Effects of Increased Elevation and Macro- and Micronutrient Additions on *Spartina alterniflora* Transplant Success in Salt-Marsh Dieback Areas in Louisiana

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ABSTRACT / *Spartina alterniflora* was transplanted into dieback areas of a salt marsh in southeast Louisiana at two elevations (ambient and +30 cm) with and without macro- (N, P, and K) and micronutrient (Fe, Mn, Cu, and Zn) additions to determine if transplant success is dependent on increasing elevation or nutrients. *Spartina alterniflora* transplanted into elevated plots had more than twice the above- and belowground biomass as compared to nonelevated plots after three months of growth. Additionally, there was significantly more vegetative reproduction (greater culm density and number of newly produced culms) in elevated plots as compared to plots at ambient elevation. Macronutrient additions increased culm densities only in elevated plots. *Spartina alterniflora* transplanted into nonelevated plots had lower survival rates even when transplants received nutrient additions. These results suggest that *S. alterniflora* may be transplanted successfully into degraded salt-marsh areas if elevation is increased. The addition of nutrients without a concomitant increase in elevation is not sufficient for transplant success.

Salt marshes in Louisiana are rapidly deteriorating because the rate of vertical accretion is not keeping pace with relative sea-level rise (eustacy plus subsidence) (Ramsey and Penland 1989, Hatton and others 1983, Turner and Cahoon 1987). The combined effects of eustatic sea-level rise and subsidence increase plant submergence, which often leads to plant death and open waterbodies (Mendelssohn and others 1981, Mendelssohn and McKee 1988). Estimates of coastal wetland loss in Louisiana as of 1983 average 79.5 km^2/yr (Dunbar and others 1990). Approximately 25% of this wetland loss is occurring in saline marshes (Craig and others 1979), with the most rapid degradation occurring in the inner marsh (marsh furthest from tidal channels and bays) (Sasser and others 1986). Inland salt marshes are vertically accreting at a rate that is less than what is needed to maintain elevations at a level similar to streamside marshes (Hatton and others 1983). Because of this sediment deficit, many inland salt marshes are often unable to remain in the intertidal zone (Baumann and DeLaune 1981).

KEY WORDS: Wetland ecology; Marsh restoration; Fertilization; Salt marshes; *Spartina alterniflora;* Louisiana

Because of the lower relative elevation and greater degree of submergence in inland as compared to streamside zones in Louisiana salt marshes (Mendelssohn and others 1981), *Spartina alterniflora* (the dominant plant in these salt marshes) grows in distinct height forms along a streamside–inland gradient: vigorous stands grow in streamside zones and shorter, less vigorous stands grow further inland (Kirby and Gosselink 1976, Mendelssohn and others 1981). In Louisiana, inland zones grade into dieback areas, which are characterized by standing water with little or no vegetation (Mendelssohn and others 1981).

In addition to having a higher elevation and shorter duration of flooding, streamside soils contain a higher proportion of mineral matter and thus a higher bulk density than inland marsh soils (DeLaune and Pezeshki 1988, DeLaune and others 1990). Mineral matter, because it is a source of nutrients and because it often precipitates sulfides (Gambrell and Patrick 1978 and references therein, Evans 1989), has been postulated to stimulate *S. alterniflora* productivity in salt marshes (DeLaune and Pezeshki 1988, DeLaune and others 1990). However, few researchers have attempted to separate the confounding effects of higher elevation and mineral matter in streamside soils.

In recent years there has been an increased interest

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in wetland restoration and creation. A review of the literature between 1970 and 1985 disclosed 304 reports and publications on the restoration and creation of marshes, forested wetlands, seagrass beds, barrier islands, and mangrove swamps (Wolf and others 1986). Restoration and/or creation efforts have occurred in 33 of the 50 states and in one U.S. territory (Wolf and others 1986).

Salt marshes have been restored successfully by transplanting *Spartina* into degraded areas and/or onto spoil deposits (Broome and others 1986, and see Knutson and others 1981 for a national survey of planted salt marshes). Experiments in southern California have demonstrated that *Spartina foliosa* transplantation does not succeed when soils are too saline (50–60 ppt), herbivores have access to the plots, competitors are too dense, and/or when wave stress is high (Zedler 1984). In the absence of these factors, transplantation is generally successful. Broome and others (1986) compared transplanted and natural marshes in North Carolina and found that they had similar above- and belowground biomass 4 yr after transplantation. In Texas, there was no difference in aboveground vegetation between a man-made salt marsh (from spoil deposits) and three natural marshes 2.5 yr after the man-made marsh was created (Webb and Newling 1984). However, because this man-made marsh was at an earlier stage of development than the natural marshes, there was less belowground biomass (Webb and Newling 1984) and total N, NH_4–N, and organic carbon (Lindau and Hossner 1981) in the man-made marsh.

In Louisiana, restoration plans recently have been initiated that require vegetative plantings (van Beek and others 1990), yet little emperical data exist on which to base successful restoration. The objective of this study was to test whether degraded salt marshes can be restored through transplantation of *Spartina alterniflora* and if success is dependent on an increase in elevation or addition of nutrients. This objective was met by transplanting *S. alterniflora* into dieback areas at different elevations with or without nutrient additions.

Materials and Methods

Study Area

The study was undertaken in a *S. alterniflora*-dominated marsh in the lower Barataria Basin near Caminada Bay, Louisiana (29°15'N, 90°9'W) from 12 July 1989 to 17 November 1989. The study area was a degraded marsh characterized by numerous dieback sites; five of these dieback sites were selected for our experiment.

Experimental Design

Treatments (elevation, macronutrients, and micronutrients) were applied to plots in a factorial treatment arrangement. Experimental plots were made from PVC cylinders (0.1 m^2; 1.9-cm wall thickness) cut to appropriate lengths. The lower 5-cm of cylinders for the elevated plots were inserted into the marsh surface for stability. Nonelevated plots were established by inserting 5-cm high cylinders into the marsh so that the tops of the cylinders were at ambient marsh elevation. Each cylinder had numerous holes (0.64-cm diameter) drilled in them above and below the sediment surface to minimize the effect of the cylinder on soil water drainage.

Elevated plot cylinders were filled with adjacent dieback soil so that elevated plots consisted of the same substrate type as nonelevated plots. Preliminary experimentation demonstrated that when plots were elevated 10 cm above ambient, very few transplants survived. Therefore, on 12 July 1989, after initial transplants were harvested and discarded, elevations were increased to a final surface elevation of 30 cm, which was an elevation equivalent to the nearby streamside marsh.

After soil was added to elevated plots, five equal-sized *S. alterniflora* transplants (culms with attached roots and rhizomes) were collected in an area adjacent to dieback areas and planted into elevated and nonelevated plots on 12 July 1989. *Spartina alterniflora* was transplanted into elevated and nonelevated plots in each of the five dieback sites (each of the five dieback sites contained all treatment combinations).

Macro- and micronutrients were applied to plots at both elevations. Nutrient treatments were as follows: control, micronutrients only, macronutrients only, and micro- and macronutrients. Macronutrients were applied in 1-oz gelatin capsules at the following rates: 1000 kg N/ha (ammoniacal N), 408 kg P/ha (as P_2O_5), and 771 kg K/ha (as K_2O). Capsules were placed into the soil to a depth of approximately 5 cm, and empty gelatin capsules were placed in plots not receiving macronutrients. Micronutrients (Fe, Mn, Zn, and Cu) were injected with a syringe and cannula to a 10-cm depth at the rates of 20 kg Fe/ha (sequestrone Fe), 5.8 kg Mn/ha (as $MnCl_2 \cdot 6H_2O$), 5.0 kg Zn/ha (as $ZnCl_2$), and 5.0 kg Cu/ha (as $CuCl_2$). Deionized distilled water was injected into plots not receiving micronutrients. Nutrient additions were applied in two applications: the first on 16 May 1989 (previous to adding the 20-cm extension), and the second after the 20-cm extension was added on 12 July 1989. Because the nutrient additions began before the elevation was increased to 30 cm, the first nutrient application experienced two populations of plants.

Movable boardwalks were used throughout the experiment to minimize the disturbance to the study area.

Soil Samples

At the conclusion of the experiment (17 November 1989), soil and plant samples were collected for analysis. Within each plot, soil redox potential (Eh) was measured at a 1-cm and a 15-cm depth with brightened platinum electrodes that were allowed to equilibrate for approximately 0.5 h. Each electrode was checked before use with quinhydrone in pH 4 buffer (218 mV at 25°C). The potential of a calomel reference electrode (+244 mV) was added to each value to calculate Eh. After Eh measurements were made, a soil core (5-cm diameter × 15-cm length) was collected into an airtight centrifuge bottle, purged with N_2 through a rubber septum in the cap, and placed on ice for transport to the laboratory. Because pH did not vary substantially among study plots (CV < 3%), Eh measurements were not corrected for pH.

Interstitial water was collected from soil cores through centrifugation at 4°C and analyzed for sulfide (sulfide electrode, Lazar Research Laboratory, Los Angeles, California), pH (Altex model 3560 digital pH meter), salinity (Fisher model 152 salinity/conductivity meter), and Fe, Mn, Cu, Zn, P, and K concentrations (Fisher inductively coupled plasma argon emission spectrometer). An additional aliquot was filtered through a 0.45-μm filter and analyzed for NH_4–N concentrations according to the Technicon Industrial Method (154-71W; Berthelot technique).

Plant Samples

The number of live and dead mature (>15-cm height) culms and newly produced culms (<15-cm height) was recorded, and above- and belowground biomass was collected in each plot. Aboveground vegetation was clipped at the soil surface and placed in plastic bags for transport to the laboratory. At the laboratory, aboveground vegetation was separated into live and dead components, dried at 65°C to a constant weight, and weighed to the nearest 0.1 g. Belowground biomass was washed through a 1.6-cm mesh screen, dried, and weighed to the nearest 0.1 g. No attempt was made to separate live and dead belowground biomass.

Data Analyses

Statistical analyses were conducted with SAS (1985). Soil and plant variables were analyzed with analysis of variance as a 2^3 factorial treatment (elevated and nonelevated, micronutrients and no micronutrients, macronutrients and no macronutrients) arrangement on a randomized block design (blocking on five sites). Means separation tests on nutrient treatments within elevations were done with contrasts.

Results

Soil Response

An increase in elevation of 30 cm in unvegetated dieback areas resulted in significant changes in soil redox potential (at a 1-cm depth) and interstitial water sulfide concentrations. Redox potential (Eh) at a 1-cm depth was 295 mV higher in elevated plots than in the nonelevated plots ($P < 0.01$) (Figure 1a). However, Eh at a 15-cm depth was not significantly different between elevated and nonelevated plots (Figure 1b). Interstitial water sulfide concentrations were significantly lower in elevated plots as compared to nonelevated plots ($P < 0.01$) (Figure 1c).

In general, soil macronutrient concentrations reflected the treatment additions: soils in plots that received macronutrient additions had greater concentrations of NH_4–N and P than plots not receiving macronutrients (NH_4–N: $P < 0.01$; P: $P < 0.01$) (Table 1). Soils in plots that received micronutrient additions had significantly higher ($P < 0.05$) interstitial water Fe concentrations than plots that did not receive micronutrient additions. Other micronutrient concentrations were not significantly elevated at the harvest date (Table 1).

Macronutrient additions had a significant effect on Eh measured at a 15-cm depth (Figure 1b) but had little effect on Eh at a 1-cm depth (Figure 1a) or interstitial water sulfide concentrations (Figure 1c). Within nonelevated plots, macronutrient additions caused the Eh at a 15-cm depth to become more reduced as compared to plots not receiving macronutrients (elevated × macronutrient interaction; $P < 0.05$) (Figure 1b). Within elevated plots, there was no effect of macronutrients on Eh. Eh at a 1-cm depth and interstitial water sulfide concentrations were also unaffected by macronutrient additions (Figure 1a and c).

Additions of micronutrients appeared to poise the Eh at a 15-cm depth at a somewhat higher level: soils in plots that received micronutrient additions were slightly less reduced than plots not receiving micronutrients ($P < 0.01$) (Figure 1b). This trend was consistent in both elevated and nonelevated plots (Figure 1b). Eh at a 1-cm depth (Figure 1a) and interstitial water sulfide concentrations (Figure 1c) were not significantly affected by micronutrient additions.

There was very little variation in interstitial water salinity and pH among study plots (Table 1). Salinity did not significantly vary with respect to elevation, or with micronutrient and macronutrient additions. Inter-

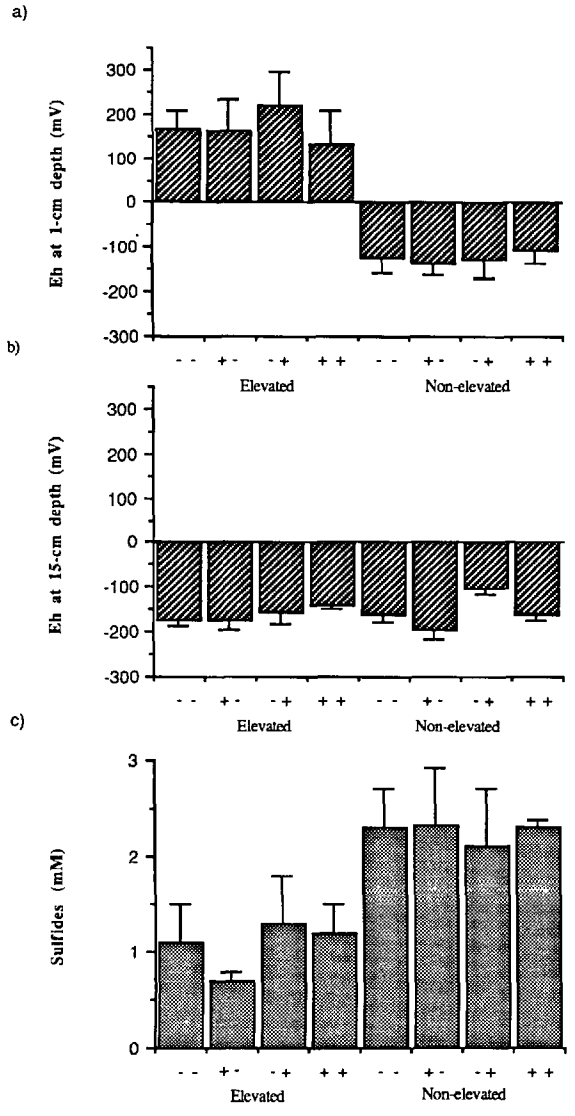

Figure 1. Eh measured at a 1-cm depth **(a)**, Eh measured at a 15-cm depth **(b)**, and interstitial water sulfides **(c)** in plots that received macronutrient (+ −), micronutrient (− +), micro- and macronutrient (+ +), and no nutrient (− −) additions in *Spartina alterniflora*-dominated marsh near (mean ± SE) Caminada Bay, Louisiana (N = 5).

stitial water pH was slightly higher in drained soils as compared to flooded soils ($P < 0.05$) (Table 1).

Plant Response

After three months of growth, there were significant differences in plant variables between elevated and nonelevated plots. Elevated plots contained more than twice the live and total (live + dead) aboveground biomass and a significantly greater number of culms than the nonelevated plots (live aboveground biomass, total aboveground biomass, and culm density: $P < 0.01$) (Figure 2a and b). Similar, but smaller, differences occurred in belowground biomass ($P < 0.01$) (Figure 2a) and newly produced culms [$P < 0.01$ (data not shown)]. There was also a greater number of live culms in elevated plots as compared to nonelevated plots ($P < 0.01$), indicating that plants in elevated plots had lower mortality rates (Figure 2b). The number of inflorescenses per plant per plot was also greater in elevated plots than in nonelevated plots ($P < 0.01$) (Figure 2c).

Micronutrient additions appeared to have had an inhibitory effect on the growth of *S. alterniflora* transplants. Live and total aboveground biomass was greater in plots not receiving micronutrients than in plots receiving micronutrients (live biomass: $P < 0.05$; total biomass: $P < 0.05$) (Figure 2a). In addition, culm density was inhibited by micronutrient additions in elevated plots (micronutrient × elevation interaction: $P = 0.051$) (Figure 2b).

There were no significant differences in live biomass or number of young culms between plots that did and did not receive macronutrient additions. However, among elevated plots, plots that received only macronutrient additions had a 61% greater culm density than control plots (contrast: control vs macronutrients only, $P < 0.05$) (Figure 2b). Fewer inflorescences per plant per plot occurred in elevated plots that received macronutrients as compared to elevated plots not receiving macronutrients (macronutrient × elevation interaction: $P < 0.01$).

Discussion

Submergence of *S. alterniflora* in inland marshes may lead to root oxygen deficiencies (Mendelssohn and others 1981, Morris and Dacey 1984), elevated soil sulfide concentrations (DeLaune and others 1983), and decreased plant N uptake (Morris and Dacey 1984, Bradley and Morris 1990, Koch and others 1990), which eventually reduces plant productivity. Sulfide inhibits *S. alterniflora* productivity primarily by depressing energy production from root respiration (Koch and others 1990) and by decreasing N uptake (Bradley and Morris 1990, Koch and others 1990).

In this study, the ambient elevation plots contained highly anoxic soils (mean Eh at 1-cm depth < −126 mV; at 15-cm depth < −156 mV) and relatively high interstitial water sulfide concentrations (averaging 2.2 mM). An increase in the elevation of the plots by 30 cm (which raised plots to the elevation of the adjacent streamside marsh) resulted in less reduced soil; elevated plots had a higher Eh at a 1-cm depth (mean: 168 mV) and lower interstitial water sulfide concentrations

Table 1. Interstitial water pH and salinity (ppt), and macro- and micronutrient concentrations (ppm) in plots in *Spartina alterniflora* dominated marsh near Caminada Bay, Louisiana (N = 5)[a]

	Elevated				Non-elevated			
Variable	(− −)	(+ −)	(− +)	(+ +)	(− −)	(+ −)	(− +)	(+ +)
pH	7.51	7.52	7.52	7.39	7.30	7.37	7.38	7.39
	(0.17)[b]	(0.08)	(0.07)	(0.12)	(0.06)	(0.05)	(0.06)	(0.02)
Salinity	19.9	20.0	19.5	19.5	19.3	20.3	19.7	19.0
	(0.6)	(0.5)	(0.2)	(0.4)	(0.2)	(0.5)	(0.4)	(0.0)
NH_4-N	6.3	21.5	5.6	30.3	6.3	34.5	8.5	26.7
	(1.6)	(2.9)	(0.7)	(7.1)	(1.0)	(5.8)	(2.4)	(5.7)
P	11.3	23.8	7.9	65.3	6.7	50.8	13.7	78.4
	(3.2)	(10.2)	(5.4)	(33.4)	(1.7)	(30.3)	(2.2)	(34.5)
K	175.5	241.9	191.3	145.3	135.0	194.9	132.5	136.0
	(40.2)	(17.9)	(31.3)	(35.2)	(32.2)	(41.8)	(46.9)	(46.5)
Cu	0.29	0.14	0.47	0.34	0.17	0.26	0.31	0.19
	(0.06)	(0.05)	(0.25)	(0.11)	(0.03)	(0.07)	(0.06)	(0.04)
Mn	0.30	0.27	0.23	0.55	0.28	0.33	0.54	0.39
	(0.11)	(0.07)	(0.02)	(0.21)	(0.09)	(0.11)	(0.14)	(0.07)
Zn	0.07	0.02	0.19	0.13	0.08	0.03	0.11	0.09
	(0.02)	(0.01)	(0.19)	(0.05)	(0.01)	(0.02)	(0.03)	(0.03)
Fe	0.25	0.19	0.56	0.48	0.30	0.26	0.67	0.51
	(0.04)	(0.01)	(0.22)	(0.09)	(0.03)	(0.32)	(0.33)	(0.14)

[a]Nutrient treatments were as follows: macronutrient additions only (+ −), micronutrient additions only (− +), micro- and macronutrient additions (+ +), and no nutrient additions (− −). Results from statistical comparisons among treatments are presented in the text.

[b]Values in parentheses are standard errors.

(mean: 1.1 mM). We suspect that these changes in soil chemistry created conditions more favorable for *S. alterniflora* survival and growth: elevated plots had significantly higher above- and belowground biomass, culm density, numbers of young culms, and inflorescences per culm as compared to nonelevated plots. The greater culm density and number of young culms in elevated plots indicate that vegetative reproduction occurred more readily in elevated plots. These data suggest that if elevation is sufficiently increased in dieback areas of salt marshes, *S. alterniflora* can be successfully reestablished through transplantation.

Although an increase in elevation of 30 cm resulted in less biochemically reduced soil, elevated plots were still more reduced than streamside soils (Mendelssohn and others 1981, DeLaune and others 1983, Mendelssohn and McKee 1988). This relatively reduced soil in both elevated and nonelevated plots was probably responsible for the smaller response in *S. alterniflora* to macronutrients compared to that observed in previous reports (Patrick and DeLaune 1976, Buresh and others 1980). Our study was conducted during months in which the rate of sulfate reduction is highest [because of high temperatures (King 1988)] and both nonelevated and elevated plots had relatively high (>1 mM) interstitial water sulfide concentrations. Interstitial water sulfide concentrations in streamside soils are often less than 0.1 mM (King and others 1982, King 1988, Mendelssohn and McKee 1988), while sulfide concentrations in inland soils can exceed 3 mM (King and others 1982, King 1988). Therefore, our elevated plots, although less reduced than plots at ambient elevation, had interstitial water sulfide concentrations that were intermediate between inland and streamside marshes. As a result of this relatively high degree of soil reduction with sulfide in excess of 1 mM, NH_4^+ uptake and growth may still have been lower in elevated plots compared to that of streamside plants (Koch and Mendelssohn 1989, Bradley and Morris 1990, Koch and others 1990).

Streamside marsh soils tend to have higher concentrations of soluble micronutrients such as Fe and Mn (DeLaune and others 1983), presumably because the low sulfide concentrations in the streamside soils preclude the precipitation of Fe and Mn as insoluble metal sulfides (Gambrell and Patrick 1978 and references therein, Evans 1989). Although Mn and Fe at high levels are often toxic to wetland plants (Ponnemperuma 1965, Tanaka and others 1966), at lower levels they could play an important nutritional role. Micronutrients could potentially increase productivity of *S. alterniflora* in the following ways: (1) by precipitating sulfides, and thus alleviating the potential for sulfide toxicity (Gambrell and Patrick 1978 and references therein,

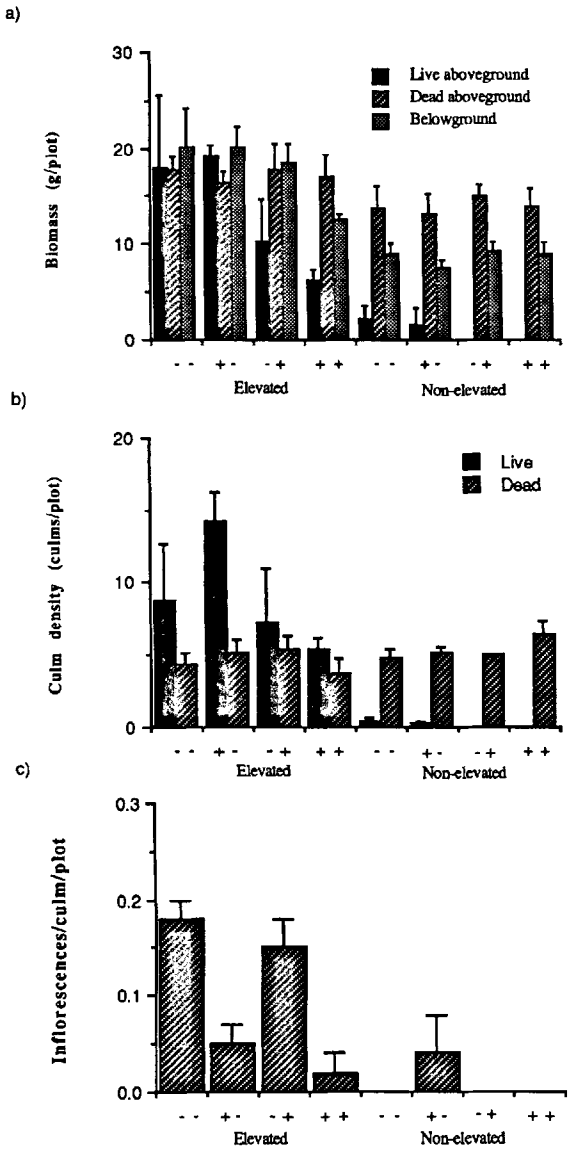

Figure 2. Biomass **(a)**, culm density **(b)**, and inflorescences per culm per plot **(c)**, in plots that received macronutrient (+ −), micronutrient (− +), micro- and macronutrient (+ +), and no nutrient (− −) additions in *Spartina alterniflora* dominated marsh near (mean ± SE) Caminada Bay, Louisiana (N = 5).

Evans 1989); (2) by poising the Eh at higher levels than ambient (Gambrell and Patrick 1978 and references therein); and/or (3) by alleviating micronutrient deficiencies. In this study, the addition of micronutrients did poise the surface Eh at levels significantly higher than plots that did not receive micronutrients. However, this increase in Eh did not stimulate growth, apparently because one or more of the micronutrient additions was toxic to *Spartina alterniflora* under these field conditions. Further research of the effects of micronutrients on *S. alterniflora* productivity should be done with single additions of these micronutrients and with various application levels.

Conclusions

Many of Louisiana's inland salt marshes are accreting at a rate that is less than what is needed to maintain elevations at a level similar to streamside marshes (DeLaune and others 1990), and as a result many inland marshes are unable to remain in the intertidal zone (Baumann and DeLaune 1981). This study demonstrated that elevation is more important than nutrients (micro and macro) in promoting survival and growth of *S. alterniflora* transplanted into dieback marshes. Moreover, the addition of nutrients to dieback areas will not result in successful plant reestablishment unless elevation is also increased. Although an increase in elevation alone will result in greater plant growth, culm densities are highest with a combination of increased elevation and fertilization. The greatest degree of transplantation success will be achieved through a concomitant addition of elevation and macronutrients.

Elevation could be increased in coastal marshes by introducing spoil from dredge activities and/or by diverting sediment from the Mississippi River into deteriorated marshes. Dredged materials, which have been proposed as a means of restoring barrier islands (Patrick and others 1984), might be useful for this purpose because they consist largely of silts and clays that should form a suitable substrate for plant growth and have already been used in many areas to create new marshes.

The proposed Mississippi River diversion projects (Bonnet Carre, Davis Pond, Caernarvon, and three sites in the southern part of the Mississippi River delta) are designed primarily to introduce fresh water rather than sediment into coastal marshes (van Beek and others 1990). The results of this study support the conclusions of Nyman and others (1990) that more emphasis should be placed on diverting sediments rather than fresh water into salt marshes.

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