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## Comments

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# Short-Term Effects of Thin-Layer Sand Placement on Salt Marsh Grasses: A Marsh Organ Field Experiment

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## Abstract

Salt marshes can build in elevation with sea-level rise through accumulation of inorganic sediment and organic matter, but marshes worldwide are under threat of drowning due to rapid rates of sea-level rise that outpace natural marsh building rates. The application of a thin layer of sediment to the marsh surface (thin-layer placement [TLP]) is a tool to build elevation and decrease flooding stress, but its effects on marsh plants are understudied, especially in New England. In a novel application of a marsh organ experiment (i.e. rows of pots at different elevations), the addition of 10 cm of sand to pots planted with Spartina alterniflora and Spartina patens resulted in fewer stems than controls for S. patens but not S. alterniflora after 2 months. However, total biomass and root mass were not significantly impacted for either species, suggesting plants will fully recover from TLP over longer timescales. Effects of TLP on biomass and stem density did not vary significantly by elevation. Although long-term research is still needed, short-term equivalency in biomass between TLP treatments and controls suggests TLP of 10 cm is a promising strategy to enhance the ability of marshes to build vertically as sea level rises in New England.

## INTRODUCTION

Salt marshes are highly productive ecosystems that occur in tidal areas with low wave energy, allowing for deposition of suspended sediment. Salt marshes are increasingly recognized for ecosystem services such as flood control, nutrient cycling, carbon storage, recreational use, and aesthetics (Barbier et al., 2011; Costanza et al., 1997). Historically, many marshes have been altered and destroyed by agriculture and development, but many consider the biggest threat facing salt marshes today to be sea-level rise (Bromberg and Bertness, 2005; Watson et al., 2017). Because ecosystem services will decline with marsh loss, resource managers in the United States and elsewhere are intent to preserve marshes that remain.

Sea-level rise can drown marsh vegetation by increasing flooding frequency and duration beyond tolerance limits (Morris et al., 2002; Watson et al., 2017). Marshes can survive

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increases in sea level by building in elevation at a similar rate. As the frequency and depth of flooding increase, a dynamic equilibrium between marsh growth and sea-level rise may result from the accumulation of belowground organic matter, trapping of inorganic sediment, and slower belowground decomposition, thereby allowing for more rapid elevation gain (Anisfeld, Tobin, and Benoit, 1999; Cahoon and Guntenspergen, 2010; Morris et al., 2002; Payne, Burdick, and Moore, 2019). Accelerating rates of sea-level rise, land subsidence, peat collapse, and reduced sediment supplies (e.g., due to dams and reforestation; see Weston, 2014) may interfere with the dynamic equilibrium, causing sea-level rise to surpass marsh elevation gain (Cahoon, 2015; Watson et al., 2017). In New England, where relative sea-level rise exceeds global rates (Goddard et al., 2015) and is approaching 5 mm/y, elevation gain is not keeping pace in microtidal (Raposa et al., 2017) or mesotidal marshes (Payne, Burdick, and Moore, 2019). Increased flooding can drown plants, causing marsh peat to collapse and convert to mudflat or open water (Day et al., 2011; DeLaune et al., 1994; Raposa et al., 2017).

One method to compensate for the higher rate of sea-level rise and low sediment supply is to artificially place sediment on the marsh, a process referred to as thin-layer placement (TLP) (Raposa et al., 2020). The type of sediment used can be sand or, more commonly, a slurry of uncontaminated dredged material (sands and silts) that may be sprayed or pumped onto the marsh (Ford, Cahoon, and Lynch, 1999; RI Coastal Resource Management Council, 2020). Studies have shown that artificially building elevation through TLP can increase plant biomass in submerging marshes (Croft et al., 2006; DeLaune et al., 1990; Ford et al., 1999; Pezeshki, DeLaune, and Pardue, 1992; Slocum, Mendelssohn, and Kuhn, 2005; Stagg and Mendelssohn, 2010; Tong et al., 2013; Walters and Kirwan, 2016). Growth may be stimulated through reduced flooding stress on plants, as shown by higher redox potential and lower sulfide levels in TLP treatments (Mendelssohn and Kuhn, 2003; Schrift, Mendelssohn, and Materne, 2008; Stagg and Mendelssohn, 2010). When dredged sediment was used, TLP sediments have also been shown to supply nutrients that may boost productivity temporarily (DeLaune et al., 1990; Mendelssohn and Kuhn, 2003; Slocum, Mendelssohn, and Kuhn, 2005). However, productivity may decrease if the final elevation after TLP lies above the species' optimal growth range (Stagg and Mendelssohn, 2010).

Whereas the benefits of TLP in Gulf of Mexico marshes are well documented, much less is known about the effect on New England marshes. North of Cape Cod, New England marshes have a shorter growing season but a 10-fold greater tidal range than Louisiana marshes (≈300 cm vs. ≈30 cm), which could cause plant and sediment processes to respond differently to TLP. Even though New England marshes are losing area due to sea-level rise, a more immediate concern is conversion of high marsh to low marsh (Smith, 2015; Watson et al., 2016), as Spartina patens, (syn. Sporobolus pumilus) is replaced by the more flood-tolerant grass, Spartina alterniflora (syn. Sporobolus alterniflorus) (Donnelly and Bertness, 2001; Warren and Neiring, 1993). Conversion to low marsh will result in a net loss of high marsh area unless new high marshes form on adjacent upland, a process termed marsh migration. Because upland slopes are often greater than slopes across high marshes in New England, high marsh area may be lost (e.g., Smith, 2020). High marsh loss reduces biodiversity and may impact the nesting success of the saltmarsh sparrow, Ammospiza caudacuta, also in decline (Gjerdrum, Elphick, and Rubega, 2005). TLP may be a method of preventing or delaying high marsh loss, but its effects on S. patens and other high marsh plants, as well as on animals, are not well studied.

A common method for studying effects of flooding on plants is to install a marsh organ experiment (Kirwan and Guntenspergen, 2015; Morris, 2007; Voss, Christian, and Morris, 2013; Wigand et al., 2016). Marsh organs consist of pots that are placed in the marsh in rows that are progressively higher in elevation, giving the structures an organ-like appearance. The marsh organ design allows for a high degree of replication and eliminates variables such as soil type and drainage. Because marsh organs are generally placed in unvegetated areas such as creeks or pools, damage to the adjacent marsh is minimal. Large-scale TLP studies on natural marshes often face regulatory barriers, making marsh organs a valuable, low-impact alternative.

It is known that TLP causes an initial disturbance, but the extent of the disturbance in New England marshes is unclear. For TLP to become an acceptable approach to increase marsh resilience to sea-level rise, it first must be shown that plants can survive burial by the added sediment. To better understand the short-term impacts of TLP on saltmarsh plants, a marsh organ experiment was used to (1) determine the initial impact of TLP on growth of the two dominant marsh grasses (S. alternilora and S. patens) and (2) determine whether effects of TLP varied by elevation.

# METHODS

The experiment was located in a small riverine marsh that is part of the Great Bay National Estuarine Research Reserve in New Hampshire (43.060717, –70.833329; Figure 1). The marsh occupies an area of roughly 2.7 ha and is bordered by forest on the north and south sides. A freshwater stream flows from a farm pond dam into the eastern end of the marsh, resulting in a gradient of brackish to saline conditions along a central tidal creek. This experiment was located in the more-saline area dominated by S. alterniflora in the low marsh and a mixture of primarily S. patens, Distichlis spicata, and Juncus gerardii in the high marsh.

## Experimental Design

Three marsh organs were constructed to determine the effects of TLP on plant biomass and stem density at different elevations. The three marsh organs (one S. patens control, one TLP, and one S. alterniflora control) were placed side by side along a tidal creek bank facing 150° SE to limit the effects of shading (Figure 2). Elevations reported as North American Vertical Datum 1988 (NAVD88) were determined using a self-leveling rotary laser that was related to a benchmark measured with a real-time kinematic GPS. Flooding rates (i.e. percent of time flooded) were based on water level recorder measurements collected over 28 days during the experiment from an Odyssey™ capacitance logger installed next to the marsh organs.

Experimental units were pots made from polyvinyl chloride (PVC) pipe (10-cm diameter, 40-cm tall), capped on one end with screened holes for drainage and filled with a mixture by volume of 45% sand, 40% peat moss, and 15% mud collected from a mudflat (for more details see Payne, Burdick, and Moore, 2019). The mixture allowed water to drain from the surface over a 6-hour period and could be easily washed from roots for belowground biomass analysis. To measure bulk density, cores were taken from four pots that were not used in the study but contained the same soil mixture. Cores were dried for 7 days at 60°C before they were weighed. Average bulk density of the soil matrix in pots was 1.56 ± 0.03 g/cm3. Pots were planted at the lab with bare-root culms collected from a nearby marsh that is breaking apart at lower elevations, likely due to sea-level rise. Spartina alterniflora plants were collected from the edges of pools, whereas S. patens plants were collected from relatively healthy areas of the high marsh. To keep biomass roughly equal between pots, the number of culms varied from 4 to 5 culms/pot for S. alterniflora or 8–9 culms/pot for S. patens, depending on the size of the plants. Pots were assigned random locations on the marsh organ structures with four replicates per elevation treatment in May 2017.

Plants were allowed to acclimate in the marsh organs until mid-July before the TLP sand treatment was applied. PVC collars and pipe were used to extend the pot height to hold the added sand (Figure 2B). To accommodate different amounts of sediment that had been deposited in pots prior to sand addition, the length of pipe extensions varied from 10.6 cm at the highest elevation to 14.6 cm at the lowest elevation. Each TLP pot received 1.27 kg of sand to increase elevation roughly 10 cm above any sediment that had already been deposited. Stems were held upright by the pipe extensions while sand was added, preventing most stems from being buried completely. The total study duration was 16 weeks or about one growing season in New England, including the 7-week period that plants acclimated on the marsh organs and the 9-week period after TLP was applied.

### Biomass Measurements

In September 2017, the number of stems taller than 3 cm was recorded, plants were clipped to the soil surface, and above and belowground biomass was measured after rinsing and drying for >2 days at 70°C. In this study, the term belowground biomass describes all plant growth beneath the soil surface, including stems that were buried in the TLP sand layer. Root mass refers to all roots and rhizomes below the soil surface (including adventitious roots) but excludes buried stems and stem bases. Root:shoot ratio is the root mass divided by aboveground biomass.

### Statistical Analysis

Plant responses were compared between TLP and control pots for two elevations of S. alterniflora and two elevations of S. patens using analysis of variance (ANOVA) in JMP Pro 15 (SAS Institute, Inc., Cary, NC). Elevations were chosen a priori to analyze as categorical or fixed variables. The Shapiro–Wilk test was used to determine whether residuals met the assumption of normality. Stem density data for S. patens were log transformed and (1/(x + 12)) was used for S. alterniflora change in stem density to produce error homogeneity and a normal distribution of residuals.

## RESULTS

Differential settling of organ structures resulted in S. alterniflora TLP elevations that were 7 cm lower than controls and, therefore, were flooded about 4% more of the time than controls prior to sand addition (Figure 3). This difference in flooding is relatively small considering the wide range of flooding conditions S. alterniflora can tolerate, though it was considered when interpreting results. The S. patens TLP elevations more closely matched controls (TLP pots = 0.95 m and 1.05 m, controls = 0.92 m and 1.02 m NAVD88).

### Impact of TLP on S. alterniflora

The lowest elevation of S. alterniflora TLP pots fell within the elevation range of the adjacent mudflat, even with the added sand, and the second elevation fell within the lower range of S. alterniflora on the adjacent marsh (Figure 2). Overall, TLP had a minimal impact on S. alterniflora, with similar total biomass between TLP pots and controls at all elevations (Figure 4A). There were fewer S. alterniflora stems per pot in TLP treatments ($p < 0.05$), but this difference existed prior to sand addition. The effect of TLP on the change in stem density was not significant (Table 1). Despite the partial burial of stems and leaves, aboveground biomass and root:shoot ratios in TLP treatments did not differ significantly from controls. Belowground biomass was also unaffected by sand addition. Root mass was 24% lower for TLP in the upper elevation, but there was no significant effect of TLP ($p = 0.265$) nor was there any significant interaction between elevation and TLP for any responses. The upper elevation had more growth than the lower elevation in terms of total biomass, aboveground biomass, belowground biomass, buried stems, and root mass (Table 1).

### Impact of TLP on S. patens

The lowest marsh organ elevation of S. patens was equivalent to the upper range of pure S. alterniflora stands on the adjacent marsh, but the added sand extended it into the range of transitional marsh (mixture of S. patens and S. alterniflora). The higher S. patens elevation in the marsh organ was equivalent to the lower end of the adjacent high marsh (Figure 2). Overall, TLP had mixed results on S. patens. Total biomass was not significantly affected by TLP, but it was 25% lower for TLP pots than controls at the upper elevation (Figure 4B). Aboveground growth was also lower in TLP treatments ($p = 0.001$), likely due to the simple burial of some leaves and stems. The root:shoot ratio was higher for the upper elevation ($p < 0.001$), and TLP pots had a higher root:shoot ratio than controls ($p < 0.05$). The effect of TLP on root mass and belowground biomass was not statistically significant, but belowground biomass was 46% higher in TLP pots than controls at the lower elevation. TLP resulted in lower stem density ($p < 0.001$), with 46% fewer stems for TLP pots at the low elevation, and 69% fewer stems at the high elevation. The change in stem density after TLP application was also lower for TLP treatments than controls ($p < 0.001$).

## DISCUSSION

Sediment addition may be a useful tool for restoring submerging marshes, but its success depends on factors such as type of sediment added, the amount of sediment applied, the final elevation reached (DeLaune et al., 1990; Mendelssohn and Kuhn, 2003; Raposa et al., 2020), and the pretreatment conditions (e.g., deteriorating marsh vs. pond; La Peyre, Grossman, and Piazza, 2009). Whereas the benefits of TLP have been well documented in southern and mid-Atlantic marshes dominated by S. alterniflora (Table 3), few studies have examined the effects of TLP on S. patens (Table 4), and none have been in New England. The results of this study show that both S. alterniflora and S. patens were able to survive 10 cm of TLP. Plant biomass and root mass were not significantly affected by TLP 2 months after treatment, but stem density and aboveground biomass may require more time to recover for S. patens. Because belowground organic matter accumulation contributes to marsh elevation growth, short-term equivalency in root mass and belowground biomass may provide some stability to the recovering marsh system after TLP. In subsequent growing seasons, regrowth and vegetative expansion of existing plants, colonization by seeds, and targeted plantings may provide for the desirable marsh cover and community composition to sustain the marsh and build resilience (Raposa et al., 2020).

## Impacts of TLP on S. alterniflora

Long-term effects of TLP have been positive for S. alterniflora in other studies, suggesting plants in the present study may have benefited from TLP over time. In Gulf of Mexico marshes dominated by S. alterniflora, studies have shown that TLP resulted in greater aboveground growth (DeLaune et al., 1990; Mendelssohn and Kuhn, 2003; Pezeshki, DeLaune, and Pardue, 1992; Tong et al., 2013), belowground growth, total biomass (Stagg and Mendelssohn, 2010), and increased resilience to disturbances (Stagg and Mendelssohn, 2011) in the following growing season and beyond (Table 3). Similar to the present study, Croft et al. (2006) showed no effect of 10 cm of sediment addition on stem density in the first growing season. However, they found a positive effect on stem density in the second growing season. Benefits of TLP are attributed to greater redox potential (Croft et al., 2006; Mendelssohn and Kuhn, 2003) and the nutrients contained within the added sediment (DeLaune et al., 1990; Mendelssohn and Kuhn, 2003). In Louisiana, Slocum, Mendelssohn, and Kuhn (2005) found that the placement of dredged sediment on the marsh resulted in a pulse of growth that subsided after 3 years, but plant height and plant cover remained higher than in areas that did not receive sediment after 7 years. In another Louisiana marsh 7 years after sediment was added, Tong et al. (2013) found that belowground biomass was higher in TLP treatments than degraded areas but still lower than in healthy areas, suggesting that TLP may prevent marsh deterioration, but full recovery to healthy marsh may be impossible at some sites or may require more than 7 years (Tong et al., 2013) or more sediment additions over time.

## Impacts of TLP on S. patens

The effects of TLP on S. patens are less clear, mostly due to a lack of long-term studies. In Louisiana, production in marshes dominated by S. patens, D. spicata, or Juncus roemarianus was shown to increase as deposition from hurricane overwash increased from 0 to 11 cm (Baustian and Mendelssohn, 2015). Other studies show that S. patens can recover from 5 cm of deposition after a year (Burger and Shisler, 1983) and as much as 100 cm of storm overwash deposition after several years through recolonization (Travis, 1977). New England marshes dominated by S. patens have been shown to recover to 75% vegetative cover within one growing season after receiving 0.1–9 cm of sediment from ice deposition, although areas that received sediment still had lower cover than controls (Moore et al., 2021). Using marsh organs, TLP resulted in lower stem density and higher root:shoot ratios, perhaps due to burial of aboveground material. Root:shoot ratio may have also been higher in TLP treatments due to adventitious root production. Similar to these results, Matske and Elsey-Quirk (2018) found in a greenhouse study that 8 cm of TLP resulted in lower stem density of S. patens than controls after 22 weeks. In 2013, Graham and Mendelssohn (2013) reported that TLP resulted in greater total productivity only for sediment treatments >15 cm, likely because all other treatments subsided to elevations that nearly matched controls. Overall, S. patens has not been shown to benefit as strongly from sediment addition as S. alterniflora, but recovery to near-reference levels is likely within a year when burial is <10 cm.

## The Role of Elevation, Sediment Type, and Timing

Because elevation plays such an important role in determining species distribution (Bertness, 1991; Pennings and Callaway, 1992), it is essential to ensure the final elevation following TLP lies within the optimal range of the species. Sediment addition can be followed by compaction and subsidence, both in the added sediment and in the underlying peat (Cornu and Sadro, 2002; McKee and Cherry, 2009), making it difficult to predict the final elevation after sediment is applied or the final thickness after sediment redistributes and/or settles. Though not significant ($p = 0.109$), TLP application decreased total biomass at the upper elevation of S. patens but had a minimal effect on the low elevation, suggesting that lower elevations may benefit more or recover more quickly from TLP than upper elevations. In general, however, pretreatment elevation did not significantly affect the outcome of TLP, perhaps due to the small range of elevations used. In Louisiana, Stagg and Mendelssohn (2010) showed that building the marsh 13–19 cm above ambient elevations increased productivity, but higher elevations resulted in lower productivity, likely due to a lack of water or nutrients. Other studies have shown TLP to be less effective at higher elevations, but not limiting to plant growth (Croft et al., 2006; Mendelssohn and Kuhn, 2003).

Texture, grain size, organic matter, and contaminant content of the applied sediment may influence plant recovery following TLP, and most studies in natural marshes have used uncontaminated dredged material consisting of a mixture of silt, clay, and sand. Sand was used in this study because it drains well, which helps decrease sulfide concentrations and salinity that can impair productivity (Wigand et al., 2016). However, S. alterniflora plants grown in mesocosms filled with natural mud were shown to have higher aboveground productivity than those grown in sand, likely due to greater nutrient availability (Reimold, Hardisky, and Adams, 1978; Wigand et al., 2016). Similarly, Slocum, Mendelssohn, and Kuhn (2005) found that nutrient availability was lower in the coarser sediment that was applied to a marsh in Louisiana, presumably due to leaching. Therefore, trade-offs should be considered before choosing sediment type for TLP projects.

Timing of sediment application is also an important consideration. Because sand was applied during the growing season in this study, a large portion of live aboveground material was smothered. Applying sediment in early spring while plants are dormant in New England could reduce damage to plants and minimize impacts to nesting birds such as saltmarsh sparrows. Future work should investigate how timing of application affects plant and animal responses to TLP. In addition, further study is needed to determine long-term effects of TLP on plants in New England, particularly on S. patens and other high marsh plants.

## CONCLUSIONS

Thin-layer placement is a promising strategy for preventing loss of submerging marshes. The finding that TLP of 10 cm reduced stem density and aboveground biomass for S. patens does not discount the many studies showing benefits of TLP but shows that short-term effects (2 months) on aboveground growth may be negative. However, TLP did not significantly impair total biomass or root mass for either species. The effectiveness of TLP in restoring S. alterniflora marshes in Louisiana is well established, but more studies must be done to determine recovery time using a variety of species, elevations, materials, and application types in New England. If frequent TLP treatment is required or dredged sediment is not readily available, resource managers may wish to prioritize more cost-effective strategies such as preserving land along marsh boundaries and removing barriers to facilitate migration inland. Still, TLP is likely an effective technique for enhancing marsh resilience to sea-level rise, especially when migration of a deteriorating marsh is blocked by steep slopes or development (Bozek and Burdick, 2005).

## Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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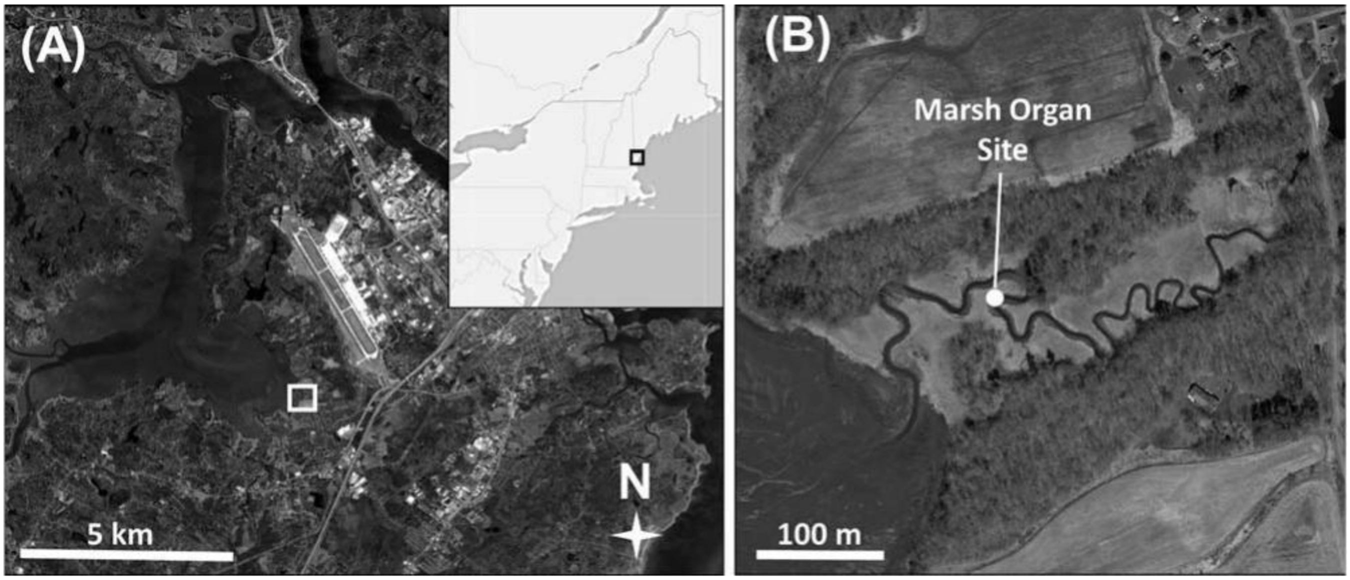

**Figure 1.**

The study site in the Great Bay Estuary, New Hampshire, showing (A) an overview of the estuary with the study site marked by a white box and (B) a close-up of the marsh organ location. Imagery: Google Earth, 2020.

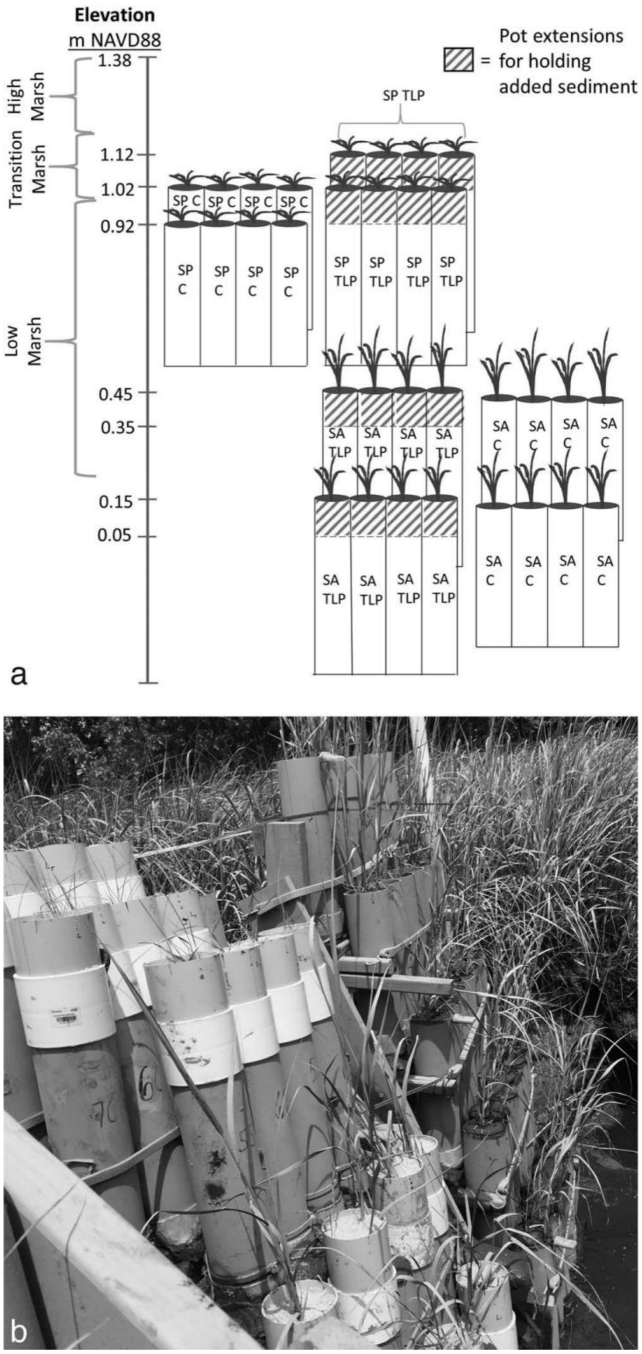

**Figure 2.**

(A) Setup of three marsh organ structures placed side by side in a tidal creek. Brackets on the left show elevation ranges of habitat types of the adjacent marsh. Letters indicate pot treatments: SP C = S. patens controls, SP TLP = S. patens thin-layer placement, SA C = S. alterniflora controls, SA TLP = S. alterniflora thin-layer placement. (B) Experimental pots after 10 cm of sand was added to TLP treatments.

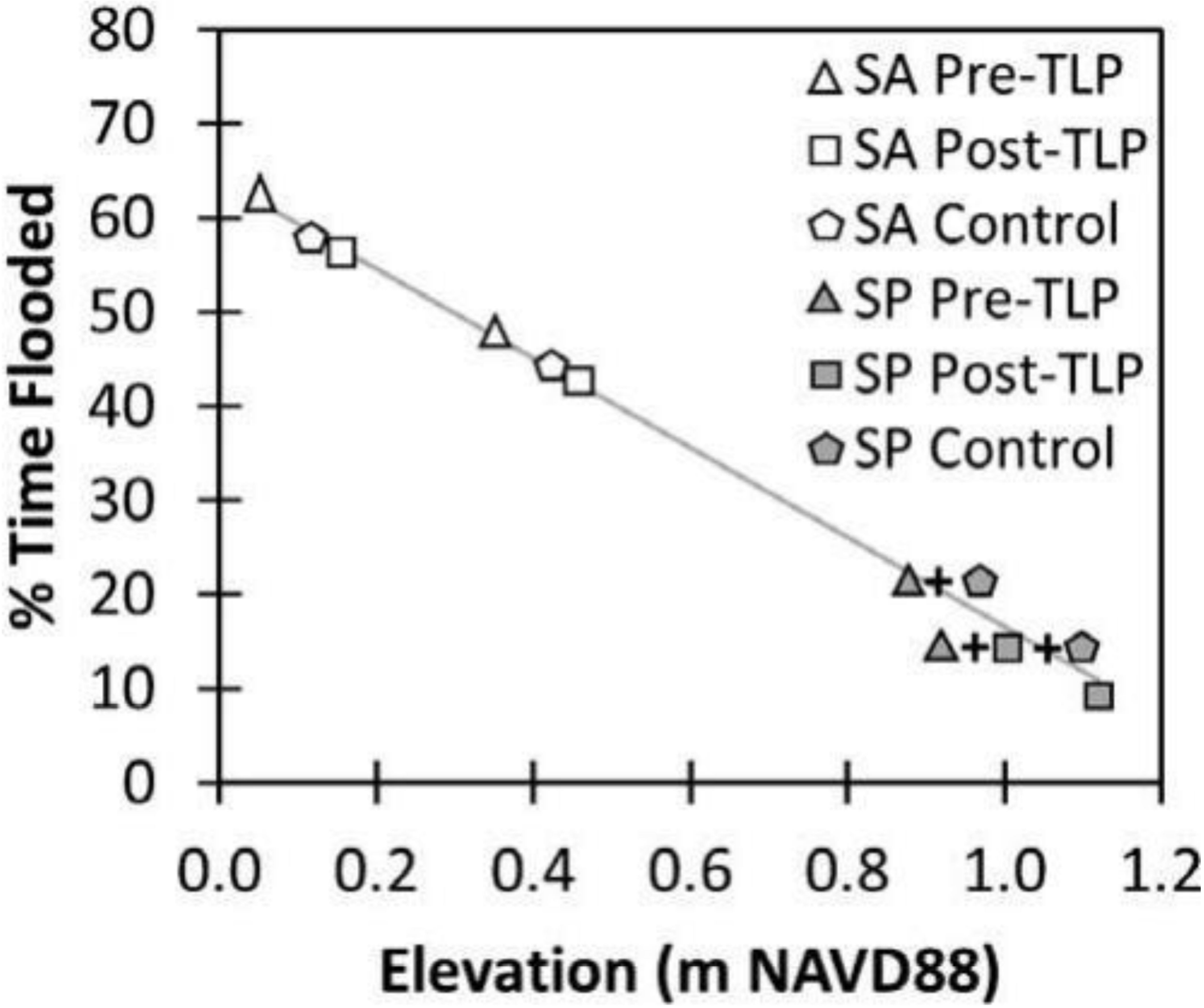

**Figure 3.**

Relationship between elevation and percent time flooded. Symbols indicate the placement of each treatment. SA = S. alterniflora, SP = S. patens.

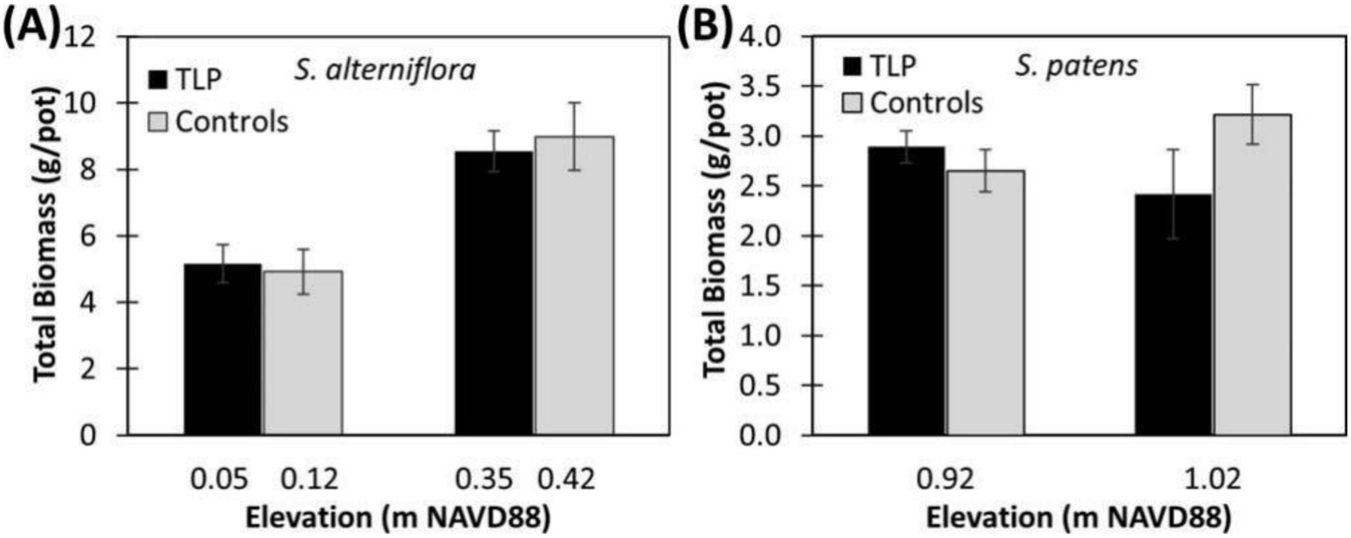

**Figure 4.**

Total biomass (dry weight) of (A) S. alterniflora and (B) S. patens. Error bars show standard error.

## Table 1

Spartina alterniflora biomass metrics for TLP vs. controls at initial elevations.

| | | | | | ***p* Values** | | |
|---|---|---|---|---|---|---|---|
| | **0.05 m NAVD88 TLP** | **0.12 m NAVD88 Control** | **0.35 m NAVD88 TLP** | **0.42 m NAVD88 Control** | **Elevation** | **TLP** | **Elev. × TLP** |
| Total biomass | 5.16 ± 0.58 | 4.92 ± 0.67 | 8.54 ± 0.62 | 8.98 ± 1.02 | <0.001[***] | 0.896 | 0.658 |
| AG biomass | 2.06 ± 0.47 | 2.53 ± 0.38 | 3.52 ± 0.28 | 3.49 ± 0.33 | 0.007[**] | 0.577 | 0.520 |
| BG biomass | 3.10 ± 0.45 | 2.40 ± 0.34 | 5.02 ± 0.51 | 5.49 ± 0.73 | <0.001 [***] | 0.830 | 0.289 |
| Buried stems | 0.72 ± 0.12 | NA | 1.24 ± 0.13 | NA | 0.026[*] | | |
| Roots | 2.23 ± 0.29 | 2.10 ± 0.32 | 3.68 ± 0.38 | 4.85 ± 0.67 | <0.001 [***] | 0.265 | 0.170 |
| Adventitious roots | 0.15 ± 0.04 | NA | 0.11 ± 0.03 | NA | 0.472 | | |
| Rootrshoot ratio[†] | 1.23 ± 0.28 | 0.85 ± 0.08 | 1.06 ± 0.13 | 1.38 ± 0.13 | 0.310 | 0.849 | 0.063 |
| Final stems/pot[‡] | 5.3 ± 0.8 | 6.5 ± 0.6 | 4.8 ± 0.8 | 7.5 ± 0.6 | 0.727 | 0.014[‡] | 0.305 |
| Δ stems/pot | + 1.3 ± 0.8 | + 1.3 ± 1.0 | +0.5 ± 0.9 | +2.5 ± 0.6 | 0.820 | 0.295 | 0.242 |

Aboveground (AG) biomass includes all plant matter above the final soil surface. Belowground (BG) biomass includes lower roots, adventitious roots, and buried stems I stem bases. Root biomass only includes lower roots and adventitious roots (not buried stems). A Stems /pot is the final number of stems minus the initial number of stems just before TLP was applied. Data shown are means ± standard error of 4 replicates.

[†] Does not include buried stem biomass.

[‡] Difference between controls and TLP pots was significant before TLP was applied.

[*] $p < 0.05$,

[**] $p < 0.01$,

[***] $p < 0.001$

### Table 2

Spartina patens biomass metrics for TLP vs. controls at initial elevations.

| | **0.92 m NAVD88** | | **1.02 m NAVD88** | | ***p* Values** | | |
|---|---|---|---|---|---|---|---|
| | **TLP** | **Control** | **TLP** | **Control** | **Elevation** | **TLP** | **Elev. × TLP** |
| Total biomass | 2.89 ± 0.16 | 2.65 ± 0.21 | 2.42 ± 0.45 | 3.21 ± 0.30 | 0.883 | 0.373 | 0.109 |
| AG biomass | 0.93 ± 0.04 | 1.31 ± 0.13 | 0.58 ± 0.15 | 1.22 ± 0.12 | 0.094 | 0.001 ** | 0.300 |
| BG biomass | 1.96 ± 0.13 | 1.34 ± 0.10 | 1.83 ± 0.32 | 1.99 ± 0.21 | 0.240 | 0.300 | 0.090 |
| Buried stems | 0.78 ± 0.09 | NA | 0.47 ± 0.07 | NA | 0.041 * | | |
| Roots | 0.99 ± 0.13 | 1.10 ± 0.11 | 1.31 ± 0.28 | 1.83 ± 0.21 | 0.018 * | 0.127 | 0.307 |
| Adventitious roots | 0.19 ± 0.10 | NA | 0.07 ± 0.04 | NA | 0.316 | | |
| Root:shoot ratio † | 1.06 ± 0.11 | 0.87 ± 0.13 | 2.45 ± 0.37 | 1.52 ± 0.15 | <0.001 *** | 0.025 * | 0.115 |
| Final stems/pot | 11.3 ± 1.1 | 20.8 ± 1.7 | 6.5 ± 1.8 | 20.8 ± 2.1 | 0.072 | <0.001 *** | 0.075 |
| Δ stems/pot | +1.3 ± 1.9 | + 12.0 ± 2.4 | −5.5 ± 1.7 | + 10.3 ± 1.9 | 0.060 | <0.001 *** | 0.241 |

Aboveground (AG) biomass includes all biomass above the final soil surface. Belowground (BG) biomass includes lower roots, adventitious roots, and buried stems I stem bases. Root biomass only includes lower roots and adventitious roots (not buried stems). Δ Stems/pot is the final number of stems minus the initial number of stems just before TLP was applied. Data shown are means ± standard error of four replicates.

† Does not include buried stem biomass.

* $p < 0.05$,

** $p < 0.01$,

*** $p < 0.001$

## Table 3

Summary of TLP benefits to S. alterniflora shown in this and other studies.

| Study Details | | | | TLP Effect | | | | |
|---|---|---|---|---|---|---|---|---|
| Study | Location | Study Period (~mo) | Sediment Depth (cm) | AG Biomass | Total Biomass | Cover % | Plant Height | Stem Dens. |
| DeLaune et al., 1990 | Louisiana | 4, 16[†] | 4–6 | = | | | | + |
| | | | 8–10 | + | | | | + |
| Pezeshki, DeLaune, and Pardue, 1992 | Louisiana | 10, 22[†] | 4–6 | + | | | | + |
| | | | 8–10 | + | | | | + |
| Ford, Cahoon, and Lynch, 1999 | Louisiana | 12 | 2.3 | | | =[‡] | | |
| Mendelssohn and Kuhn, 2003 | Louisiana | 22–31 | Trace | | = | = | = | |
| | | | <15 | | = | + | = | |
| | | | 15–30 | | + | + | + | |
| | | | >30 | | + | + | + | |
| Slocum, Mendelssohn, and Kuhn, 2005 | Louisiana | 20–83 | −5–20[§] | +[‖] | | +[‖] | +[‖] | |
| Croft et al., 2006 | North Carolina | 17 | 2.5 | | | | | +[¶] |
| | | | 5 | | | | | +[¶] |
| | | | 10 | | | | | +[¶] |
| Stagg and Mendelssohn, 2010 | Louisiana | 35–59 | 29–32[§] | | +[¶] | | | |
| | | | 30–36 veg[§,#] | | +[¶] | | | |
| | | | 35–38[§] | | =[¶] | | | |
| | | | 37–2[§] | | =[¶] | | | |
| Tong et al., 2013 | Louisiana | 89 | 30.7[§] | =[††] | | | =[††] | =[††] |
| | | | 34.1 veg[§,#] | =[††] | | | =[††] | =[††] |
| | | | 36.8[§] | =[††] | | | =[††] | +[††] |
| | | | 39.4[§] | =[††] | | | –[††] | =[††] |
| Walters and Kirwan, 2016 | Virginia | 6 | 5 | | + | | | |
| | | | 10 | | = | | | |
| | | | 15 | | = | | | |
| | | | 30 | | Died | | | |
| | | | 60 | | Died | | | |
| Payne *et al.* (this study) | New Hampshire | 2 | 10 | = | = | | | =[††] |

Plus signs denote increases compared to untreated areas, equal signs indicate a nonsignificant difference, and minus signs denote decreases.

[†] Sediment was applied over two phases, one in 1986 and one in 1987.

[‡] Higher than pretreatment but not reference areas

[§] Height above ambient marsh

[‖] Initially positive relationship with elevation / sediment depth that diminished over time

[¶] Compared to degraded marsh controls

[#] Veg plots recovered much faster (within 1 year) than other plots and were made a separate treatment.

[††] Compared to ambient marsh controls. All plants died in degraded marsh controls.

[‡‡] Stem density was lower in TLP treatments but the difference existed prior to sediment addition.

## Table 4

Summary of effects of sediment addition on S. patens and marshes dominated by S. patens shown in this and other studies.

| Study Details | | | | Effect of Sediment | | | |
|---|---|---|---|---|---|---|---|
| **Study** | **Location** | **Study Period (~Months)** | **Sediment Depth (cm)** | **AG Biomass** | **Total Biomass** | **Cover %** | **Stem Dens.** |
| Ford, Cahoon, and Lynch, 1999 | Louisiana | 12 | 2.3 | | | Died[†] | |
| La Peyre, Grossman, and Piazza, 2009[‡] | Louisiana | 84 | Marsh 15.2 | = | | = | |
| | | | Pond 15.2 | = | | = | |
| | | 96 | Marsh 15.2 | - | | - | |
| | | | Pond 15.2 | = | | = | |
| Graham and Mendelssohn, 2013 | Louisiana | 26 | <10 | = | = | | |
| | | | 10–15 | = | = | | |
| | | | >15 | + | + | | |
| Matske and Elsey-Quirk, 2018 | Greenhouse | 5 | 8 | | | | - |
| Moore et al. (in press) | Massachusetts | 8 | 0.1–1.9 | | | - | |
| | | | 2.0–3.9 | | | - | |
| | | | 4.0–9.0 | | | - | |
| Payne et al. (this study) | New Hampshire | 2 | 10 | - | = | | - |

Studies on sediment deposition from storms as well as from TLP were included. Plus signs denote increases compared to untreated areas, equal signs indicate no significant difference, and minus signs denote decreases.

[†] Plants died in both reference and treated areas.

[‡] Interpreted from Figure 6. Only the two sites where sediment thickness was stated (Bayou Dupont and Lake Salvador) were included.