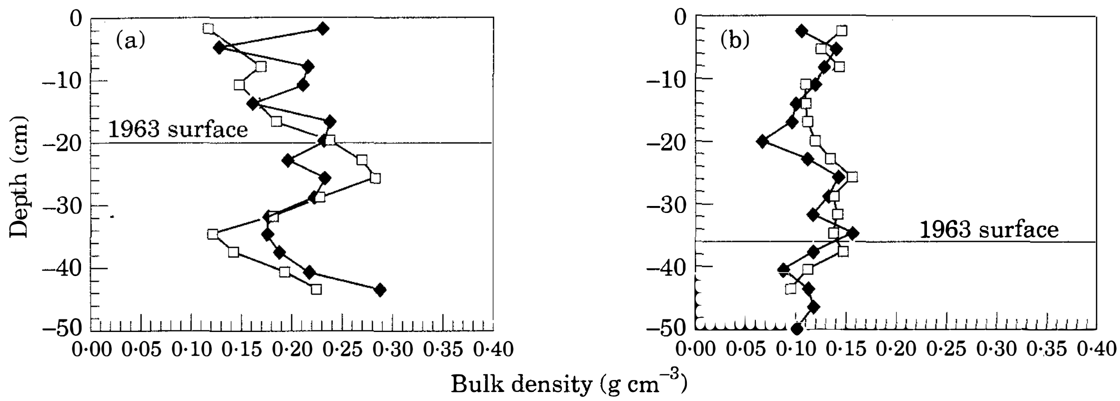

Figure 3. Soil bulk-density profiles in pairs of cores collected at sites 5 (a) and 11 (b) prior to hurricane Andrew indicate that mineral sedimentation was greater at the more western site (5) for several decades even though vertical accretion was greater at the more eastern site (11). The mineral lens slightly below the 1963 surface of the more western site was probably deposited by a hurricane in the late 1950s or early 1960s. The marsh at site 5 is now buried by a 9-cm-thick deposit that has a bulk density of about 0·70 g cm^{-3}.

S. alterniflora stands on three of the four transects. The exception was a transect located parallel to a natural drainage channel such that *S. alterniflora* was consistently lower in elevation and closer to the drainage channel than *J. roemerianus*. Stem density, which was measured on three of the transects, was greater (P=0·0039) in *J. roemerianus* stands (mean=2095 m^{-2}, n=8, SD=484) than in *S. alterniflora* stands (mean=428 m^{-2}, n=8, SD=136).

Discussion

No hurricane sediments were found at Marsh Island (site 1), which was closest to the eye's track but also the only site that lay west of the eye's track. Lack of sediments there are likely to have resulted from the anti-clockwise circulation of winds about the eye, which causes storm surges to be greater on the right-hand side of the storm track than on the left-hand side (Hsu, 1988). Thus, west of the eye, winds blew from the north as the storm approached, which lowered rather than raised water levels near Marsh Island (Stone *et al.*, 1993) and thereby limited the opportunity for sedimentation. The most eastern site experienced storm surge, but no hurricane sediments were observed there either. It therefore appears that hurricane sedimentation extended at least 50 km but less than 90 km to the east of the eye's track.

The hurricane sediments noted in this study were broad, unbroken blankets that should not be confused with overwash deposits, which are limited to narrow bands along shorelines (e.g. Ehlers *et al.*, 1993). Overwash deposits along the Louisiana coast following hurricane Andrew approached 60 cm thick and reached 50 m inland along some sections of the gulf shore (Hester, pers. comm.).

The bulk density of hurricane sediments was more similar to that of mineral deposits such as bay bottoms (0·4–0·8 g cm^{-3}; DeLaune *et al.*, 1978) rather than to that of marsh soils, which average <0·30 g cm^{-3} in Louisiana (Nyman *et al.*, 1990). These mineral deposits on otherwise peaty soils were equivalent to 4–11 times the average annual vertical accretion rate (Table 1). Baumann *et al.* (1984) also noted that hurricane sedimentation is greater than long-term annual vertical accretion rates, and Rejmanek *et al.* (1988) reported hurricane sedimentation of 2·2 cm in *Phragmites communis* stands.

The increase in marsh surface elevation resulting from the hurricane sediments will probably reduce marsh flooding. Reed and Cahoon (1992) noted that elevational differences of 12 cm were associated with differences in hydroperiod of over 200%; the effect is large partly because of the lack of a strong elevational gradient in Louisiana marshes. Reduced flooding could affect plant community composition because flooding has long been considered a major factor affecting plant species zonation in estuarine marshes (Wells, 1928; Adams, 1963; Eleuterius & Eleuterius, 1979). However, such shifts may be slight and temporary because the dominant species are perennials and because rapid increases in elevation should be compensated for by reductions in future vertical accretion (Mitsch & Gosselink, 1984).

In marshes with a vertical accretion deficit, that is, where marsh vertical accretion is not sufficient to counter sea-level rise and local subsidence (e.g. DeLaune *et al.*, 1983; Hatton *et al.*, 1983; Nyman *et al.*, 1993), hurricane sediments may partially restore marsh elevations to mean water levels and thereby reduce flooding stress on marsh vegetation. However, hurricane sedimentation was insufficient to negate the vertical accretion deficit in the eastern end of our study area where marsh elevation lost 11 cm of elevation relative to mean water levels since 1963 (Nyman *et al.*, 1993). Three more hurricanes would be required to negate the accumulated vertical accretion deficit there, with an additional hurricane required every 12 years to counter the continuing deficit, which is 0·4 cm year^{-1} (estimated from data in Nyman *et al.*, 1993). However, we roughly estimated that long-term hurricane sedimentation in Louisiana averages only 0·24 cm year^{-1} over the long term [given 460 km of coastline, a hurricane frequency of 0·41 year^{-1} (from data in Hsu & Blanchard, 1993), an affected area of 60 km (from this study), and an average of 4·5 cm of sediments per hurricane (from this study)]. This may be an overestimate because we assumed that all classes of hurricanes deposited the same amount of material over the same width of coastline as we observed in this study from a class 4 hurricane, whereas 45% of the hurricanes that make landfall in Louisiana are merely class 1 (Hsu & Blanchard, 1993). In other regions with slower subsidence rates and similar hurricane landfall rates, hurricane sedimentation might be adequate to counter submergence.

We expected hurricane sediments from widely scattered sites to have similar textures if they originated from a common sediment pool. But the erratic variability in element concentration, organic matter content and texture of hurricane sediments over the study area suggests otherwise. Nor does it appear that the hurricane sediments originated from the Gulf of Mexico immediately adjacent to the estuaries where they were deposited. The Gulf adjacent to Terrebonne Bay contains sandy ebb-tidal deltas, split platform deposits, and flood tide deltas that are constantly being resupplied with sands by long-shore transport (Suter *et al.*, 1991), but hurricane sediments at site 9 were only 42% sand. This sand content is similar to that within the lake and bay system that drains site 9 (Adams, unpubl. data). Sand bodies in the Gulf adjacent to site 2 are buried by approximately 3 m of silts and clays (Suter *et al.*, 1991), but hurricane sediments at site 2 contained approximately 70% sand. This sand probably originated from the tidal pass system that drains site 2, which is a highly energetic connection between southern end of Four League Bay and the Gulf of Mexico. Thus, hurricane sediments varied spatially partly because the sediment sources contained different types of sediments. However, hurricane sediments in other estuaries could exhibit little spatial variability if different sediment sources contain similar types of sediments.

Some of the variability in element concentration of hurricane sediments from different sites may be related to organic matter content. Feijtel *et al.* (1988) found that the concentration of several elements in Louisiana bay bottom sediments was related to the organic matter content. A *post priori* correlation analyses of our ranked data, with the Spearman rank-order correlation coefficient (Siegel & Castellan, 1988), indicated that the organic matter content was significantly related to the concentration of Fe (R=0·738, n=8, P=0·0366), K (R=0·738, n=8, P=0·0366), and S (R=0·991, n=8, P=0·0039). The positive R values indicate that these were positive relationships.

The three differences found between hurricane sediments and pre-existing sediments are understandable even though it was concluded that hurricane and pre-existing sediments originated from the same source. The lower amount of Mn in pre-existing sediments than in hurricane sediments may have resulted from post-depositional Mn mobility in marsh soils. Reducing conditions increase Mn solubility, which may increase plant uptake and subsequent detrital export (DeLaune *et al.*, 1979). Thus, pre-existing sediments would have been subjected to Mn transport longer than the hurricane sediments. The greater Na in pre-existing sediments probably resulted from the concentration of salt caused by the constant evaporation and transpiration of tidal water in the marsh. Increased evaporation following the storm would be expected from the change in hydroperiod. A third difference, the higher Ca concentration in hurricane sediments, is likely to have resulted from the presence of mollusc shell fragments (primarily the clam *Rangia cuneata* and the oyster *Crassostrea virginica*) in bay sediments that were transported by the hurricane but not by winter storms. Large particles such as shell fragments could not be mined by lower energy events even though they would be available in the source sediments.

The hurricane sediments introduced large amounts of nutrients into the marshes. Nutrients that rapidly mineralize may be quickly introduced into the ecosystem, but nutrients that mineralize very slowly will gradually be buried and removed from the system. Even if nutrients are buried, they will be available for uptake by marsh vegetation until they are below the living root zone, that is, ~35 cm deep. Marsh vertical accretion rates determine exactly how long it will take for the root zone to migrate above the nutrients. Hurricane sediments will be within the root zone of marsh plants for about 50 years at our western sites where vertical accretion is roughly 0·7 cm year^{-1} (DeLaune, unpubl. data), and for approximately 35 years at our eastern sites where vertical accretion averages 0·98 cm year^{-1} (Nyman *et al.*, 1993). Thus, even infrequent hurricane sedimentation can have large and long-lasting effects on estuarine nutrient budgets. Our N input estimate is probably a minimum because we measured N input only from the sediment blanket at site 2, which had the lowest organic matter content, and Craft *et al.* (1991) found a positive relationship between organic matter content and total N in marsh soils.

Living organisms have long been recognized as a major factor influencing soil formation (Jenny, 1958; Buol *et al.*, 1980). In uplands, soil development is affected by plant communities on large scales (White & Riecken, 1955) and by plants and animals on small scales (Nye, 1955; Salem & Hole, 1968; Gersper & Holowaychuk, 1971; Crozier & Boerner, 1986). Our data show that *S. alterniflora* and *J. roemerianus* may influence soil formation differently. Close-growing vegetation and vegetative debris can trap sediments and reduce erosion in both uplands (Bennett, 1955) and wetlands (Gleason *et al.*, 1979; Rejmanek *et al.*, 1988; Dieter, 1990; James & Barko, 1990). The most likely reason that *J. roemerianus* stands trapped more hurricane sediments than the *S. alterniflora* stands is the greater stem density in *J. roemerianus* stands. Greater stem density in *S. patens* than in *S. alterniflora* (Hopkinson *et al.*, 1980) may also have contributed to the greater thickness of hurricane sediments in brackish marsh at site 9 than in saline marshes in the sediment-rich portion of our study area (we have since noted that a 9-cm-thick layer is common in the brackish marshes in the western portion of our study area). In contrast to previous studies that addressed the effect of environmental gradients on plant species distribution (Stalter & Batson, 1969; Eleuterius & Eleuterius, 1979; Keddy, 1990; Bertness, 1991), our data indicate that plant species are also capable of creating topographical differences associated with their distribution.

It is therefore possible that slight elevational differences noted between *S. alterniflora* and *J. roemerianus* stands in both Gulf coast and Atlantic coast marshes of the U.S.A. (Wells, 1928; O'Neil, 1949; Adams, 1963; Sasser, 1977; Chabreck & Condrey, 1979; Eleuterius & Eleuterius, 1979; Gardner *et al.*, 1992) are merely the result of interspecific differences in sediment capture. However, studies of plant zonation along elevational gradients suggest that *J. roemerianus* is better adapted to higher elevations than *S. alterniflora* (Wells, 1928; Eleuterius & Eleuterius, 1979; Gardner *et al.*, 1992). If so, then differences in flood tolerance and sediment trapping may reinforce each other, maintaining *J. roemerianus* at higher landscape positions. Differential sediment capture might be important only at the boundary between these species where they occur on a pre-existing elevational gradient (e.g. Wells, 1928; Eleuterius & Eleuterius, 1979; Gardner *et al.*, 1992). However, on a relatively flat landscape such as the Louisiana coast, these factors may reinforce each other and allow the maintenance of a more heterogeneous plant community than would exist otherwise. This might then be an example of a feed-forward process, suggested to be important in the self-maintenance of ecosystems (Jorgensen *et al.*, 1992). However, we are unaware of any mechanistic studies of habitat partitioning among *J. roemerianus* and *S. alterniflora* that have clearly demonstrated differential flood tolerance.

Conclusions

The extent of hurricane sedimentation, the thickness of hurricane sedimentation, and the nutrient content of hurricane sediments noted are probably unique to this study. However, the following generalities probably apply to numerous estuarine marshes. The amount of hurricane sedimentation appears to vary with stem density among adjacent stands of emergent vegetation in many estuarine marshes. Hurricane sediments probably originate from the same sediment sources mined by other sedimentation events. However, the texture of hurricane sediments may be coarser than non-hurricane sediments. The texture of hurricane sediments and non-hurricane sediments are most likely to differ in estuaries where normal tidal currents are too weak to mine coarse sands from sediment source areas. The chemical composition of the two types of sediments will vary with texture. Thus, hurricane sediments may differ from non-hurricane sediments in texture and chemical composition, may vary spatially across marshes, and may also vary within marshes among adjacent stands of different plant species. This variability may help maintain diversity in the emergent plant community in estuarine marshes lacking strong environmental gradients.

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