BROWN MARSH TASK 5.4: FACTORS CONTROLLING THE RESTORATION OF BROWN MARSH SITES WITH SMALL DREDGE ENRICHMENT

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ABSTRACT

During the spring of 2000, a large, severe disturbance known as the "brown marsh phenomenon" caused a massive dieback of *Spartina alterniflora*, the dominant salt marsh plant in Louisiana. We sought to restore the rapidly subsiding marshes denuded by the dieback by reducing waterlogging stress via the addition of a sediment-slurry (dredged material with a high water to sediment ratio). We examined how the following five treatment-levels, which were created by addition of the sediment-slurry onto marshes denuded by the dieback of 2000, affected initial plant recruitment: high (28 - 36 cm above ambient marsh), medium (20 - 25 cm), and low (13 -18 cm) elevations, vegetated (areas revegetated by fall 2003) and pop-up (highly organic sections of the original substrate that detached during slurry application and settled on top of the sediment-slurry). We compared the treatment-levels to reference healthy marsh sites that were unaffected by the dieback and to reference brown marsh sites, which were denuded as a result of the dieback event. We measured (fall 2003, spring 2004, and fall 2004) plant recovery and soil physico-chemical characteristics following the sediment-slurry application. By fall 2004, the vegetated (98 %), pop-up (100 %), and low (84 %) treatment-levels had plant cover equivalent to the reference healthy marsh sites (92 %). The reference brown marsh sites had minimal vegetation cover (8 %) equivalent to the high treatment-level (12 %) while the medium elevation (29 %) had marginal vegetation cover. Low elevation, high percent time flooded, and high sulfide concentrations could explain the low recovery rate in the reference brown marsh sites. In contrast, optimal time flooded (as seen in the low elevation), the presence of viable rhizomes (vegetated treatment-level), and a high elevation concurrent with high organic matter and moisture (pop-up treatment-level) could explain rapid plant colonization at the study site. To increase the rate of recovery in a denuded, rapidly subsiding salt marsh, elevation should be

raised approximately 18 cm above ambient healthy marsh. The presence of viable rhizomes and/or a high percentage of organic matter in the soil can promote a more rapid recovery

INTRODUCTION

Disturbance drives the structure of many ecosystems (Foster et al. 1998, Turner et al. 2003, Walker and Del Moral 2003, Callaway 2005, Nieuwstadt and Sheil 2005). The severity of some disturbances can drastically alter the landscape and cause primary or secondary succession to be reinitiated. For example, the eruption of Mount St. Helens in 1980 violently impacted the adjacent volcanic plain with searing blasts and pumice and tephra deposits. This disturbance was so severe that all plant life was effaced and seven years later only a few plants had recolonized the area (Del Moral and Wood 1993). Although, succession on denuded landscapes has been extensively investigated (Del Moral and Wood 1993, Shumway 1994, Allison 1996), ecological trajectories are still difficult to accurately predict, in part, because plant recruitment is often dependent on stochastic processes (Del Moral and Wood 1993).

During the spring and summer of 2000, a record drought in the northern Gulf of Mexico caused a severe, large-scale disturbance of coastal salt marshes. This event, known as the "brown marsh phenomenon," resulted in the sudden dieback of large expanses of *Spartina alterniflora* dominated salt marshes (hereafter referred to as "brown marshes") (McKee et al. 2004) within the Mississippi River Deltaic Plain (MRDP), Louisiana. Approximately 28% (44,500 ha) of intertidal salt marshes in southeast Louisiana were severely affected by the brown marsh event (http://www.brownmarsh.net/qa.htm). Although some salt marshes did revegetate, many became mudflats and are still devoid of vegetation (I. A. Mendelssohn, personal observation). The loss of live plant material from the substrate can lead to soil compaction and marsh subsidence as plant roots collapse and organic material in the soil decomposes (DeLaune et al. 1994). Unvegetated mudflats may convert to shallow ponds as the marsh surface further subsides and erodes.

An understanding of how disturbances control succession is a pre-requisite to successful restoration of disturbed ecosystems. A plethora of research has been conducted on disturbances (Pennings and Richards 1998, Brinson and Christian 1999, Vankvik 2004) resulting in the development of assembly rules that predict plant succession subsequent to small patch formation (Wu and Levin 1994, Gutzerova and Herben 2001, Platt and Connell 2003). However, these assembly rules do not often apply to patches created from large, severe disturbances (Turner and Dale 1998). Although there has been some research on plant reestablishment following large, severe disturbances (Turner and Dale 1998), the low frequency of mega-disturbances has prevented detailed research in a variety of ecosystems. To my knowledge, there have been no studies of primary or secondary succession following a sudden, large-scale, severe disturbance in a salt marsh. The size and severity of the brown marsh event of 2000 provided the opportunity to evaluate effects of a mega-disturbance, to quantify primary and secondary succession, and to assess the restoration potential of mudflats created by the die-off.

Because wetlands in the MRDP are rapidly subsiding and subsidence rates were likely accelerated at dieback sites by the brown marsh event (DeLaune et al. 1994), the hydraulic application of sediment-slurries, a relatively new wetland restoration technique (Closure Report: Initial Funding Allocation, DNR Dedicated Dredging Program (LA-1) 2000, Mendelssohn and Kuhn 2003, Slocum et al. 2005), was tested in this research to increase mudflat elevation and to stimulate restoration. This restoration technique utilizes low-pressure hydraulic dredging to disperse sediments long distances (ca. 900 m) from the discharge pipe (Cheramie et al. 1995, Slocum et al. 2005). We used the new application technique to test how different levels of sediment addition effect plant recruitment, vegetation recovery, and successional trajectories.

Although the cause of the brown marsh event has not been unequivocally identified (McKee et al. 2004), the brown marsh event provided the unique opportunity to determine if a sediment-slurry subsidy could rehabilitate these degraded marshes, located in a region with very high rates of relative sea-level rise (Penland and Ramsey 1990). The objective of this study was to determine if the new application technique and the resultant sediment-slurries could create a substrate and a suitable elevation that would allow successful restoration of the brown marsh sites. We investigated how initial plant recruitment differed between an experimental area that received the sediment-slurry amendment and adjacent reference areas that did not receive any additional sediment. In addition, soil physico-chemical properties were measured to evaluate their control on plant recolonization and vegetation recovery. We sought to answer the following questions: (1) What hydro-edaphic factors control vegetation recruitment and recovery, with and without sediment amendments, after sudden marsh dieback? and (2) Do sediment-slurry amendments accelerate vegetation restoration? If so, is the speed of recovery directly related to the degree of sediment addition?

METHODOLOGY

Site description

The study site is in a rapidly subsiding salt marsh located within the Terrebonne Basin and is part of the Mississippi River Deltaic Plain (MRDP). A reduction of sediment input resulting from a combination of delta lobe switching, canal construction, hydrologic alterations, and artificial levees (Day et al. 1993) have resulted in high rates of relative sea level rise (1.11cm/yr, 1947-1986, (Penland and Ramsey 1990). The diminished sediment supply, a result of human alterations and natural processes, has reduced the capacity of the marsh to keep pace with relative sea-level rise (a combination of eustacy and isostacy) (Penland et al. 1990). This process has facilitated high rates of land loss ranging from 65 to 91 square kilometers of land each year (Coast 2050: Toward a Sustainable Coastal Louisiana 1998).

The specific study site is located within a salt marsh approximately 5.5 kilometers southwest of Leeville, LA adjacent to the west bank of Bayou Lafourche at 29º 11.17'N and 90º 14.23'W. Soils are characterized as a scatlake muck, which is a semifluid, mineral soil that is frequently flooded with salt water (Matthews 1984). Vegetation in reference healthy areas is dominated by *Spartina alterniflora* and is sparsely interspersed with *Salicornia virginica*. Large expanses of vegetation within the study site were denuded by the dieback event of 2000 and remained unvegetated while other areas remained unaffected by the dieback event (McKee et al. 2004). See Figure 1 *Study Site Location*, for additional location information.

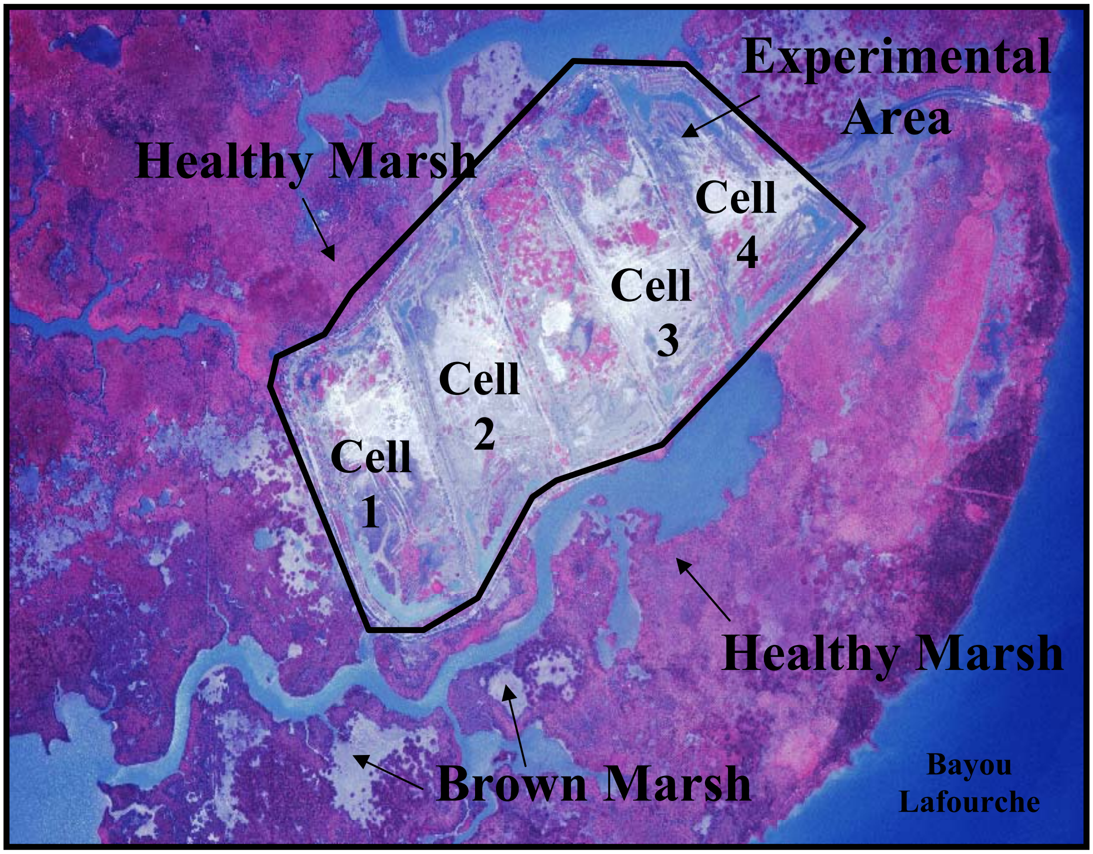

FIGURE 1 – Study site location - the geographical relationship between the experimental area (cells 1, 2, 3, and 4) and the reference area (brown marshes and healthy marshes)

Experimental Design

The study site was divided into an experimental area and a reference area. The experimental area consisted of a salt marsh that died as a result of the brown marsh event of 2000. The impacted marsh was divided into five cells, described below, and each cell independently received hydraulically dredged material from Bayou Lafourche in the form of a sediment-slurry. The sediment-slurry was approximately 20-30 % solids and 70-80 % water by volume (Brian Kendrick, personal communication, Morris P. Hebert, Inc., Houma, LA 2005). The experimental area was bordered and divided into five cells by small earthen levees, four of which were used in this research as statistical blocks. The cells provided replicated brown marshes that independently received sediment-slurry amendments and containment of the sediment-slurry. Five different conditions were created by the application of the sediment-slurry and were used as treatment-levels: 1) Low elevation: 13-18 cm above ambient healthy marsh and unvegetated in the fall of 2003; 2) Medium elevation: 20-25 cm above ambient healthy marsh and unvegetated in the fall of 2003; 3) High elevation: 28-36 cm above ambient healthy marsh and unvegetated in the fall of 2003; 4) Vegetated: areas with 100 % vegetative cover in the fall of 2003 with an average elevation of 20 cm above ambient healthy marsh; 5) Pop-up: portions of the original substrate consisting of a thick root and rhizome mat which, separated from the underlying substrate, became buoyant, and settled on top of the sediment-slurry amendment resulting in an average elevation of 36 cm above ambient healthy marsh. The formation of pop-ups during the application of the sediment-slurry is a common occurrence when sediment-slurries are added to a confined site (Brian Kendrick, personal communication). High, medium, low elevation and vegetated treatment-levels were identified in each of the four cells while the pop-up treatment-level occurred in two cells. Ten sampling transects, 2.75 m in length were established within each high, medium, and low elevation area. In each vegetated area, we established seven sampling transects, 2.75m in length. Each pop-up area had ten sampling transects, 2.00 m in length for a total of 168 haphazardly placed, experimental sampling transects.

To assess the effectiveness of the sediment-slurry amendment, we compared the experimental area with two different types of reference marshes, which did not receive the sediment-slurry amendment: 1) Healthy marsh: unaffected by the brown marsh event of 2000 and dominated by *Spartina alterniflora* and interspersed with *Salicornia virginica*; 2) Brown marsh: denuded as a result of the brown marsh event of 2000 and remained unvegetated in the fall of 2003. The two healthy marsh sites and the two brown marsh sites were located adjacent to the experimental area to minimize spatial variability. Within each reference marsh we haphazardly established, ten sampling transects, 2.75m in length, for a total of 40 reference sampling transects.

Elevation and Hydrological Measurements

We used a laser level (Sokkia LP30) to determine elevation in both the experimental and reference areas. Elevation measurements were referenced to the average elevation of the healthy marshes as determined in the spring of 2003 and tied into a temporary benchmark. At least two measurements were taken at each transect to determine an average elevation during the summer of 2004. Sediment-slurry thickness was determined by measuring from the marsh surface (top of the sediment-slurry layer) to the top of the former substrate (bottom of the sediment-slurry layer). The top of the former substrate was easily identifiable because the former marsh surface was highly organic. A YSI water sonde was installed during August of 2004 in a bayou adjacent to the study site to record the water depth from August 2004 until December 2004.

Plant and Soil Physico-Chemical Measurements

We analyzed vegetation parameters during the fall of 2003, spring of 2004, and fall of 2004 to assess initial plant recovery. Stem density was measured within a 0.1 m^2 quadrat at five randomly chosen points along each transect for all treatment-levels except pop-ups. The short transect length on pop-ups forced us to systematically select five sampling points to avoid overlapping quadrats. Stem density (stems/m^2) was calculated by summing the stem counts from the five sampling points and multiplying by two. Frequency of occurrence was calculated by dividing the number of times species A intersected one of ten fixed points along each transect by the total number of fixed points on a transect. Percent of unvegetated transect was calculated by dividing the total length of the transect that was devoid of vegetation by total transect length and multiplying by 100. Plant cover was then calculated by subtracting the percent of unvegetated transect from 100. The influence of each species within a treatment-level/marsh type was rated with an importance value. To calculate the importance value, we first determined species cover by dividing the total distance species A covered the transect by total transect length and multiplying by 100. Relative species cover was then calculated by dividing the cover of species A by the total cover of all species and multiplying by 100. Next, we determined relative frequency by dividing the frequency of species A by the frequency of all species and multiplying by 100. Finally, we determined relative density by dividing the density of species A by the density of all species and multiplying by 100. Once these three relative values were determined, we added relative species cover, relative frequency, and relative density together to determine the importance value. Because we added three relative values together, which separately had a maximum value of 100, the maximum importance value was 300.

Several soil physico-chemical variables were measured during each sampling period (fall of 2003, spring of 2004, and fall of 2004). Two adjacent soil cores were taken at a haphazardly chosen location along each transect. At the time of soil coring, we used three bright platinum electrodes and a calomel reference electrode to measure redox potential at 15 cm depth along each transect. An average of the three readings was used for statistical analysis. The smaller soil core (5 cm in diameter x 10 cm in length) was used to determine bulk density, organic matter, percent moisture, electrical conductivity, and particle size. Once the core was taken, it was placed in a Ziplock bag and transported it to the laboratory. The core was then weighed, placed in a drying oven at 65 °C until a constant weight was reached, and weighed again to determine dry bulk density and percent moisture. Electrical conductivity was determined by shaking 5 grams of dry soil with 30 mL of distilled water for one hour in a centrifuge tube, which was subsequently centrifuged (6000 rpm for five minutes), decanted, and measured for electrical conductivity (Cole Parmer 19820-00). To determine organic matter content, approximately 2-3 grams of dry soil was treated with 1N HCl until all of the inorganic carbonates were volatilized. The soil was then analyzed for percent organic matter using the loss on ignition method (Nelson and Sommers 1996). The remaining portion of the cores were consolidated, homogenized, and analyzed for particle size using the pipet method (Soil Survey Laboratory Investigations Manual 2004). Once collected, the second soil core (5 cm in diameter x 15 cm in length) was immediately put in a Ziplock bag and placed on ice. Once in the laboratory, the soil core was homogenized and analyzed for pH and extractable NH_4-N, NO_3-N, P, and exchangeable Ca, Mg, K, Na, Fe, Mn, Cu, and Zn. Soil extractions were used to derive the following elements: NH_4-N and NO_3-N using 2 M KCl (Bremner and Kenney 1966); P using Bray-2 (Byrnside and Sturgis 1958); Ca, Mg, K, Na using ammonium acetate (Thomas 1982); Fe, Mn, Cu, Zn using DTPA (Lindsay and Norvell 1978). Following extraction, NH_4-N and NO_3-N samples were filtered through a 0.45 µm syringe filter and were measured using a segmented flow O-I Auto Analyzer. NH_4-N + NO_3-N was calculated by summing NH_4-N and NO_3-N. The remaining extracts were measured with a Spectro Ciros inductively coupled argon plasma emission spectrometer (ICP). During the fall of 2004, an additional soil core (2 cm in diameter x 10 cm in length) was taken adjacent to the other two cores to measure interstitial sulfide concentration. The soil core was immediately placed in an air-tight centrifuge tube with a septum cap, purged with N_2 for a minute, and placed on ice. In the laboratory, these samples were centrifuged at 6000 rpm for ten minutes. The interstitial water was immediately decanted, placed into an antioxidant buffer, and analyzed for total soluble sulfide (Sulfide electrode model DJM-146, Lazar Research Laboratories, Los Angeles, CA, USA).

Statistical Methods

Because the experimental design for the experimental area was different from that of the reference area, the data from the two designs were analyzed separately with different models. The experimental area, which was bordered and divided into 5 cells (only 4 cells were utilized in this study) via earthen levees, was analyzed as a randomized block design with the cells serving as statistical blocks. The reference area, which did not contain levees, was analyzed as a nested completely randomized design. We analyzed the vegetative and soil physico-chemical data from the experimental area and reference area with separate one-way ANOVAs using the PROC MIXED procedure of SAS version 9.0 (SAS Institute 1990). In the experimental area, we tested the effect of treatment-level, time, and the treatment-level by time interaction. In the reference area, we tested the effect of marsh type, time, and the marsh type by time interaction. Model residuals were tested for normality (Shapiro-Wilks test) and homogeneity of variance (plot of residuals). Where necessary, log, natural log, arc-sine root, square, and square-root transformations were used to improve normality and homogeneity of variance.

The dimensionality of the experimental and reference soil data sets was reduced by a Principal Components Analysis (PCA) using the FACTOR procedure of SAS version 9.0 (SAS Institute 1990) with a varimax rotation. First, we combined the experimental and reference datasets to run the PCA. Following the PCA, we separated the data back into the experimental and reference datasets and then analyzed the principal components with one-way ANOVAs to determine the effect of treatment-level/marsh type, time, and the treatment-level/marsh type by time interaction on the soil principal components. Elevation, which was measured during one sampling period, was assumed to remain constant over time and was included in the PCA. Since organic matter was only measured during one sampling period, values for the missing sampling periods were estimated through a regression with bulk density and included in the PCA. Conversely, soil variables with high temporal variability that were not measured during all sampling periods, such as NH_4-N, and NH_4-N + NO_3-N, were analyzed separately, and not included in the PCA of the soil data.

Soil physico-chemical variables were analyzed separately with a MANOVA using the PROC GLM procedure of SAS version 9.0 (SAS Institute 1990). Highly significant effects for treatment level/marsh type, time, and treatment level/marsh type by time interactions (experimental area: $p < 0.0001$, $p < 0.0001$, $p < 0.0001$; reference area: $p = 0.0001$, $p < 0.0001$, p

< 0.0001, respectively) enabled us to use univariate ANOVAs to analyze the individual soil environmental variables in both the experimental and reference areas.

Differences between treatment-levels/marsh types, time periods, and treatment-levels/marsh types by time interactions were tested with post-hoc, Tukey-adjusted pairwise comparisons. All tests of significance used an alpha level of 0.05 unless otherwise stated. Least-square means and confidence intervals are reported and graphed in their original units. The data from the experimental and reference areas were compared using 95 % confidence intervals. In addition, relationships between variables were analyzed with a correlation analysis using the PROC CORR procedure of SAS version 9.0 (SAS Institute 1990).

RESULTS

Vegetation Parameters

Vegetation in the experimental area showed a positive response to the slurry addition (Fig. 2). The extent of vegetation development over time was dependent on the sediment-slurry treatment-level (treatment-level by time interaction, $p < 0.0001$; Fig. 2). The low elevation and pop-up treatment-level had significant increases in plant cover over time while the high, medium, and vegetated treatment-levels did not demonstrate increases in recovery during the study period. By the fall of 2004, three of the five treatment-levels (low elevation, vegetated, and pop-up) had plant cover equal to that of the healthy reference marshes. In contrast, the reference brown marsh sites, which received no sediment-slurry additions, showed minimal plant cover, i.e., recovery (Fig. 2). The high elevation treatment-level had as little plant cover as the reference brown marsh sites. The medium elevation treatment-level had in an intermediate degree of plant cover, which was significantly more than the reference brown marsh sites (92 % confidence interval, Fig. 2).

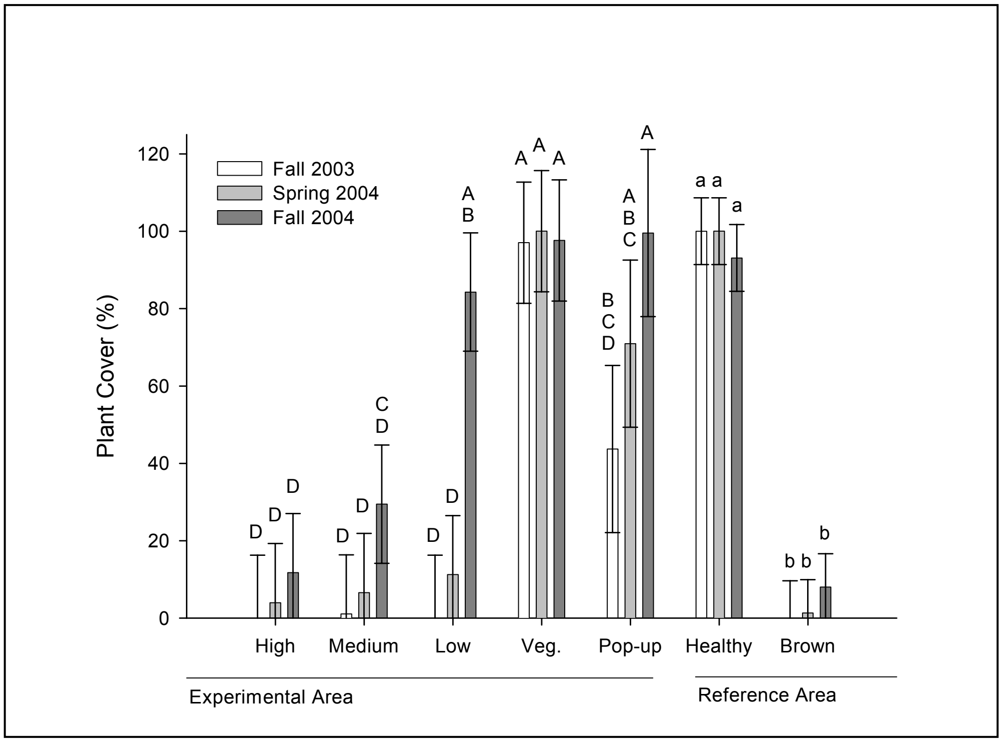

FIGURE 2 – Percent vegetative cover (live and dead) over time in sediment-amended and reference marshes (least-square mean with 95% confidence intervals) following sediment slurry addition in 2002. The same letters indicate no significant differences between treatment means within either the experimental or reference areas ($p < 0.05$). Non-overlapping confidence intervals identify significant differences between experimental and the reference areas.

Species richness, like plant cover, increased with recovery duration, but this increase significantly differed with sediment-slurry treatment-level (significant treatment-level by time interaction, $p < 0.0001$, Fig. 3). Species richness in the medium, low, and pop-up treatment-levels increased over time while species richness in the high and vegetated treatment-levels remained constant. Species richness in the medium and low elevation, vegetated, and pop-up treatment-levels was equal to that of the reference healthy marsh sites by the spring of 2004 (Fig. 3). Conversely, low species richness occurred in the high elevation treatment-level and reference brown marsh sites almost two years after the sediment-slurry addition (Fig. 3). The pop-up treatment-level had the highest species richness (Table 1, Fig. 3).

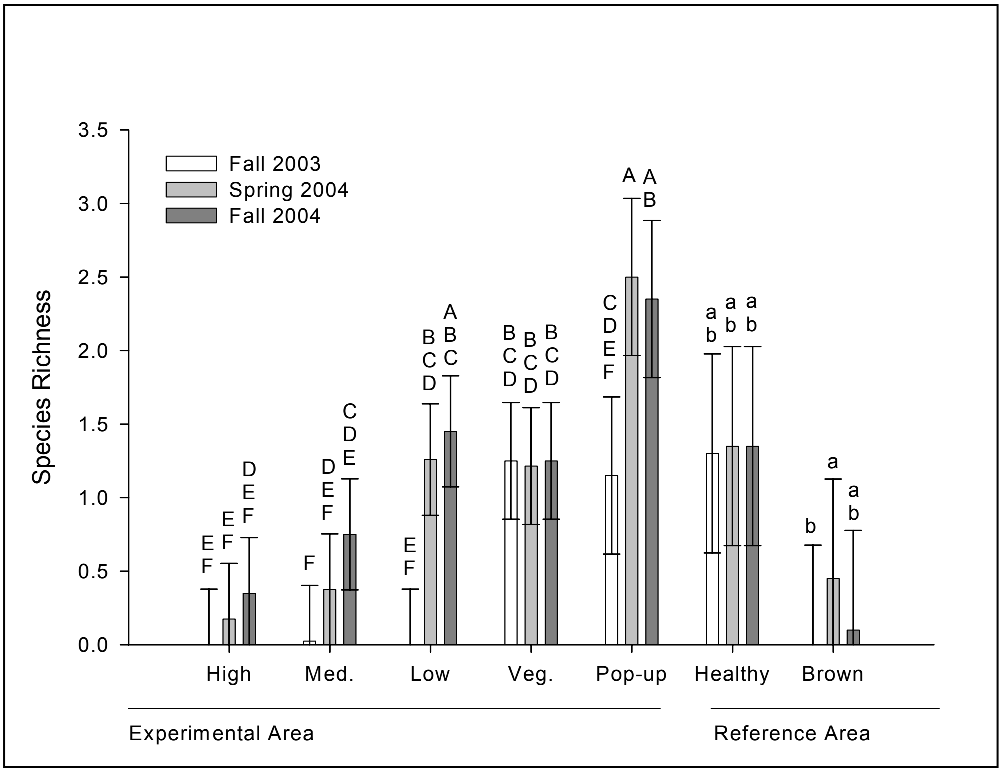

FIGURE 3 – Species richness over time in the experimental area that received sediment-slurry amendments and in reference areas that did not receive sediment-slurry amendments (least-square mean with 95 % confidence interval). The same letters indicate no significant differences between treatment means ($p < 0.05$) within either the experimental or reference areas. Non-overlapping confidence intervals identify significant differences between experimental and the reference areas.

TABLE 1 – Presence (+) or absence (-) of live plant species.

	Experimental Area					Reference Area	
Plant species	High	Medium	Low	Vegetated	Pop-up	Healthy	Brown
Avicennia germinans	-	-	-	-	+	-	-
Batis maritima	-	-	-	+	+	-	-
Blutaparon vermiculare	-	-	-	+	+	-	-
Cyperus oxylepis	-	-	-	-	+	-	-
Distichlis spicata	-	-	-	-	+	-	-
Salicornia bigelovii	+	+	+	-	+	-	-
Salicornia virginica	+	+	+	+	+	+	-
Sesuvium maritimum	-	-	-	-	+	-	-
Spartina alterniflora	+	+	+	+	+	+	+

Importance values (Table 2), which are indices of species dominance, were determined for all live species (Table 1) within each SSTL and reference marsh type. *Spartina alterniflora* was the most important initial colonizer and, overall, the dominant species within the experimental and reference areas (Table 2). The pop-up treatment-level, which had the highest diversity, was also dominated by *Spartina alterniflora,* the succulent, *Blutaparon vermiculare,* and the salt marsh grass, *Distichlis spicata*, were important subdominants (Table 1, Fig. 4a).

Depending on treatment-level, the importance value of some species increased over time while others decreased (significant treatment-level by time interaction, Table 3). From the fall of 2003 to the fall of 2004, the importance values for *S. alterniflora* increased in the high, medium, low, and pop-up treatment-levels, and reference brown marsh sites (Fig. 4b). By the fall of 2004, the low elevation and vegetated treatment-levels had *S. alterniflora* importance values equivalent to that of the reference healthy marsh sites (Fig. 4b). In the pop-up treatment-level, the dominance of *S. alterniflora* increased over time, as did that of *D. spicata* and the succulent *Salicornia virginica* (Fig. 4a). In contrast, other species, like *B. vermiculare*, decreased over time. By the fall of 2004, *S. alterniflora* was the overwhelming dominant of the pop-up treatment-level (Fig. 4a). Due to the limited species richness and abundance in treatment-levels other than the pop-up, the overall time effect followed the trends of species dominance over time in the pop-up treatment-level (Table 3). *Sesuvium maritimum* was only present in the pop-up treatment-level during the spring of 2004 and hence, the overall effect of time (Table 3) indicated that the spring of 2004 had significantly higher importance values than the fall of 2003 or the fall of 2004 (data not shown). Similarly, the importance values of *Batis maritima* and *Salicornia virginica* in the pop-up treatment-level significantly varied over time (Table3, Fig. 4a).

TABLE 2 – Plant Species Value

Experimental Area	*Avicennia germinans*	*Batis maritima*	*Blutaparon vermiculare*	*Cyperus oxylepis*	*Distichlis spicata*
High	n/a	n/a	n/a	n/a	n/a
Medium	n/a	n/a	n/a	n/a	n/a
Low	n/a	n/a	n/a	n/a	n/a
Vegetated	n/a	1.65 A (-1.44 to 4.75)	n/a	n/a	n/a
Pop-up	0.02 (-0.14 to 0.18)	7.99 A (4.01 to 11.96)	14.95 (1.68 to 28.21)	2.35 (-0.80 to 5.50)	28.49 (16.44 to 40.53)
Reference Area					
Healthy	n/a	n/a	n/a	n/a	n/a
Brown	n/a	n/a	n/a	n/a	n/a

Experimental Area	*Salicornia bigelovii*	*Salicornia virginica*	*Sesuvium maritimum*	*Spartina alterniflora*
High	n/a	0.29 B (-0.17 to 1.00)	n/a	32.38 B (-20.51 to 85.27)
Medium	n/a	0.43 B (-0.08 to 1.20)	n/a	129.92 B (77.03 to 182.81)
Low	n/a	0.88 B (0.21 to 1.91)	n/a	296.34 A (243.45 to 349.23)
Vegetated	n/a	0.87 B (0.51 to 2.03)	n/a	286.46 A (231.58 to 341.35)
Pop-up	0.44 (-3.83 to 4.70)	13.84 A (7.00 to 26.52)	n/a	131.25 AB (56.45 to 206.04)
Reference Area				
Healthy	n/a	10.21 (-2.37 to 22.78)	n/a	288.31 a (217.44 to 369.16)
Brown	n/a	n/a	n/a	3.00 b (0.25 to 15.73)

Importance value for each live plant species two years (fall 2004) following the sediment amendment (least-squared mean with 95 % confidence interval). Values are not listed for species that were absent (n/a) within a treatment-level or marsh type. The same letters indicate no significant differences between treatment means ($p < 0.05$) within either the experimental or reference areas. Non-overlapping confidence intervals identify significant differences between experimental and the reference areas.

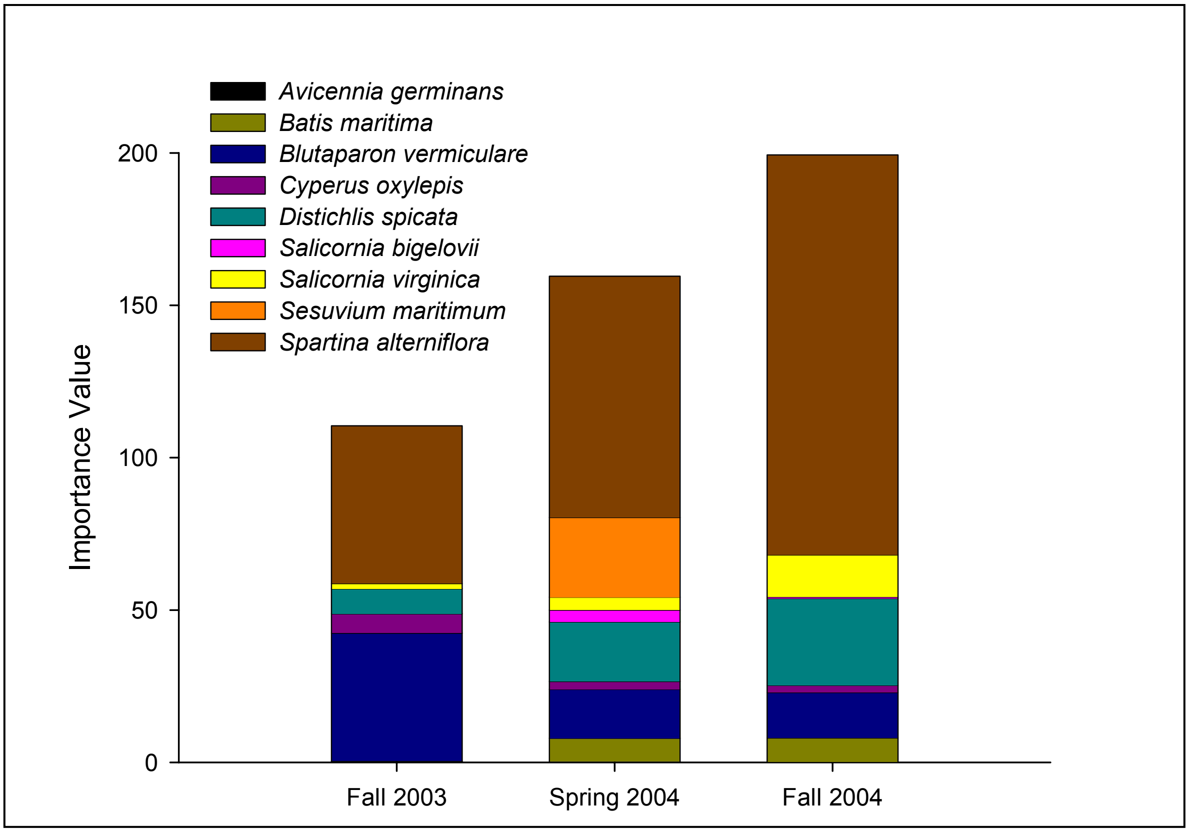

FIGURE 4A. – Plant importance values over time in the pop-up treatment-level, an area with a high diversity (least-square means).

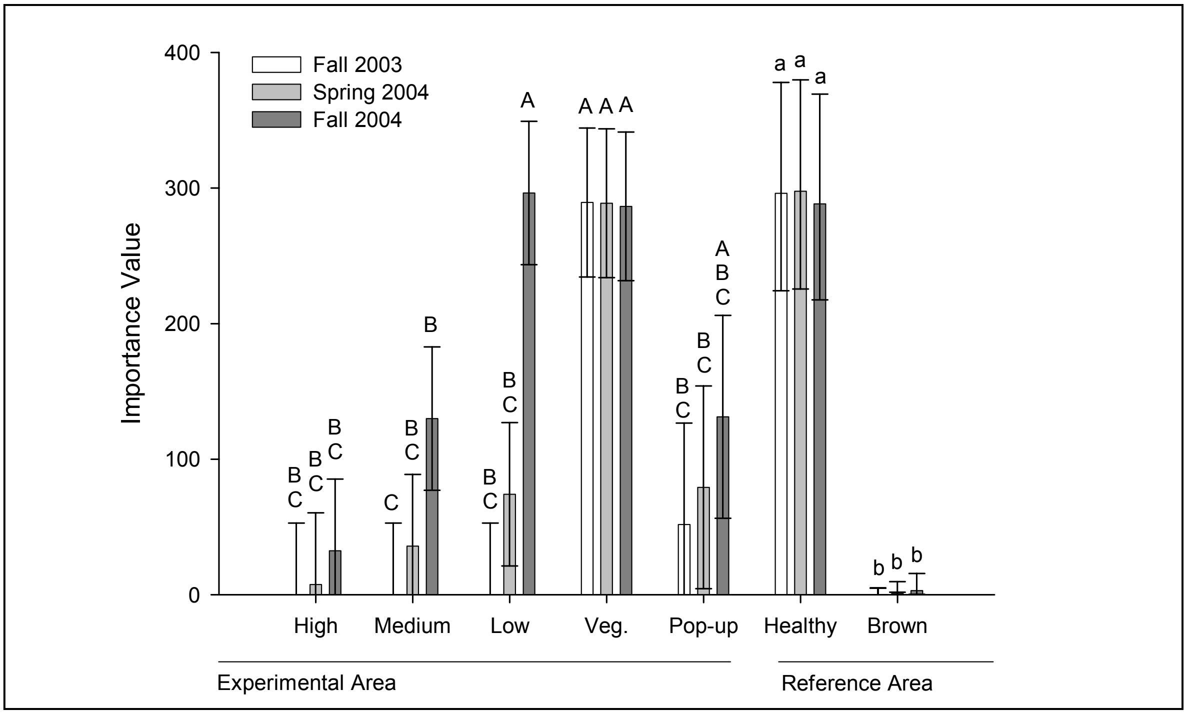

FIGURE 4B. – Importance of the primary initial colonizer, *Spartina alterniflora* (least-square mean with 95 % confidence interval). The same letters indicate no significant differences between treatment means ($p < 0.05$) within either the experimental or reference areas. Non-overlapping confidence intervals identify significant differences between experimental and the reference areas.

TABLE 3 – Treatment Effect

	Experimental Area			Reference Area		
Plant Species	TL	T	TL*T	MT	T	MT*T
Avicennia germinans	0.1463	0.1041	0.1339	n/a	n/a	n/a
Batis maritima	0.1109	**0.0095**	**0.0389**	n/a	n/a	n/a
Blutaparon vermiculare	**0.0333**	**0.0067**	**0.0071**	n/a	n/a	n/a
Cyperus oxylepis	0.0887	0.4291	0.7541	n/a	n/a	n/a
Distichlis spicata	0.0816	0.0640	0.0651	n/a	n/a	n/a
Salicornia bigelovii	0.3963	0.1275	0.4077	n/a	n/a	n/a
Salicornia virginica	**0.0001**	**0.0009**	0.2660	0.4226	0.4444	0.4444
Sesuvium maritimum	**0.0016**	**<.0001**	**<.0001**	n/a	n/a	n/a
Spartina alterniflora	**<.0001**	**<.0001**	**<.0001**	**0.0029**	0.5307	0.3776

The effect of treatment level (TL) / marsh type (MT), time (T) (fall 2003, spring 2004, and fall 2004), and the interaction of treatment level/marsh type and time on the importance of a plant species. Plants that were not present (n/a) could not be analyzed. Bold indicates significant differences.

Soil physico-chemical characteristics

Principal Components Analysis. The PCA grouped 16 of the soil environmental variables into four principal components (PC1, PC2, PC3, PC4), which explained 86% of the variation (Table 4; Fig. 5). The factor scores of the principal components experimental area were significantly affected by treatment-level, time, and/or treatment-level by time interactions. However, principal component factor scores in the reference area only had one significant main effect and one significant interaction (Table 5).

Although the reference area's principal component factor scores did not have any significant main effects or interactions, some of the principal components in the PC1 explained 52 % of the variation and had high positive loadings for Mn, Zn, and Cu and can be interpreted as a trace metal-related component (Table 4). PC1 varied among treatment-levels (Table 5). PC1 was significantly higher in the high and medium elevation treatment-levels than the low and vegetated treatment-levels. The pop-up treatment-level had the lowest PC1 factor score and was significantly lower than the reference marsh types. PC1 was similar between reference marsh types and the vegetated treatment-levels. PC1 was also statistically similar between the reference brown marsh and the low elevation treatment-level (Fig. 5a). There was also a significant treatment-level by time interaction with PC1's factor scores (Table 5). All SSTLs remained constant over time except for the vegetated treatment-level, which had a slight increase from the fall of 2003 to the spring of 2004 (data not shown). The reference area had a significant time effect and a significant marsh type by time interaction (Table 5). PC1 was significantly lower in the fall of 2003 compared to the spring of 2004 and the fall of 2004. PC1 decreased over time in the reference brown marsh sites while PC1 in the reference healthy marsh sites did not have a consistent trend over time.

TABLE 4 – Principal Components Analysis

Variable	PC 1	PC 2	PC 3	PC 4
Moisture	-0.55	**-0.74**	-0.04	-0.27
Bulk Density	0.59	**0.74**	0.13	0.18
% Organic Matter	-0.57	**-0.74**	-0.1	-0.14
Electrical Conductivity	-0.33	**-0.72**	0.06	-0.39
pH	0.59	0.50	0.08	-0.30
P	0.47	**0.72**	0.18	0.10
Fe	-0.09	**0.84**	0.10	0.06
Cu	**0.92**	0.16	0.07	0.20
Mn	**0.92**	0.21	0.11	0.19
Zn	**0.92**	0.21	0.11	0.19
Ca	0.49	0.57	0.50	0.17
Mg	0.08	0.17	**0.95**	-0.02
K	0.18	0.55	**0.69**	-0.14
Na	0.04	-0.12	**0.92**	0.07
Eh	0.17	0.17	-0.03	**0.86**
Elevation	0.17	0.12	0.05	**0.88**
Variation Explained	52%	15%	10%	9%

Results of a principal components analysis that combined 16 soil variables into 4 principal components. Values shown are coefficients that describe how strongly a variable relates to the component. Coefficients with high absolute values are in bold because they define the principal component.

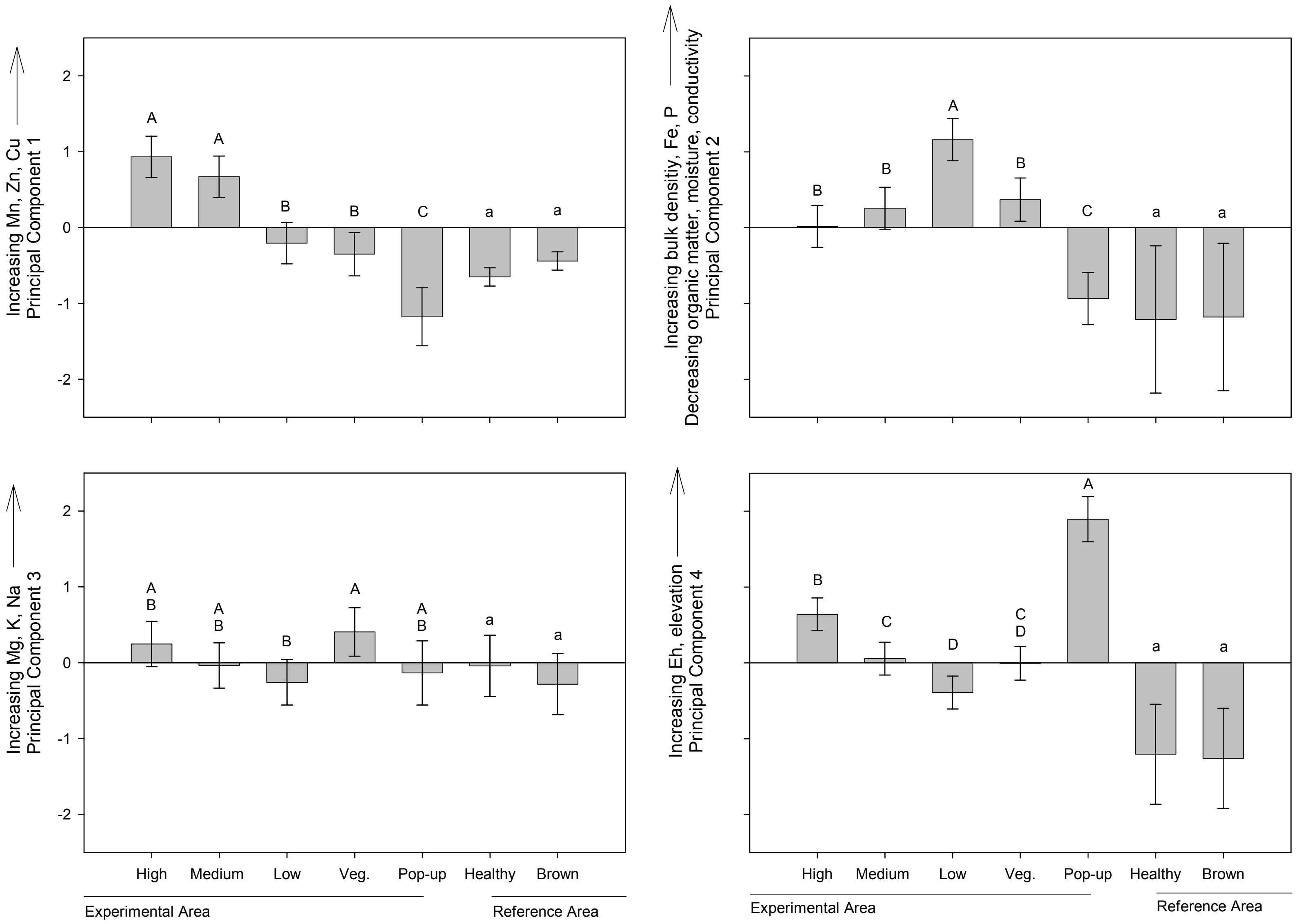

FIGURE 5 – Principal component loadings across treatment-levels and marsh types averaged over time. The same letters indicate no significant differences between treatment means ($p < 0.05$) within either the experimental or reference areas. Non-overlapping confidence intervals identify significant differences between experimental and the reference areas.

TABLE 5 – Principal Component Scores

	Experimental Area			Reference Area		
Principal Component	Treatment-Level	Time	Interaction	Marsh Type	Time	Interaction
(PC1) Trace metals	**< .0001**	0.9914	**0.0201**	0.0549	**0.0332**	**0.0421**
(PC2) Minerals	**< .0001**	0.8764	0.7463	0.9453	0.3627	0.4549
(PC3) Salts	**0.0286**	0.1543	**0.0214**	0.2961	0.4018	0.5405
(PC4) Inundation	**< .0001**	**0.0084**	0.7569	0.8665	0.0762	0.1446

The effect of treatment level/marsh type, time (fall 2003, spring 2004, and fall 2004), and the interaction of treatment level/marsh type by time on principal component scores. Data in bold indicate significant differences.

PC2 explained 15 % of the variation and had high positive loadings for bulk density, Fe, and P and highly negative loadings for organic matter, moisture, and conductivity and can therefore, be interpreted as a mineral-related component. Treatment-level had a significant effect on PC2's factor scores (Table 4). PC2 was significantly lower in the high, medium, and vegetated treatment-levels than the low elevation treatment-level. The pop-up treatment-level, which had the lowest PC2 scores in the experimental area, and the high elevation treatment-level were statistically similar to the reference marsh types (Fig. 5b).

PC3 explained 10 % of the variation, had high positive loadings for Mg, K, Na, and can be interpreted as a salt-related component (Table 4). The factor scores from PC3 varied between treatment-levels (p = 0.0286; Table 5). PC3 was significantly higher in the vegetated treatment-level than in the low elevation treatment-level; all other treatment-levels were statistically similar. The reference marsh types were statistically similar to all treatment-levels in the experimental area (Fig. 5c). In addition, PC3 had a significant interaction between treatment-level and time (Table 5). Over time, factor scores from PC3 remained constant within all SSTLs except the high elevation treatment-level, which increased from the fall of 2003 to the spring of 2004 (data not shown).

PC4 explained 9 % of the variation and had high loadings for elevation and Eh and can be interpreted as and inundation-related component (Table 4). Treatment-level significantly affected PC4 (Table 5). PC4's factor scores were highest in the pop-up treatment-level and in general, significantly decreased with decreasing elevation. PC4 significantly decreased from the pop-up to high elevation treatment-level and from the high to low elevation treatment-level. The vegetated treatment-level was statistically similar to both the medium and low elevation treatment-levels. The factor scores for the reference marsh types were statistically similar to those for the low elevation treatment-level and were significantly lower than those for all other SSTLs (Fig. 5d). Time also significantly affected PC4 (Table 5). Factor scores were significantly higher in the spring of 2004 than the fall of 2003 and the fall of 2004 (data not shown).

Univariate comparisons. The following results present responses of specific variables of interest that were either grouped into a principal component via the PCA or that could not be analyzed by the PCA because of the frequency of data collection. Because of their importance in interpreting plant response and recovery, we present them individually.

Sediment-slurry amendments significantly increased elevation within the experimental area (Table 6). Elevation within the sediment-slurry treatment area was directly related to the nature of treatment-level and all levels were significantly different from each other except for the vegetated and medium elevation treatment-levels ($p = 0.8491$; Table 7, Fig. 6). Elevation of the pop-up treatment-level was the highest because sections of the original marsh (pop-ups) settled on top of the added sediment-slurry. The designation of high, medium, and low elevation treatment-levels were decided based on elevation measurements taken near the sampling

TABLE 6 – Univariate Comparisons

	Experimental Area						Reference Area					
	Degrees of Freedom			Significance			Degrees of Freedom			Significance		
Variable	TL	T	TL*T	TL	T	TL*T	MT	T	MT*T	MT	T	MT*T
Moisture	4,10	2,26	8,26	**<.0001**	**0.0063**	0.3049	1,2	2,4	2,4	0.7599	0.7257	0.1922
Bulk Density	4,10	2,26	8,26	**<.0001**	**0.0025**	0.6202	1,2	2,4	2,4	0.7881	0.3975	**0.0285**
Elevation	4,10	n/a	n/a	**<.0001**	n/a	n/a	1,2	n/a	n/a	0.0729	n/a	n/a
% Sand	4,10	n/a	n/a	**0.0057**	n/a	n/a	1,2	n/a	n/a	0.3898	n/a	n/a
% Silt	4,11	n/a	n/a	**0.0085**	n/a	n/a	1,2	n/a	n/a	0.6894	n/a	n/a
% Clay	4,12	n/a	n/a	**0.0337**	n/a	n/a	1,2	n/a	n/a	0.5032	n/a	n/a
% Organic Matter	4,10	2,26	8,26	**<.0001**	0.0221	0.1672	1,2	2,4	2,4	0.6863	0.9968	0.7028
Electrical Conductivity	4,10	2,26	8,26	0.0361	**<.0001**	**0.0004**	1,2	2,4	2,4	0.6768	**0.0066**	0.3749
Eh	4,10	2,26	8,26	0.0571	**<.0001**	0.2065	1,2	2,4	2,4	0.5370	0.2508	0.1580
Ca	4,10	2,26	8,26	**0.0014**	**<.0001**	0.1935	1,2	2,4	2,4	0.9187	0.3741	0.8335
Mg	4,10	2,26	8,26	**0.0269**	0.0146	0.0414	1,2	2,4	2,4	0.8020	0.2289	0.3330
K	4,10	2,26	8,26	**0.0006**	0.1256	0.3903	1,2	2,4	2,4	0.9931	**0.0430**	0.2596
Na	4,10	2,26	8,26	0.2031	**0.0006**	**0.0003**	1,2	2,4	2,4	0.3128	0.9408	0.4651
pH	4,10	2,26	8,26	**<.0001**	**0.0002**	**0.0216**	1,2	2,4	2,4	0.5917	**0.0490**	0.8812
Cu	4,10	2,26	8,26	**0.0012**	**0.0412**	**0.0002**	1,2	2,4	2,4	0.5869	**0.0144**	0.0957
Fe	4,10	2,26	8,26	**0.0049**	0.2317	0.2955	1,2	2,4	2,4	0.7963	**0.0106**	0.0974
Mn	4,10	2,26	8,26	**0.0005**	0.2804	**0.0002**	1,2	2,4	2,4	0.3692	**0.0261**	0.3181
Zn	4,10	2,26	8,26	**0.0005**	0.2830	**0.0002**	1,2	2,4	2,4	0.3691	**0.0262**	0.3175
P	4,10	2,26	8,26	**0.0001**	**0.0406**	0.4146	1,2	2,4	2,4	0.9061	**0.0435**	0.9449
NH_4-N	4,10	1,13	4,13	**0.0453**	0.2861	0.3761	1,2	1,2	1,2	0.5461	0.0587	0.9352
NH_4-N + NO_3^--N	4,10	1,13	4,13	0.2375	**0.0267**	0.5695	1,2	1,2	1,2	0.5837	0.1110	0.7212
Sulfide	n/a	n/a	n/a	n/a	n/a	n/a	1,2	n/a	n/a	0.3469	n/a	n/a
% Sand	4,10	n/a	n/a	**0.0057**	n/a	n/a	1,2	n/a	n/a	0.3898	n/a	n/a
% Silt	4,11	n/a	n/a	**0.0085**	n/a	n/a	1,2	n/a	n/a	0.6894	n/a	n/a
% Clay	4,12	n/a	n/a	**0.0337**	n/a	n/a	1,2	n/a	n/a	0.5032	n/a	n/a

The degrees of freedom (numerator, denominator) and the effect of treatment level (TL) / marsh type (MT), time (T) (fall 2003, spring 2004, and fall 2004), and the interaction of treatment level/marsh type and time on soil characteristics. Data for specific variables are not available (n/a) because they were not sampled in multiple time periods. Data is not available for sulfide in the experimental area because sulfide was either below detection limits or unable to be analyzed. Data for organic matter was obtained by direct measurement in the spring of 2004. A linear regression with bulk density was used to predict values for organic matter during the fall of 2003 and the fall of 2004.

TABLE 7 – Substrate Characteristics

Experimental Area	Bulk Density (g cm^{-3})	% Moisture	% Organic Matter	pH
High	1.04 A (0.91 to 1.18)	31.41 C (27.56 to 35.79)	5.08 C (1.95 to 8.2)	7.63 A (7.45 to 7.8)
Medium	0.97 A (0.83 to 1.10)	33.86 C (29.72 to 38.57)	6.48 C (3.36 to 9.61)	7.71 A (7.54 to 7.89)
Low	0.98 A (0.84 to 1.11)	35.86 C (31.47 to 40.83)	6.34 C (3.23 to 9.47)	7.56 A (7.38 to 7.73)
Vegetated	0.75 B (0.61 to 0.89)	43.81 B (38.41 to 49.96)	1.94 B (8.75 to 15.12)	7.14 B (6.96 to 7.32)
Pop-up	0.34 C (0.17 to 0.51)	65.30 A (55.40 to 76.94)	24.65 A (20.69 to 28.60)	5.91 C (5.67 to 6.15)
Reference Area				
Healthy	0.19 a (-0.05 to 0.44)	81.36 a (58.54 to 96.31)	28.76 a (12.74 to 44.79)	6.78 a (6.10 to 7.46)
Brown	0.20 a (-0.04 to 0.45)	79.03 a (55.66 to 95.13)	26.28 a (10.26 to 42.30)	6.64 a (5.96 to 7.32)

Experimental Area	Sulfide (mM)	Eh (mV)	Electrical Conductivity (mS)
High	n/a	211.64 A (154.61 to 268.67)	9.33 AB (7.17 to 12.07)
Medium	n/a	169.35 A (112.32 to 226.38)	8.83 AB (6.77 to 11.44)
Low	n/a	141.90 A (84.87 to 198.92)	7.05 B (5.67 to 9.19)
Vegetated	n/a	121.77 A (64.21 to 179.32)	9.53 AB (7.30 to 12.36)
Pop-up	n/a	258.45 A (177.80 to 339.09)	13.77 A (9.77to 19.26)
Reference Area			
Healthy	3.82 a (-0.17 to 26.93)	-11.57 a (-74.59 to 83.00)	27.08 a (11.06 to 64.38)
Brown	1.38 a (-0.59 to 12.81)	8.49 a (-62.19 to 110.72)	23.55 a (9.54 to 56.17)

Substrate characteristics averaged over time (treatment-level and marsh type effects) in sediment-amended marshes and reference marshes (least-square means with 95 % confidence intervals). The same letters indicate no significant differences between treatment means ($p < 0.05$) within either the experimental or reference areas. Non-overlapping confidence intervals identify significant differences between experimental and the reference areas. Sulfide values not available (n/a) were below our detection limits (0.1 ppm) or unable to be analyzed.

TABLE 7 – Continued

Experimental Area	% Sand	% Silt	% Clay
High	8.80 A (7.07 to 10.90)	41.33 A (34.89 to 48.92)	48.61 AB (40.14 to 58.82)
Medium	8.44 A (6.77 to 10.46)	42.88 A (36.21 to 50.76)	47.79 AB (39.47 to 57.83)
Low	9.18 A (7.39 to 11.36)	43.39 A (36.64 to 51.36)	46.31 B (38.24 to 56.05)
Vegetated	9.35 A (7.52 to 11.56)	43.82 A (37.01 to 51.87)	46.11 B (38.07 to 55.81)
Pop-up	4.23 B (3.00 to 5.85)	31.29 B (25.66 to 38.12)	60.65 A (48.87to 75.22)
Reference Area			
Healthy	10.25 a (1.09 to 59.37)	38.65 a (0.17 to 105.76)	39.49 a (7.69 to 187.69)
Brown	5.16 a (0.14 to 32.08)	33.11 a (0.10 to 90.84)	59.98 a (12.08 to 283.18)

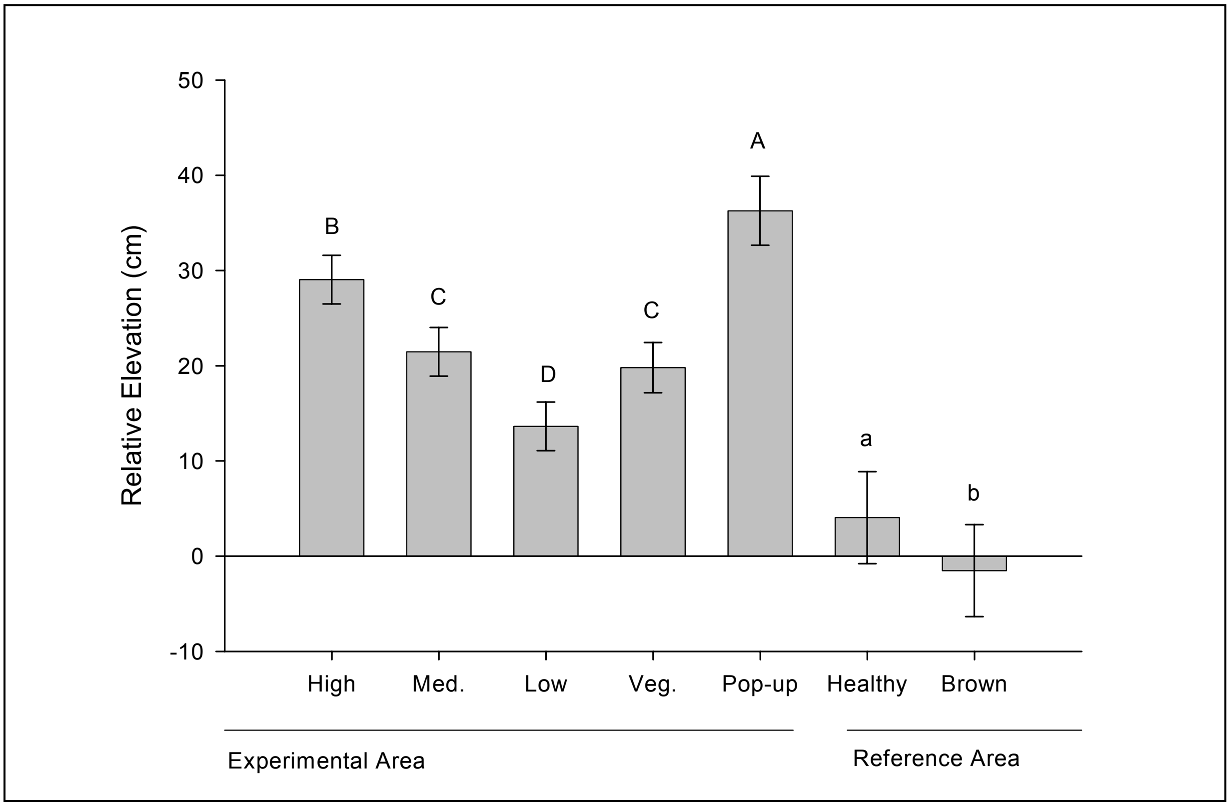

FIGURE 6 – Elevation of all treatment-levels and marsh types referenced to ambient healthy marsh elevation (least-square mean with 95 % confidence interval). The same letters indicate no significant differences between treatment means ($p < 0.05$) within either the experimental or reference areas. Non-overlapping confidence intervals identify significant differences between experimental and the reference areas. Reference healthy marshes and reference brown marshes were significantly different at $p < 0.0729$.

transects (before transects were established) and, as expected, these three elevations were significantly different (Fig. 6). The vegetated treatment-level, which was identified and selected based on the presence of live vegetation in the fall of 2003 when most of the experimental area was devoid of vegetation, had an elevation higher than the reference marshes but similar to the medium treatment-level (Fig. 6). Compared to the experimental area, elevation was significantly lower in marshes that did not receive the sediment-slurry amendment (Fig. 6). The reference healthy marsh sites had significantly higher elevation than the reference brown marsh sites ($p < 0.0729$; Fig. 6).

Percent time flooded (Fig. 7) and water depth (Fig. 8) were inversely related to elevation in both the experimental and reference areas. The reference marshes, which were at the lowest elevations, were flooded approximately 30-50% of the time during a month of high water levels (October 2004) while all of the SSTLs were flooded less than half the time of the reference marshes (Fig. 7). On average, minimum water depths during a five-month period demonstrate a daily draining of all marshes in the experimental area and reference area (Fig. 8). Elevation controlled water depth in the experimental and reference areas. Treatment-levels with high elevations were infrequently flooded and as elevation decreased, water depth was more commonly above treatment-level/marsh type elevation (Fig. 8).

Time effects for Eh (redox potential) were highly significant in the experimental area ($p < 0.0001$), with non-significant treatment-level effects and interactions (Table 6). All three sampling periods were significantly different with the highest overall Eh (mean, 95 % confidence interval: 230, 200 to 261) in the spring of 2004 and the lowest overall Eh (135, 105 to 165) in the fall of 2004. There were no significant main effects or interactions with Eh in the reference area. During the fall of 2004, a period of relatively low redox potential, the experimental (135, 105 to

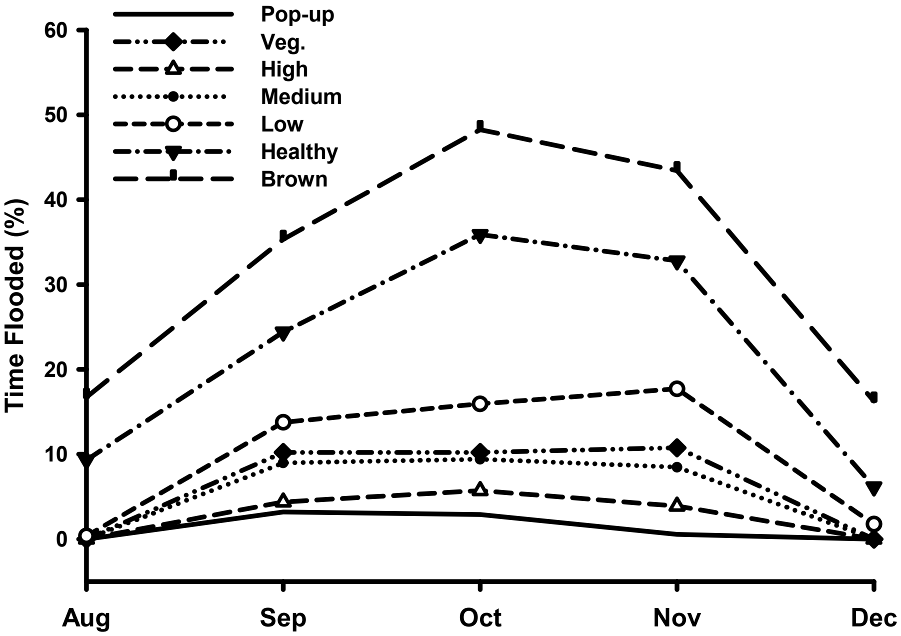

FIGURE 7 – Percent time flooded from August thru December of 2004. Percent time flooded is based upon the water depth recorded from the water sonde and the average elevation of each treatment-level and marsh type.

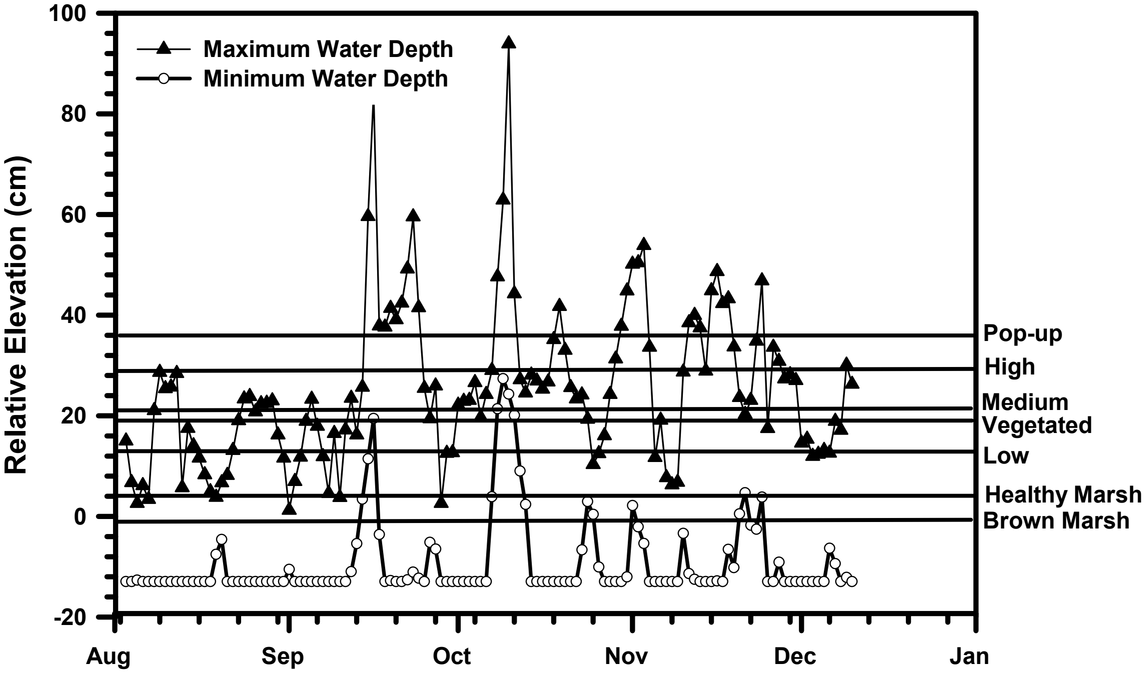

FIGURE 8 – Water depth recorded from the water sonde and referenced to the ambient healthy marsh elevation. Horizontal lines indicate the relative elevation of each treatment-level and marsh type. Treatment-levels/marsh types were flooded when maximum water depth was higher than the elevation of the corresponding treatment-level/marsh type. Negative values indicate depth beneath the ambient marsh surface. The minimum water depth detectable by the water sonde was 13 cm below the ambient marsh surface.

105 to 165) and reference (85, 45 to 139) area had similar redox potentials. In comparison, during a period of high redox potential (spring 2004), the experimental (230, 200 to 261) had significantly higher redox potentials than the reference (107, 61 to 166) area.

The high elevations, relatively low percent time flooded, and high redox potentials in the experimental area resulted in sulfide levels below our detection limits (< 0.1 ppm). Conversely, the low elevations and long hydroperiods (Figs. 7 and 8) in the reference marshes resulted in low redox potentials and sulfide concentrations (Table 7) above levels known to cause reductions in growth of *Spartina alterniflora* (1.0 mM, (Koch et al. 1990).

Bulk density significantly varied among treatment-levels in the experimental area (Table 6) but did not significantly differ between the reference marsh types. High, medium, and low elevation treatment-levels had statistically similar bulk densities that were significantly higher than the vegetated and pop-up treatment-levels (Table 7). The vegetated treatment-level had a higher bulk density than the pop-up treatment-level (Table 7). The reference marshes had low bulk densities that were equivalent to that of the pop-up treatment-level but significantly lower than all other SSTLs. There was also a significant time effect in the experimental area, but differences between time periods were minimal (fall 2003: 0.77, 0.67 to 0.87; spring 2004: 0.81, 0.71 to 0.92; fall 2004: 0.86, 0.76 to 0.96). Similarly, there was a significant interaction with time (Table 6) in the reference area. However, the Tukey-Kramer adjustment was not significant, indicating that the interaction was minor.

Treatment-level effects for organic matter were highly significant (Table 6). The pop-up treatment-level had a high organic matter content that was significantly higher than all other SSTLs (Table 7). The vegetated treatment-level had a moderate organic matter content that was significantly greater than the high, medium, and low treatment-levels, which were statistically similar. References marshes were equivalent to the pop-up and vegetated treatment-levels and had significantly more organic matter than the high, medium, and low elevation treatment-levels. Although time was significant in the experimental area ($p = 0.0221$), differences between time periods were minimal. As expected, similar trends were seen between bulk density and organic matter because they were highly correlated and inversely related ($r = -0.87$, $p < 0.0001$).

Treatment-level had a significant effect on the percent sand, silt, and clay while marsh type had no effect (Table 6). The pop-up treatment-level had significantly lower percentages of sand and silt than all other SSTLs. There were no statistical differences in the percentages of sand, silt, and clay between the high, medium, low, and vegetated treatment-levels. Although, the percent of clay within the pop-ups was substantially higher than all other SSTLs, it was only significantly different from the vegetated and low treatment-levels. The small sample size and low replication in the reference area reduced the power of the model resulting in confidence intervals that do not accurately reflect the variation in the raw data (Table 7).

Nitrogen (NH_4-N + NO_3^--N and NH_4-N), one of the most important and often limiting nutrients in the salt marsh, did not vary among marsh types (Table 6). Although there was a significant treatment-level effect for NH_4-N, the Tukey-Kramer adjustment showed no significant difference, indicating that the effect was minor (Tables 6 and 8). NH_4-N + NO_3^--N did vary over time in the experimental area and was significantly higher in the spring of 2004 compared to the fall of 2004. Nitrogen (NH_4-N + NO_3^--N and NH_4-N) did not vary between the experimental and reference area (Table 8).

TABLE 8 – Exchangeable Soil Nutrients

Experimental Area	Ca	Mg	K	Na
High	50.38 A (42.68 to 58.08)	45.00 AB (40.91 to 49.07)	18.92 A (16.89 to 20.94)	251.69 A (213.76 to 289.62)
Medium	41.57 A (33.87 to 49.27)	42.22 AB (38.14 to 46.30)	19.71 A (17.69 to 21.74)	227.85 A (189.92 to 265.77)
Low	40.40 A (32.70 to 48.10)	41.94 AB (37.86 to 46.02)	21.21 A (19.18 to 23.23)	189.74 A (151.81 to 227.67)
Vegetated	37.62 A (29.76 to 45.48)	49.49 A (45.14 to 58.84)	21.34 A (19.19 to 23.49)	233.43 A (194.54 to 272.33)
Pop-up	17.33 B (6.93 to 27.73)	37.06 B (31.28 to 42.83)	10.86 B (8.00 to 13.73)	223.87 A (170.28 to 277.45)
Reference Area				
Healthy	12.58 a (6.41 to 23.88)	37.39 a (26.77 to 52.07)	12.56 a (5.10 to 29.14)	215.33 a (185.09 to 250.49)
Brown	12.27 a (6.24 to 23.32)	36.24 a (25.94 to 50.48)	12.59 a (5.12 to 29.21)	201.47 a (173.16 to 234.38)

Experimental Area	Fe	Mn	Cu	Zn
High	2.50 B (1.84 to 3.23)	0.06 A (0.05 to 0.06)	0.04 A (0.03 to 0.04)	0.05 A (0.04 to 0.05)
Medium	2.88 B (2.18 to 3.65)	0.05 AB (0.04 to 0.06)	0.03 AB (0.03 to 0.04)	0.04 AB (0.04 to 0.05)
Low	4.81 A (3.94 to 5.74)	0.04 BC (0.03 to 0.04)	0.02 BC (0.01 to 0.03)	0.03 BC (0.02 to 0.04)
Vegetated	3.23 AB (2.48 to 4.05)	0.03 C (0.02 to 0.04)	0.02 BC (0.02 to 0.03)	0.03 C (0.02 to 0.03)
Pop-up	2.13 B (1.26 to 3.13)	0.02 C (0.01 to 0.03)	0.01 C (0.00 to 0.02)	0.02 C (0.01 to 0.02)
Reference Area				
Healthy	1.00 a (-0.15 to 3.37)	0.01 a (-0.00 to 0.03)	0.01 a (-0.00 to 0.02)	0.01 a (-0.00 to 0.02)
Brown	0.84 a (-0.21 to 3.30)	0.02 a (0.00 to 0.03)	0.01 a (-0.00 to 0.02)	0.01 a (-0.00 to 0.03)

Average exchangeable soil nutrient concentrations (treatment-level/marsh type effects; umol/cm^3) in marshes that received a sediment amendment and in reference marshes (least-square means with 95 % confidence intervals). The same letters indicate no significant differences between treatment means ($p < 0.05$) within either the experimental or reference areas. Non-overlapping confidence intervals identify significant differences between experimental area and the reference area.

TABLE 8 – Continued

Experimental Area	P	NH_4-N	NH_4-N + NO_3^--N
High	5.47 A (4.75 to 6.20)	0.05 A (-0.00 to 0.10)	0.11 A (0.04 to 0.18)
Medium	5.15 A (4.42 to 5.88)	0.11 A (0.06 to 0.16)	0.14 A (0.07 to 0.22)
Low	5.48 A (4.76 to 6.20)	0.14 A (0.09 to 0.19)	0.16 A (0.09 to 0.24)
Vegetated	4.55 A (3.80 to 5.30)	0.04 A (-0.02 to 0.09)	0.06 A (-0.02 to 0.13)
Pop-up	1.38 B (0.37 to 2.38)	0.06 A (-0.02 to 0.13)	0.07 A (-0.03 to 0.18)
Reference Area			
Healthy	0.60 a (-0.30 to 2.64)	0.19 a (-0.06 to 0.45)	0.19 a (-0.05 to 0.43)
Brown	0.54 a (-0.32 to 2.51)	0.13 a (-0.12 to 0.39)	0.14 a (-0.10 to 0.38)

Phosphorus varied significantly over treatment-level ($p < 0.0001$; Table 6). Phosphorus concentrations were statistically similar between high, medium, low, and vegetated treatment-levels (Table 8). The pop-up treatment-level had phosphorus concentrations equivalent to that of the reference marshes. Both the pop-up treatment-level and the reference marshes had significantly lower phosphorus compared to all other treatment-levels (Table 8). Phosphorus also varied over time in both the experimental ($p < 0.0406$ and reference areas (Table 6). Phosphorus concentrations significantly decreased from fall of 2003 to the fall of 2004 (data not shown).

DISCUSSION

This study demonstrated that the addition of sediment-slurries can increase the rate of recovery following disturbance in a rapidly subsiding salt marsh. Elevations averaging 14 and 20 cm above ambient marsh located in the low and vegetated treatment-levels had rapid plant recruitment and species richness similar to that of the healthy reference marsh sites. The medium elevation treatment-level, averaging 21 cm in elevation, had marginal increases in recovery. Pop-ups, which were highly organic and located at elevations averaging 26 cm, had rapid recovery and high species diversity. Recovery was the lowest in the high elevation treatment-level and in the reference brown marsh sites.

One of the primary factors influencing plant distribution (Adams 1963, DeLaune et al. 1983b, Edwards and Proffitt 2003) and function (DeLaune et al. 1983b) is elevation. In Louisiana salt marshes, *Spartina alterniflora* is the dominant low marsh plant, in part, because of its superior oxygen transport mechanisms and high sulfide tolerance. As waterlogging stresses decrease via increasing elevation, competitive interactions cause the replacement of *S. alterniflora* with other species (Bertness 1991a, 1991b) such as *S. patens* and *Iva frutescens* (Mitsch and Gosselink 2000). Although elevations optimal for rapid plant colonization in salt marshes have not been conclusively identified, Cornu and Sadro (2002) showed colonization of restored wetlands to be directly related to the degree of the sediment amendment. Additionally, DeLaune et al. (1990) found significant increases in aboveground biomass with 8–10 cm of sediment additions and Mendelssohn and Kuhn (2003) concluded that sediment additions of 15 cm significantly increased plant cover and additions of 15-30 cm significantly increased plant biomass.

Frequency and duration of inundation (Sasser 1977, Day et al. 1993, Brinson et al. 1995, Hacker and Bertness 1999) and redox potential (DeLaune et al. 1983b, Wilsey et al. 1992, Hacker and Bertness 1999, Mendelssohn and Kuhn 2003) have been found to correlate with elevation in tidal salt marshes. Similarly, we found Eh and elevation to be highly related (Table 4) and we identified an inverse relationship between percent time flooded and elevation at our study site (Fig. 8). The markedly reduced redox potentials seen in the reference marshes can be attributed to their low elevation and resultant increases in flooding (DeLaune et al. 1983a, Mendelssohn and McKee 1988b, Wilsey et al. 1992, Cornu and Sadro 2002, Mendelssohn and Kuhn 2003). The reference area was low in elevation and frequently flooded while the experimental area had higher elevations, which resulted in less flooding. When soils become flooded, oxygen depletion is rapid due to its slow rate of diffusion (Gambrell and W. H. Patrick 1978) and consumption by facultative and anaerobic microorganisms during respiration (DeLaune et al. 1991). These microorganisms use oxygen as a terminal electron acceptor converting oxidized compounds into their reduced states, potentially forming toxins, such as hydrogen sulfide, which are harmful to plants.

High sulfide levels, similar to those found in Louisiana marshes (DeLaune et al. 1983b), have been found to decrease productivity (Koch and Mendelssohn 1989) and may therefore, be detrimental to the growth of *S. alterniflora* (Mendelssohn and Morris 2000). Soil sulfide concentrations have been shown to sharply decrease with the addition of sediment (Mendelssohn and Kuhn 1999, Slocum et al. 2005). At our study site, soils that received the sediment amendment did not become reduced enough to have measurable concentrations of interstitial sulfide. In contrast, both reference marsh types had interstitial sulfide concentrations high enough to limit the uptake of nitrogen and to cause reductions in plant growth (Koch and Mendelssohn 1989, Koch et al. 1990). The high sulfide concentrations may have limited seedling establishment and restricted vegetative recruitment from rhizome expansion of plants surrounding the reference brown marsh sites. This would explain why the few seedlings noted in the reference brown marshes in the spring of 2004 were not present in the fall of 2004 (personal observation A. Schrift). Sulfide was not a factor limiting plant establishment in the experimental area. However, it may have contributed to the slow rate of recovery in the reference brown marsh sites.

Elevation and the resultant time flooded can also affect nutrient availability. Nitrogen is generally the most limiting nutrient in the salt marsh (Valiela et al. 1975), in part, because the constant fluctuation between oxidized and reduced conditions promotes denitrification, rapidly reducing nitrogen concentrations. Ammonium is the most readily useable form of nitrogen for *Spartina alterniflora*, the dominant plant in the study area, and is therefore, an important factor governing marsh vigor. Similar concentrations of inorganic nitrogen throughout marshes with various elevations and different recovery rates imply that nitrogen was not a factor controlling recovery in the experimental area. High sulfide concentrations (Bradley and Morris 1990, Koch et al. 1990) and/or low root oxygen concentrations (Morris and Dacey 1984) in the reference marshes may have inhibited nitrogen uptake and contributed to the high average NH_4-N concentrations seen in the reference marshes during the fall of 2004 (data not shown).

Marshes that are seldom flushed and subjected to radiating heat and resultant water evaporation can generate high substrate salt concentrations, which have been shown to limit plant colonization in bare patches (Bertness et al. 1992) and to limit growth rates of *Spartina alterniflora* (Smart 1980). The relationship between salinity and elevation may change depending upon marsh location. Some researchers (Adams 1963, DeLeeuw et al. 1991, Mendelssohn and Kuhn 2003) found differences in salt concentration to be based upon elevation while others (Silvestri et al. 2005) found no differences between high and low elevations. The concentration of salts such as Mg, Ca, Na, and K throughout our study area were within normal ranges and in many instances were not significantly different among or between treatment-levels and marsh types (Fig. 6, Table 8). These results imply that salt concentrations were not a factor limiting plant colonization at our study site.

High bulk density (a measure of mineral content) has been shown to increase plant recovery (Mendelssohn and Kuhn 2003, Slocum et al. 2005) and productivity (DeLaune et al. 1979). Mineral matter can improve marsh vigor by increasing nutrient availability (Mitsch and Gosselink 2000) and by decreasing toxicity via providing metals (Fe and Mn) that precipitate with sulfide (Gambrell and W. H. Patrick 1978, Gambrell 1994, Mendelssohn and Morris 2000). Bulk density was significantly higher in sediment-subsidized areas, and specific treatment-levels had marked increases of Fe, Cu, Mn, Zn, Ca, and P compared to reference marshes (Table 8). Soils with extremely low bulk densities, like those seen in the reference marshes, have lower plant production than soils with high bulk densities (DeLaune et al. 1990). However, increases in plant recovery were not always associated with higher bulk density.

We also found other factors, which were not wholly dependent on elevation, to be important determinants for successful recovery in our study site. The high rate of recovery in the pop-up treatment-level may be attributed to its highly organic substrate, which can readily retain moisture (Neill and Turner 1987). The pop-up treatment-level had moist soils while nearby areas in the high and medium treatment-levels were often dry enough to have cracked soils. This retention of moisture may have promoted plant recruitment, which led to the high rates of recovery seen in the pop-up treatment-level.

Viable rhizomes in the sediment may have promoted a high rate of recovery seen in the vegetated treatment-level. Immediately following slurry deposition, standing dead *S. alterniflora* was identified in areas that were later classified as the vegetated treatment-level (observations by M. D. Materne and I. A. Mendelssohn). Rhizomes may have been able to survive sediment burial. It has been reported that rhizomes can survive sediment additions up to 15 cm thick (Ford 1999). In the vegetated treatment-level, the sediment-slurry layer varied in thickness (6-41 cm thick). It is also possible that maximum burial depth for viable rhizomes reported by Ford (1999) is underestimated for areas receiving sediment-slurries due to the high water content and low density associated with non-dewatered sediment-slurries compared to other types of sediment addition. We conclude that elevation, in combination with other factors including organic matter, moisture retention, and possibly rhizome viability, played an important role in rapid plant recruitment.

CONCLUSIONS

Salt marsh deterioration in Louisiana has been a major problem since the early 1900's due to human modification of the landscape and natural processes associated with the delta cycle. Chronic natural and anthropogenic disturbances on this once pristine ecosystem have reduced the resilience of many salt marshes in the MRDP making them susceptible to natural perturbations. Before the brown marsh phenomenon of 2000, droughts had been recorded in the MRDP (Swenson et al. 2003) but they were not associated with a marsh dieback event. The brown marsh phenomenon of 2000 may be the first of many large-scale, severe perturbations to affect the region, signaling the need to develop restoration techniques suitable to a variety of disturbances.

Sediment-slurry additions were identified as a possible restoration method because vegetation health in southern Louisiana was found to depend upon the degree of plant inundation and soil reduction resulting from changes in elevation (Mendelssohn and McKee 1988a). Many researchers have shown sediment subsidies to effectively rehabilitate degraded marshes (Cahoon and Cowan 1988, DeLaune et al. 1990, Wilsey et al. 1992, Ford 1999, Mendelssohn and Kuhn 1999, Shafer 2002, Slocum et al. 2005). Mounting concern regarding application distance, resultant elevation, and cost prompted researchers to investigate new sediment application techniques. The hydraulic application of sediment-slurries allows dredged material to travel an extended distance from the discharge pipe. The high water content and intense mixing reduces separation of particle sizes. This even distribution of particle sizes reduces the number of times the dredge operator has to move the discharge pipe, decreasing costs. Because sediment-slurries can be transported miles from the dredging location, Louisiana has readily available materials from the Mississippi River, Gulf of Mexico, and frequently dredged navigable waterways for many otherwise unreachable interior marshes.

The cost associated with slurry additions and marsh recovery rate are essential factors when evaluating and designing marsh restoration projects. Plants help sustain salt marsh integrity by maintaining substrate cohesion, which decreases erosion, and by producing organic matter, which can control vertical accretion rates (Hatton et al. 1983, DeLaune et al. 1991, Nyman et al. 1993). It is essential to determine the appropriate amount of sediment-slurry to deposit to most effectively use the resources available and to decrease the cost of marsh restoration.

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