Estuaries Vol. 28, No. 4, p. 519–528 August 2005

Effects of Sediment Slurry Enrichment on Salt Marsh Rehabilitation: Plant and Soil Responses Over Seven Years

MATTHEW G. SLOCUM†, IRVING A. MENDELSSOHN*, and NATHAN L. KUHN‡

Wetland Biogeochemistry Institute, School of the Coast and Environment, Louisiana State University, Baton Rouge, Louisiana 70803

ABSTRACT: In deltaic marshes, mineral sediment promotes positive elevation change and counters subsidence and sea level rise. In many such marshes sediment deficits result in wetland loss. One new way to address sediment deficiency is to supply marshes with sediments in a slurry that deposits the sediment in a thin layer over a large area. The long-term effects of this strategy are poorly understood. In a rapidly submerging, *Spartina alterniflora* salt marsh, we tested how different amounts of sediment ameliorated the effects of sea level rise and subsidence over 7 yr (1992–1998). Sediment slurry enrichment likely affected plants and soils by two mechanisms. It increased elevation and soil bulk density, leading to increased plant vigor and soil condition. These effects were long lasting, such that by 1998 areas receiving moderate amounts of sediment (5–12 cm relative elevation) had better plant vigor and soil condition compared to areas not receiving sediment (55% cover versus 20%; bulk densities of 0.4–1.0 g cm^{-3} versus 0.2 g cm^{-3}; 0 mM hydrogen sulfide versus >1.0 mM). The sediment slurry also had high nutrient content, which resulted in a pulse of growth, especially in areas receiving the most sediment (areas >12 cm relative elevation initially had >90% cover and canopy heights >1.6 m). This nutrient-induced growth spurt was short lived and faded after 3 yr, at which point the long lasting effects of increased elevation probably became the dominant factor promoting plant vigor and soil condition. Moderate levels of sediment generated the most beneficial and long lasting effects to the vegetation and soils. This degree of sediment slurry addition countered the effects of subsidence and sea level rise, but not so much as to surpass the intertidal position to which *S. alterniflora* is best adapted.

Introduction

Deltaic marshes are some of the most productive ecosystems in the world and provide critical ecological functions and services (Dawes 1998; Mitsch and Gosselink 2000). Unfortunately they are being lost at high rates; between 1978 and 2000 the Mississippi River Delta Complex lost coastal wetlands at a rate of 77 km^2 yr^{-1} (Barras et al. 2003). One primary reason for this wetland loss is that they become excessively inundated (Baumann et al. 1984; Reed and Cahoon 1992), which kills vegetation by reducing substrate aeration (Mendelssohn et al. 1981; Mendelssohn and McKee 1988) and by producing the phytotoxin hydrogen sulfide (Mendelssohn and McKee 1988; Koch and Mendelssohn 1989). Excessive inundation is largely due to the combined effects of subsidence and eustatic sea level rise, processes that must be offset by positive marsh elevation change if the wetland is to maintain its intertidal position and remain viable. In deltaic saline marshes, positive elevation change depends on inputs of mineral sediment to fertilize plants and increase organic matter production (Nyman et al. 1990). Mineral sediment also precipitates hydrogen sulfide by providing iron (Fe) and manganese (Mn), leading to further plant growth and organic matter production (King et al. 1982). Sediment also increases elevation by directly adding to soil volume.

Unfortunately, deposition of mineral sediments in river deltas has been disrupted by man-made constructions such as dams, flood-control levees, canals, and spoil banks (Swenson and Turner 1987; Stanley and Warne 1993; Day et al. 1995; Turner 1997; McManus 2002). This problem is exacerbated by the rise in sea level due to global warming (Day et al. 1995), which has an estimated rate of 1.1 mm yr^{-1} (Wadhams and Munk 2004). This rate is expected to accelerate and to result in 9–88 cm of increased sea level by 2100 (Intergovernmental Panel on Climate Change 2001). In the Mississippi Delta, sea level rise and lack of sediment, when combined with tectonic faulting and the compaction of unconsolidated Holocene alluvial sediments (Morton and Purcell 2001), has resulted in rates of relative sea level rise (the combined effects of eustacy and isostacy) of 0.36–1.77 cm yr^{-1} (Penland and Ramsey 1990).

One way to reverse the loss of deltaic marshes is by artificially supplying sediment. As little as 2–8 cm of artificially supplied sediment can stimulate plant cover and productivity in *Spartina alterniflora* Loisel salt marshes (Reimold et al. 1978; DeLaune et al. 1990; Wilber 1993; Ford et al. 1999). Although

† Present address: Department of Biological Sciences, Louisiana State University, Baton Rouge, Louisiana 70803.

* Corresponding author; tele: 225/578-6425; fax: 225/578-6423; e-mail: imendel@lsu.edu

‡ Present address: Texas Parks and Wildlife, 3000 South IH-35, Suite 320, Austin, Texas 78704.

sediment enrichment levels over 15 cm can completely smother *S. alterniflora* stands, colonization by seed or rafts of rhizome material can be rapid (Reimold et al. 1978; Proffitt and Young 1999; Edwards and Proffitt 2003; Mendelssohn and Kuhn 2003).

More coastal wetlands will start deteriorating as their rate of positive elevation change lags behind relative sea level rise. To counter this, techniques for rehabilitating coastal wetlands are needed. We propose that a relatively new method, sediment slurry enrichment, should be considered. In this method sediment is piped onto a marsh using a slurry with a high water to solids ratio (approximately 85% water). The high water content helps spread the sediment in a thin layer over long distances (up to 1,000 m) from the discharge pipe. This technique has been studied at only one site with 43 ha of sediment-affected area, and only over 2 yr (Mendelssohn and Kuhn 2003). To our knowledge all other studies examining the use of sediment to rehabilitate marshes have been short term (<2 yr; Reimold et al. 1978; DeLaune et al. 1990; Ford et al. 1999) or on small scales (Reimold et al. 1978; DeLaune et al. 1990). In this study, we sought to extend our initial evaluation of sediment slurry enrichment (Mendelssohn and Kuhn 2003) and to determine if positive effects endured over a longer period (7 yr) or if they faded as nutrient stocks became depleted and sediment compacted. Did some effects (e.g., plant growth and soil fertility) last longer than others, and how did this depend on the amount of sediment added?

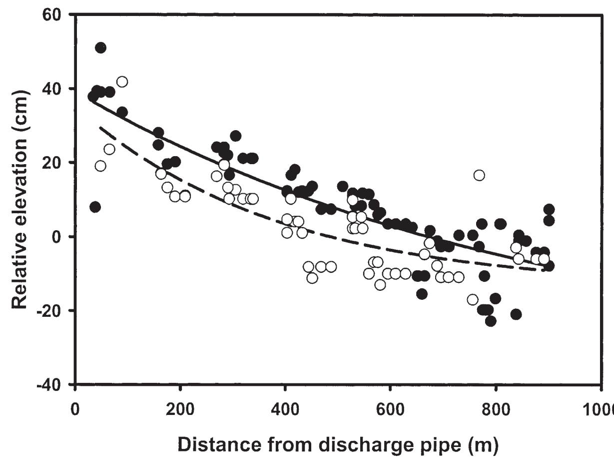

Fig. 1. Relationship between relative elevation and distance to the opening of the pipe discharging the sediment slurry. Two surveys of elevation were conducted with a laser level, with elevations being relative to nearby marsh that did not receive sediment. The first survey (1993, dark circles and solid line) was a general survey of the marsh and included the areas in which study plots were later located. The second survey (1998, white circles and dashed line) was of the study plots. For each survey, the relationship between relative elevation and distance to the discharge pipe was modeled with an exponential decay curve. 1993: $elev = -35.4 + (74.5 \times e^{-0.0011*dist})$, $R^2_{adj} = 69\%$. 1998: $elev = -13.9 + (49.0 \times e^{-0.0026*dist})$, $R^2_{adj} = 62\%$.

Materials and Methods

Study Site

Our study site (29°12.31′N, 89°26.23′W) was a degrading, intertidal, *Spartina alterniflora* salt marsh near Venice, Louisiana. This marsh lies within the Modern (Birdsfoot) Delta of the Mississippi River Delta Complex and has rates of relative sea level rise 9 times that of worldwide eustatic rise (0.94 cm yr^{-1} at Port Eads, Louisiana, from 1944 to 1988; Penland and Ramsey 1990). These rates have resulted in land loss rates of 5.7–11.4 km^2 yr^{-1}, some of the highest in the delta (Dunbar et al. 1992).

In January 1992, a canal adjacent to the study site was filled with hydraulically dredged sediment from the Gulf of Mexico. Some of the sediment slurry (85% water and 15% solids) accidentally spilled into the study site, creating an elevation gradient that reached 40 cm above the original marsh surface (Fig. 1). This increase in elevation was measured relative to a nearby marsh that did not receive sediment and is hereafter referred to as relative elevation. With time, the sediment consolidated and compacted such that by 1998 relative elevations ranged from 0 to 22 cm. Trace amounts of sediment were transported ~1,000 m from the discharge pipe, affecting 43 ha of marsh.

Experimental Design and Sample Collection

We used the elevation gradient to evaluate how the degree of sediment slurry enrichment affected soil physicochemistry and vigor of *S. alterniflora* stands over 7 yr. Along the gradient, 25 permanent plots (2 × 2 m) were randomly located in 1992 (the same plots used in Mendelssohn and Kuhn [2003]). In each plot, vegetation was described at the end of the growing season (August–November) from 1993 to 1998. This description included a visual estimate of percent cover and average canopy height. We also collected aboveground biomass (all live and dead material) in 0.25-m^2 biomass collection plots located adjacent to each permanent plot. These plots were haphazardly located in an area representative of the permanent plot's vegetative composition (i.e., similar canopy height and percent cover). Plant biomass was dried to a constant weight at 65°C and weighed. Species richness data were also collected, but we do not report them here because substantial changes were not found.

Except for 1993, soil physicochemical characteristics were measured at the same sampling periods as the vegetation. Soil oxidation-reduction potential (Eh) was measured using six bright platinum electrodes and a calomel reference electrode with three subsamples taken at 2 cm soil depth and three at 15 cm. An average of the three subsamples for each depth was used for statistical analysis. Bulk density was measured by drying (at 65°C) and weighing cores (5 cm diameter × 9.5 cm tall) taken from the biomass collection plots. Interstitial water was collected using a second core (5 cm diameter × 25–30 cm tall) from the biomass collection plots. After removal, each core was immediately placed into a 500 ml centrifuge bottle that was quickly sealed and purged with nitrogen gas. Each bottle was then placed on ice and centrifuged within 48 h. Its interstitial water was then removed and filtered (0.45 μm). Salinity was measured with a temperature-corrected refractometer. Total soluble sulfide was measured using an antioxidant buffer and a sulfide electrode (Lazar Research Laboratories, Los Angeles, California). Ammonium-nitrogen (NH_4-N) was measured using the colorimetric, automated phenate method (USEPA 1979). Nitrate was also determined, but concentrations were so low (8 μM), even at the highest elevations where nitrification could have occurred, that these data are not reported. Phosphorus (P), calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), iron (Fe), and manganese (Mn) were measured using a Fisher inductively coupled argon plasma emission spectrometer. These subsamples were preserved with nitric acid (USEPA 1979).

Statistical Analyses

The data were modeled using response surface regressions, a technique that provides an equation that predicts the linear, quadratic, and interactive (cross product) effects of time and elevation (fixed continuous effects) on a dependent variable. This equation describes a three dimensional surface that allows for easy interpretation of how time and elevation influence a dependent variable. A lack of fit test indicates if a significant portion of variation is not explained by the response surface. In all of our analyses, we found no significant lack of fit, indicating that the models adequately detailed the data's linear and quadratic trends. Response surfaces were modeled using the RSREG procedure of SAS version 6.12 (SAS Institute 1990).

For the vegetation data there were three dependent variables: percent cover, canopy height, and aboveground biomass. These variables correlated only moderately (all r values <0.50), and we modeled each individually with a response surface regression and adjusted our type 1 error using a Bonferoni correction (i.e., $p \leq 0.017$). Normality of residuals was examined using box plots and Shapiro-Wilk statistics, and for all variables we found that a natural log transformation normalized their distributions.

For soils we had 13 highly intercorrelated dependent variables, and we used principal components analysis (PCA) to condense them into linear combinations. Before this analysis, all of the dependent variables were examined for normality and were transformed when necessary (natural log and square-root transformations). PCA was conducted using the FACTOR procedure of SAS version 6.12 (SAS Institute 1990) with a varimax rotation, which constrained the analysis to providing axes that were uncorrelated (i.e., orthogonal). Only principal components with eigenvalues >1 were kept for analyses. Factor scores from these components were then analyzed using response surface regressions. After each response surface analysis, residuals were tested for normality as above. The factor scores of one principal component required a square-root transformation.

Results

Vegetation

Approximately 2 yr after sediment slurry enrichment (end of 1993), elevation had a strong and positive relationship with percent cover, canopy height, and aboveground biomass of *S. alterniflora* (Fig. 2). With time this trend weakened and, for some growth variables, a shift towards better growth at more moderate elevations occurred.

In 1993 percent cover reached >90% at 10–22 cm relative elevation, but by 1998 the highest percent covers were 55% and were found at more intermediate elevations (5–15 cm relative elevation; Fig. 2). The lowest percent covers (20%) were found at the lowest elevations (−6 cm) throughout the study. These trends were highly significant (response surface regression: significant linear and quadratic trends for year and elevation; Table 1). The statistical model explained 48% of the variation in the data set, and based on F values it appeared that elevation was more important than year.

Canopy height followed a trend similar to that of percent cover, except that the positive effect of elevation faded more rapidly. In 1993, canopy heights reached 180 cm at 19 cm relative elevation, but by 1996 there was little effect of elevation and the tallest canopies reached 100 cm (Fig. 2). These trends were statistically significant (response surface regression: significant linear and cross product effects for year and elevation; Table 1). Time and elevation were roughly equal in importance, and the model explained 30% of the variation in the data set.

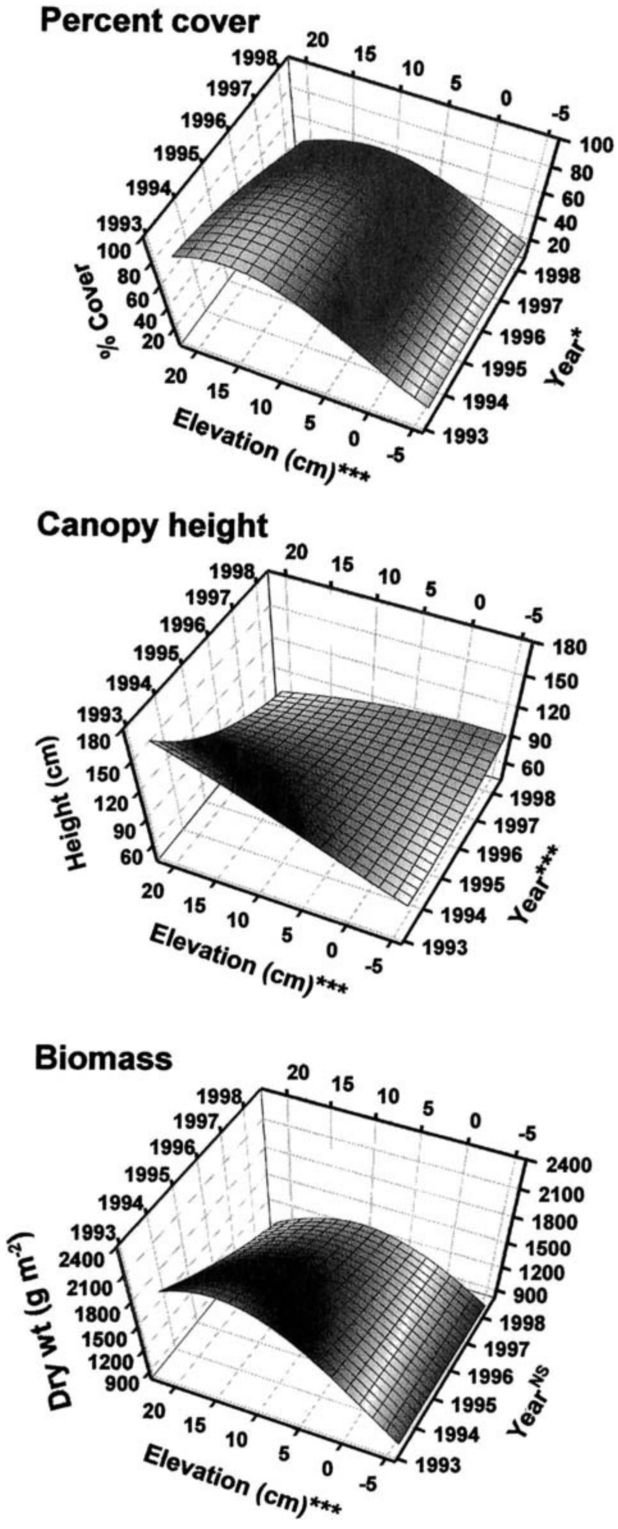

Fig. 2. Response surfaces describing the linear and quadratic effects of year and relative elevation on three variables describing vegetation (percent cover, average canopy height, and aboveground biomass) in a deteriorating salt marsh receiving sediment slurry enrichment. Significance of the effects are * $p < 0.01$ and *** $p < 0.0001$; NS = not significant.

TABLE 1. Linear, quadratic, and cross product effects of year and elevation on three variables describing *Spartina alterniflora* stands in a deteriorating salt marsh receiving sediment slurry enrichment. Variables describing the vegetation include percent cover, average canopy height, and aboveground biomass. For each variable, statistically significant statistics are in bold (tested at a Bonferoni corrected alpha of $p \leq 0.017$).

Source	df	F	p	R^2
Percent cover (natural log transformed)				
Linear	2, 144	49	**0.0001**	**0.35**
Quadratic	2, 144	18	**0.0001**	**0.13**
Cross product	1, 144	2.6	0.11	0.01
Lack of fit	102, 42	1.3	0.15	
Time	3, 144	4.2	**0.006**	
Elevation	3, 144	42	**0.0001**	
Canopy height (natural log transformed)				
Linear	2, 144	13	**0.0001**	0.13
Quadratic	2, 144	2.8	0.06	0.03
Cross product	1, 144	29.1	**0.0001**	0.14
Lack of fit	102, 42	1.3	0.12	
Time	3, 144	14	**0.0001**	
Elevation	3, 144	16	**0.0001**	
Aboveground biomass (natural log transformed)				
Linear	2, 144	13	**0.0001**	**0.14**
Quadratic	2, 144	5.3	**0.006**	**0.06**
Cross product	1, 144	1.5	0.22	0.01
Lack of fit	102, 42	1.1	0.36	
Time	3, 144	2.8	0.04	
Elevation	3, 144	10	**0.0001**	

Aboveground biomass reached its maximum of 2,200 g m^{-2} at 10–22 cm relative elevation in 1993 (Fig. 2). By 1998, the maximum biomass levels were 1,200 g m^{-2} and were found at 5–15 cm elevation. Like percent cover and canopy height, elevation was statistically significant in the model and affected biomass in a quadratic and linear fashion; time was not significant (at Bonferoni adjusted $p \leq 0.017$; Table 1). The response surface explained only 20% of the variation in the biomass data, probably because these data were highly variable due to the small size of the sampling plots (0.25 m^2 compared to 1 m^2 for canopy height and percent cover).

Considering the combined trends for percent cover, canopy height, and biomass, we concluded that the vegetation had an initial pulse of growth due to sediment slurry enrichment, especially at the highest elevations. This pulse declined rapidly, but remained above that found in the areas receiving no sediment (< 0 cm elevation). By the end of the study, areas receiving moderate amounts of sediment (5–15 cm elevation) had 10% more cover than areas receiving the most sediment (> 20 cm elevation).

Soils

The variables describing soil status were highly intercorrelated, such that PCA revealed three components that together explained 75% of the data's variation (Table 2). The principal components included one that was heavily loaded with interstitial salinity, Mg, Na, and Ca (41% of the variation in the data set). The second component was positively loaded with Eh, bulk density, interstitial Mn, and interstitial Fe, and was negatively loaded with interstitial NH_4-N and hydrogen sulfide (25% of the variation in the data set). A third component was associated with interstitial P and explained 9% of the variation.

The salinity related variables were strongly affected by time and elevation. In 1994, interstitial salinity ranged from 7‰ to 9‰ across the elevation gradient (Fig. 3), but by 1998 salinity had risen at both ends of the gradient, ranging from 19‰ at the highest elevations to 15‰ at the lowest. The other salinity variables (Mg, Na, and Ca) were similarly affected (data not shown). These effects of time and elevation on the salinity principal component were statistically significant (response surface regression: significant linear and quadratic effects of time and elevation; Table 3). Time was more important than elevation in its importance on the salinity component, and the response surface explained 66% of the variation in the data set. The response surface and the raw data outlined a hill peaking in 1997 at the highest elevations, with the minimum occurring in 1994 at −6 cm elevation (Figs. 3 and 4).

The soil reduction/bulk density component was positively related to elevation and negatively related to time. In 1994, Eh at 2 cm soil depth was +150 mV at 15 cm relative elevation and −200 mV at −6 cm elevation (Fig. 3). By 1998, Eh at 15 cm relative elevation had fallen to −50 mV, while it remained at −200 mV at −6 cm elevation. In 1994, bulk densities were 1.2 g cm^{-3} at the highest elevations and 0.2 g cm^{-3} at the lowest elevations. By 1998, bulk density at the highest elevations had decreased to 0.8–1.0 g cm^{-3}, while remaining 0.2 g cm^{-3} at the lowest elevations. Interstitial Fe and Mn had similar patterns (data not shown). Interstitial NH_4-N and hydrogen sulfide, unlike the other variables, did not change smoothly with time; some years had more hydrogen sulfide or NH_4-N than others (Fig. 3). Elevation had marked negative effects on these variables.

These effects of elevation and time on the soil reduction/bulk density component were highly significant (response surface regression: significant linear effect of time and elevation; Table 3). Elevation was relatively more important than time in describing the response surface, and the response surface explained 60% of the variation in the data set. The surface described by the regression equation was mostly flat, peaking in 1994 at 19 cm relative elevation and sloping downwards with decreasing elevation and to a lesser extent with time (Fig. 4). The minima for this surface were at the lowest elevations and were consistent over the study period.

TABLE 2. Results of principal components analysis on 13 variables describing soils of a deteriorating salt marsh that received sediment slurry enrichment. Listed are coefficients that describe how strongly each soil characteristic associates with each principal component. High coefficients that define a principal component are in bold, resulting in three general trends: a salinity trend, a soil reduction/bulk density trend, and a trend associated with interstitial P. Also provided are measures of the importance of each component (eigenvalues and percent variation explained).

Soil Characteristic	PC 1 (salinity)	PC 2 (reduction)	PC 3 (P)
Salinity	**0.94**	−0.06	−0.08
Mg	**0.92**	0.26	0.04
Na	**0.90**	0.11	−0.12
Ca	**0.86**	0.38	0.00
Sulfide	−0.22	**−0.79**	−0.22
Bulk density	0.30	**0.78**	−0.28
Eh (2 cm)	−0.23	**0.78**	−0.28
Fe	0.04	**0.78**	0.06
Eh (15 cm)	−0.50	**0.69**	0.05
NH_4-N	−0.45	**−0.66**	−0.21
Mn	0.17	**0.63**	−0.04
P	−0.04	0.06	**0.94**
K	0.58	−0.05	0.29
Eigenvalue	5.4	3.2	1.2
% variation explained	41%	25%	9%

Interstitial P (highly loaded on the third component) was at its highest concentration at low to intermediate elevations and did not appear to vary predictably with time (Figs. 3 and 4). This trend was found to be statistically significant (response surface regression: significant linear and quadratic effects of year and elevation; Table 3). Time was found to be relatively less important than elevation, and the surface only explained 34% of the variation in the data set. The resultant surface was a ridge centered at 6–10 cm relative elevation, with lows at the highest and lowest elevations (Fig. 4). There was a dip in this ridge in 1995.

Discussion

When marsh elevation cannot keep pace with the combined effects of subsidence and sea level rise, one way to reverse the resulting land loss is to artificially supply sediment. This builds marsh elevation and ameliorates stresses caused by excessive inundation. To effectively use this strategy, engineers must know how much sediment to add to achieve long lasting restoration. Our study examined a relatively new technique, sediment slurry enrichment, to determine the amount of sediment needed for long-term rehabilitation of a deteriorating *S. alterniflora* salt marsh. Sediment slurry enrichment positively affected plant vigor and ameliorated soil stressors, and these effects changed over time depending on the amount of sediment added. These dynamic effects have several management implications.

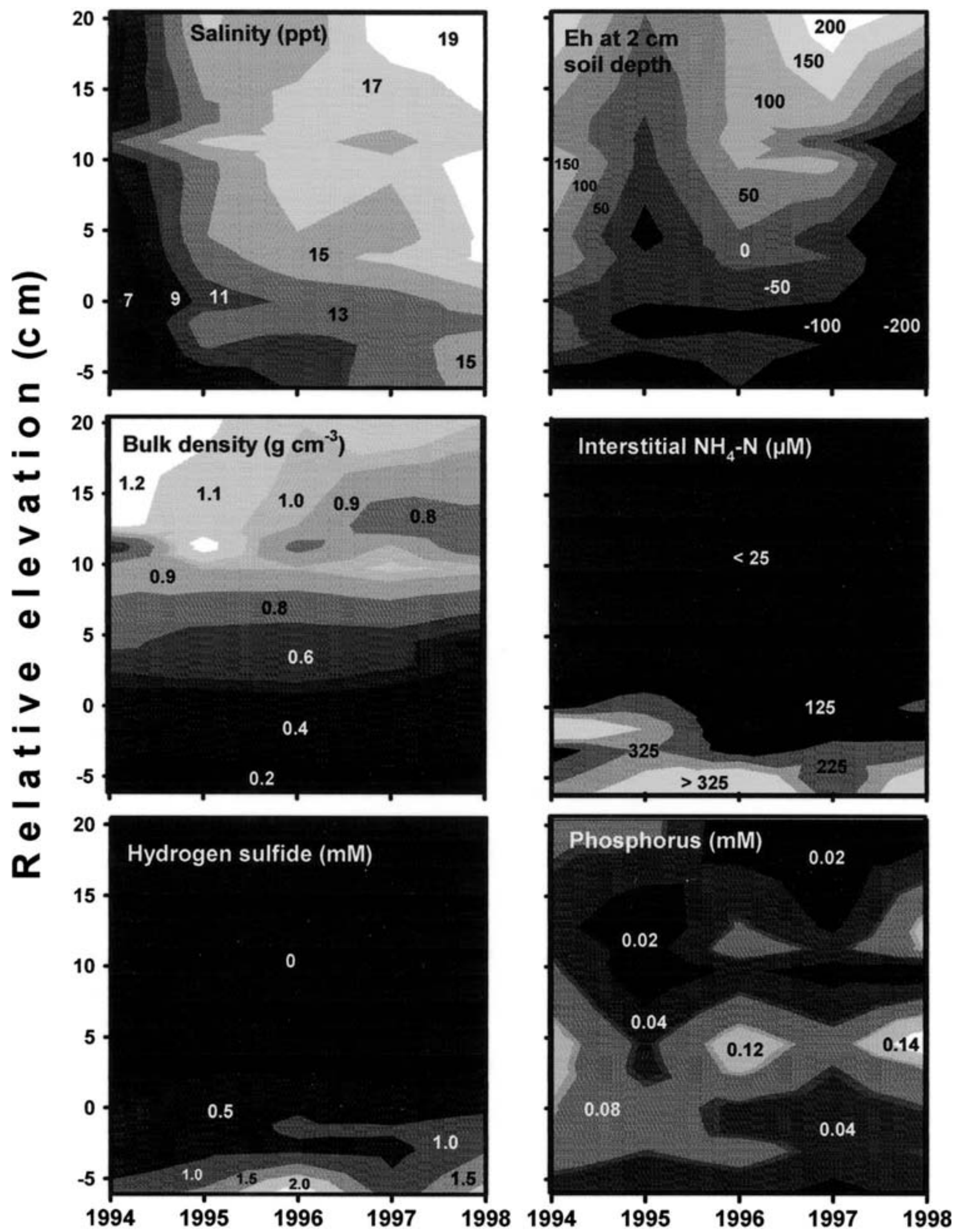

Fig. 3. Contour plots detailing the effects of year and relative elevation on soil variables describing a deteriorating salt marsh receiving sediment slurry enrichment.

Effects of Sediment Slurry Enrichment on Plants and Soils

Because sediment slurry enrichment has a high fluid:solids ratio, trace amounts of sediment can travel long distances (approximately 1,000 m) from the discharge pipe. The high fluid content prevents the creation of a substantial mound of sediment near the pipe; only 7% of the marsh receiving sediment could be classified as having relatively high deposition (relative elevations >12 cm). This area also received heavier sediment particles, having a sand content of 58 ± 6% at 25 cm soil depth (mean ± 1 SE; n = 5; Mendelssohn and Kuhn 2003). The rest of the area received more moderate amounts of sediment (2–12 cm elevation) and had less sand (9–22%). Areas not receiving sediment had 4–7% sand. We can divide the study area into three zones: a high deposition zone, moderate zone, and no deposition zone. In terms of soil fertility and

TABLE 3. Response surface statistics for three principal components describing soils in a deteriorating salt marsh receiving sediment slurry enrichment. Principal components include PC 1 (salinity), PC 2 (soil reduction/bulk density), and PC 3 (interstitial P). For each variable, the statistically significant statistics are in bold.

Source	df	F	p	R^2
PC 1 (salinity)				
Linear	2, 119	81	**0.0001**	**0.46**
Quadratic	2, 119	24	**0.0001**	**0.20**
Cross product	1, 119	0.2	0.62	0
Lack of fit	84, 35	1.3	0.14	
Time	3, 119	64	**0.0001**	
Elevation	3, 119	13	**0.0001**	
PC 2 (soil reduction/bulk density)				
Linear	2, 119	87	**0.0001**	**0.58**
Quadratic	2, 119	2.6	0.07	0.02
Cross product	1, 119	0	0.98	0
Lack of fit	84, 35	1.0	0.56	
Time	3, 119	14	**0.0001**	
Elevation	3, 119	46	**0.0001**	
PC 3 (Phosphorus, square-root transformed)				
Linear	2, 119	8.0	**0.005**	0.09
Quadratic	2, 119	23	**0.0001**	**0.25**
Cross product	1, 119	0.8	0.38	0
Lack of fit	84, 35	1.2	0.32	
Time	3, 119	5.3	**0.002**	
Elevation	3, 119	16	**0.0001**	

vigor of marsh plants, by the end of the study these zones could be ranked as: moderate deposition > high deposition ≫ no deposition.

The moderate deposition zone appeared to benefit from an increase in marsh elevation and bulk density, along with an initial input of sediment-sorbed nutrients. These effects declined with time as sediment compacted and nutrients became depleted, but despite these declines the sediment-enriched soils remained very different from those not receiving sediment. We have also observed more recently (2000–2002) that the moderate zone maintained its increased elevation and bulk densities compared to the no deposition zone (Mendelssohn unpublished data). It appears that moderate sediment-slurry enrichment offset the negative effects of subsidence for more than 11 yr, and resulted in positive effects on the growth of *S. alterniflora*.

The first of these positive effects was that the resultant higher elevations reduced flooding (Mendelssohn and Kuhn 2003). This improved soil aeration and oxygen concentrations in the rooting zone and likely increased plant growth by reducing the dependence of plants on inefficient anaerobic metabolism for energy production (Mendelssohn et al. 1981; Mendelssohn and McKee 1988; Wilsey et al. 1992). Improved aeration also partly contributed to low to undetectable levels of hydrogen sulfide. When this phytotoxin is at concentrations > 1 mM, it reduces the growth of *S. alterniflora* by

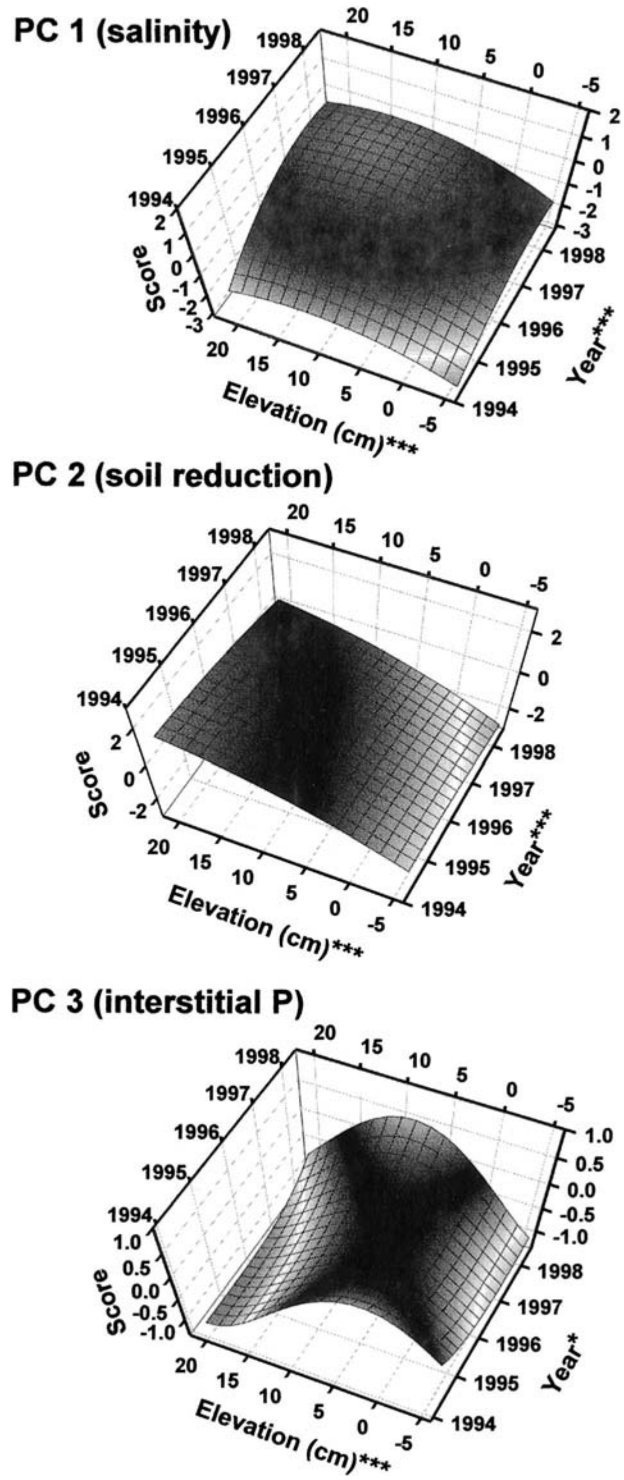

Fig. 4. Response surfaces describing the linear and quadratic effects of year and relative elevation on three principal components describing soils (salinity, soil reduction/bulk density, and interstitial P) in a deteriorating salt marsh receiving sediment slurry enrichment. Significance of the effects are * p < 0.01 and *** p < 0.0001.

interfering with energy production and metabolic processes that depend on energy production, such as NH_4-N uptake (Koch and Mendelssohn 1989; Koch et al. 1990). Increased aeration may also have been partially due to better drainage caused by the additional sand in the soil.

A second positive influence of sediment slurry enrichment in the moderate deposition zone was that it increased bulk density to > 0.40 g cm^{-3}. Higher bulk densities generally result in more Fe and Mn, which precipitate sulfide and reduce its toxicity (King et al. 1982). Because bulk density indicates the presence of mineral matter, these soils contain available minerals such as K, P, and NH_4-N (Nyman et al. 1990; Mendelssohn and Kuhn 2003).

Sediment enrichment also provided nutrients. The sediment slurry had 11 times the concentration of exchangeable NH_4-N as marsh soils not receiving sediment, and 4 times the amount of exchangeable P (mean $\pm$ 1 SE for NH_4-N: 4.44 ± 0.94 μmol cm^{-3} in the sediment versus 0.40 ± 0.09 μmol cm^{-3} in the marsh [n = 5]; exchangeable P: 160 ± 20 μmol cm^{-3} versus 40 ± 10 μmol cm^{-3} [n = 5]; Mendelssohn and Kuhn 2003). These added nutrients, especially NH_4-N, likely explained the pulse of plant growth at the beginning of the study (Buresh et al. 1980; Mendelssohn and Morris 2000). The nutrients were apparently rapidly leached from the system or fixed into organic matter and became unavailable for plant growth. Plant vigor in the moderate zone rapidly fell during the first several years. By the end of the study plant vigor remained considerably above that found in the no deposition zone, probably because of the more durable effects of increased elevation. The nutrient effect would not have been strong without increased elevation, as poor aeration largely negates the effects of additional nutrients (e.g., hydrogen sulfide interferes with plant metabolism; Mendelssohn and McKee 1988; Wilsey et al. 1992).

The high deposition zone had many of the desirable characteristics of the moderate zone, including improved soil aeration, high bulk densities, little or no hydrogen sulfide, and an initial pulse of nutrients. This pulse was even stronger than that found in the moderate deposition zone, and just as ephemeral. But like in the moderate zone, vegetation levels remained above that found in the no deposition zone (40–50% cover versus 20% cover). The high zone also had some undesirable characteristics, which led us to rank it second after the moderate zone in marsh vigor. Its soils had more sand (Mendelssohn and Kuhn 2003) and likely had less sorption capacity than the more clayey and silty soils in the moderate zone (Brady and Weil 1996). This may explain the high zone's low concentrations of NH_4-N. Lower soil fertility may also have been caused by intermittent periods of flooding and draining, which promotes denitification and leaching (Patrick and Wyatt 1964). This cycle of flooding and draining may also have concentrated salts; interstitial salinity started at 9‰ in 1994 but reached 22‰ in some plots by 1998. (Note that salinity levels also rose in the lowest elevations from 7‰ in 1994 to 15‰ in 1998). Another concern in the high deposition zone that we observed in later censuses (2000–2002) was an invasion by high marsh species (*Schoenoplectus robustus*, *Distichlis spicata*, and *Spartina patens*). This suggests that the hydroperiod of the zone had become sufficiently altered to favor less flood tolerant species and not *S. alterniflora*.

These problems in the high deposition zone are minor. The invading high marsh species can tolerate the zone's moderate to high salinities, and there was not an extensive invasion of high marsh shrubs like *Iva frutescens* and *Baccharis halimifolia* or of upland species such as the shrub *Myrica cerifera*. The area of the high deposition zone was small in size (7% of the total area receiving appreciable amounts of sediment), and its additional elevation suggests that it will endure longer against sea level rise and subsidence.

Compared to the high and moderate deposition zones, the no deposition zone continued to be severely deteriorated. It was continuously flooded, resulting in highly reduced soils (Mendelssohn and Kuhn 2003) that likely forced plants to rely on anaerobic metabolism for energy (Mendelssohn et al. 1981; Mendelssohn and McKee 1988). Its soils also had growth-reducing levels of hydrogen sulfide (>1 mM; Koch and Mendelssohn 1989), which negated the benefits of high concentrations of exchangeable NH_4-N, which results from more reduced soils (Koch et al. 1990). The zone did have sufficient bulk densities to sustain plant growth (>0.20 g cm^{-3}) (DeLaune et al. 1979), but without fresh mineral matter to build soil volume and stimulate organic matter production, it probably would not be able to build elevation quickly enough to match sea level rise and subsidence (Nyman et al. 1990). The area will likely convert to open water, a process that has already started as evidenced by its many small ponds and highly fragmented physiognomy.

Management Implications and Conclusions

Many deltaic marshes are deteriorating because they no longer receive periodic river flooding and the associated mineral sediment (Stanley and Warne 1993; Day et al. 1995; McManus 2002; Barras et al. 2003; Yang et al. 2003). Such marshes can be restored or rehabilitated by providing sediment from dredging operations (Costa-Pierce and Weinstein 2002). This strategy comes with an additional benefit: it provides engineers with ecologically sensitive methods for dredge material disposal (Cahoon and Cowen 1988; Costa-Pierce and Weinstein 2002). Traditionally, spoil has been deposited in spoil banks, which interfere with the tidal flow of marshes and lead to marsh degradation (Swensen and Turner 1987).

Currently there are two methods by which dredge material has been used to restore wetlands. The first is to pipe in dredge material to create marshes in areas of open water. This older method is the best studied and most commonly used, and has proved successful in creating productive marshes. The ecological functions of these marshes often take many years to reach that of natural marshes (depending on the function in question; Minello and Webb 1997; Proffitt and Young 1999; Shafer and Streever 2000; Edwards and Proffitt 2003), and some ecological functions may never recover (Minello 2000; Streever 2000). A second method, spray dredging, is newer and less frequently used (Ford et al. 1999). In this method dredge material is sprayed from a boat and deposited up to 80 m away in a thin layer on deteriorating marshes (Cahoon and Cowan 1988; Ford et al. 1999). When successful, this thin layer offsets the effects of subsidence and sea level rise, but does not completely smother vegetation or allow upland species to invade.

We propose that sediment slurry enrichment is a third way to dispose of dredge material and restore marshes. In this method, a highly fluid sediment slurry is piped in a thin layer onto the surface of marshes with degrading vegetation. Like spray dredging, the correct amount of sediment is used to revitalize a marsh, but unlike spray dredging, sites deep in the marsh interior can be reached because the method uses standard pipes that can be moved, and because the method's high water content can transport sediment up to 1,000 m away from the discharge pipe. The method leads to improvements in vegetation, soil bulk density, and other important marsh characteristics that in this study lasted at least 11 yr. We found one small disadvantage in this method; it created a region of high sand content and increased elevation, but this area was small relative to the areas receiving moderate amounts of sediment. This high deposition zone did not cause serious problems in terms of plant vigor, change in species composition, or soil chemistry.

This study is the only long-term investigation of sediment slurry enrichment conducted on a realistic scale. One of our important findings was that the positive long lasting effects appeared to be due more to increased elevation than additional nutrients, whose effects appeared to be mostly ephemeral. This suggests that attempts to rehabilitate marshes by fertilizing them may lead to short-term benefits only and will require repeated application. It also suggests that sediment enrichment studies of 1–2 yr overestimate restoration success when there is an increase in growth due to a fertilizer effect. Another important aspect of our research was that it was conducted on the same scale as an actual restoration attempt, and its findings are more relevant than smaller scale studies.

Now additional long-term, appropriately-scaled studies are needed that test how sediment slurry enrichment and the other methods rehabilitate coastal marshes. These studies should be done in a variety of ecological settings and should compare characteristics of restored wetlands with those in both deteriorating and healthy ones. Such long-term, large-scale studies will be essential in addressing the worldwide loss of deltaic wetlands as sea levels rise and as the effects of insufficient river-derived mineral sediment continue to compound.

Acknowledgments

We would like to thank the Louisiana State Sea Grant College Program (National Oceanographic and Atmospheric Administration) for their primary financial support, and the U.S. Environmental Protection Agency for their initial funding. For help in the field we thank Eric Webb, Jeannine Lessmann, Megan LaPeyre, Jim Pahl, and Rich Courtemanche, and we thank Jay Geaghan for help with statistical analysis. Lastly, we thank T. Baker Smith & Sons for elevation surveys and the Soil Testing and Plant Analysis Laboratory of Louisiana State University for soils analyses.

Literature Cited

Barras, J., S. Beville, D. Britsch, S. Hartley, S. Hawes, J. Johnston, P. Kemp, Q. Kinler, A. Martucci, J. Porthouse, D. Reed, K. Roy, S. Sapkota, and J. Suhayda. 2003. Historical and projected coastal Louisiana land changes: 1978–2050. U.S. Geological Survey Open File Report 03-334. http://www.nwrc.usgs.gov/special/NewHistoricalland.pdf

Baumann, R. H., J. W. Day, Jr., and C. A. Miller. 1984. Mississippi deltaic wetland survival: Sedimentation versus coastal submergence. *Science* 224:1093–1095.

Brady, N. C. and R. R. Weil. 1996. The Nature and Properties of Soils, 11th edition Prentice Hall, Upper Saddle River, New Jersey.

Buresh, R. J., R. D. Delaune, and W. H. Patrick, Jr. 1980. Nitrogen and phosphorus distribution and utilization by *Spartina alterniflora* in a Louisiana Gulf Coast marsh. *Estuaries* 3:111–121.

Cahoon, D. R. and J. H. Cowan, Jr. 1988. Environmental impacts and regulatory policy implications of spray disposal of dredge material in Louisiana wetlands. *Coastal Management* 16:341–362.

Costa-Pierce, B. A. and M. P. Weinstein. 2002. Use of dredged materials for coastal restoration. *Ecological Engineering* 19:181–186.

Dawes, C. J. 1998. Marine Botany. 2nd edition John Wiley and Sons, New York.

Day, J. W., D. Pont, P. F. Hensel, and C. Ibanez. 1995. Impacts of sea-level rise on deltas in the Gulf of Mexico and the Mediterranean—The importance of pulsing events to sustainability. *Estuaries* 18:636–647.

DeLaune, R. D., R. J. Buresh, and W. H. Patrick, 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.

DeLaune, R. D., S. R. Pezeshki, J. H. Pardue, J. H. Whitcomb, and W. H. Patrick, Jr. 1990. Some influences of sediment addition to a deteriorating salt marsh in the Mississippi River deltaic plain: A pilot study. *Journal of Coastal Research* 6:181–188.

Dunbar, J. B., L. D. Britsch, and E. B. Kemp, III. 1992. Land loss rates. Report 3: Louisiana coastal plain. U.S. Army Corps of Engineers, Waterways Experiment Station, Technical Report GL-90-2, Vicksburg, Mississippi.

Edwards, K. R. and C. E. Proffitt. 2003. Comparison of wetland structural characteristics between created and natural salt marshes in southwest Louisiana, USA. *Wetlands* 23:344–356.

Ford, M. A., D. D. Cahoon, and J. C. Lynch. 1999. Restoring marsh elevation in a rapidly subsiding salt marsh by thin layer deposition of dredged material. *Ecological Engineering* 12:189–205.

Intergovernmental Panel on Climate Change. 2001. Climate Change 2001: The Scientific Basis. Cambridge University Press, Cambridge, United Kingdom.

King, G. M., M. J. Klug, R. G. Wiegert, and A. G. Chalmers. 1982. Relation of soil water movement and sulfide concentration to *Spartina alterniflora* production in a Georgia salt marsh. *Science* 218:61–63.

Koch, M. S. and I. A. Mendelssohn. 1989. Sulphide as a soil phytotoxin: Differential responses in two marsh species. *Journal of Ecology* 77:565–578.

Koch, M. S., I. A. Mendelssohn, and K. L. McKee. 1990. Mechanism for the hydrogen sulfide-induced growth limitation in wetland macrophytes. *Limnology and Oceanography* 35:399–408.

McManus, J. 2002. Deltaic responses to changes in river regimes. *Marine Chemistry* 79:155–170.

Mendelssohn, I. A. and N. L. Kuhn. 2003. Sediment subsidy: Effects on soil-plant responses in a rapidly submerging coastal salt marsh. *Ecological Engineering* 21:115–128.

Mendelssohn, I. A. and K. L. McKee. 1988. *Spartina alterniflora* die-back in Louisiana: Time-course investigation of soil waterlogging effects. *Journal of Ecology* 76:509–521.

Mendelssohn, I. A., K. L. McKee, and W. H. Patrick, Jr. 1981. Oxygen deficiency in *Spartina alterniflora* roots: Metabolic adaptation to anoxia. *Science* 214:439–441.

Mendelssohn, I. A. and J. T. Morris. 2000. Eco-physiological constraints on the primary productivity of *Spartina alterniflora*, p. 59–80. *In* M. P. Weinstein and D. A. Kreeger (eds.), Concepts and Controversies of Tidal Marsh Ecology. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Minello, T. J. 2000. Temporal development of salt marsh value for nekton and epifauna: Utilization of dredged material marshes in Galveston Bay, Texas, USA. *Wetlands Ecology and Management* 8:327–342.

Minello, T. J. and J. W. Webb, Jr. 1997. Use of natural and created *Spartina alterniflora* salt marshes by fishery species and other aquatic fauna in Galveston Bay, Texas, USA. *Marine Ecology Program Series* 151:165–179.

Mitsch, W. J. and J. G. Gosselink. 2000. Wetlands. 3rd edition Van Nostrand Reinhold, New York.

Morton, R. A. and N. A. Purcell. 2001. Wetland subsidence, fault reactivation, and hydrocarbon production in the U. S. Gulf Coast region. U.S. Geological Survey, Fact Sheet 091-01. http://pubs.usgs.gov/fs/fs091-01

Nyman, J. A., R. D. DeLaune, and W. H. Patrick, 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.

Patrick, W. H. and R. Wyatt. 1964. Soil nitrogen loss as a result of alternate submergence and drying. *Soil Science Society of America Proceedings* 28:647–653.

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

Proffitt, C. E. and J. Young. 1999. Salt marsh plant colonization, growth, and dominance on large mudflats created using dredged sediments, p. 218–228. *In* L. P. Rozas, J. A. Nyman, C. E. Proffitt, N. N. Rabalais, D. J. Reed, and R. E. Turner (eds.), Proceedings. Recent Research in Coastal Louisiana: Natural System Function and Response to Human Influence. Louisiana Sea Grant College Program, Baton Rouge, Louisiana.

Reed, D. J. and D. R. Cahoon. 1992. The relationship between marsh surface topography, hydroperiod, and growth of *Spartina alterniflora* in a deteriorating Louisiana salt marsh. *Journal of Coastal Research* 8:77–87.

Reimold, R. J., M. A. Hardisky, and P. C. Adams. 1978. The effects of smothering a *Spartina alterniflora* salt marsh with dredged material. U.S. Army Corps of Engineers, Technical Report D-78-38, Washington, D.C.

SAS Institute, Inc. 1990. SAS/STAT User's Guide. version 6, 4th edition SAS Institute, Inc., Cary, North Carolina.

Shafer, D. J. and W. J. Streever. 2000. A comparison of 28 natural and dredged material salt marshes in Texas with an emphasis on geomorphological variables. *Wetlands Ecology and Management* 8:353–366.

Stanley, D. J. and A. G. Warne. 1993. Nile Delta—Recent geological evolution and human impact. *Science* 260:628–634.

Streever, W. J. 2000. *Spartina alterniflora* marshes on dredged materials: A critical review of the ongoing debate over success. *Wetlands Ecology and Management* 8:295–316.

Swenson, E. M. and R. E. Turner. 1987. Spoil banks: Effects on a coastal marsh water-level regime. *Estuarine Coastal and Shelf Science* 24:599–609.

Turner, R. E. 1997. Wetland loss in the northern Gulf of Mexico: Multiple working hypotheses. *Estuaries* 20:1–13.

U.S. Environmental Protection Agency (USEPA). 1979. Methods for chemical analysis of water and wastes. U.S. Environmental Protection Agency, Cincinnati, Ohio.

Wadhams, P. and W. Munk. 2004. Ocean freshening, sea level rising, sea ice melting. *Geophysical Research Letters* 31:L11311.

Wilber, P. 1993. Environmental Effects of Dredging Technical Notes: Managing of dredged material via thin-layer disposal in coastal marshes. U.S. Army Corps of Engineers. Technical Note EEDP-01-32. http://el.erdc.usace.army.mil/dots/pdfs/eedp01-32.pdf

Wilsey, B. J., K. L. McKee, and I. A. Mendelssohn. 1992. Effects of increased elevation and macro- and micronutrient additions on *Spartina alterniflora* transplant success in salt-marsh dieback areas in Louisiana. *Environmental Management* 16:505–511.

Yang, S. L., I. M. Belkin, A. I. Belkina, Q. Y. Zhao, J. Zhu, and P. Ding. 2003. Delta response to decline in sediment supply from the Yangtze River: Evidence of the recent four decades and expectations for the next half-century. *Estuarine Coastal and Shelf Science* 57:689–699.

Received, January 10, 2005
Revised, May 4, 2005
Accepted, May 4, 2005