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Controls on resilience and stability in a sediment-subsidized salt marsh

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Abstract. Although the concept of self-design is frequently employed in restoration, reestablishment of primary physical drivers does not always result in a restored ecosystem having the desired ecological functions that support system resilience and stability. We investigated the use of a primary environmental driver in coastal salt marshes, sediment availability, as a means of promoting the resilience and stability of submerging deltaic salt marshes, which are rapidly subsiding due to natural and human-induced processes. We conducted a disturbance–recovery experiment across a gradient of sediment slurry addition to assess the roles of sediment elevation and soil physico-chemical characteristics on vegetation resilience and stability in two restored salt marshes of differing age (a 15-year-old site and a 5-year-old site).

Salt marshes that received moderate intensities of sediment slurry addition with elevations at the mid to high intertidal zone (2–11 cm above local mean sea level; MSL) were more resilient than natural marshes. The primary regulator of enhanced resilience and stability in the restored marshes was the alleviation of flooding stress observed in the natural, unsubsidized marsh. However, stability reached a sediment addition threshold, at an elevation of 11 cm above MSL, with decreasing stability in marshes above this elevation. Declines in resilience and stability above the sediment addition threshold were principally influenced by relatively dry conditions that resulted from insufficient and infrequent flooding at high elevations. Although the older restored marsh has subsided over time, areas receiving too much sediment still had limited stability 15 years later, emphasizing the importance of applying the appropriate amount of sediment to the marsh. In contrast, treated marshes with elevations 2–11 cm above MSL were still more resilient than the natural marsh 15 years after restoration, illustrating that when performed correctly, sediment slurry addition can be a sustainable restoration technique.

Key words: climate change; drought; ecological restoration; experimental disturbance; Mississippi Delta Plain, Louisiana, USA; sea-level rise; sediment slurry addition; salt marsh; Spartina alterniflora; *submergence.*

INTRODUCTION

Restoration of degraded ecosystems to specific ecological endpoints, historic or projected, can be difficult and result in unexpected outcomes, a problem for natural resource managers. Further, the reintroduction of historically important system drivers, e.g., fire for grasslands or hydrology for wetlands, does not necessarily result in desired ecological endpoints (Anderson et al. 2000, Seabloom and van der Valk 2003). An understanding of the factors that control the resilience and sustainability of restored ecosystems and whether environmental thresholds exist that can drive a change in ecosystem state during restoration are of critical importance to the ecological restoration community. This is especially true for large river deltas, which are rapidly degrading worldwide due to a variety of natural and human-induced factors (Ericson et al. 2006, Syvitski et al. 2009).

Wetlands associated with deltas provide a suite of valuable ecological services to the half-billion people that live on or near deltas (Syvitski and Saito 2007, Day et al. 2008). Salt marshes located in delta plains commonly experience higher than average rates of relative sea-level rise because of sediment compaction and geological subsidence (Milliman et al. 1989, Ramsey and Penland 1992, Sestini 1996, Syvitski et al. 2009). Furthermore, the additional anthropogenic influence of hydrologic alteration, such as levee building, exacerbates the effects of sea-level rise and can lead to salt marsh submergence and extensive land loss (Ericson et al. 2006, Day et al. 2008). One relatively new method of salt marsh restoration, sediment slurry addition, aims to ameliorate the effects of submergence by increasing the elevation of the marsh surface. This approach is based on the understanding that excessive flooding can lead to

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inhibited growth, or even mortality, of *S. alterniflora* (Mendelssohn and McKee 1988, Wilsey et al. 1992), whereas increasing elevation (Fragoso and Spencer 2008) and soil drainage (Mendelssohn and Seneca 1980, Wiegert et al. 1983) can improve plant production.

We used experimental disturbances ("nonlethal" as clipping, and "lethal" as herbicide applications) to measure resilience (rate of recovery after disturbance) and stability (ability to recover to steady state after disturbance) (Grimm and Wissel 1997) of the dominant salt marsh grass, *S. alterniflora*, providing an indicator of ecosystem response to the restoration driver, i.e., sediment slurry addition. As emergent properties of ecosystems, resilience and stability are influenced by the interaction of multiple factors and processes, and thus provide an integrated measure of ecological status (Costanza 1992, Costanza et al. 1998, Rapport et al. 1998, Whitford et al. 1999, Gunderson 2000). The use of experimental disturbances to measure resilience and stability has recently been shown to accurately reflect underlying stresses in restored salt marsh systems (Slocum and Mendelssohn 2008), and gradients in disturbance regime can be used to identify hydrologic and biogeochemical thresholds that govern ecosystem behavior (Heffernan et al. 2008). Because sediment subsidy is an increasingly popular wetland restoration technique to remediate submergence impacts (Mendelssohn and Kuhn 2003, Croft et al. 2006, Cornell et al. 2007, Schrift et al. 2008), an understanding of the capacity for this restoration method to promote long-term resilience and stability in the face of future disturbances is clearly important. Additionally, the Mississippi Delta Plain presently has rates of relative sea-level rise (1.04–1.19 cm/yr; Penland and Ramsey 1990, NOAA 2009) that are equivalent to year 2100 predictions for the rest of the world due to global climate change (Meehl et al. 2007); hence, this research also provides insight into whether sediment slurry restoration may be suitable for non-deltaic wetlands that will likely experience higher rates of eustatic sea-level rise in the future (Bianchi and Allison 2009).

The addition of hydraulically dredged materials to degraded salt marshes increases the elevation of the salt marsh platform, soil mineral content, aeration, nutrient availability, and helps restore vegetative structure and function (Mendelssohn and Kuhn 2003, Slocum et al. 2005, Croft et al. 2006, Schrift et al. 2008). However, because sediment slurry addition is a relatively new restoration technique, little research has been conducted on the long-term sustainability of sediment-subsidized salt marshes; most investigations have been short-term: seven years or less (Reimold et al. 1978, DeLaune et al. 1990, Day et al. 1999, Ford et al. 1999, Mendelssohn and Kuhn 2003, Slocum et al. 2005, Croft et al. 2006, D'Alpaos et al. 2007, Schrift et al. 2008), or do not examine a range of sediment addition levels, or elevations, that is experimentally replicated (Edwards and Proffitt 2003, Edwards and Mills 2005, LePeyre et al. 2009). Therefore, we sought to increase our understanding of the long-term effects of sediment subsidies by comparing vegetation resilience and stability among different levels of sediment slurry addition in two marshes that were restored at different times: a marsh restored 15 years prior to the study (1992) and a newly restored marsh that received sediment subsidy 5 years prior to this study (2002).

We used sediment slurry addition to restore submerging salt marshes in the Mississippi Delta Plain along the Northern Gulf of Mexico, Louisiana, USA, to test whether sediment subsidies generate restored salt marshes that are resilient after disturbance and whether a sediment subsidy threshold exists, which when surpassed, fails to generate the desired ecological endpoint. We asked the following questions: (1) How does sediment subsidy improve resilience and stability compared to natural, unsubsidized marshes? (2) At what elevation, or level of sediment subsidy, are resilience and stability maximized? (3) Is there a sediment addition threshold, beyond which no improvement to resilience or stability occurs? (4) What soil physico-chemical factors influence resilience and stability at each level of sediment treatment? We hypothesized that either too much or too little sediment will reduce vegetation resilience and stability, while intermediate sediment subsidies will promote long-term sustainability of salt marshes.

Materials and Methods

Study-site description and experimental design

The study sites included two submerging salt marshes that were restored using sediment slurry addition (Fig. 1). The two sites were restored at different times, providing the opportunity to study an older sediment-subsidized marsh (Venice, 15 years old) and a newly restored marsh (Fourchon, 5 years old) in the Mississippi Delta Plain, Louisiana, USA. Although the reason for restoration and the method of sediment slurry application were different at the two sites, the resulting elevation change after sediment addition was similar and allowed for a qualitative comparison of ecological responses to the restoration effort. Rates of sea-level rise were comparable between the two sites (Venice, 0.94 cm/yr [Penland and Ramsey 1990]; and Fourchon, 0.92 cm/yr [NOAA 2009]), and both sites had similar tidal amplitude (Venice = 37 cm; Fourchon = 44 cm) (Table 1). The natural marsh surrounding both restored sites was characteristic of salt marshes in this region (Visser et al. 1998). The intertidal salt marsh was dominated by *Spartina alterniflora* and interspersed with *Avicennia germinans*, *Juncus roemerianus*, *Batis maritima*, and *Distichilis spicata*.

Venice study site.—The 15-year old Venice site (29°12.31′ N, 89°26.23′ W) was located within the Modern (Bird foot) Delta of the Mississippi River Delta Complex (Fig. 1A). High rates of relative sea-level rise, extensive canal dredging, and restricted

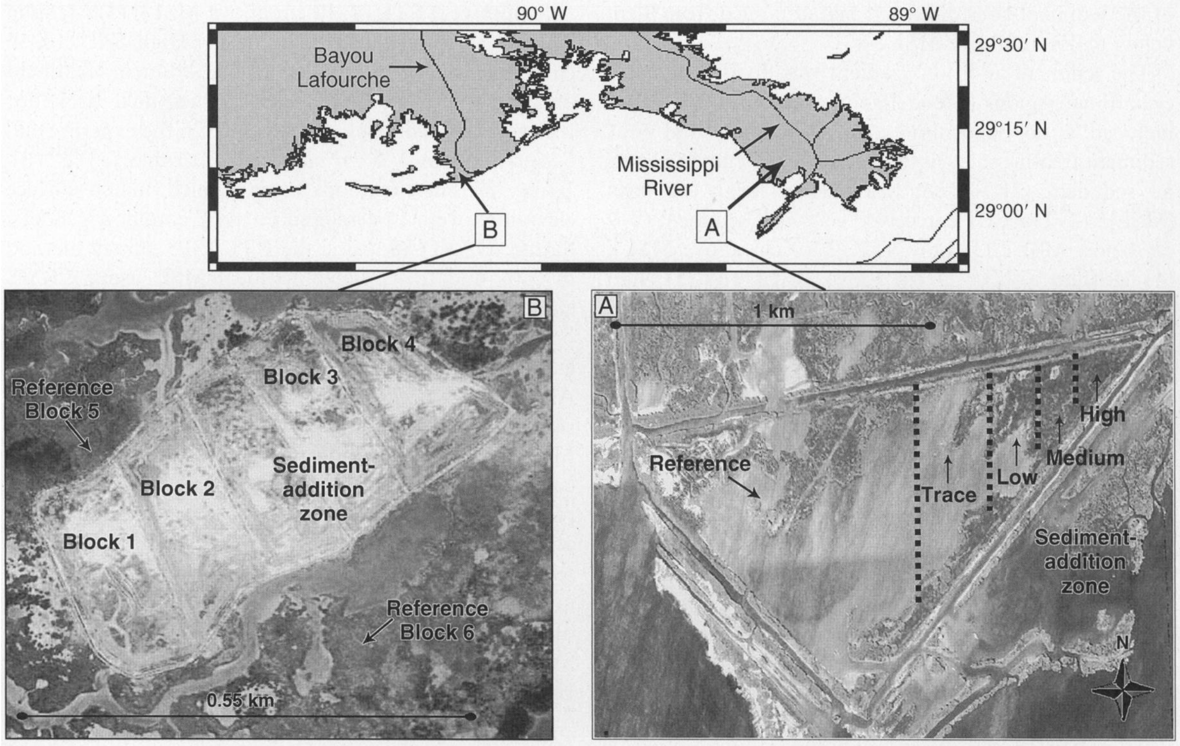

FIG. 1. Sediment addition in (A) Venice (sediment addition: 1992) and (B) Fourchon (sediment addition: 2002) restoration sites, Louisiana, USA. In Venice, differential addition of sediment resulted in five sediment treatment levels: High, Medium, Low, Trace, and a Reference that did not receive sediment. Five replicated study plots were located within each of these sediment treatment levels. In Fourchon, the sediment addition zone was composed of four separate marshes (blocks) that each included four levels of sediment addition: High, Medium, Medium vegetated (Medium-veg), and Low. A reference that did not receive sediment was included in the experimental design. Please see Table 1 for sediment treatment level elevations.

sediment deposition resulted in the submergence and degradation of the salt marshes in this area (Dunbar et al. 1992).

In 1992, an adjacent canal filled with sediment slurry accidentally overflowed into the salt marsh during the filling of a nearby pipeline canal, depositing differential amounts of sediment over 43 ha of marsh. The sediment slurries were composed of ~15% solids and 85% water by volume. The sediment overflow created an elevation gradient ranging from 8 cm below to 31 cm above local mean sea level (MSL). However, over time these sediments compacted, and by 2008, the relative elevation

TABLE 1. Elevations of sediment-treated and reference marsh surfaces and water levels relative to local mean sea level (MSL), North American Vertical Datum of 1988 (NAVD 88), and ambient marsh surface in Venice and Fourchon, Louisiana, USA.

	Elevation (cm)					
	Relative to MSL		Relative to NAVD 88		Relative to ambient marsh surface	
Variable	Venice	Fourchon	Venice	Fourchon	Venice	Fourchon
Sediment treatment level (STL)						
High	10–17	10–15	52–59	37–42	19–26	15–20
Medium	8–11	9–12	50–53	35–38	17–20	13–16
Medium vegetated	⋯	4–10	⋯	30–36	⋯	9–15
Low	2–10	3–6	44–52	29–32	11–19	7–10
Trace	−9 to −2	⋯	33–40	⋯	0–7	⋯
Reference	−21 to −1	−6 to −3	20–42	19–22	−12–8	2–5
Local water level						
Mean high water	19	20	61	46	28	25
Mean low water	−18	−24	24	2	−9	−19

Note: Fourchon elevations are different from those reported in Schrift et al. (2008) due to the use of a more accurate survey methodology that integrates the Louisiana State University C4G GULFNet Real-Time Network, which incorporates continually operating GPS reference stations (CORS) that deliver real-time network error corrections. Ellipses indicate that the sediment treatment level was not applicable for that site location.

of the sediment-subsidized salt marsh ranged from 9 cm below to 17 cm above MSL.

The sediment addition gradient was divided into five elevational regions (Mendelssohn and Kuhn 2003) that included a no deposition zone (Reference) and four sediment treatment levels (STLs): (1) Reference, received no sediment (21.7–1 cm below local mean sea level [MSL]); (2) Trace STL, received very little sediment (2–9 cm below MSL); (3) Low STL (2–10 cm above MSL); (4) Medium STL (8–11 cm above MSL), and (5) High STL (10–17 cm above MSL; Table 1). Marsh surface elevations were first referenced to a common geodetic datum, North American Vertical Datum of 1988 (NAVD 88), using the Networked Real-Time Kinematic (RTK) GPS survey method in 2008. Local MSL, measured at Coastwide Reference Monitoring Station 0163, was related to NAVD 88, allowing us to adjust our treatment and reference sites to the tidal datum (CRMS 2009).

Experimental stations were randomly selected in each of the five deposition zones (Fig. 1A). Soil texture varied significantly between STLs, with the greatest sand content in areas of highest sediment addition, High STL (58% sand), compared to all other areas of lower sediment addition (22–4% sand) (Mendelssohn and Kuhn 2003). Clay content was highest in the reference zone (59%) and decreased with increasing sediment addition, and silt content ranged between 23% and 51% across all treatments (Mendelssohn and Kuhn 2003).

Fourchon study site.—The five-year old Fourchon site (29°10.58′ N and 90°14.23′ W) was located in the Terrebonne Basin, a part of the Mississippi River Deltaic Plain (Fig. 1B). The specific area of interest was a submerging, degraded salt marsh located on the west bank of Bayou Lafourche near Leeville, Louisiana. This area was affected by a sudden marsh dieback (SMD) event, which was linked to extreme drought conditions during the summer of 2000 (McKee et al. 2004, Alber et al. 2008). Thousands of acres of *S. alterniflora* dominated salt marshes died and subsequently submerged (Lindstedt et al. 2006, Materne and Mendelssohn 2006). To restore the degraded area, sediment slurries were applied to the site in 2002.

The degraded salt marsh was divided into four cells through the construction of small earthen dikes. The cells were hydraulically connected through culverts and breaks in the levees that allowed for tidal exchange. Hydraulically dredged sediments from adjacent Bayou Lafourche were pumped into each cell, resulting in four separate sediment-subsidized treatment blocks (Fig. 1B). The sediment slurries were composed of ~20–30% solids and 70–80% water by volume. The terminus of the pipe was placed in the center of each cell, and the sediment slurries flowed away from the discharge pipe, creating areas of different elevation not associated with any fixed gradient. Four separate sediment treatment levels (STLs) were created in each of the four blocks: (1) Low STL (3–6 cm above MSL); (2) Medium vegetated (Medium-veg) STL (4–10 cm above MSL); (3) Medium STL (9–12 cm above MSL); and (4) High STL (10–15 cm above MSL). In addition to the sediment treatment areas, a reference area, which neither died back nor received sediment, was also included in the experimental design and was 3–6 cm below MSL (Table 1, Fig. 1B). Using the same methods as in Venice, marsh surface elevations were first referenced to a common geodetic datum, NAVD 88, using the RTK GPS survey method in 2009 and then related to local MSL using CRMS station 0292 (CRMS 2009).

Sediment treatment levels were exclusively defined by elevation, with the exception of the Medium-veg STL. Although the Medium-veg STL fell within the elevation range of the Medium and Low STLs, marsh in the Medium-veg STL rapidly revegetated to 100% canopy cover within one year of sediment addition. This recovery was distinct from the other STLs and was attributed to the presence of live rhizomes before sediment addition (Schrift et al. 2008). In 2003, at the initiation of research at this site (Scrift et al. 2008), none of the STLs were vegetated, except for the Med-Veg STL. By the start of the present study, Medium and High STLs had intermediate and minimal cover, respectively, and Low and Medium-veg STLs had 100% cover. Soil texture in the sediment addition zone did not differ significantly between treatment levels and contained 8.94% ± 0.20% sand, 42.89% ± 0.54% silt, and 47.21% ± 0.60% clay, and sediments in the reference zone contained 7.71% ± 2.55% sand, 34.88% ± 1.77% silt, and 49.74% ± 10.25% clay (Schrift et al. 2008).

Resilience and stability

We assessed the resilience and stability of both sediment-subsidized salt marshes by measuring the response of *S. alterniflora* to two intensities of experimental disturbances (Slocum and Mendelssohn 2008). At each sediment treatment level, experimental disturbances were randomly applied to three plots (1 × 1 m), one for each disturbance intensity and one control (no disturbance; see Plate 1). Experimental disturbances used nonlethal and lethal methods. (1) Nonlethal disturbance: Aboveground vegetation was removed at the soil surface using a hand-held gasoline-powered trimmer at both sites in the summer of 2006. (2) Lethal disturbance: Herbicide (Aquamaster Pro-active ingredient N-(phosphonomethyl) glycine, Monsanto Industrial, St. Louis, Missouri, USA) was applied in a water/detergent solution at recommended levels to aboveground vegetation in the summer of 2006. Two herbicide applications were made at each site to ensure complete mortality. Standing dead vegetation was removed from experimental plots using a handheld gasoline-powered trimmer.

Although resilience has been defined in multiple ways in the literature (Grimm and Wissel 1997), we followed Holling's (1996) protocol, where resilience is defined as the rate of recovery after disturbance (engineering resilience; Holling 1996). To measure recovery, canopy cover (percent cover) of the disturbed plots was normalized to canopy cover of the control plots through percentage recovery, which was calculated as

$$\text{Percentage recovery} = (\text{percent cover disturbed}/\text{percent cover control}) \times 100.$$

Canopy cover was measured five times (every 2–3 months) after experimental disturbances, from September 2006 to October 2007, using visual estimates of cover following the Braun-Blanquet cover scale (Mueller-Dombois and Ellenberg 1974). Percent cover estimates were performed by the same investigator (C. L. Stagg) throughout the study to reduce operator error. Based on the percent cover estimates, percentage recovery was calculated for each sampling event, and the rate of recovery (percentage recovery per month) was derived using a regression analysis with a natural log model:

$$Y = a{\cdot}\ln(t)$$

where Y is the percentage recovery, a is the slope (rate of recovery), and t is time (months).

We operationally defined stability as the ability of the vegetation to recover to within at least 95% of the disturbance control within one year. Percent cover values from the last sampling period (one year after disturbance), in disturbed and control plots, were used to determine if a plot was stable or not stable, based on whether they recovered to within 95% confidence intervals of the control plots. The likelihood of stability in the disturbed plots was described using odds ratios, which were calculated as the odds of stability (probability of being stable : probability of not being stable) for disturbed plots at each STL, compared to the odds of stability in the reference area (no sediment subsidy). This method of determining likelihood of occurrence provides a relative scale by which one can judge statistical differences between multiplicative comparisons that would otherwise exceed 100% probability (Allison 1999). The logistic model used to calculate odds ratios was derived using the Proc GENMOD procedure of SAS 9.1.2 (SAS Institute 2004).

Soil physico-chemical parameters

Several soil physical and chemical properties were measured on 12 February 2007 in Venice and on 23 February 2007 in Fourchon. Although certain soil characteristics, such as bulk density, are generally not temporally variable, other soil parameters, such as soil extractable nutrients, may vary seasonally, and thus provide a snapshot of soil status at the two study sites. A core (5 cm diameter × 10 cm long) was taken at each STL and reference replicate to measure soil bulk density, organic matter content, percentage moisture, and electrical conductivity. After collection, the cores were analyzed for wet mass, dried at 65°C, and weighed again to determine bulk density and percentage moisture. A portion of the dried soil was also used to measure electrical conductivity and organic matter content. To determine electrical conductivity, 5 g of dried soil was mixed vigorously with 30 mL of distilled water for 1 h. The mixture was then centrifuged at 2817 *g* for 5 min, and the supernatant was analyzed for electrical conductivity on a Cole Parmer 19820–00 meter (Cole Parmer, Vernon Hills, Illinois, USA). To determine organic matter content, ~2–3 g of dry soil was treated with 1 mol/L HCl until all inorganic carbonates were volatilized. The soil was then analyzed for percentage organic matter through loss on ignition at 550°C in a Fisher Isotherm combustion oven (Programmable Forced Draft Furnaces, model 10-750-126; Fisher Isotherm, Pittsburg, Pennsylvania, USA) (Nelson and Sommers 1996). A second soil core (5 cm diameter × 15 cm long) was simultaneously taken at each STL and reference replicate to measure soil pH (moist sediment), soil extractable nutrients, and other elements (NH_4-N, NO_3-N, P, Fe, K, Mg, Mn, Na, and S). The soil cores were immediately placed on ice in the field and transported back to the laboratory at Louisiana State University, Baton Rouge, Louisiana, USA. where they were homogenized. After homogenization, several soil aliquots were collected to perform the following extractions: NH_4-N and NO_3-N (2 mol/L KCl [Bremner and Kenney 1966]); P (Bray-2 [Byrnside and Sturgis 1958]); Ca, K, Mg, and Na (ammonium acetate [Thomas 1982]); and Fe and Mn (DTPA [Lindsay and Norvell 1978]). Following extraction, NH_4-N and NO_3-N samples were filtered through a 0.45-μm filter and measured on a segmented flow AutoAnalyzer (Flow Solution IV AutoAnalyzer, O-I Analytical, College Station, Texas, USA). The remaining extracts were measured with an inductively coupled argon plasma emission spectrometer (ICP) (Spectro Ciros CCE, Spectro Analytical Instruments, Kleve, Germany).

Redox potential (Eh) was measured simultaneously using bright platinum electrodes, a calomel reference electrode, and a portable Cole-Parmer digital pH-mV meter. Eh was determined by adding +244 mV, the potential of the reference electrode, to the measured millivolt reading. Three platinum electrodes were placed 15 cm below the soil surface at each STL replicate, allowed to equilibrate for one hour, and the average of the three readings was used in statistical analysis.

Additionally, a third soil core was taken to measure soil sulfide concentrations. The cores (5 cm diameter × 10 cm long) were taken from each treatment replicate and immediately placed in centrifuge tubes (500 mL) containing air-tight septa. The cores were purged with nitrogen gas for 2 min to maintain an anoxic environment, and then stored on ice. Once the cores were returned to the laboratory, they were centrifuged at 27625 m/s^2 for 20 min to extract porewater from the soil. The supernatant was decanted, stabilized with an antioxidant buffer, and analyzed for total soluble

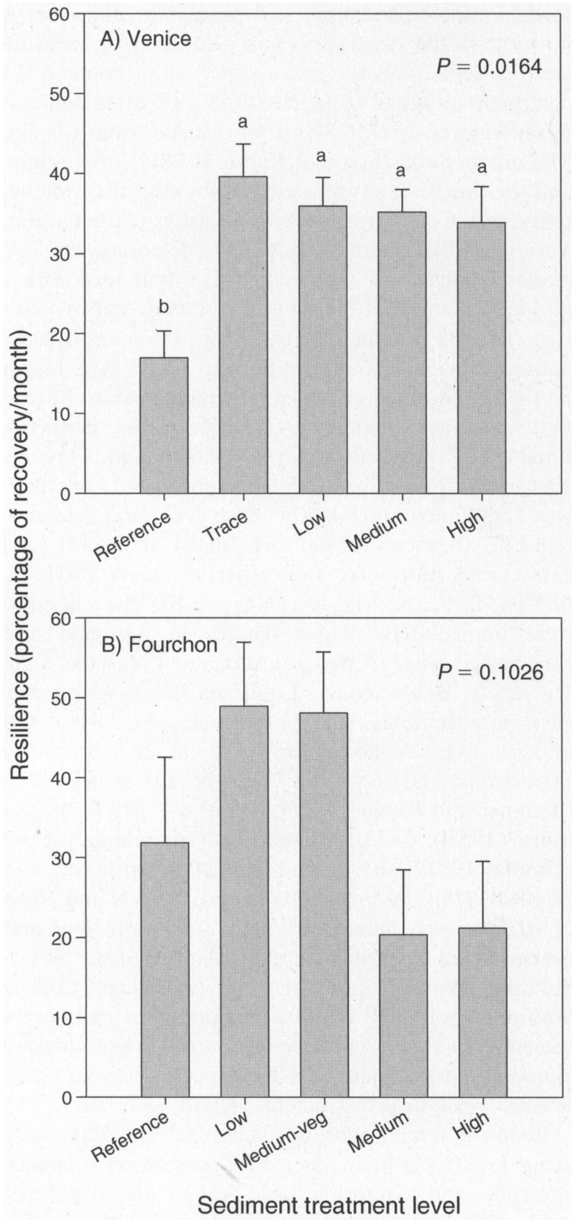

FIG. 2. Effect of sediment addition on resilience in (A) Venice and (B) Fourchon. Resilience is measured as the rate of recovery of total cover after disturbance relative to the control (percent cover disturbed/percent cover control). See *Materials and Methods* for descriptions of the sediment treatments. Error bars represent standard errors, and different lowercase letters denote significantly different means (Fisher's protected LSD, $P < 0.05$).

sulfides (Lazar Model IS-146 sulfide electrode, Lazar Research Laboratories, Los Angeles, California, USA).

Statistical analyses

Fundamental differences in experimental design between Venice and Fourchon precluded quantitative comparison between the two sites. However, similar elevations resulting from sediment addition allowed for qualitative comparisons between Venice and Fourchon. Quantitative contrasts using relevant statistical models were made within each restoration site to determine the effects of sediment addition on resilience, stability, and soil physico-chemical characteristics.

Sediment-addition treatments at the Venice study site were applied in a completely randomized design (CRD), and a randomized incomplete block design (RICBD) was used at the Fourchon study site (Fig. 1). The incomplete designation arises from the fact that not all treatment levels occurred in every replicate block. For example, the four blocks containing the sediment subsidy treatments did not contain reference treatments, and the reference blocks did not contain sediment subsidy treatments. The disturbance treatments were nested at each sediment treatment level and reference replicate, resulting in a split-plot design, where level of sediment addition was the whole plot and disturbance intensity was the split plot.

We determined how sediment subsidy and disturbance intensity affected resilience at Venice using a split-plot mixed-model ANOVA, with sediment treatment level (whole plot) and disturbance (split plot) as the fixed effects and block as the random effect. The mixed-model ANOVA used for Fourchon recovery rates was similar; however, the random effect was the block and the block × STL interaction. To determine the effect of sediment subsidy on selected soil variables, we used a one-way mixed-model ANOVA, with sediment treatment level as the fixed effect and block (Venice) or block and block × STL interaction (Fourchon) as the random effect.

For all statistical tests, normality and homogeneity of variance were determined by using the Shapiro-Wilks test, and box plots. Natural log-transformations were used to improve normality only in the PCA. Pairwise comparisons were made using Fisher's protected LSD tests. All statistical tests were performed using the MIXED procedure of SAS 9.1.2 unless otherwise noted (SAS Institute 2004).

RESULTS

Resilience

In Venice, sediment subsidy resulted in significantly higher resilience (33–39% ± 4% recovery/month) compared to the reference area, which did not receive sediment (17% ± 4% recovery/month; Fig. 2A), demonstrating that sediment addition enhances resilience. In contrast, because of high variation, the effect of sediment addition on resilience was not statistically significant at Fourchon (Fig. 2B). However, there was a tendency for resilience to be higher in areas of intermediate sediment addition (Low and Medium-veg STLs) compared to areas of more intense sediment addition and higher elevation (Medium and High STLs) and compared to the reference area. This nonlinear pattern suggests the existence of a threshold, where sediment addition resulting in elevations above 11 cm leads to decreased resilience in the newly restored marsh.

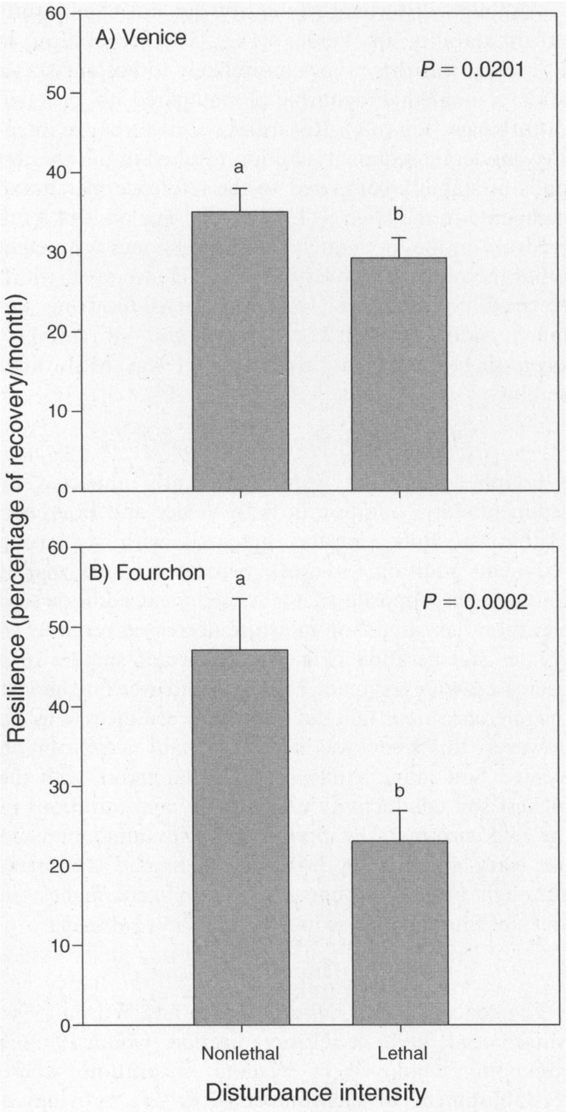

FIG. 3. Effect of disturbance intensity (nonlethal and lethal) on resilience in (A) Venice and (B) Fourchon. Resilience is measured as the rate of recovery of total cover after disturbance relative to the control (percent cover disturbed/percent cover control). Error bars represent standard errors, and different lowercase letters denote significantly different means (Fisher's protected LSD, $P < 0.05$).

In contrast, a sediment addition threshold was not apparent at the older site, Venice.

Disturbance intensity significantly influenced resilience in both the newly restored and older marshes (Fig. 3). More intense, lethal, disturbances resulted in significantly lower resilience compared to recovery of nonlethally disturbed vegetation. Although the effect of sediment addition on overall resilience did not vary with disturbance intensity (no significant interaction, Venice, $P = 0.98$; Fourchon, $P = 0.52$), recovery after lethal disturbance did appear to decrease over time in areas of high sediment addition (Venice, High STL; Fourchon, High and Medium STL) compared to intermediate STLs in both restored marshes (Fig. 4).

Stability

At both the Venice and Fourchon restoration sites, there was no significant interaction between sediment addition level and disturbance intensity (Venice, $P = 0.13$; Fourchon, $P = 0.96$). However, sediment addition did have a positive effect on *S. alterniflora* stability (Figs. 5A and 6B), with greater odds of stability occurring in areas of intermediate sediment addition compared to the reference area.

At Venice, all areas that received sediment slurries had better odds of recovering to 95% of the control within one year after disturbance (becoming stable) compared to the reference area (Fig. 5A). Odds of stability increased with increasing elevation up to the Medium

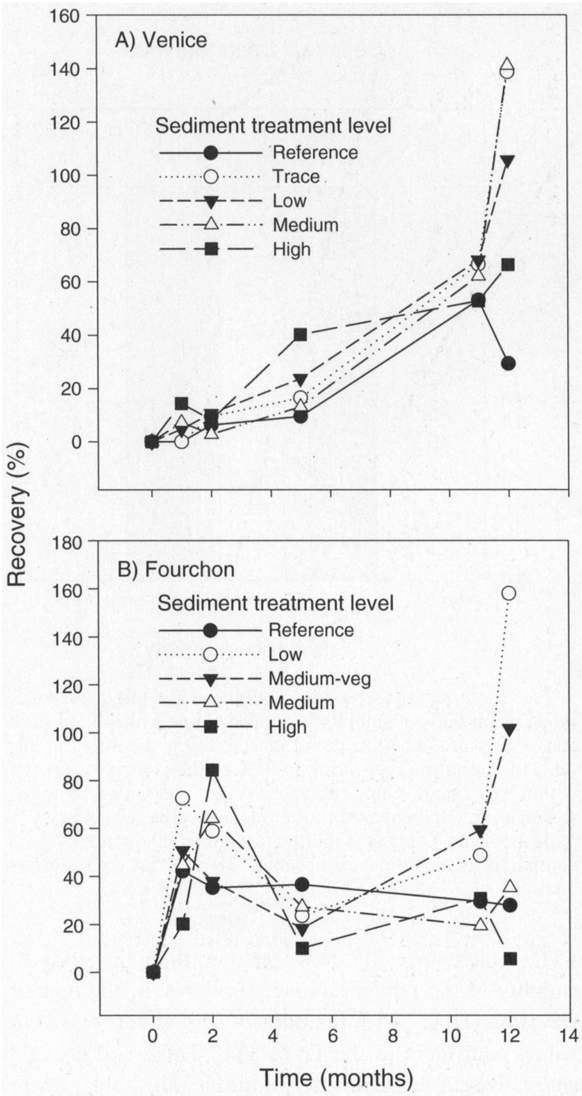

FIG. 4. Vegetation recovery (%) over time at different levels of sediment addition in (A) Venice and (B) Fourchon.

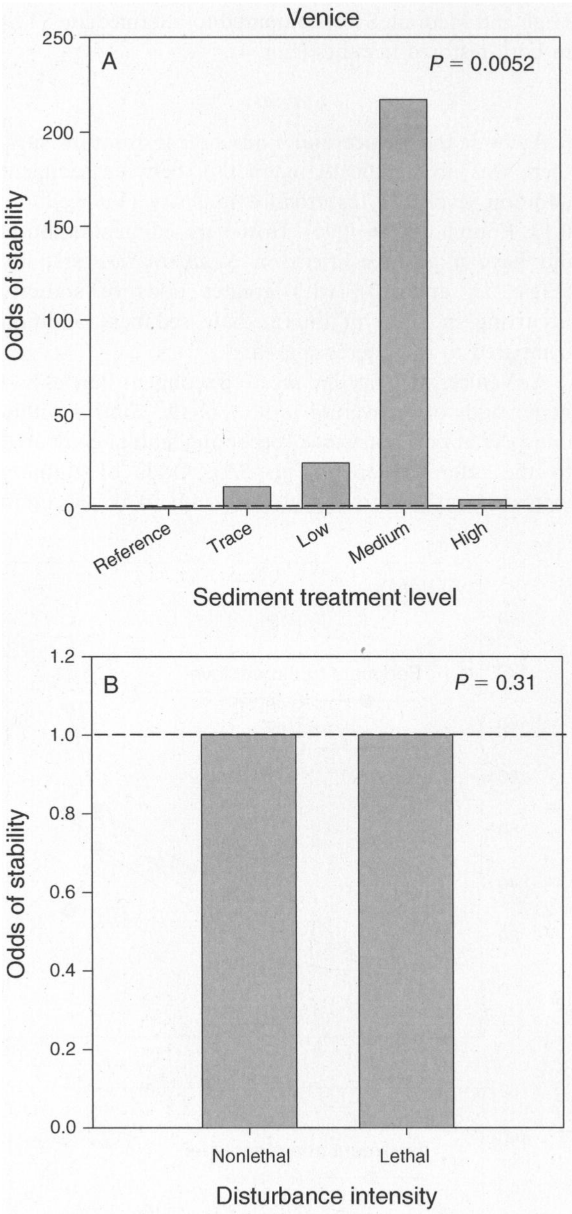

FIG. 5. Effect of (A) sediment addition and (B) disturbance intensity on odds of stability in Venice (Type 3 likelihood ratio test, $P < 0.05$). The likelihood of stability is measured as the odds of vegetation recovering to 95% of the control or greater within one year. Odds of stability in areas that received sediment are all compared to the reference area, which is set to 1 (dashed line). Odds of stability after nonlethal disturbance are compared to the lethal disturbance, which is set to 1 (dashed line).

STL, which were 217 times greater than the odds of stability in the reference zone. However, at the highest elevation (High STL), the odds of stability decreased to values equivalent to the Trace STL. This trend is again suggestive of a sediment addition threshold, where stability increases with greater elevation up to a point, above which benefits of higher elevation disappear.

Although disturbance intensity did not significantly affect stability in Venice (Fig. 5B), vegetation in Fourchon was three times more likely to become stable after a nonlethal disturbance compared to a lethal disturbance (Fig. 6A). Regardless of disturbance intensity, moderate sediment addition resulted in the greatest odds of stability compared to the reference marsh and compared to the High STL (Fig. 6B). The odds of a full recovery in the moderately subsidized zones were eight times the odds of recovery in the reference area, which received no sediment. However, areas receiving too much sediment had the lowest odds of stability, suggesting that elevations above 11 cm MSL limit stability.

Soil physico-chemical characteristics

Edaphic properties were significantly impacted by sediment slurry addition in both Venice and Fourchon (Table 2). Bulk density increased with increasing sediment addition, whereas percent organic matter followed the opposite trend. As sediment addition and elevation increased, soil moisture decreased resulting in greater soil aeration (Fig. 7). Porewater sulfides also decreased with sediment addition, and were highest in the reference areas that did not receive sediment (Fig. 8); however, this trend was not statistically significant in Venice. Soil salinity followed a similar trend, with the highest soil conductivity and sodium concentrations in the reference marshes. Soil extractable ammonium did not vary significantly with the sediment treatment, although both phosphorus and iron were highest in areas of intermediate sediment addition (Table 2).

DISCUSSION

The concept of self-design (Mitsch and Wilson 1996, Mitsch et al. 1998) or self-organization (Odum 1969) is commonly employed in wetland restoration, where reestablishment of environmental drivers provides a template for biotic recovery. However, restoration outcomes are often difficult to predict, and restoration of a primary driver may result in a system that is rather different from pre-degradation or undisturbed conditions (Seabloom and van der Valk 2003). Even successful restoration of ecological structure does not guarantee the restoration of ecological function or resilience (Zedler and Callaway 1999, Hilderbrand et al. 2005, Berumen and Pratchett 2006). Thus, it is of paramount importance that restoration success is measured by not only abiotic and structural benchmarks, but also the sustainability of the system that is maintained through ecological function and resilience. Although the self-design approach can produce unexpected outcomes in certain systems, our results indicate that careful manipulation of primary drivers to achieve the necessary physical and chemical conditions can be successful in promoting biotic recovery and resilience of salt marshes. Further, accurate manipulations can result in resilience and stability that is maintained over time.

Resilience

It is likely that intermediate levels of sediment addition (2–11 cm MSL) promoted resilience by ameliorating impacts of excessive inundation while still maintaining sufficient soil moisture. In areas of sediment addition, decreases in flood duration and frequency at higher elevations resulted in more aerated soils (Croft et al. 2006) that promote *S. alterniflora* growth (Howes et al. 1981). In contrast, low-lying and frequently flooded soils displayed low redox potentials, resulting in the accumulation of sulfide (Patrick and DeLaune 1972, Linthurst 1980, Mendelssohn and McKee 1988), which has been directly linked to inhibited growth and mortality of *S. alterniflora* (Mendelssohn et al. 1981, Bradley and Dunn 1989, Koch and Mendelssohn 1989).

However, not all sediment-subsidized areas had equivalent resilience in the newly restored site (Fourchon), and recovery rate was limited above a sediment addition threshold (Edwards and Mills 2005). Like resilience at the older Venice site, resilience at Fourchon was negatively associated with edaphic conditions typical of water-logged soils, which appeared to be ameliorated with increasing elevation. However, above the threshold a severe drop in soil moisture may have limited recovery in areas of high elevation and low flood frequency (Naidoo et al. 1992, Brown and Pezeshki 2007, Schrift et al. 2008). Although *S. alterniflora* responds positively to well-drained soils in the field (King et al. 1982), experimental evidence from greenhouse studies shows that production of *S. alterniflora* is better under flooded conditions when phytotoxic sulfides are not present (Mendelssohn and Seneca 1980). In addition, significant decreases in phosphorus, compared to the regularly flooded marshes, may have also limited recovery at the Medium and High STLs (Edwards and Mills 2005). The fact that the older site, Venice, did not show this limitation at high levels of sediment addition may be due to higher soil ammonium concentrations in sediment treatments compared to the Fourchon sediment slurries (Mendelssohn and Kuhn 2003), emphasizing the importance of sediment source and quality for restoration managers.

Stability

Stability at both Venice and Fourchon also increased with sediment subsidy. The relationship between sediment addition and stability is not linear; however, and both sites show an elevation threshold (Clements et al. 2010). At Fourchon, the threshold pattern for stability agrees with the pattern observed for resilience; therefore, stability is likely influenced by the same parameters that limit resilience at high elevations: insufficient flooding and low soil nutrient availability. However, the nonlinear stability pattern at Venice is interesting, because resilience did not show a threshold pattern in Venice, but stability did, indicating that stability is more sensitive to sediment addition than resilience.

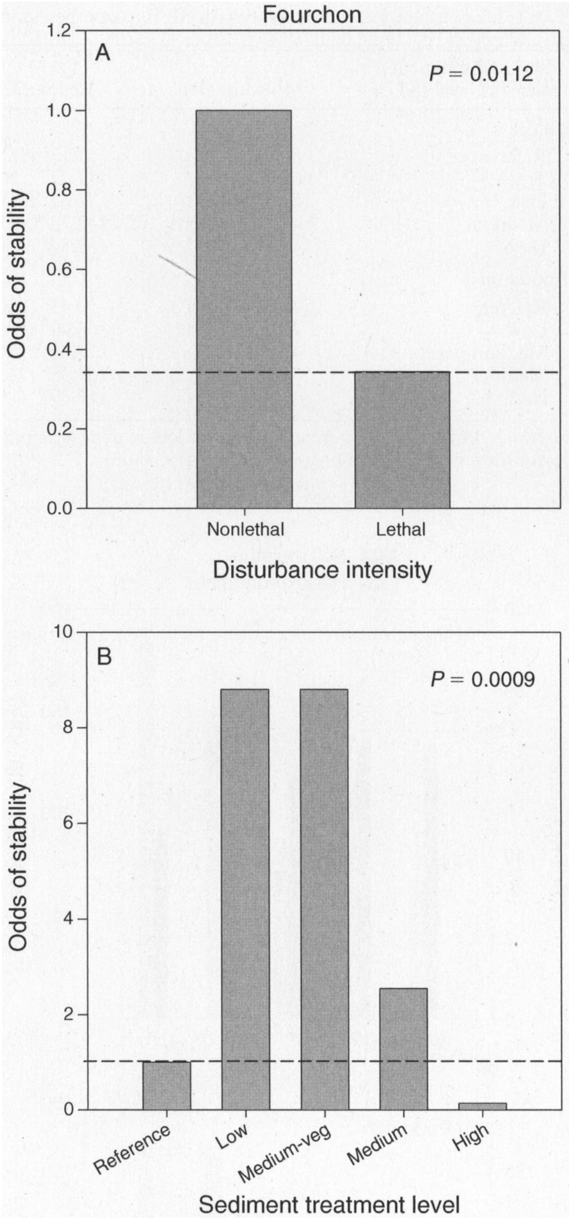

FIG. 6. Effect of (A) disturbance intensity and (B) sediment addition on odds of stability in Fourchon (Type 3 likelihood ratio test, $P < 0.05$). The likelihood of stability is measured as the odds of vegetation recovering to 95% of the control or greater within one year. Odds of stability after nonlethal disturbance are compared to the lethal disturbance, which is set to 1 (dashed line). Odds of stability in areas that received sediment are all compared to the reference area, which is set to 1 (dashed line).

This trend may be explained by the differential effect of disturbance intensity on soil nutrient content. Specifically, recovery rates after lethal disturbance may have been stimulated by a nutrient release after plant mortality (McKee et al. 2004), which would have masked the deleterious effects of low soil moisture at the High STL. However, these nutrient pulses tend to be

TABLE 2. Selected soil parameters (with SE in parentheses) in sediment-treated and reference marshes in Venice and Fourchon.

Site and sediment treatment level (STL)	Moisture (%)	Redox (mV)	Bulk density (g/cm^3)	Organic matter (%)	Conductivity (mS)
Venice					
Reference	66.95^{a} (1.00)	67.13^{c} (28.82)	0.45^{c} (0.02)	12.47^{a} (0.85)	10.70^{a} (0.44)
Trace	67.90^{a} (2.38)	117.13^{bc} (20.06)	0.42^{c} (0.04)	11.85^{a} (1.29)	11.29^{a} (0.95)
Low	59.00^{b} (2.69)	71.67^{c} (9.34)	0.59^{b} (0.06)	7.64^{b} (0.72)	8.57^{b} (0.68)
Medium	44.48^{c} (0.72)	142.33^{ab} (31.05)	0.90^{a} (0.03)	4.23^{c} (0.42)	4.04^{c} (0.32)
High	45.97^{c} (2.60)	182.87^{a} (7.48)	0.81^{a} (0.07)	5.44^{bc} (1.16)	3.56^{c} (0.41)
Fourchon					
Reference	76.78^{a} (1.57)	−50.43^{c} (12.45)	0.27^{c} (0.02)	22.58^{a} (1.60)	33.62^{a} (2.28)
Low	44.56^{b} (1.44)	68.09^{b} (18.58)	0.89^{b} (0.04)	7.42^{b} (0.51)	11.07^{b} (0.63)
Medium vegetated	47.34^{b} (2.15)	77.50^{ab} (29.32)	0.84^{b} (0.05)	8.14^{b} (1.06)	11.56^{b} (0.60)
Medium	36.68^{c} (1.53)	159.38^{a} (21.90)	1.09^{a} (0.03)	6.45^{b} (0.40)	11.01^{b} (0.59)
High	32.83^{c} (0.86)	147.39^{ab} (15.61)	1.167^{a} (0.02)	5.66^{b} (0.26)	11.98^{b} (0.63)

Notes: Values with different superscript letters denote significantly different means among STLs within parameter columns and restoration site (Fisher's protected LSD, $P < 0.05$).

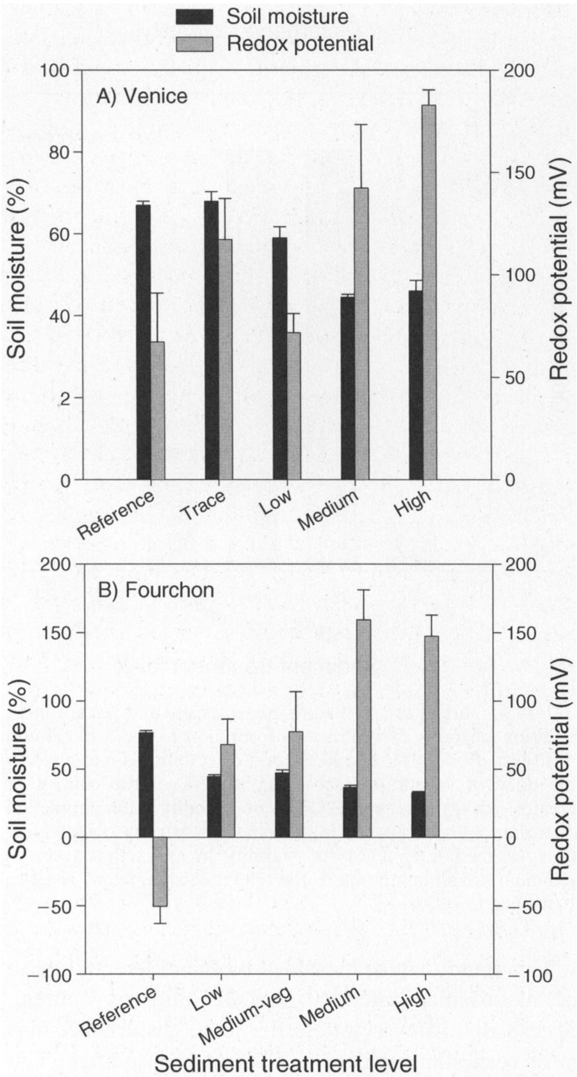

FIG. 7. Effect of sediment addition on soil moisture and redox potential in (A) Venice and (B) Fourchon. Error bars represent standard errors.

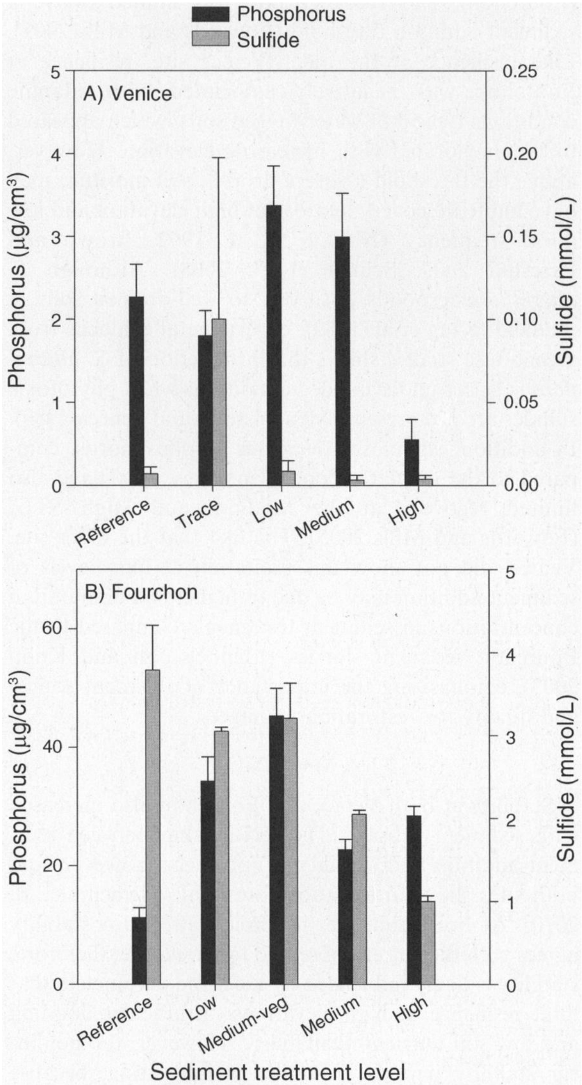

FIG. 8. Effect of sediment addition on soil extractable phosphorus and porewater sulfide in (A) Venice and (B) Fourchon. Error bars represent standard errors.

TABLE 2. Extended.

Sodium (μg/cm^3)	Ammonium (μg/cm^3)	Phosphorus (μg/cm^3)	Iron (μg/cm^3)	Manganese (μg/cm^3)	Sulfide (mmol/L)
3071.40[b] (176.29)	17.65[a] (5.77)	2.27[ab] (0.40)	38.21[bc] (2.56)	418.48[b] (4.66)	0.007[a] (0.004)
3411.80[b] (212.83)	14.20[a] (3.61)	1.80[b] (0.30)	54.46[b] (5.31)	459.38[b] (26.14)	0.100[a] (0.098)
4249.80[a] (160.54)	20.81[a] (9.16)	3.37[a] (0.48)	104.08[a] (9.70)	560.74[a] (39.16)	0.008[a] (0.006)
3962.20[a] (130.65)	28.70[a] (9.53)	2.99[a] (0.53)	108.6[a] (10.08)	550.4[a] (11.60)	0.003[a] (0.003)
2540.60[c] (126.60)	26.83[a] (3.563)	0.55[c] (0.25)	31.40[c] (7.15)	426.96[b] (22.87)	0.004[a] (0.002)
8917.77[a] (281.69)	4.01[a] (1.29)	11.27[c] (1.66)	76.64[b] (10.52)	1.89[b] (0.44)	3.789[a] (0.538)
5988.12[b] (413.42)	1.83[a] (0.45)	34.28[ab] (4.12)	282.59[a] (21.88)	47.21[b] (5.05)	3.05[a] (0.050)
7046.27[ab] (328.17)	2.05[a] (0.36)	45.31[a] (4.67)	263.99[a] (28.15)	37.25[ab] (11.28)	3.208[a] (0.423)
8356.43[a] (637.72)	1.86[a] (0.52)	22.71[bc] (1.77)	130.70[b] (14.41)	39.06[ab] (8.22)	2.05[b] (0.050)
7559.71[ab] (805.63)	2.04[a] (0.26)	28.44[bc] (1.61)	96.98[b] (12.54)	35.23[ab] (9.15)	1.00[c] (0.069)

short lived (McKee et al. 2004, Slocum and Mendelssohn 2008), and because stability shows that vegetation in the High STL is less likely to make a full recovery within one year, it is probable that the initial release of nutrients after plant mortality was not sufficient to sustain high recovery rates to reach full stability. This theory is supported by the recovery trends we observed after lethal disturbances, specifically, a decline in recovery after an initial spike in areas of high sediment addition. In contrast, recovery in areas of intermediate sediment addition was constant or increased over time. Thus, the stability data reveals that a threshold still exists 15 years after sediment addition, and elevations above 11 cm MSL are less stable than intermediate elevations. This finding further emphasizes the importance of measuring multiple indices to determine restoration success (Rapport et al. 1998).

Although direct quantitative comparison between the older and younger site is limited in this study, the difference in scale between the stability response in Venice and Fourchon deserves mention. The odds of stability, i.e., the odds of recovery after a disturbance, are an order of magnitude higher in the older site (Venice) compared to the younger site (Fourchon), which may reflect greater stability in the older restored marsh. This indicates that these restored sites become more stable over time, which is not unreasonable given that it may take years for a restored marsh to develop the complex soil–plant interactions of a mature natural marsh (Craft et al. 2003). Investigations of ecosystem resilience and stability over time in different restored ecosystems are needed to test this hypothesis to better understand stability trajectories in restored systems.

Conclusions and implications

These results support our hypothesis that sediment addition increases resilience and stability compared to natural unsubsidized marshes. However, addition of too much sediment can result in low resilience and stability. The sediment addition threshold appears to occur at elevations greater than 11 cm MSL, thereby surpassing the intertidal position of *S. alterniflora* and negating the benefits of increased elevation. The use of sediment addition to increase the relative elevation of the marsh to intermediate elevations (2–11 cm MSL) effectively reduced the stress of prolonged inundation and optimized resilience and stability through increasing soil aeration, and decreasing phytotoxic sulfide concentrations. Additionally, intermediate sediment addition treatments in the 15-year old site had similar resilience and stability to the five-year old site, indicating that moderate sediment subsidy resulting in intermediate elevations is a sustainable restoration technique.

It must be emphasized that any coastal restoration approaches have to be planned in the context of global climate change and subsequent increases in sea level that will be observed in the future. This study shows that sediment slurry addition resulting in elevations between 2 and 11 cm MSL enhances resilience of subsiding marshes, and that even under a regime of relatively high sea-level rise (1.04–1.19 cm/yr; Penland and Ramsey 1990), resilience is still maintained 15 years after restoration. However, at extreme rates of sea-level rise (up to 2.0 m by 2100; Copenhagen Diagnosis 2009), this method along with others will be seriously challenged. In addition to higher sea levels, predicted increases in hurricane intensity (Hoyos et al. 2006, Elsner et al. 2008) may influence natural sediment dynamics, resulting in erosion (Stone et al. 1997) or deposition (McKee and Cherry 2009), requiring adaptive management of these systems in order to maintain optimal elevations.

Given the likelihood of accelerated sea-level rise and more intense storms, we caution against the temptation to increase surface elevations above the optimum elevation in an attempt to avoid the need for future applications. Although this study indicates that areas of excessive sediment addition will eventually subside and reach suitable elevations for resilience, the precise addition of sediment resulting in elevations between 2 and 11 cm above MSL provides a resilient system almost immediately (five years), in comparison to waiting 15 years for the high STLs to reach functional equivalency. Furthermore, stability in the High STL was still less than optimal 15 years after restoration, indicating that it

PLATE 1. Experimental plots two weeks after disturbance applications in a Venice, Louisiana, USA, reference marsh. Photo credit: C. L. Stagg.

would be an even longer time span between the initial restoration effort and a stable, functioning system (Morgan and Short 2002).

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