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Evaluating Thin-Layer Sediment Placement as a Tool for Enhancing Tidal Marsh Resilience: a Coordinated Experiment Across Eight US National Estuarine Research Reserves

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Abstract
Thin-layer sediment placement (TLP) is a promising management tool for enhancing tidal marsh resilience to rising seas. We conducted a 3-year experiment at eight US National Estuarine Research Reserves using a standardized implementation protocol and subsequent monitoring to evaluate effects of sediment placement on vegetation in low and high marsh, and compared this to control and reference plots. Sediments added to experimental plots were sourced from nearby quarries, were sandier than ambient marsh soils, and had more crab burrowing, but proved effective, suggesting that terrestrial sources can be used for tidal marsh restoration. We found strong differences among sites but detected general trends across the eight contrasting systems. Colonization by marsh plants was generally rapid following sediment addition, such that TLP plot cover was similar to control plots. While we found that 14-cm TLP plots were initially colonized more slowly than 7-cm plots, this difference largely disappeared after three years. In the face of accelerated sea-level rise, we thus recommend adding thicker sediment layers. Despite rapid revegetation, TLP plots did not approximate vegetation characteristics of higher elevation reference plots. Thus, while managers can expect fairly fast revegetation at TLP sites, the ultimate goal of achieving reference marsh conditions may be achieved slowly if at all. Vegetation recovered rapidly in both high and low marsh; thus, TLP can serve as a climate adaptation strategy across the marsh landscape. Our study illustrates the value of conducting experiments across disparate geographies and provides restoration practitioners with guidance for conducting future TLP projects.

Keywords Tidal marsh · Sediment addition · Sea-level rise · Resilience · National Estuarine Research Reserves

Introduction

Accelerated climate change is leading to rapid changes in environmental conditions, including increased temperatures, decreasing extent of ice caps, rising seas, and altered ocean chemistry (Karl and Trenberth 2003; Doney et al. 2011). These changes can lead to reduced ecological function and services provided by ecosystems, such as decreased carbon sequestration and thus decreased climate change mitigation (Schröter et al. 2005; Runting et al. 2017). Conservation scientists and resource managers are increasingly recognizing the need for adaptation strategies to enhance resilience of ecosystems in the face of climate change (Munang et al. 2013); we use the term "resilience" as it has been developed in the ecological literature (e.g., Holling 1973; Gunderson 2000) to indicate the ability of a system to resist and recover from perturbation.

Tidal marshes are a highly valued ecosystem found along protected coastlines in middle and high latitudes worldwide. They provide many regionally important ecosystem services, including nursery habitat for commercially fished species, shoreline protection from storms, and water quality improvement (Gedan et al. 2009, 2011), as well as the global service of climate change mitigation through carbon sequestration (Mcleod et al. 2011; Drake et al. 2015). Human activities, especially diking and draining of marshes, have resulted in

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extensive loss of tidal marsh extent over the past century (Kennish 2001; Coverdale et al. 2013; Brophy et al. 2019). An increasing threat to tidal marshes comes from rising sea level whereby marshes must continually gain sufficient elevation to keep pace with accelerated sea-level rise (SLR) or be lost in their current locations (Kirwan and Megonigal 2013; Cahoon et al. 2019). Some tidal marshes will be able to move inland, migrating to higher ground (Kirwan et al. 2016; Osland et al. 2022), but this is not possible where steep slopes or human infrastructure are adjacent to marshes (Molino et al. 2021). To ensure future representation of tidal marshes in coastal systems, managers have begun exploring climate adaptation strategies to build resilience to SLR (Wigand et al. 2017).

To protect tidal marshes in their current footprint, one potential approach is to increase their "elevation capital" so the vegetation remains high enough to avoid excessive inundation (Fig. 1) (Cahoon et al. 2019). Thin-layer sediment placement (TLP) is the application of sediment to increase marsh surface elevation (Wilbur 1992). Typically, TLP involves spraying or piping a sediment slurry under high pressure, using a similar approach to hydraulic dredging (Ray 2007). Indeed, early examples of TLP on marshes were conducted for convenience, as a mechanism to dispose of sediments dredged from nearby ditches or channels. But interest soon grew in potentially beneficial effects on marshes (Reimold et al. 1978). While TLP may seem like an artificial anthropogenic management strategy, it can mimic

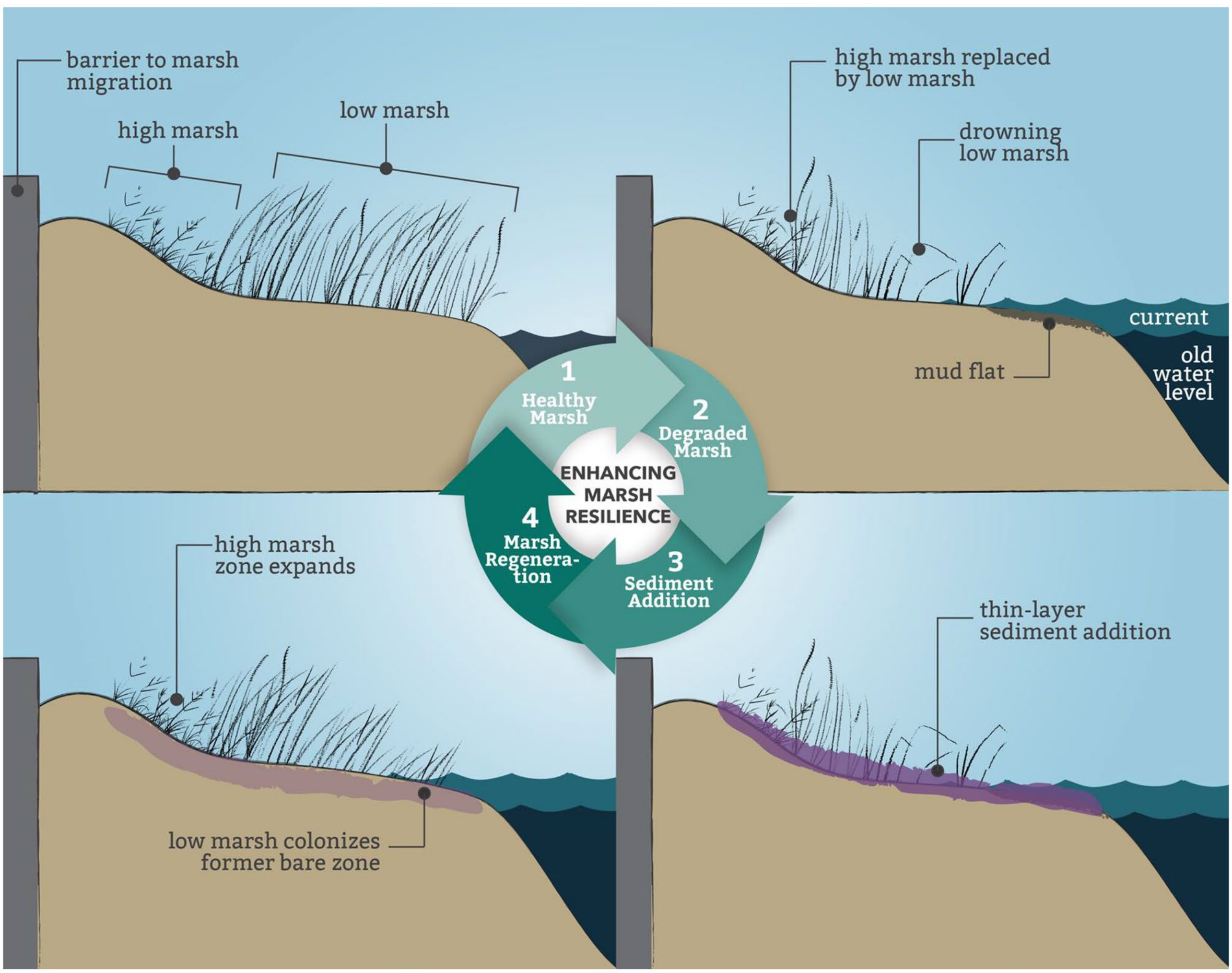

Fig. 1 Conceptual diagram illustrating effects of sea-level rise on high and low salt marsh habitats and the use of sediment addition as a restoration tool to increase resilience of both these habitats. At time 1 (upper left), there is an extensive low marsh, dominated by a single species, and landward of that, high marsh with other species represented. At time 2 (upper right), accelerated sea-level rise has drowned the low marsh, resulting in bare ground, and high marsh has been largely replaced by the low marsh dominant; further landward migration of high marsh is prevented by a barrier. At time 3 (lower right), thin-layer sediment addition raises the elevation so the marsh platform is inundated similarly as at time 1. At time 4 (lower left), low and high marsh habitat is well on the way to recovering back to baseline time 1 conditions. Diagram created by caravanlab.com

episodic sediment deposition from storms (Allison 1996; Roman et al. 1997; Walters and Kirwan 2016). Any sediment that falls within acceptable ranges of physical and chemical characteristics can theoretically be used in TLP projects, not only dredged material, and many application methods beyond high pressure spraying may be feasible. Long term, an estuary where sediment supply is too limited to sustain marshes may benefit more from augmentation with sediment provided from a source outside the estuary, such as sediment generated by upland construction projects, than from movement of dredged sediment from nearby channels to marshes, which does not increase net supply for the estuary (Ganju 2019).

Despite the promise of TLP as one of very few broadly applicable climate adaptation strategies to protect tidal marshes within their current footprints, it has been thoroughly investigated in relatively few places. The majority of published studies of TLP in marshes come from Louisiana, USA (e.g., DeLaune et al. 1990; Slocum et al. 2005; La Peyre et al. 2009). More recently, investigations have been undertaken elsewhere in the USA, including Oregon (Cornu and Sadro 2002), North Carolina (Croft et al. 2006), New Jersey (VanZomeren et al. 2018), and California (Thorne et al. 2019), with more projects underway in other states (e.g., Rhode Island, New York, Virginia). Most past studies focused on low marsh areas that had already deteriorated or were at risk of imminent loss, employing TLP as a triage strategy to save drowning marshes. In addition to saving drowning low marshes, which are often dominated by a single widespread species, TLP also could also be used to restore high marsh communities, which are typically more diverse than the low marsh and are at risk of loss due to landward migration of low marsh species in the face of SLR (Fig. 1). Low versus high marsh communities often receive different amounts of natural sediment deposition (Butzeck et al. 2015; Moore et al. 2021) and respond differently to nutrient-enrichment (Krause et al. 2019), highlighting the need for more studies across the elevational landscape of marshes. Most past TLP studies also used dredged sediments, which are typically fairly sandy (e.g., Thorne et al. 2019). Sediment thickness and type can affect outcomes of TLP (Reimold et al. 1978), but relatively few studies have conducted controlled experiments manipulating sediment thickness and type. To determine where large-scale TLP projects would be effective for marsh conservation or restoration, and with what sediment types and thickness, there is a critical need for more robust tests of TLP in different geographies, plant communities, salinities, and marsh elevations (Nelson et al. 2020).

We conducted a coordinated restoration experiment across eight tidal marshes associated with US National Estuarine Research Reserves (NERRs) to test TLP as a climate adaptation strategy for enhancing tidal marsh resilience. We engaged an advisory committee of ten representatives from coastal management agencies to inform the design of the experiment and ensure questions, treatment levels, and outputs were relevant to end-users. Our overarching goal was to examine TLP with replicated plots in a field experiment across disparate geographies, to seek both general similarities in responses across all sites, and to identify differences among sites. Another objective was to compare the use of TLP to achieve restoration goals in low vs. high marsh communities. At low elevations, we focused on areas where mudflats or pannes had recently formed, to assess whether TLP can increase vegetation cover and reduce bare ground. At high elevations, we focused on enhancing representation by high marsh species that are in danger of local extirpation as low marsh species migrate landward. We also examined the effect of sediment thickness, comparing thinner vs. thicker layer additions. Bioturbation by crabs can play an important role in tidal marsh sediment dynamics (Koo et al. 2019) and can affect restoration of tidal marsh vegetation (Liu et al. 2020), so we also quantified crab burrowing. Finally, we were interested in the influence of sediment composition, which can affect porewater conditions and plant growth. At a subset of the sites, we examined biochar soil amendments and compared upland sediments from quarries vs. marine sediments from dredged channels. The coordinated experiment was conducted within a robust spatial and temporal monitoring framework, with comparisons among control, treatment, and reference plots, and assessments at multiple timepoints to track the trajectory of change.

Methods

Study Sites

Our experiment was conducted at tidal marshes, or “sites,” in eight NERRs to examine effects of TLP across diverse geographies (Fig. 2). Six sites were located along the eastern coast of the USA in Great Bay NH (GRB), Waquoit Bay MA (WQB), Narragansett Bay RI (NAR), Chesapeake Bay MD (CBM), Chesapeake Bay VA (CBV), and North Carolina (NOC), and two on the western coast of the USA in San Francisco Bay CA (SFB) and Elkhorn Slough CA (ELK) (Online resources: Study sites). These eight sites collectively span a broad range of geomorphic and hydrologic conditions, and each supported intact areas of low and high marsh with representative plant communities but also exhibited recent indicators of SLR impacts, allowing us to test whether TLP can reverse these changes (Table 1).

Fig. 2 Study sites. Locations of the eight NERRs participating in this experiment (blue marker pins), with locations of all remaining Reserves in the conterminous USA also shown for context

TLP in Low vs. High Marsh

One objective of the experiment was to compare TLP effects in low vs. high marsh habitats. Low marsh plots were located near the seaward elevational limit of marsh vegetation at each site, in areas with low vegetation cover (0–50% target) due to recent marsh conversion to mudflats or pannes. High marsh plots were located in areas just seaward of the elevation that sustains high marsh communities representative of each site (for species found at each site, see Online resources: Study sites). These were typically areas where the low marsh dominant had recently increased its distribution landward, leading to reduced cover of the high marsh species. Thus, initial vegetation cover targets (i.e., degraded conditions) were different for the two elevations: in the low marsh, we sought areas with low total cover; in the high marsh, we sought areas with low cover by high marsh species (but these areas often had high total cover).

Sediment Type and Thickness

Our original intent was to add sediments dredged from subtidal areas close to each marsh, but dredged material was not readily available at some sites. Instead, we used upland sediments obtained from local quarries. There is precedent for using quarried sediments in large-scale TLP projects (Berkowitz and VanZomeren 2020), and we identified a standardized target grain-size mixture to ensure that relatively similar sediments were added to plots at all sites for consistency (target of 75% sand, 25% silt + clay), similar to dredged and quarry sediments used in local TLP projects. All quarry sediments were obtained without amendments or fertilizers, but to provide some replication of estuarine organic material and chemical composition, especially sulfur species, a 10% addition by volume of local estuarine mud was mixed in before adding sediment to plots.

All eight sites added the quarry/mud mixture (hereafter, quarry), but to examine effects of sediment type on marsh

Table 1 Characteristics of the marshes in the eight NERR sites included in this study

Reserve	Code	Latitude (Decimal degrees)	Longitude (Decimal degrees)	Marsh name	Salinity regime (5-year average ppt)	Tide range (Mean daily range, m)	Mean high water (m NAVD)
Great Bay, NH	GRB	43.095	−70.87	Great Bay	25.6	2.7	0.18
Waquoit Bay, MA	WQB	41.555	−70.511	Sage Lot Pond	30	0.55	0.18
Narragansett Bay, RI	NAR	41.65	−71.342	Coggeshall	28	1.2	0.69
Chesapeake Bay, MD	CBM	38.152	−75.905	Deal Island State Wildlife Management Area	10.8	0.74	0.61
Chesapeake Bay, VA	CBV	37.22	−76.404	Goodwin Islands	20.3	0.76	0.27
North Carolina	NOC	34.169	−77.828	Masonboro Island	32.6	1.2	0.43
San Francisco Bay, CA	SFB	37.882	−122.516	Manzanita	26.8	1.25	1.61
Elkhorn Slough, CA	ELK	36.811	−121.749	Yampah Island	30	1.6	1.52

responses to TLP, three sites also added dredged sediments to supplemental plots. Dredged plots (14 cm thickness, in low and high marsh) were included at CBV, NOC, and SFB, using sediments from a nearby dredging operation or recent TLP project. Three other sites mixed in a small amount of biochar (10% by volume addition of Blacklite Pure at WQB and Blacklite Mix #6 at ELK and NAR, composed of wood biochar, worm castings and rice bran, from Pacific Biochar, Santa Rosa CA) with quarry sediments in supplemental plots (14 cm thickness, in low and high marsh). Biochar is a durable form of solid elemental carbonaceous material produced via anoxic combustion (pyrolysis) (Fang et al. 2015). Biochar application can condition soil, increasing its cation exchange capacity (Liang et al. 2006; Takaya et al. 2016), and decreasing its acidity, and thus enhance plant growth and nutrition. It remains a novel technique in coastal environments, but has shown promise in enhancing carbon sequestration in marsh ecosystems (Luo et al. 2016). Since dredged sediments are often sandy and nutrient-poor, amendment with biochar may enhance success of sediment addition in marsh ecosystems.

Another study objective was to compare the effects of adding thinner vs. thicker sediment layers to marshes. In large-scale thin-layer sediment placement projects, sediment thickness is often determined as the difference between elevations of degraded and healthy areas. In our project, the advisory committee identified a sediment thickness of 10–15 cm as the highest priority to evaluate. Based on this, we chose 14 cm as the high sediment thickness treatment to evaluate and coupled this with a low-end treatment of 7 cm, which may be valuable to represent sites where incremental maintenance applications over a series of years (or periods) may be better suited than a one-time thick sediment addition. The selection of 7 and 14 cm of sediment addition represents typical real-world application depths that resonates with end-users and acts to standardize treatments across all eight participating Reserves.

Experimental design

Five types of square plots (i.e., treatments) were used at all eight sites, in low and high marsh:

1. Thin 7 cm sediment addition with 7 cm high containment frame (“7 cm”)
2. Thick 14 cm sediment addition with 14 cm high containment frame (“14 cm”)
3. No sediment addition, no frame (control; “C”)
4. No sediment addition with 7 cm high frame (procedural control; “PC”)
5. Reference plots, about 10 cm higher than the others, representing desired target (“R”)

Additional treatments included 14 cm dredged (“D”) and 14 cm biochar (“B”), as described above. All plots were 0.7 m × 0.7 m in size and the corners of unframed plots were marked with PVC stakes or flags. Frames were constructed from untreated pine, using screws to connect pieces (Fig. S1). Holes were drilled in the sides of the frames to allow drainage and long anchor pieces were used on two or four sides to ensure the frames remained firmly in place. At all plots with frames (sediment addition and PC), a spade was used to sever roots around the edge of the frame (to 20–30 cm depth) to decrease the likelihood of rhizomes from surrounding plants entering the plots from outside. To examine possible effects of severing on plot vegetation, Waquoit Bay added an additional sever treatment (no frame, roots severed; Online resources: Study design).

To assess restoration success relative to reference targets, we identified reference plots that were located approximately

10 cm in elevation above treatment plots in low and high marsh. Ten cm was chosen because this was intermediate between the thin and thick sediment treatments. In low marsh, we sought areas that had higher total cover than the experimental plots; in high marsh, we sought areas that had higher cover by high marsh species than the experimental plots (which had more cover by the low marsh dominant). The goal was to identify site-specific, realistic examples of the outcome that might be achieved through sediment addition.

We used a block design, with five blocks containing a high and low marsh zone at each of the eight sites (Fig. S4). Within each zone in each block, every treatment was represented once; thus every site had five replicates per treatment within each marsh zone. The order of treatments in a block was determined by a random number generator and was different in each block. Plots within a block were located at least 1 m, but no more than 20 m, apart. The treatment plots were typically all quite near each other but in areas with gentle slopes, the reference plots were sometimes considerably farther away (as needed to achieve the desired target of 10 cm higher than treatment plots).

Monitoring

Plots were initially monitored prior to sediment addition to establish baseline conditions, and periodically monitored into the third growing season after sediment addition to track responses to TLP. All sites adhered to a standardized project monitoring protocol, and all of the indicators that were monitored were associated with key objectives or hypotheses. All Reserves began initial monitoring in fall 2017 prior to sediment addition and added sediment in spring 2018, except SFB, which started 1 year later.

Sediments We conducted an initial assessment of sediment properties to compare the sediment mix we added to TLP plots (90% quarried sediments) to local ambient marsh sediments at the sites, and where possible, to local dredged sediments. One year after sediment addition, we monitored sediment properties such as moisture and oxygenation in experimental plots, since these properties might affect vegetation recovery in the treatment plots (Online resources: Sediments).

Elevation and Vegetation Plot elevations were measured immediately before and after sediment addition to quantify increases from experimental TLP and ensure target elevations were achieved, and annually in late summer for three growing seasons after, including an additional early summer survey during the second growing season. During each sampling period, surface elevations were measured from five locations within each plot using Leica Sprinter 150 M survey equipment (or comparable equipment with a similar vertical accuracy of ~ 1.5 mm) referenced to previously-established vertical control benchmarks (Fig. S5). Plots in all treatments (C, PC, 7 cm, 14 cm; B and D when present) were surveyed each time except reference plots, which were only measured before sediment addition and in year three. Mean elevation (NAVD88) of each plot on each survey date was calculated from the five replicate measures. We attempted to monitor accretion rates, but this proved problematic due to loss of feldspar horizons (Online Resources: Elevation and accretion).

We examined multiple indicators of vegetation condition including cover, canopy height, and revegetation source (cover was our primary interest; information on canopy height and revegetation source is provided in the Online Resources: Vegetation section). Vegetation monitoring was conducted in the fall before sediment addition and annually in late summer for three growing seasons after, including an additional early summer survey during the second growing season. All treatments were sampled on each date except reference plots, which were only sampled during the first and last surveys. To sample, we first scanned each plot and recorded all plant species present, then used the point-intercept method (Kent and Coker 1992) at 25 grid intercepts (5 × 5) to quantify percent cover of all species present and bare ground. All unambiguously dead vegetation was recorded as bare. Immediately prior to vegetation sampling, a digital photograph was taken of each plot. In addition to vegetation, we quantified indicators of crab activity, because crabs can exert strong effects on marshes and their abundance may be affected by changes in sediment condition or elevation (Wasson et al. 2019). In each plot, any marsh crab that was visible with simple observation was identified to species (when possible) and counted, and immediately after vegetation sampling all crab burrows > 5 mm were counted to calculate burrow density.

Data Analysis

Data analysis was primarily focused on assessing vegetation recovery and restoration goals and comparing crab burrow density among plots. To examine recovery rates and how elevation and vegetation change over time—key for evaluating TLP projects—we plotted elevation, vegetation cover relative to target reference conditions, and proportion of high marsh species (those that typically only grow in high marsh zones at each site) over time to visualize temporal trajectories and variability among treatments and sites.

To analyze the ability of TLP to achieve restoration goals, we determined (1) whether TLP increased vegetation cover in mudflats and pannes in the low marsh to levels comparable with reference plots and (2) in high marsh, whether it enhanced representation of high marsh plants to levels comparable with reference conditions (i.e., whether it altered vegetation composition via an increased dominance by high marsh species). To answer these restoration questions, we used a modified Restoration Performance Index (RPI; Moore et al. 2009; Raposa et al. 2017). The RPI was originally designed to quantify effectiveness of restoration projects relative to reference site conditions by combining many parameters into one comprehensive restoration score. In our project, we used the RPI to quantify the degree to which vegetation shifted from initial degraded to reference conditions and used just one parameter for each RPI score, calculated for individual plots using the following formula (modified from Moore et al. 2009):

$$RPI = \frac{(T_f - T_i)}{(R_{if} - T_i)}$$

where T_f is the final treatment measurement (C, 7 cm, 14 cm, B or D treatments), T_i is the initial measurement from these same treatments, and R_{if} is reference conditions averaged between initial and final measurements. RPI was calculated separately for each block, treatment, and zone (e.g., 5 RPI values for 7 cm in high marsh at each site). Note that this formula includes both comparison to reference conditions and assessment of change over time. The rationale is that in some cases, natural recovery occurs for reasons unrelated to the restoration. By comparing the RPI of the sediment addition to the RPI of control treatments, we can distinguish between such natural recovery and recovery attributed to the sediment addition treatments. RPI scores were calculated using total cover of all vegetation species in low marsh and proportionate cover of high marsh species in high marsh (i.e., high marsh cover/total vegetation cover). Mean reference condition was used because it was most relevant to RPI scores, which also use initial and final data.

To analyze vegetation recovery (total vegetation cover and RPI scores) in TLP plots across sediment thicknesses and sites, we used generalized linear mixed models (GLMMs) to compare final (year 3) vegetation data among C, PC, 7 cm, 14 cm, B and D when present, and R plots. One global model was used to explore generality across sites, which included site and block (nested within site) as random factors. For this global model, the biochar and dredged plot data were pooled into one treatment prior to analysis. To examine vegetation recovery among different specific treatment types and combinations of treatments, we used GLMMs with custom contrasts to compare total cover and RPI scores between (1) sediment addition (7 cm, 14 cm, and B or D) and controls (PC and C), (2) reference (R) and controls, (3) reference and sediment addition, (4) thin (7 cm) and thick (14 cm), (5) biochar amended (B) and unamended quarry (14 cm), (6) unamended quarry and dredged (D), and (7) unframed control (C) and framed control (PC), separately for low and high marsh at each site. In these models, block within site was the random factor. Hypotheses and rationale behind statistical custom contrasts between treatment groups are listed in Table 3.

Crab burrow density distributions had more zeros than expected for standard discrete distributions, so we used zero-inflated negative binomial (ZINB) models to compare burrow densities among plots. We ran global models using all sites, and custom contrasts for low and high marsh at each site, as described for vegetation recovery above, except that they were run as generalized linear models and therefore did not incorporate random effects.

Prior to data analysis for the RPI, vegetation cover, and crab burrow density data, we assessed appropriate distributions for each response variable using Anderson–Darling goodness-of-fit tests, and residual plots were further used for each model to verify the appropriateness of distribution and link functions used. Vegetation cover data were normally distributed, while RPI data, which were highly right- and left-skewed, only fit Johnson's S_U distribution and were transformed using this distribution prior to analysis. All the GLMMs were run using an identity link function (used for normal distributions), and Kenward-Roger denominator degrees of freedom approximations were used to adjust for small sample sizes and unbalanced data. The ZINB models were run using a log link function for the non-zero portion of the model, and a logit link function for the zero portion of the model.

Ideally, each analysis would include data from every plot at each site, but all low marsh plots at CBM were damaged or lost soon after installation due to wave action; thus, low marsh data are unavailable from this site. Low marsh plots were also lost at SFB due to wave action, but not until after year two; thus, low marsh data only through year two are used for this site and SFB low marsh was excluded from all analyses that require final year three data (GLMM, RPI scores). These unequal treatments among sites, combined with the lack of dredged and biochar plots in GRB, resulted in vegetation cover custom contrasts not being calculable. To obtain these contrasts, all vegetation cover data from CBM, GRB, and SFB were not included in the global model and associated custom contrasts. Finally, we were unable to calculate high marsh RPI scores for CBM based on proportionate cover of high marsh species because all treatment and reference plots at this site contained 100% high marsh species at the initial and year 3 sampling periods used to calculate RPI.

When possible, we report actual *p* values to help interpret differences in treatments reported as significant (Smith 2020). We used JMP© Pro, Version 16 (SAS Institute Inc., Cary, NC, 1989–2021) for distribution assessments, and we generated GLMMs, ZINB models, and diagnostic residual plots using SAS/STAT, Version 15.1 of the SAS system for Windows (Copyright © 2019 SAS Institute Inc.). For the GLMMs we used the GLIMMIX procedure, and we used the GENMOD procedure for the ZINB models.

Results

Sediments

The sediment experimentally added to the TLP plots differed in a suite of characteristics from ambient marsh sediments, but not from that used in local sediment addition restoration projects (Fig. S7, Table S2). A year into the experiment, sediment addition plots were drier, more oxygenated, and more nutrient-poor than control and reference plots (Fig. S8, Table S3). Details on sediment results, including comparisons between biochar-amended and unamended sediments, are provided in Online resources: Sediments.

Plot Elevations

Mean plot elevations at all sites generally increased by the target amount after sediment addition (i.e., either 7 cm or 14 cm) to approximate reference plot elevations (Fig. 3). Enhanced elevations were maintained through year three, but declines were apparent at most sites, particularly in low marsh. Across all sites, mean low marsh plot elevation initially increased by 8.2 cm, 14.6 cm, and 15.2 cm for 7 cm, 14 cm, and B/D treatments, respectively, but these gains declined to 6.7 cm for 7 cm and 10.8 cm for 14 cm and B/D after 3 years (Table S4). Similar elevation increases were observed initially in high marsh plots (mean increases of 8.1 cm, 14.8 cm, and 15.4 cm for 7, 14, and B/D treatments, respectively), but these were more stable over time than in low marsh; by year three, mean elevation gain over initial was 7.1 cm, 12.4 cm, and 12.8 cm for these same treatments. Although most feldspar marker horizons washed away during the study, we found higher accretion rates in low marsh compared to high, and in 7 cm compared to 14 cm (further details provided in Online resources: Elevation and accretion).

Vegetation Cover

Total vegetation cover increased relatively quickly in most sediment addition plots (Figs. 4 and 5; Fig. S9). Overall, final cover was different among sites and treatments and between low and high marsh, with multiple interactions (Table 2). We

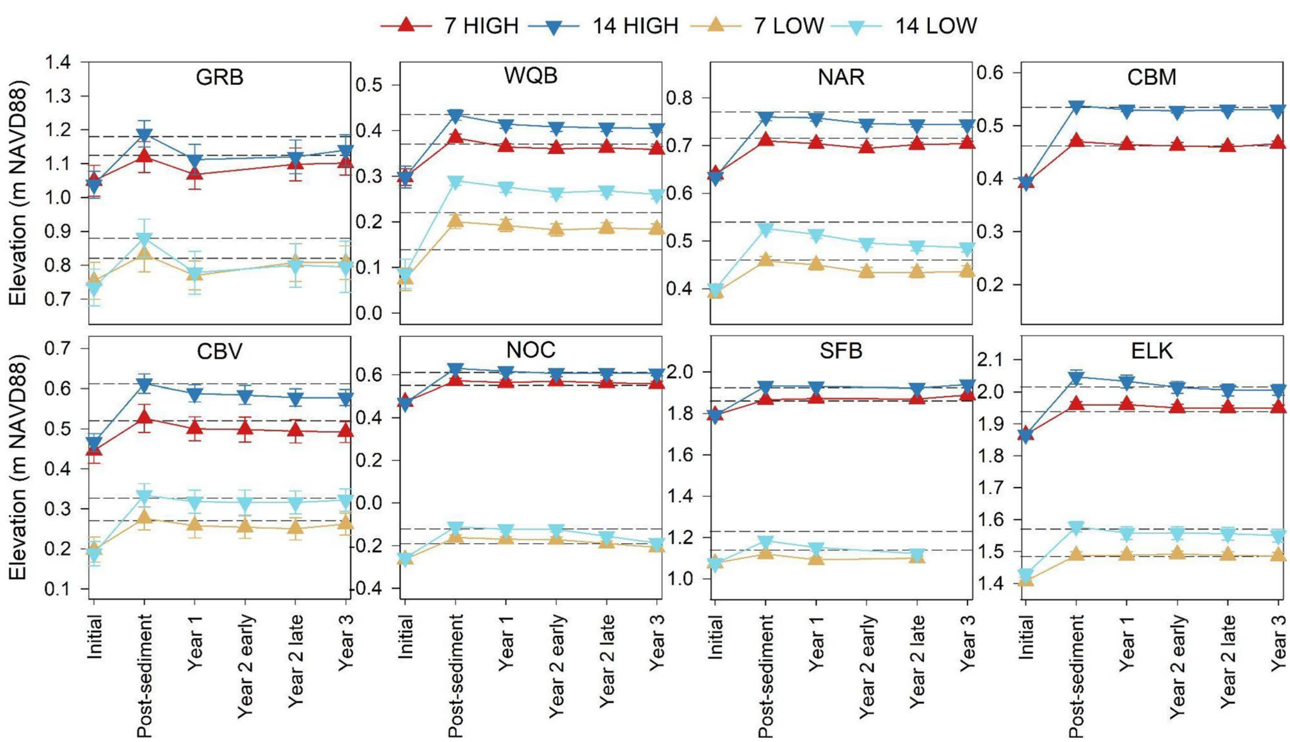

Fig. 3 Plot elevations over the duration of the study at each NERR. From left to right and top row to bottom row, sites are arranged north to south, starting with east coast, then west coast. Treatments shown include 7 cm and 14 cm additions in low and high marsh. Error bars are ± 1 SE. In each plot, dashed lines indicate the target elevations, 7 cm and 14 cm higher than controls in low and high marsh. These visualizations show that most sites were able to achieve and maintain target elevations. 'Initial' = before sediment addition, "post-sediment" = immediately after sediment addition, "Year 1" = late summer of first growing season after sediment addition, "Year 2 early" = early summer of second growing season, "Year 2 late" = late summer of second growing season, "Year 3" = late summer of third growing season

thus separately examined low and high marsh at each site, focusing on key contrasts of interest (Table 3).

Sediment Addition vs. Control Final cover was not significantly different between sediment addition and control plots in low marsh at any site except CBV (higher in sediment addition, $t = -3.29$, $p = 0.0037$) and ELK (control higher, $t = 8.93$, $p < 0.0001$) and in high marsh at any site except SFB (control higher, $t = 9.29$, $p < 0.0001$) (Table 4a). Final cover in sediment addition plots in both low and high marsh exceeded initial conditions at most sites; surprisingly, it also exceeded initial in controls at all sites in low marsh and at six of eight sites in high marsh (Fig. 6).

Reference vs. Control Year 3 cover was significantly higher in reference compared to controls in five of six low marsh sites and three of eight high marsh sites (Fig. 6; Table 4a).

Sediment Addition vs. Reference Year three cover was significantly lower in sediment addition vs. reference in four of six low marsh and six of eight high marsh sites (Table 4a). However, cover in low marsh sediment addition plots trended towards reference levels over time at four of six sites and reached reference by year 3 at CBV (Fig. 5; Table 4a). Cover also trended towards reference in high marsh at most sites, and 7-cm sediment addition plots reached reference by year 3 at GRB and ELK.

Thin vs. Thick Sediment Addition In low marsh, recovery of total cover was initially faster in 7 cm vs. 14 cm at almost all sites. Final cover, however, was generally similar in the two sediment thicknesses, although it was significantly higher in 7 cm at CBV ($t = -2.44$, $p = 0.0243$) (Fig. 5; Table 4a). The same patterns also occurred in high marsh where cover in 7 cm remained significantly higher than 14 cm by year

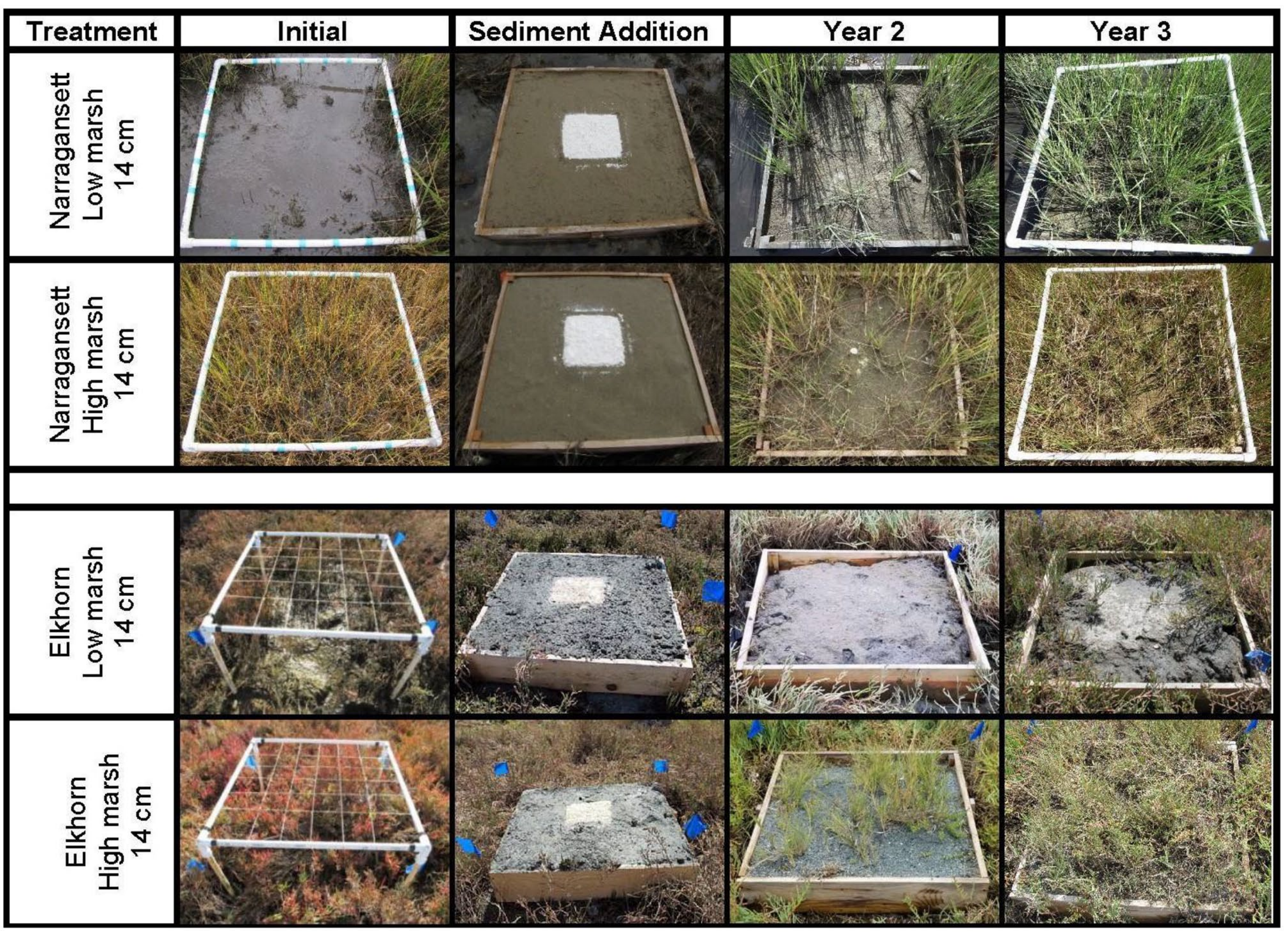

Fig. 4 Contrasts in recovery by site and elevation. Comparison of time-series photographs of one treatment (14 cm sediment addition) in low and high marsh at Narragansett Bay, RI, and Elkhorn Slough, CA. Time periods shown include initial conditions, immediately after sediment addition and at the end of the growing season in years two and three. By the end of the study year three, the low marsh sediment addition plots at Narragansett looked much better than at Elkhorn, but the reverse was true for high marsh

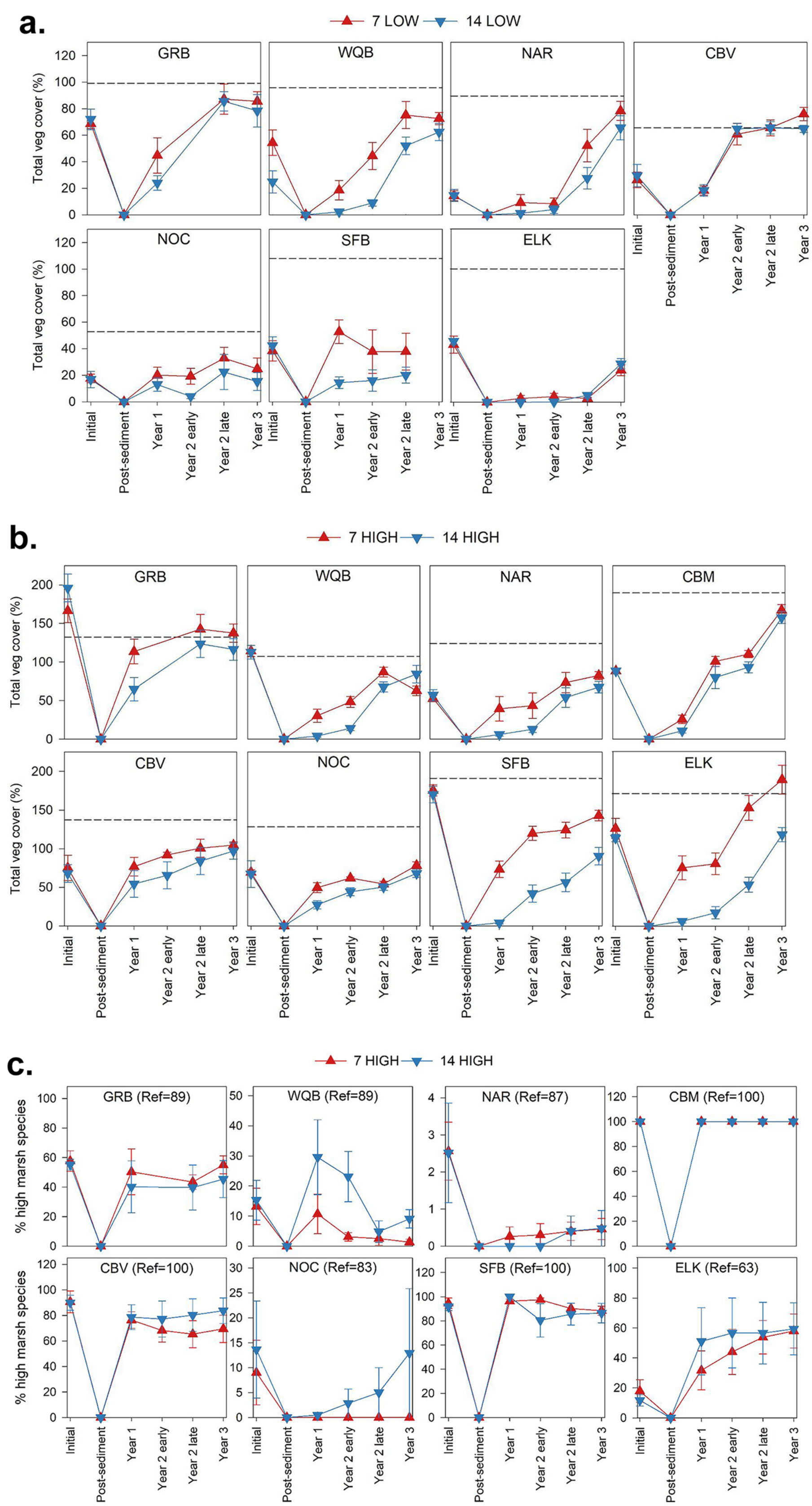

Fig. 5 Temporal trajectory of vegetation cover and proportion of high marsh species. Mean total vegetation cover (all species combined) over time in 7 cm and 14 cm treatments in low (**a**) and high (**b**) marsh, and proportion of all high marsh species in high (**c**). Error bars are ± 1 SE. Reference levels (mean of reference plots) are indicated by dashed lines for cover and shown parenthetically after each site code for proportion of high marsh species due to differences in scale at some sites. Note that percent cover can exceed 100% due to canopy layering, and this is common in some sites in high marsh. Vegetation cover recovered faster in 7 cm vs. 14 cm sediment addition, but by the end of the study period this difference had disappeared at most sites. In almost all cases, final cover in the sediment addition plots was lower than in the reference plots. The proportion of high marsh species increased in year one at most sites, and continued to trend higher into year three, especially in 14 cm plots, at many sites

Table 2 Global model summaries for vegetation cover, RPI, and crab burrow density. Model effects are shown in the left column, with degrees of freedom (Df), statistical test values (*F* value and chi-square), and *p* values (*p*) shown for each response variable in subsequent columns

	Vegetation cover			RPI			Crab burrow density		
	Df	*F* value	*p*	Df	*F* value	*p*	Df	Chi-square	*p*
Treatment	5	22.25	< 0.0001	4	0.97	0.427	5	39.49	< 0.0001
Elevation	1	331.83	< 0.0001	1	82.00	< 0.0001	1	10.03	0.0015
Elevation × treatment	5	1.11	0.3546	4	3.98	0.004	5	3.00	0.7002
NERR site	4	24.81	< 0.0001	6	6.18	0.000	4	170.24	< 0.0001
NERR site × treatment	20	1.45	0.1000	23	1.93	0.008	20	41.71	0.0030
NERR site × elevation	4	45.13	< 0.0001	5	29.25	< 0.0001	4	36.26	< 0.0001
NERR site × treatment × elevation	20	3.01	< 0.0001	19	2.21	0.004	20	65.00	< 0.0001

three at both west coast sites (SFB $t = -4.22$, $p = 0.0004$; ELK $t = -3.53$, $p = 0.0021$).

Sediment Type Comparisons There were no significant differences in final cover between quarry and biochar at any site in low and high marsh (Fig. 6; Table 4a). Cover in locally-sourced dredged sediments was significantly higher than quarry at SFB high marsh ($t = 4.49$, $p = 0.0002$) and trended higher in three additional cases.

Control Comparisons Cover in framed and unframed controls was not significantly different at any site in low or high marsh except NOC low ($t = -2.72$, $p = 0.0133$) (Table 4a).

Achieving Restoration Goals

Overall, RPI scores were different among sites and between low and high marsh, but not among treatments, with interactions in all cases (Table 2). Due to the interactions, we focused on a few key results separated by elevation and site (Table 3).

Sediment Addition vs. Control The RPI of sediment addition plots was significantly higher than controls (indicating restoration goals were met) at only one of six low marsh sites (CBV), and one of seven high marsh sites (ELK) (Fig. 7; Table 4b). At one low marsh site (ELK), the RPI of control plots was significantly higher than sediment addition, while at the remaining sites there was no significant difference (i.e., in 10/13 cases, sediment addition did not make things significantly worse or better). RPI scores for sediment addition and control tended to be positive in the low marsh (indicating both improved between initial and final assessment); the reverse was true in the high marsh.

Thin vs. Thick Sediment Addition There was no significant difference in RPI between 7 and 14 cm sediment addition by year three in any marsh (Fig. 7; Table 4b). For low marsh, 7 cm tended to perform better; for high marsh, 14 cm performed better at more sites. In many cases, however, the total cover and proportion of high marsh species parameters that make up RPI scores trended higher throughout the study, suggesting that year three RPI scores were not the endpoint (Fig. 5).

Sediment Type Comparisons There were no significant differences in RPI between sediment types at any site, in low or high marsh plots (Fig. 7; Table 4b), and results were generally mixed except that RPI was generally higher in biochar vs. quarry in high marsh at each site.

Control Comparisons The only significant differences in RPI between framed and unframed controls were at NOC low marsh where RPI was higher in unframed controls ($t = -3.36$, $p = 0.0040$) and WQB high marsh where it was higher in framed controls ($t = 2.72$, $p = 0.0152$) (Table 4b).

Crab Responses to Sediment Addition

Eight crab species were observed in plots across all sites, with *Uca* spp. (particularly *Uca pugnax*) dominating east coast sites and only *Pachygrapsus crassipes* present on the west coast, at ELK (Table S7). Crab abundance in plots was highest in NAR, WQB and NOC, intermediate at CBV and ELK, and very low or zero in GRB, CBM, and SFB. Using data pooled across sites, the percentage of low marsh plots observed with crabs increased above initial in all sediment addition plots more than it did in controls, suggesting an association between sediment addition and increased crab abundance (Table S8). In high marsh, the percentage of sediment addition plots with crabs observed also increased after year 1, but then declined slightly in years 2 and 3, perhaps because many plots continued to revegetate. The same patterns occurred in high marsh control plots.

Burrow density was very low or zero at GRB, CBM, and SFB throughout the study (Table S9), but increased after sediment addition at the other five sites. Burrow density

Table 3 Hypotheses and rationale behind statistical custom contrasts between treatment groups. In each contrast below (results in Table 4), the treatment expected to be higher is listed first in light blue. "7" = 7-cm addition, "14" = 14 cm addition, "C" = control with no frame, "PC" = procedural control with frame, "R" = reference, "B" = 14-cm quarry amended with biochar, "D" = 14-cm dredged

SEDIMENT ADDITION (7/14/B/D) vs. **CONTROLS** (PC/C).
Hypothesis: sediment addition plots have greater vegetation cover and RPI than control plots
Rationale: enhanced elevation of sediment addition plots improves vegetation condition
Outcome: hypothesis not supported: at most sites, vegetation cover and RPI did not differ between sediment addition and control plots

REFERENCE (R) vs. **CONTROLS** (PC/C).
Hypothesis: reference plots have greater vegetation cover than control plots
Rationale: enhanced elevation (10 cm above control) of reference plots increases vegetation cover
Outcome: hypothesis supported: vegetation cover was higher in reference plots compared to controls at almost all sites

REFERENCE (R) vs. **SEDIMENT ADDITION** (7/14/B/D).
Hypothesis: reference plots have greater vegetation cover than sediment addition plots
Rationale: even though elevation of sediment plots has been raised to similar level as reference, vegetation condition is lower because it takes time to recover
Outcome: hypothesis supported: after three years, vegetation cover was lower in sediment addition plots compared to reference at almost all sites

THIN (7) vs. **THICK** (14) sediment addition
Hypothesis: thin sediment addition plots have greater vegetation cover and RPI than thick
Rationale: if vegetation recovery is by underlying, buried vegetation not new colonization from seeds, then recovery should be faster through a thinner vs. thicker layer of overlying sediment
Outcome: hypothesis not supported: while vegetation cover initially recovered more quickly in thin vs. thick sediment addition, by year three there were almost no differences between the two sediment thicknesses

BIOCHAR AMENDED (B) vs. **UNAMENDED QUARRY** (14) sediment addition
Hypothesis: biochar-amended sediment addition plots have greater vegetation cover and RPI than unamended
Rationale: biochar addition can help retain moisture and facilitate microbial processes, enhancing vegetation recovery
Outcome: hypothesis not supported: there were no significant differences in vegetation cover and RPI between biochar amended and unamended plots after three years

UNAMENDED QUARRY (14) vs. **DREDGED** (D) sediment addition
Hypothesis: quarried sediment addition plots have greater vegetation cover and RPI than sediment addition plots filled with dredged material
Rationale: quarried sediments have less organic matter that can decompose and become anoxic, and lower sulfate concentrations, and thus should foster better vegetation recovery
Outcome: hypothesis not supported: there were no significant differences in cover or RPI between the two sediment types, and at most sites, vegetation actually performed better in dredged sediments

UNFRAMED CONTROL (C) vs. **FRAMED CONTROL** (PC)
Hypothesis: unframed control plots have greater vegetation cover and RPI than framed control plots
Rationale: only framed plots also had rhizomes cut at edge during installation, and frames could result in poorer drainage
Outcome: hypothesis not supported: there were no differences in vegetation cover and RPI between the two types of control plots at almost all sites (for this reason, these two treatments were combined for various analyses, such as the first two listed above)

Table 4 GLMM custom contrast summaries. Summary of custom contrast test results between select treatments at each site and elevation from GLMM analyses for total vegetation cover (t values; **a**) and RPI (t values; **b**), and ZINB analyses for crab burrow density (z values; **c**). Light blue cells indicate that cover/RPI was higher in the first treatment within each custom contrast pair; brown cells indicate it was higher in the second treatment. See Table 3 for hypotheses and rationale behind each contrast. Significant differences are indicated with asterisks (* $p<0.05$; ** $p<0.01$; *** $p<0.001$). For example, in CBV low marsh, plant cover was significantly higher in sediment addition plots compared to controls (t value = − 3.29), whereas it was higher, but not significantly so, in controls at NOC

a.

VEGETATION COVER

CONTRAST		Sediment addition	Reference	Reference	Thin	Biochar amended	Unamended quarry	Unframed control
		Controls	Controls	Sediment addition	Thick	Unamended quarry	Dredged	Framed control
LOW MARSH	GRB	-0.28	**-2.17** *	-1.95	0.16			
	WQB	-0.48	**-3.68** ***	**-3.54** ***	-0.97	-0.11		-1.54
	NAR	-0.93	**-3.16** ***	**-2.62** **	-1.44	-0.47		-0.45
	CBV	**-3.29** **	-1.81	0.67	**-2.44** *		0.17	-1.39
	NOC	1.93	**-5.22** ***	**-7.08** ***	-1.65		0.55	**-2.72** *
	ELK	**8.93** ***	**-2.99** ***	**-10.23** ***	0.54	0.54		-0.54
HIGH MARSH	GRB	-0.76	-0.94	-0.32	-0.16			
	WQB	0.86	-1.54	**-2.32** *	1.16	0.70		-0.09
	NAR	1.63	**-2.81** *	**-4.28** ***	-1.05	-0.36		0.10
	CBM	1.93	-0.70	**-2.28** *	-0.70			-1.10
	CBV	-1.05	**-3.65** **	**-3.05** **	-0.47		-0.35	0.29
	NOC	2.03	**-5.51** ***	**-7.45** ***	-1.15		0.98	-0.13
	SFB	**9.29** ***	0.85	**-6.43** ***	**-4.22** ***		**4.49** ***	1.37
	ELK	-0.34	-1.27	-1.08	**-3.53** **	-1.98		0.12

b.

RPI

CONTRAST		Sediment addition	Thin	Biochar amended	Unamended quarry	Unframed control
		Controls	Thick	Unamended quarry	Dredged	Framed control
LOW MARSH	GRB	0.21	-0.67			-0.03
	WQB	0.03	0.34	0.25		-0.10
	NAR	-1.07	-1.32	-0.46		0.30
	CBV	**-2.95** **	-1.51		-0.76	-0.72
	NOC	1.82	-1.59		-0.43	**-3.36** ***
	ELK	**6.49** ***	0.47	0.84		-0.43
HIGH MARSH	GRB	0.64	-0.02			-0.77
	WQB	-0.39	1.26	-0.84		**2.72** *
	NAR	-0.44	0.00	-0.06		2.06
	CBV	-0.38	0.48		0.33	0.91
	NOC	-0.14	0.92		0.83	0.84
	SFB	-0.30	0.81		-2.01	-0.83
	ELK	**-3.48** **	-0.35	-1.44		0.55

c.

CRAB BURROWS

CONTRAST		Sediment addition	Reference	Reference	Thin	Biochar amended	Unamended quarry	Unframed control
		Controls	Controls	Sediment addition	Thick	Unamended quarry	Dredged	Framed control
LOW MARSH	WQB	**-7.86** ***	**3.11** **	**6.45** ***	0.79	0.35		0.55
	NAR	**-3.44** ***		**4.02** ***	-0.11	0.90		0.71
	CBV	**-4.05** ***	**-3.14** **	0.06	-0.08		**-2.92** **	0.00
	NOC	**-4.10** ***	-0.79	**2.41** *	0.14		-0.32	**2.58** **
	ELK	-0.21	**2.84** **	**3.18** **	0.39	0.47		0.67
HIGH MARSH	WQB	**-7.27** ***	**-1.97** *	**4.25** ***	1.26	0.07		0.00
	NAR	-0.41	1.34	**2.27** *	**2.63** **	**-2.20** *		-0.20
	CBV	-1.77	0.84	**2.31** *	-0.53		0.10	-0.29
	NOC	-1.72	0.39	1.88	0.42		-0.63	0.00
	ELK	0.04	0.15	0.03	-0.02	-0.03		0.53

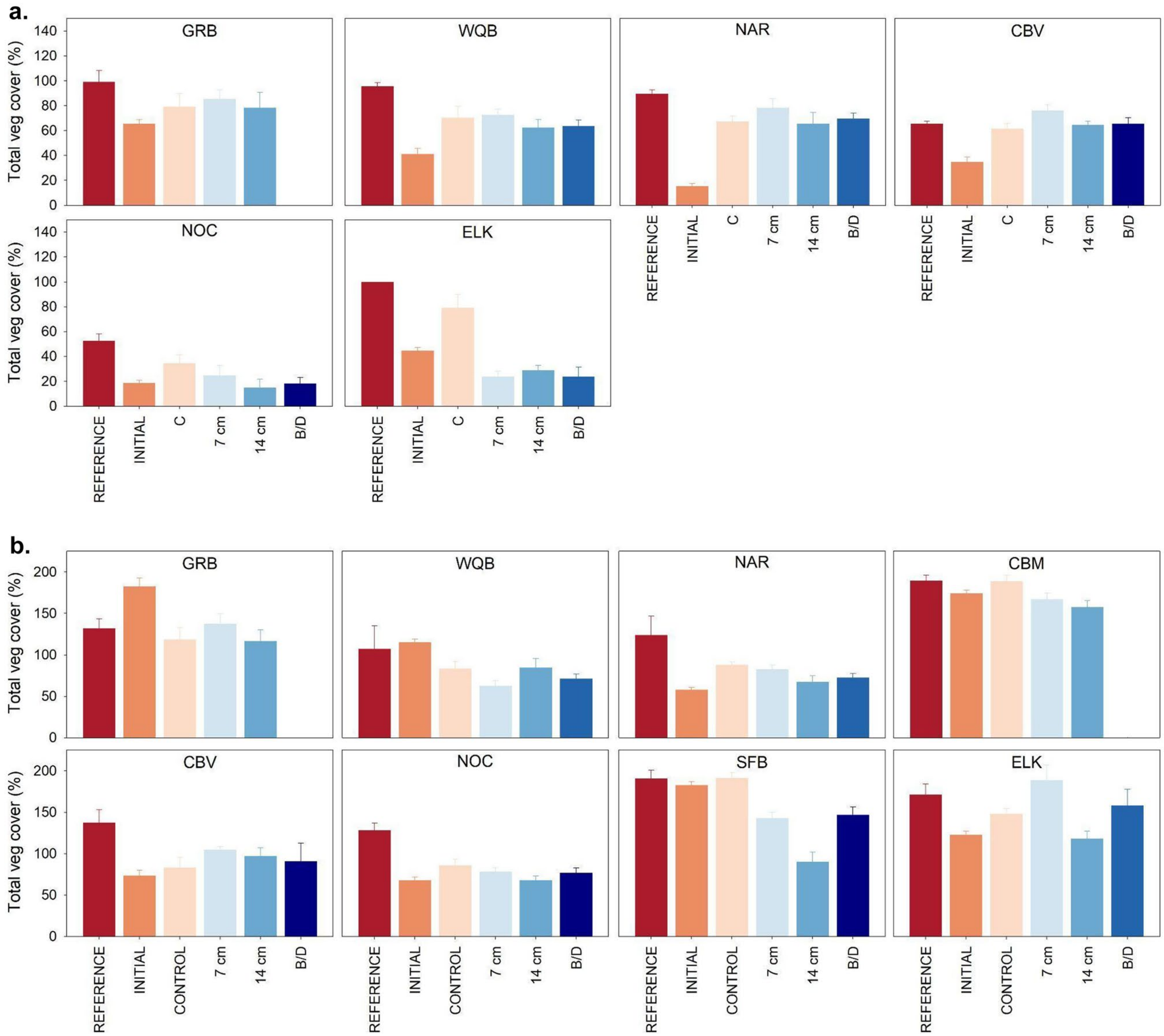

Fig. 6 Effect of treatment on vegetation cover. Total vegetation cover (all species combined) by treatment and site in low (**a**) and high (**b**) marsh. Sites are arranged north to south, east to west (CBM and SFB low marsh not shown due to lack of year three data). Reference data are from year three, except SFB which is year two. Initial data (i.e., prior to sediment addition) are combined across all other treatments and all remaining data are year three. Error bars are ± 1 SE. Note that WQB, NAR and ELK show biochar plots (B) in medium blue, CBV and NOC show dredged plots (D) in dark blue. From a restoration perspective, the desired outcome was to have the sediment addition plots (blue) exceed the control plots in year 3 (tan), and approximate the reference plots (red); the former was often achieved but the latter was not

typically increased more in low marsh compared to high. Overall, final crab burrow density was different among sites and treatments and between low and high marsh, with interactions in almost all cases (Table 2).

Sediment Addition vs. Control Final burrow density was significantly higher in sediment addition compared to controls at four of five low marsh sites and one of five high marsh sites, suggesting a relationship between sediment addition and higher crab abundance (Tables 4c and S9).

Reference vs. Control There was no clear pattern when comparing burrow density between reference and control plots; density was significantly higher in controls at two low marsh sites and higher in reference at one low and one high marsh site (Table 4c).

Sediment Addition vs. Reference Burrow density was significantly higher in sediment addition compared to reference at four of five low marsh sites and three of five high marsh sites (Table 4c).

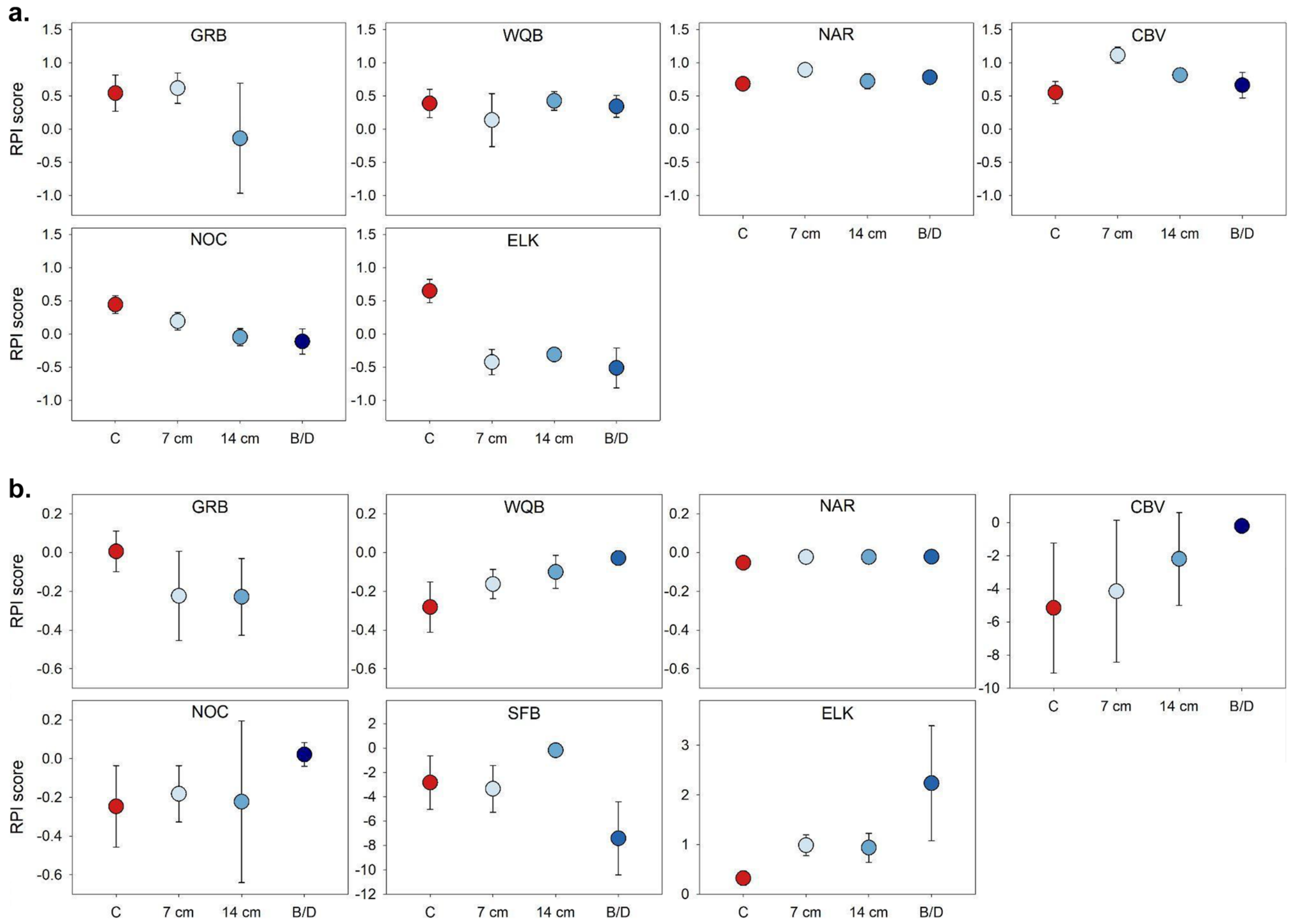

Fig. 7 Restoration Performance Index. RPI scores for control, 7 cm, 14 cm, B, and D treatments in low (**a**) and high (**b**) marsh at each site. Symbols are means from 5 replicate plots; error bars are ±1 SE. WQB, NAR, and ELK show biochar plots (B) in medium blue, CBV and NOC show dredged plots (D) in dark blue. For high marsh, all plots are set to the same *y*-axis scale except CBV, SFB, and ELK due to a much higher range of scores at those sites. RPI scores were calculated using total cover of all vegetation species in low marsh and proportionate cover of high marsh species in high marsh. A restoration treatment is effective if the RPI is significantly higher than the control; these plots show that that was only rarely the case for these sediment addition treatments (rare instances where blue dot is significantly higher than red)

Thin vs. Thick Sediment Addition Burrow density was not significantly different between 7 and 14 cm at any site except NAR high (higher in thick; $z = 2.63$, $p = 0.0085$) (Tables 4c and S9).

Sediment Type Comparisons Burrow density was not significantly different between sediment types in almost all cases. Exceptions include NAR high marsh where density was higher in biochar than quarry ($z = -2.20$, $p = 0.0281$) and CBV low marsh where it was higher in quarry than dredged ($z = -2.92$, $p = 0.0035$) (Table 4c).

Control Comparisons The only significant difference in burrow density between framed and unframed controls was at NOC low marsh, where density was higher in framed controls ($z = 2.58$, $p = 0.0099$; Table 4c).

Discussion

Overall, while the elevation of our sediment addition plots resembled that of target reference plots, marsh vegetation in sediment addition plots remained distinct from that in reference plots. Recovery of buried vegetation was fairly rapid, such that vegetation cover in sediment addition plots generally was similar to that in control plots after three years at most sites, but more time is apparently needed for the full benefits of increased elevation to accrue so that the vegetation resembles reference conditions. Nevertheless, the robust recovery observed at most sites in both high and low marshes suggests TLP holds promise as a coastal management strategy, but also sets realistic expectations of a long, multi-year timeline for achieving vegetation targets. Only by monitoring TLP projects for many years or even decades can it be determined whether they eventually approximate reference conditions.

Value of Coordinated Experiments of Marsh Response to TLP

Coordinated experiments, conducted consistently across disparate sites, can greatly advance understanding of generality and scale in environmental disciplines (Fraser et al. 2013). Such experiments are still rare in restoration ecology, but there is a pressing need for restoration experiments using a networked approach (Gellie et al. 2018). The NERR System offers an ideal platform for consistent comparisons across diverse tidal marsh systems, conducted within a robust monitoring framework (Raposa et al. 2017; Wasson et al. 2019). By imposing the same experimental conditions (two thicknesses of sediment addition in high and low marsh zones) at eight contrasting sites, we had an unprecedented potential to broadly examine TLP effects on tidal marshes. Our investigation detected some general trends, including a rapid rate of recovery of existing vegetation following sediment addition and association of increased crab burrow crab densities with sediment addition. These results are broader than those of single-site studies, because they emerged from general models across diverse sites, filling a key need to scale up in ecological investigations (Estes et al. 2018).

While some generalities emerged, another critical lesson learned from the coordinated experiment was that TLP does not have the same effect across all marshes. Site was a highly significant factor in the model for all vegetation response variables examined. There were also various significant interactive effects between treatment, site, and elevation. For example, sediment addition at ELK was the least successful among the eight sites at achieving a resemblance to vegetation of reference plots in the low marsh, but the most successful in the high marsh. One main factor behind site differences was vegetation type: the woody, perennial, bush-forming marsh plant dominant in the California marshes (*Salicornia pacifica*) appears to recover much more slowly from sediment addition than the dominant grass in the Atlantic marshes (*Spartina alterniflora*). These contrasts among sites highlight the importance of reviewing results from nearby, similar systems when planning and predicting outcomes of TLP projects.

Coordinated restoration experiments can be conducted at any scale. Larger plots more effectively simulate restoration-scale conditions (and indeed can accomplish local restoration objectives in addition to testing hypotheses); smaller plots are more tractable for maintaining internal consistency of sediment conditions and allow for greater replication and/or greater numbers of treatments to be tested. Our experimental plots were small (0.7 × 0.7 m), to allow for replication within similar areas of the marshes, to avoid the need for extensive permitting, and to make them logistically feasible for small teams hauling heavy sediment. We are confident that the *relative* comparisons that resulted are robust (e.g., comparisons within and among sites of thick vs. thin sediment addition, high vs. low marsh zones). However, the *absolute* rate of vegetation colonization was likely higher than what would be obtained from large-scale TLP projects due to recovery by vegetation at the edge of plots. In Elkhorn Slough, a 20-ha sediment addition project (Hester Marsh) was conducted in the marsh immediately adjacent to our experimental TLP plots, and colonization has been much slower there (13% cover after 1.5 years, Thomsen et al. 2021; 31% after 3 years, K. Wasson, unpublished data), as virtually no existing vegetation survived and conditions were challenging for seedling establishment. However, in Rhode Island, a 12-ha sediment addition project (Ninigret Marsh) conducted 40 km from our TLP plots showed comparable rates of colonization as in our TLP plots in this state, about 20% cover in year 1 and 73% in year 3 (Raposa et. al. 2022). Elsewhere, others reported variable rates of colonization, ranging from 0% in the first year (La Peyre et al. 2009) to 77.5% after 2.5 years (Mendelsohn and Kuhn 2003). Thus, variation observed across sites in our small plots mirrors the variability that has been observed across large-scale restoration projects.

TLP Effects on Low vs. High Marsh Vegetation

Our experiment detected marked differences in how low vs. high marsh communities responded to TLP; elevation was a significant factor in the general model for all our response variables. After three years, low marsh vegetation cover in sediment addition plots remained lower than high marsh vegetation cover. For both low and high marsh, only at a single site did sediment addition plots have a significantly higher RPI than controls. However, there was a trend towards sediment addition plots having greater RPI than controls at many more high than low marsh sites (Table 4b). Thus, our study suggests TLP is at least as effective at restoring high marsh as low marsh. This is a novel finding, because most previous studies have demonstrated TLP benefits at low elevation, to reverse the runaway panne enlargement processes that can lead to wholescale marsh degradation (Mariotti 2016). Studies in North Carolina (Croft et al. 2006) and Louisiana (La Peyre et al. 2009) detected significant benefits of TLP to lower, unvegetated areas but not to higher, vegetated areas. Our results highlight the potential for TLP as a climate adaptation strategy across the entire marsh landscape.

Sediment Source and Thickness

The sediment we used in the coordinated experiment was obtained from local quarries, supplemented by a small amount (10% by volume) of local marsh mud, in order to provide similar sediment grain size composition across the eight estuaries. Our analysis revealed that the sediment used for our TLP experiments resembled the physical properties of dredged sediment and sediment used in local TLP projects, but differed from ambient marsh sediment by being much sandier, drier, more oxygenated, and lower in nutrient concentrations.

Planning for TLP in marsh restoration involves balancing the benefit of adding thicker layers (for longer lasting elevation capital) with the risk of slowing vegetation recovery (reliant on seed arrival and germination, if underlying vegetation is killed), as well as considering trade-offs between one-time thicker addition versus repeated thinner additions (Nelson et al. 2020). We found that surface sediment accretion rates declined when a greater quantity of sediment was added, as would be expected, since surface accretion occurs during inundation, which is less frequent and of lower duration and depth at higher elevations. Ideally, restored marshes will be self-sustaining and track SLR following TLP, with substantial below-ground organic accumulation driving the long-term elevation increase of marshes (Nyman et al. 2006).

We found that thinner addition plots (7 vs. 14 cm) revegetated more quickly, in general, especially in the high marsh, presumably due to recovery of vegetation below the sediment addition layer. By the end of the monitoring period, however, there were few significant differences in vegetation cover or composition between the 7 cm and 14 cm treatments at any of our eight disparate sites. Given the enhanced elevation capital gained by the thicker addition, our results suggest TLP of at least 14 cm should be considered for future projects. This quantity of sediment addition has been shown to allow for revegetation in several larger-scale TLP projects (Reimold et al. 1978; Payne et al. 2021). The optimum thickness for rapid response of marsh productivity is only 5–10 cm, and decreases with marsh elevation (Walters and Kirwin 2016). However, to accomplish more lasting benefits, even thicker sediment addition, such as 30 cm, may produce desired elevation (and may be needed where loss of vegetation has led to peat collapse) and then vegetation communities if restoration success is evaluated at least 2–3 years post sediment application (Slocum et al. 2005; Stagg and Mendelsohn 2010), especially with additional seeding or planting in the high marsh. Optimal thickness of sediment addition may decrease with local tidal range and may depend on vegetation characteristics, so pilot studies are recommended prior to large-scale addition.

Bioturbation by Crabs at TLP Sites

Crab burrow density varied greatly among sites but was much higher in sediment addition than control plots, and much higher in low than high marsh. The high variance among sites and tidal gradient effects are similar at these restoration sites as in a synthesis of 15 natural marshes that included the same estuaries as in this study (Wasson et al. 2019). Our finding of increased crab abundance in sediment addition plots has implications for TLP projects. Crabs may positively (e.g., Walker et al. 2021; Beheshti et al. 2022) or negatively (e.g., He and Sillman 2016, Angelini et al. 2018) affect tidal marsh vegetation. Crab burrows can also alter sediment biogeochemistry, for instance by enhancing burial of heavy metals or by facilitating their resuspension (Pan et al. 2022). Such effects could be important at TLP sites using dredged material, which might contain contaminants. There are few studies of crab effects on tidal marsh restoration, but they appear to emphasize negative effects on vegetation (e.g., Liu et al. 2020). Crabs could however also facilitate colonization at TLP sites, as burrows are known to increase sediment oxygenation and depth of oxygen penetration (Koo et al. 2019; Pan et al. 2022). At a TLP restoration site in New Jersey, plants did not colonize until crab burrows broke through a compacted layer of fine sediments near the surface (L. Tedesco, personal communication). Crabs moving into a marsh restoration site also can increase its habitat value by serving as food for fish and wildlife.

Importance of Robust Monitoring of TLP Projects

We used multiple approaches to monitoring marsh response to TLP. The simplest approach would have been to compare plots before and after adding sediment. However, we also monitored controls where we had not added sediment, before and after, and it turned out this was critical. Low control plots unexpectedly improved over the monitoring period at all eight sites—pannes were naturally closing, and vegetation cover also increased in low control plots at many sites over the study period. Perhaps this recovery in areas of previous marsh drowning was due to the phase of the Metonic cycle leading to less inundation of these plants located near the seaward edge of their tolerance (Peng et al. 2019). In any case, this coincidental and presumably temporary recovery of the low marsh could have erroneously suggested recovery was due to TLP when it was actually also happening in non-TLP plots.

Likewise, the simplest approach would have been just to assess plots after a predetermined recovery period of a few years. However, we sampled before sediment addition and at various intermediate time points during recovery. If we had not done that, we would have gained a less rich understanding of mechanisms. For example, we found 7 cm plots recovered much faster than 14 cm plots initially in the high marsh, which strongly suggests that it was existing vegetation that recovered, not colonization by seedlings. By year 3 post-sediment addition, 7 cm and 14 cm plots were similar, and we would have been unable to infer the likely source of recovery. Monitoring the vegetation trajectory also helped us to determine that recovery was continuing when we ended the study (positive slope between year two and three) at various sites, especially for the high marsh, suggesting the full restoration potential of TLP had not been reached. Monitoring should continue, at least at a basic level, for many years or even decades following

TLP at restoration sites, until they achieve reference conditions or other desired targets.

In addition to comparing control and treatment plots, we also compared both to reference plots. This added an extremely important dimension to assessing restoration success. For instance, high marsh total cover recovered rapidly (2–3 years), so TLP apparently led to success based on that metric. But our reference plots (10 cm higher than controls) had much greater representation of high marsh species relative to the low marsh dominant. So, the comparison between TLP and high reference plots showed that we did not achieve restoration success with respect to desired species composition and abundance.

These examples of the value of a robust, sophisticated monitoring approach apply not only to small-scale experiments, but also to landscape-scale TLP in marshes (see Raposa et al. 2020 for monitoring guidance). We recommend incorporation of reference sites, control sites, and monitoring before/after restoration at various time points, to understand and document restoration trajectories. Well-designed and thoughtfully monitored coordinated restoration experiments, from the plot to landscape scale, will help managers test potential climate adaptation strategies to protect valued ecosystems in the future.

Implications for Management

Overall, our investigation yielded the following five main take-home messages of relevance to coastal managers.

1. *Terrestrial sediments can be effective for marsh restoration*. Quarried terrestrial sediments have been much more rarely used for TLP projects, but our study found they supported marsh plant growth, in some instances better than dredged sediment. Using terrestrial sediments external to the estuarine system increases net sediment supply to the estuary, and also opens up possibilities for sediment addition projects at marshes far from dredging operations.
2. *If you build it they'll come.* Across eight contrasting systems, in both high and low marsh, colonization by marsh plants—and by crabs—was generally rapid following sediment addition. Managers can expect fairly fast revegetation as well as appearance of crab burrows at TLP sites. Rapid revegetation following sediment addition is critical in locations exposed to extreme weather events such as hurricanes and episodic extreme precipitation events that can be highly erosive on a barren intertidal landscape.
3. *TLP may be valuable across elevations in the marsh landscape.* Most past TLP has focused on enhancing low marsh vegetation, but our study showed that TLP may be at least as effective for restoration of high marshes—total cover of marsh vegetation was higher in high vs. low marsh sediment addition plots, and sediment addition plots performed better than controls in terms of attaining restoration goals at more sites in the high vs. low marsh zones. Given our results, coastal managers can include enhancing high marsh resilience as a target for future TLP projects. This may be a novel and timely intervention to support species dependent on high marsh habitat (such as salt marsh sparrow or salt marsh harvest mouse), which have declined in many US marsh systems.
4. *Achieving reference conditions is much slower for marsh vegetation communities than elevation targets.* While TLP immediately resulted in achieving the elevations of our reference plots, our vegetation targets were not met at the end of three years. At many sites, progress was still gradually being made towards those targets when our study ended, suggesting that they may eventually be met. In any case, vegetation was generally similar in sediment addition vs. control plots by the end of three years, so TLP did not ultimately decrease vegetation abundance or species composition relative to desired targets. We caution coastal restoration stakeholders such as practitioners, funders, permitting agencies or the community managers to have realistic expectations—vegetation will not resemble that in existing, naturally higher marshes for many years post sediment addition, and may never approximate reference conditions. Until multiple TLP projects have been monitored for decades, we will not know how fast or even whether they eventually approximate reference marshes.
5. A*dding thicker sediment layers may be better than thinner.* While we found 14 cm TLP plots initially colonized more slowly than 7 cm plots, this difference had largely disappeared after just three years. In the face of accelerated SLR, and given the permitting and funding challenges of conducting TLP projects, we recommend adding thicker sediment layers. While vegetation recovery is optimized in the short-term with thinner additions, thicker additions build long-term resilience to climate change.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12237-022-01161-y.

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Study sites

Below we provide a brief description and map of each of the eight NERR study sites.

Great Bay NERR, NH

The Great Bay National Estuarine Research Reserve is made up of 10,000 acres of natural land and open water along New Hampshire's coast encompassing a diversity of land and water areas around Great Bay, an expansive estuary in southeastern New Hampshire. The Reserve is host to a wide range of species, from oysters, lobsters, striped bass, and horseshoe crabs to migratory osprey and annually spawning river herring. Great Bay occupies approximately 7,300 acres of open water and wetlands that include salt marshes, rocky shores, bluffs, woodlands, open fields, fed by eight tidal rivers connecting to the sea through the Piscataqua River. The salt marshes of the Great Bay Estuarine system are dominated by smooth cordgrass (*Spartina alterniflora*) in low marsh habitats while the high marsh comprises a wider diversity of species adapted to the fluctuating salinity of the Estuary, including salt hay (*Spartina patens*), black grass (*Juncus gerardii*), spike grass (*Distichlis spicata*), slender glasswort (*Salicornia depressa*), saltmarsh bulrush (*Schoenoplectus robustus*) and seaside goldenrod (*Solidago sempervirens*), among others (Moore et al. 2011). In addition, the Estuary contains state-listed rare natural communities including Tidal Riverbank Marsh which provides habitat for equally rare estuarine plant species including Eastern grasswort (*Lilaeopsis chinensis*), false water pimpernel (*Samolus valerandi*), and saltmarsh false foxglove (*Agalinis maritima*) that occur along several of the Estuary's tidal tributaries (Moore *et al.* 2009). While some salt marsh sites in Great Bay seem to be relatively resilient to the effects of accelerated sea level rise (Payne *et al.* 2019), most do not appear so fortunate. Our study site, located nearby the University of New Hampshire's Jackson Estuarine Laboratory at Adams Point, has been in decline for the past ~10 years. Transition from high marsh to low marsh conditions has been documented anecdotally by a number of researchers and land managers in the region (*i.e.*, prevalence of short-form *S. alterniflora* in the high marsh, marsh collapse and fragmentation, and prolonged surface flooding). We believe that given the continued degradation of the system, Adams Point could be a good candidate marsh for future broad-scale thin-layer placement based on its low to moderate elevation range and increasing evidence of marsh dieback.

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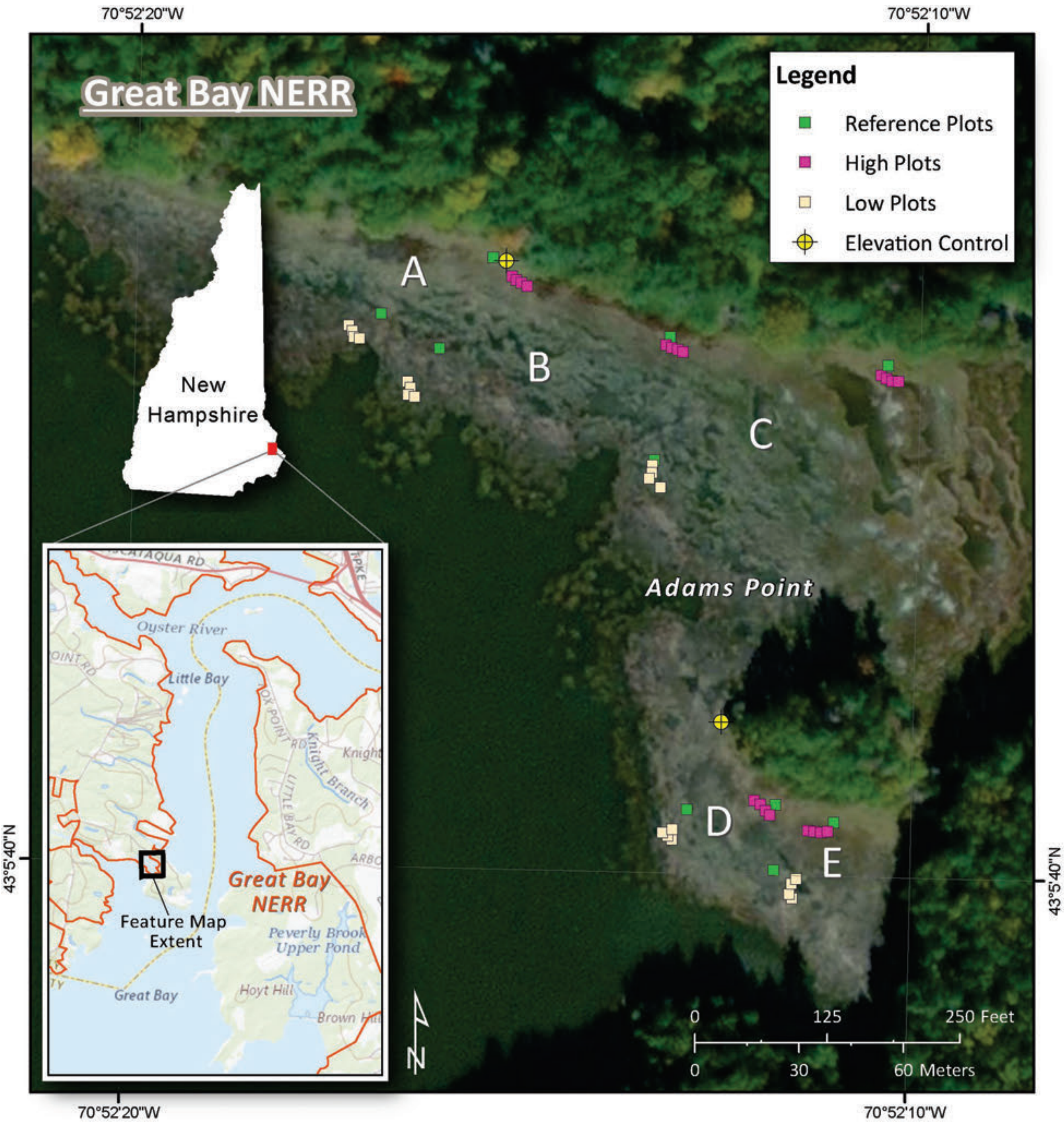

70°52'20"W
70°52'10"W
Great Bay NERR
Legend
Reference Plots
High Plots
Low Plots
Elevation Control
New Hampshire
A
B
C
D
E
Adams Point
Oyster River
Little Bay
Great Bay NERR
Feature Map Extent
Peverly Brook Upper Pond
Hoyt Hill
Great Bay
Knight Branch
LITTLE BAY RD
43°5'40"N
0
125
250 Feet
0
30
60 Meters
N

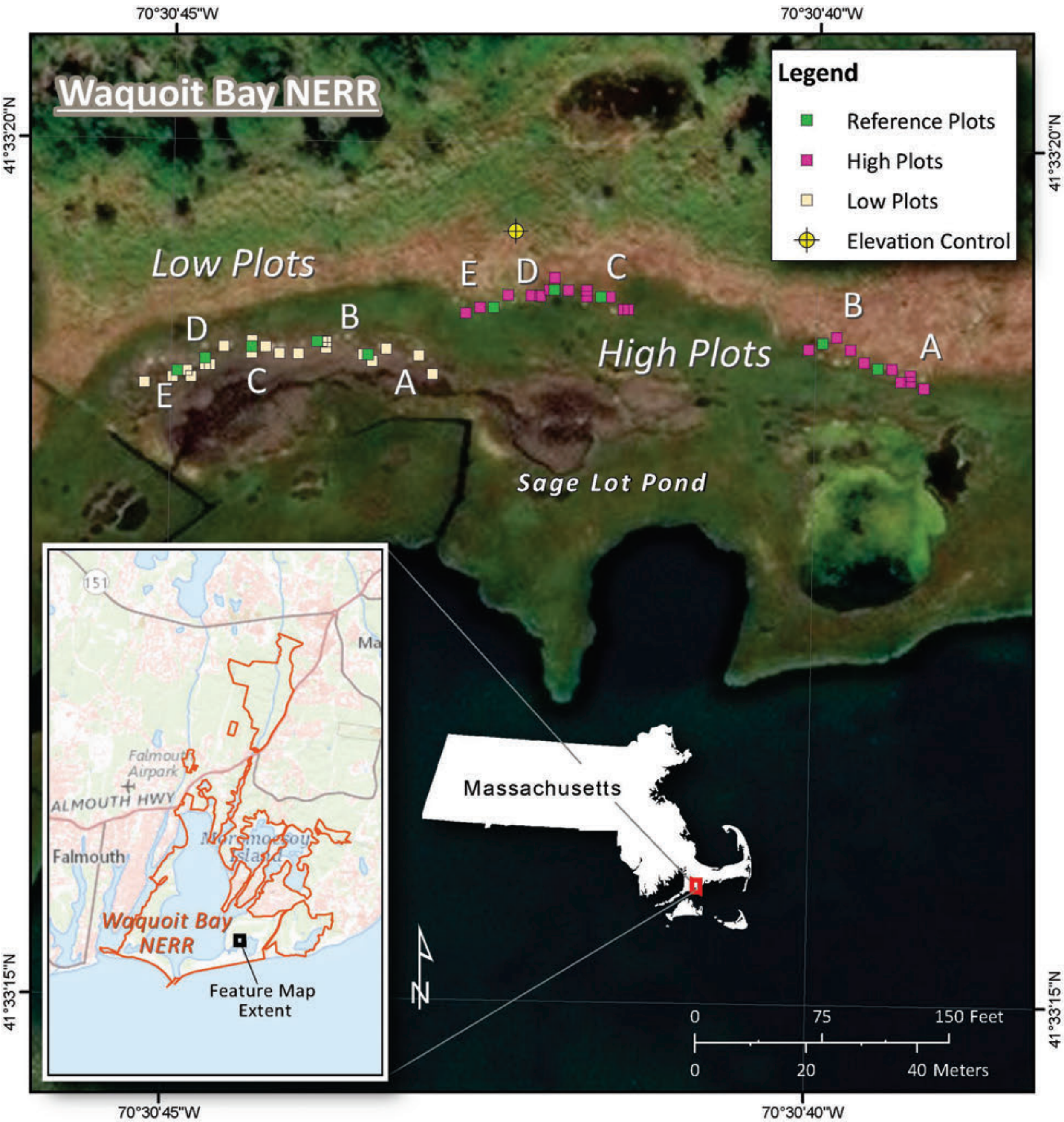
Waquoit Bay NERR, Sage Lot Pond, Mashpee, MA

The Waquoit Bay National Estuarine Research Reserve (WBNERR) is located on the southern coast of Cape Cod, Massachusetts. WBNERR's estuaries are representative of shallow tidal lagoons that occur from Cape Cod to Sandy Hook, New Jersey. Aside from climate change related stressors, excessive nitrogen input from upland land development is one of the greatest contributors to declining water quality in the bay. Sage Lot Pond, at the southeast side, is in the least developed sub-watershed of Waquoit Bay and contains a back-barrier salt marsh ecosystem bordered by South Cape Beach State Park on Nantucket Sound. Salt marsh monitoring conducted by WBNERR staff includes vegetation, elevation change, and habitat mapping in various locations around Sage Lot Pond. The dominant marsh vegetation is *Spartina alterniflora* with flooding sensitive species such as: *Distichilis spicata, Juncus gerardii* and *Spartina patens* occurring in linear swaths at the upland borders of the marsh plain and in small, isolated patches with higher elevations, for example near creek banks. Shrubs of *Iva fructescens* and the forb, *Plantago maritima*, also occur in the higher elevations of Sage Lot Pond where the thin layer placement study was conducted. Sage Lot Pond's salt marsh vegetation and general resilience to climate change related threats was among the lowest of 15 marshes examined in the marsh assessment study by Raposa et al. 2016. The microtidal marsh, like others that dominate southern New England, is more vulnerable to vegetation dieback and interior pond formation, which, coupled with lower sediment delivery rates due to lower flood velocities, renders its recovery from vegetation loss or other disturbances less likely (Kearney and Turner 2016). Sea level rise induced excessive inundation and increasing summer wind speeds (Foster and Fulweiler 2014) are putatively leading to expansion of unvegetated pools near the mean high water elevation (WBNERR unpub). This pool expansion and replacement of flooding sensitive species with more flooding tolerant species such as *Spartina alterniflora* are the motivating factors behind the thin-layer sediment placement experiment at Sage Lot Pond. Our aim was to provide a sufficient elevation boost to slow the replacement of flooding sensitive species with *S. alterniflora* so that the sediment addition plots resemble the species composition and abundance of our high marsh reference plots (average elevation 0.357 m NAVD88 which is, on average, 0.09 m higher than the high zone elevations where work was performed). The high marsh reference plots had, on average, just under half of their cover (45%) by species other than *S. alterniflora*. In the low zone where vegetation cover is sparse, our primary goal with sediment placement was to increase the amount and species diversity of vegetation. The average elevation of our low zone reference plots was 0.191 m NAVD88, and the pre-experiment average elevation of the plots where we added sediment was 0.07 m lower. The low zone reference plots were dominated by *S. alterniflora,* with, on average, 13% of cover composed of other vegetation species (*Distichilis spicata* and *Spartina patens).*

Foster, S.Q. and Fulweiler, R.W., 2014. Spatial and historic variability of benthic nitrogen cycling in an anthropogenically impacted estuary. *Frontiers in Marine Science*, 1:56.

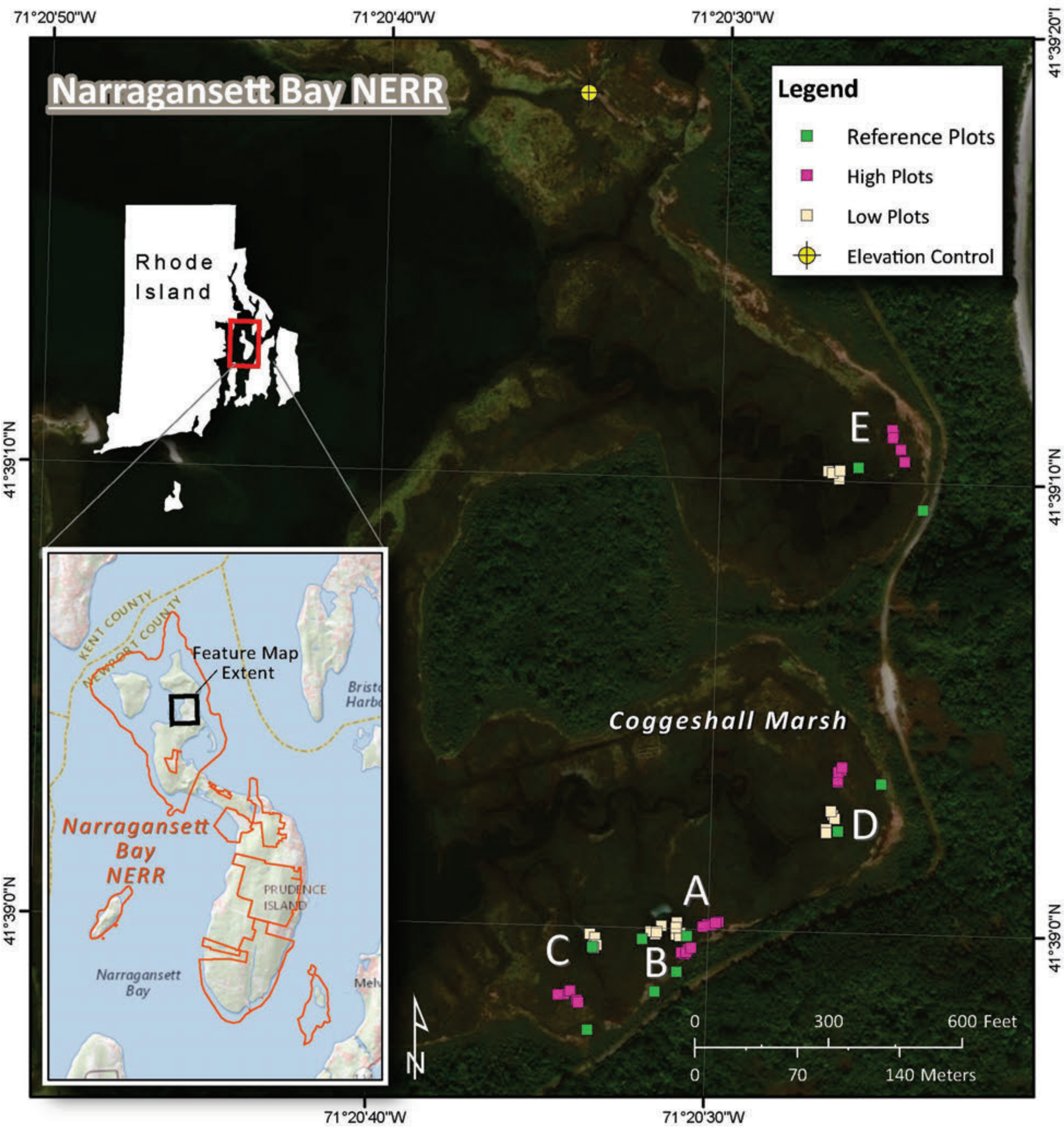
Kearney, M.S. and Turner, R.E. 2016. Microtidal marshes: Can these widespread and fragile marshes survive increasing climate–sea level variability and human action? *Journal of Coastal Research*, 319, pp. 686-699. https://doi.org/10.2112/JCOASTRES-D-15-00069.1

Raposa, K.B., et al., 2016. Assessing tidal marsh resilience to sea-level rise at broad geographic scales with multi-metric indices. *Biological Conservation*, 204(B), pp. 263-275.


70°30'45"W
70°30'40"W
41°33'20"N
41°33'15"N
Waquoit Bay NERR
Legend
Reference Plots
High Plots
Low Plots
Elevation Control
Low Plots
High Plots
A
B
C
D
E
Sage Lot Pond
Massachusetts
Falmouth Airpark
FALMOUTH HWY
Falmouth
Waquoit Bay NERR
Feature Map Extent
N
0
75
150 Feet
20
40 Meters

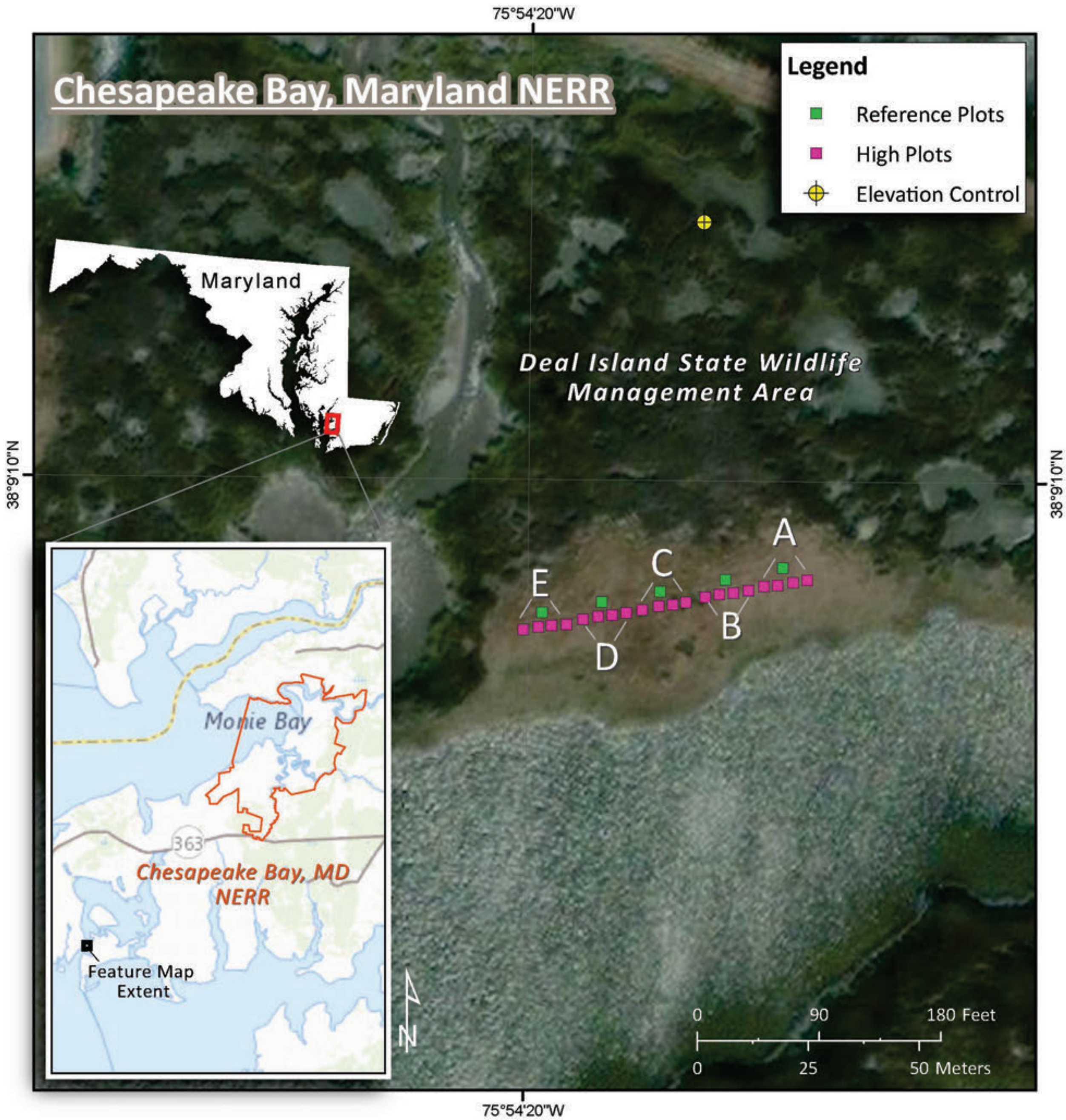
Narragansett Bay NERR, RI

Coggeshall Marsh is a 22-ha polyhaline marsh located in the approximate geographic center of Narragansett Bay RI, within the Narragansett Bay NERR on Prudence Island. Coggeshall is a meadow/fringe marsh dominated by *Spartina alterniflora* in the low marsh zone and typical salt meadow species (i.e., *Spartina patens, Distichlis spicata* and *Juncus gerardii*) in the high marsh. The marsh/upland ecotone consists largely of the shrubs *Iva frutescens* and *Baccharis halimifolia*, with an understory of *J. gerardii*. The area of Rhode Island marshes has declined approximately 17% since the 1970s due to factors associated with sea-level rise (SLR). The primary stressors affecting Coggeshall Marsh specifically are sea-level rise in conjunction with highly abundant marsh crab species and low sediment supplies. Possible management strategies for building resilience of Coggeshall against these stressors are few – there are no viable local sources for large-scale sediment addition and the adjacent upland is relatively steep with a dirt road and colonial-era stone walls inhibiting upland migration. In this project, low marsh treatment plots were established in degraded platform areas near the marsh/water edge that had recently undergone vegetation die-back, likely due to SLR. In contrast, low marsh reference plots were monocultures of stunted *S. alterniflora*. High marsh treatment plots were established in high marsh platform areas where salt meadow species had recently been replaced by stunted *S. alterniflora* – a characteristic response to SLR. High marsh reference plots remained dominated by typical salt meadow species as described above. Therefore, we expected TLP to result in increased cover of *S. alterniflora* in low marsh plots and increased cover of salt meadow species in high marsh plots.


Narragansett Bay NERR
71°20'50"W
71°20'40"W
71°20'30"W
41°39'20"N
41°39'10"N
41°39'0"N
Legend
Reference Plots
High Plots
Low Plots
Elevation Control
Rhode Island
KENT COUNTY
NEWPORT COUNTY
Feature Map Extent
Narragansett Bay NERR
PRUDENCE ISLAND
Narragansett Bay
Coggeshall Marsh
A
B
C
D
E
0
300
600 Feet
0
70
140 Meters
N

Chesapeake Bay Maryland NERR, Monie Bay Component

The project site is within the Deal Island Wildlife Management area, a part of the Monie Bay component of the Chesapeake Bay Maryland Reserve in Somerset County. The brackish salt marsh is located at the mouth of the Manokin River where it opens to the Chesapeake Bay. The extensive, low lying marsh complex is managed by the Maryland Department of Natural Resources' Wildlife and Heritage unit and commonly used for fishing, crabbing, and waterfowl hunting. Land subsidence has been observed in many similar marshes on the eastern shore of Maryland and across the Delmarva peninsula. An increasing area and number of unvegetated salt pannes have been observed opening up in the project area. Boat traffic and a southwestern fetch of up to 10 miles also contribute to wave driven marsh edge erosion. In fact, the experiment installation was not successful in the low marsh area because of the site's exposure and wave activity causing the plots to be washed out. The high marsh area is dominated by salt meadow hay (*Spartina patens*), salt grass (*Distichlis spicata*) and black needle rush (*Juncus roemerianus*) while the low marsh is dominated by smooth cordgrass (*Spartina alterniflora*). Reference plots were placed landward of each experimental block at a slightly higher elevation, above the area of more severe swiss cheesing (intense creekbank burrowing and peat erosion). Beneficial reuse of dredged material has been identified as a management priority for the state of Maryland. Specifically, thin layer placement of dredged material has been employed with promising results in a similar eastern shoreline marsh site, at the Blackwater Nature Reserve.



75°54'20"W
Chesapeake Bay, Maryland NERR
Legend
Reference Plots
High Plots
Elevation Control
Maryland
Deal Island State Wildlife
Management Area
38°9'10"N
A
B
C
D
E
Monie Bay
363
Chesapeake Bay, MD
NERR
Feature Map
Extent
N
0
90
180 Feet
0
25
50 Meters

Chesapeake Bay Virginia NERR, Goodwin Islands

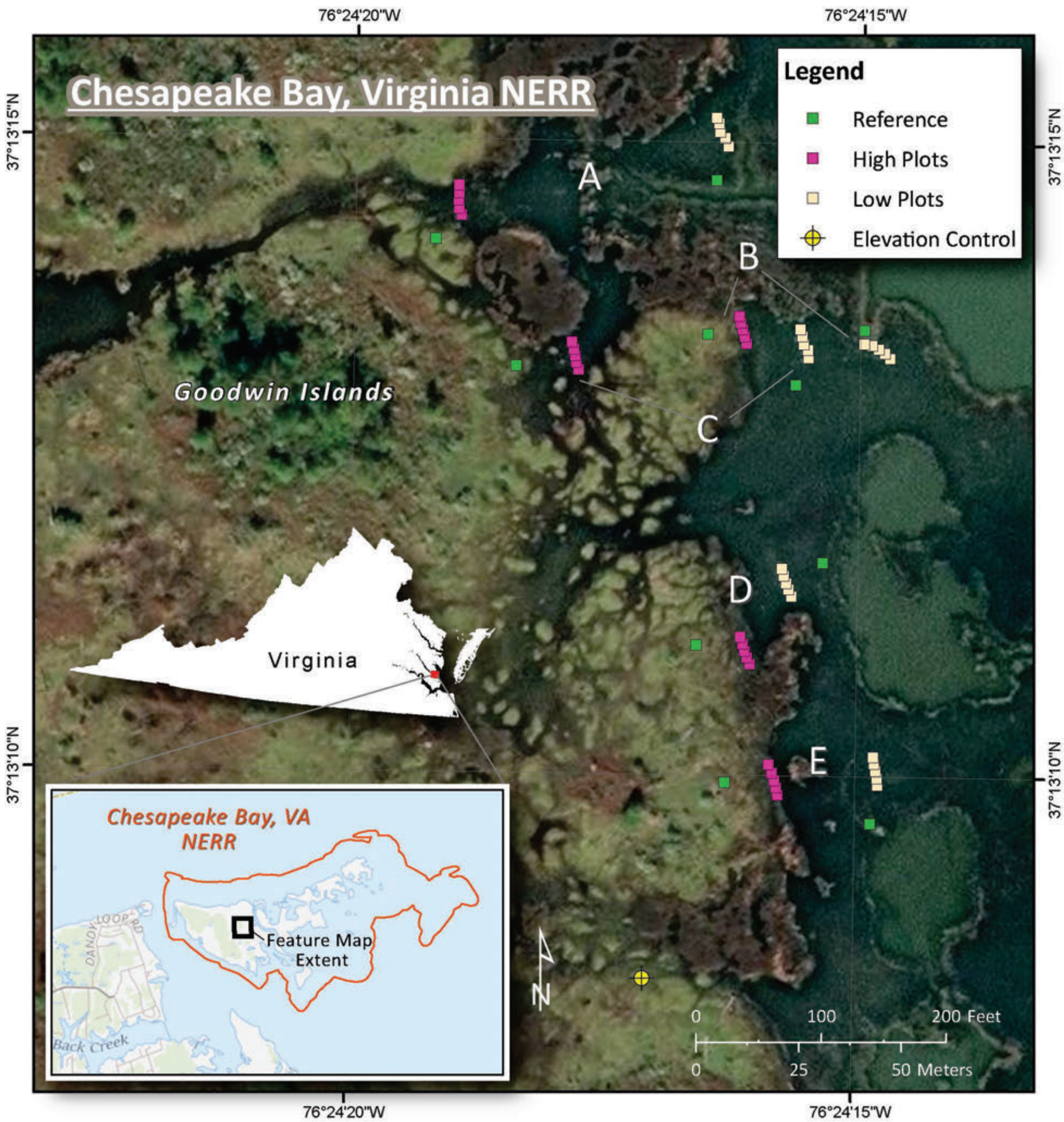
The Goodwin Islands (37° 13' N; 76° 23' W) component of the Chesapeake Bay National Estuarine Research Reserve of Virginia consists of an archipelago of salt marsh islands located on the southern side of the mouth of the York River. The islands are situated approximately 22 km down the York River from the Virginia Institute of Marine Science and are accessible only by boat. The nearest mainland is 0.2 km across the thorofare separating Goodwin Islands from the northeastern tip of York County. The Goodwin Islands are situated in a relatively high energy environment with open exposure to Chesapeake Bay and the York River, although the site for the thin layer placement experiments is relatively protected from issues of storm surge or wave erosion. The dominant wetland types within the Goodwin Island complex include smooth cordgrass, black needlerush, salt-meadow hay, and tall reed marshes. The lower elevation zones are dominated by smooth cordgrass (*Spartina alterniflora*) with few other species present. A large salt-meadow hay community exists on the west side of the islands, inland of the smooth cordgrass community. The community is dominated by a mix of salt meadow hay (*Spartina patens*) and saltgrass (*Distichlis spicata*). Several saline monotypic black needlerush (*Juncus roemerianus*) communities are also found scattered throughout the salt marsh community on the southeast side of the largest island. Some current management issues at Goodwin Islands include control of problem invasive species (especially the common reed *Phragmites australis*), control of native animal species (especially raccoons *Procyon lotor*), and protection of critical nesting/nursery habitat with emphasis on coastal shorebirds and the diamondback terrapin (*Malacyemys terrapin*).

Coastal ecosystems and their tributaries are among the most vulnerable environments to climate change induced sea-level rise (SLR). This is of particular concern in the Chesapeake Bay region where current SLR rates (~5-6 mm/yr) are elevated as compared to national and global averages. The Goodwin Islands are part of a hot spot of twentieth century sea level acceleration, driven by gradients in local and regional subsidence and changes in the position of the Atlantic Gulf Stream (Sallenger et al., 2012). Back in 2002, Stevenson et al. reported that more than half of the Chesapeake Bay's tidal marsh area shows signs of degradation due to a combination of factors including sea level rise and storm activity. Future climate impacts, including changes in precipitation, SLR, and extreme events, may result in an increased supply of sediment for marsh building; however, the impact of erosion from increased SLR and increased winter storm events may be detrimental to the salt marsh habitat.

Ongoing GIS work on Goodwin Islands indicates that, on an aerial basis, the overall contribution to marsh loss was much greater through perimeter erosion than observed for enlargement of tidal creeks or interior ponding. Results also indicate that marsh transgression rates into higher elevations previously occupied by maritime forest were greater and more sensitive to recent accelerations in local SLR than marsh perimeter erosion. The location at Goodwin Islands for the TLP study was chosen based on observations of extensive panning/ponding (i.e., unvegetated zones) in the low marsh and documented encroachment of low marsh species into areas formerly occupied by typical high marsh species. The goals of this study were to increase the cover and height of *Spartina alterniflora* in the low marsh treatment plots and increase cover by *Spartina patens* and *Distichlis spicata* in the high marsh treatment plots.

Sallenger, A.H., K.S. Doran and P. Howd. 2012. Hotspot of accelerated sea-level rise on the Atlantic coast of North America. Nature Climate Change 2:884-888. doi:10.1038/NCILMATE1597.

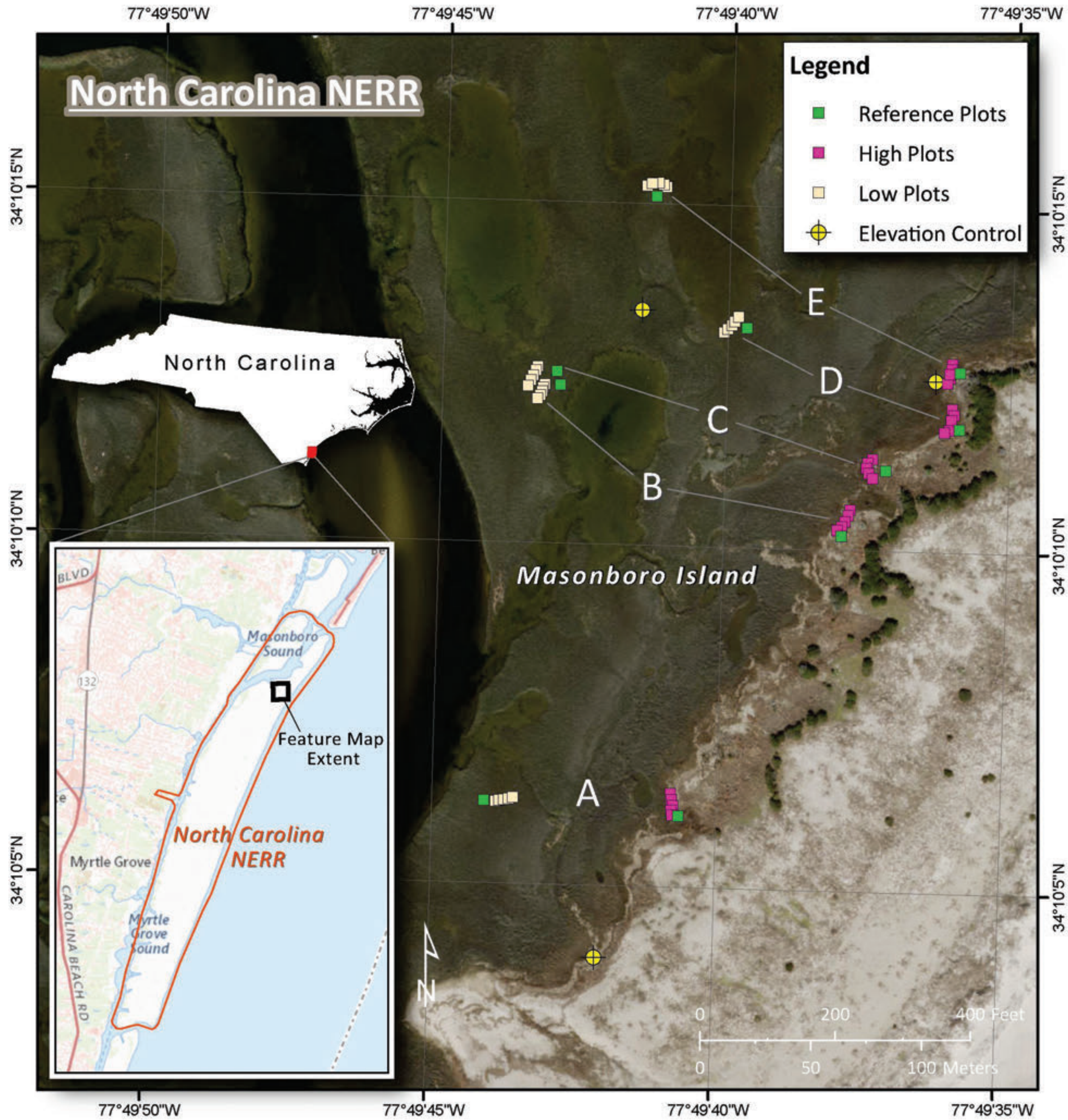
Stevenson, J., M. Kearney and E. Koch. 2002. Impacts of Sea-Level Rise on Tidal Wetlands and Shallow Water Habitats: A Case Study from Chesapeake Bay, pp. 23-36. In: N.A. McGinn (Ed.), Fisheries in a Changing Environment. American Fisheries Society Symposium No. 32, Bethesda, MD, USA.


Chesapeake Bay, Virginia NERR
76°24'20"W
76°24'15"W
37°13'15"N
37°13'10"N
Legend
Reference
High Plots
Low Plots
Elevation Control
A
B
C
D
E
Goodwin Islands
Virginia
Chesapeake Bay, VA
NERR
Feature Map
Extent
Back Creek
0
100
200 Feet
25
50 Meters
N

North Carolina NERR, Masonboro Island

The southeastern coast of North Carolina consists of a series of narrow bar-built estuaries, which lack significant riverine input of sediment and fresh water. Within this setting, the Masonboro Island NERR comprises the largest undisturbed barrier island along the southern coast of North Carolina, as well as the associated dredged material islands and surrounding salt marsh and tidal creek system. The Reserve is bounded by Masonboro Inlet to the north, the Atlantic Ocean to the east, Carolina Beach Inlet to the south, and the Atlantic Intracoastal Waterway (ICW) and Masonboro Sound to the west. Inlet stabilization practices, including jettying and continuous channel dredging, have restricted the amount of inorganic sediment available to back barrier marshes of the island (Hackney and Cleary 1987). Sentinel Site data from surface elevation tables at Masonboro Island reveal that marsh elevation is being lost at 1.8 mm y^{-1}, plant cover is decreasing at the lowest elevations, and high marsh species are being displaced by low marsh species. Masonboro Island's marshes are dominated by *Spartina alterniflora* in the low marsh, with intermittent occurrences of *Limonium* and *Salicornia spp*. The high marsh is predominantly comprised of *Spartina patens*, *Distichlis spicata*, and *Borrichia frutescens* above MHHW (0.54 m). The site of the TLP experiments could be a good candidate marsh for future broad-scale thin-layer placement based on its low allochthonous sediment supply, loss in marsh elevation, and vegetation patterns indicative of marsh migration. At the experimental site, our "Low marsh" reference plots included a higher density of *S. alterniflora* compared with our control plots, while our "High marsh" reference plots included a higher proportion of *S. patens*, *D. spicata*, and *B. frutescens* than our control plots.

Hackney, C.T. and W.J. Cleary. 1987. Saltmarsh loss in southeastern North Carolina lagoons: Importance of sea level rise and inlet dredging. Journal of Coastal Research 3: 93–97


77°49'50"W
77°49'45"W
77°49'40"W
77°49'35"W
34°10'15"N
34°10'10"N
34°10'5"N
North Carolina NERR
Legend
Reference Plots
High Plots
Low Plots
Elevation Control
North Carolina
A
B
C
D
E
Masonboro Island
Masonboro Sound
Feature Map Extent
North Carolina NERR
Myrtle Grove
Myrtle Grove Sound
CAROLINA BEACH RD
BLVD
132
N
0
200
400 Feet
0
50
100 Meters

San Francisco Bay NERR, CA

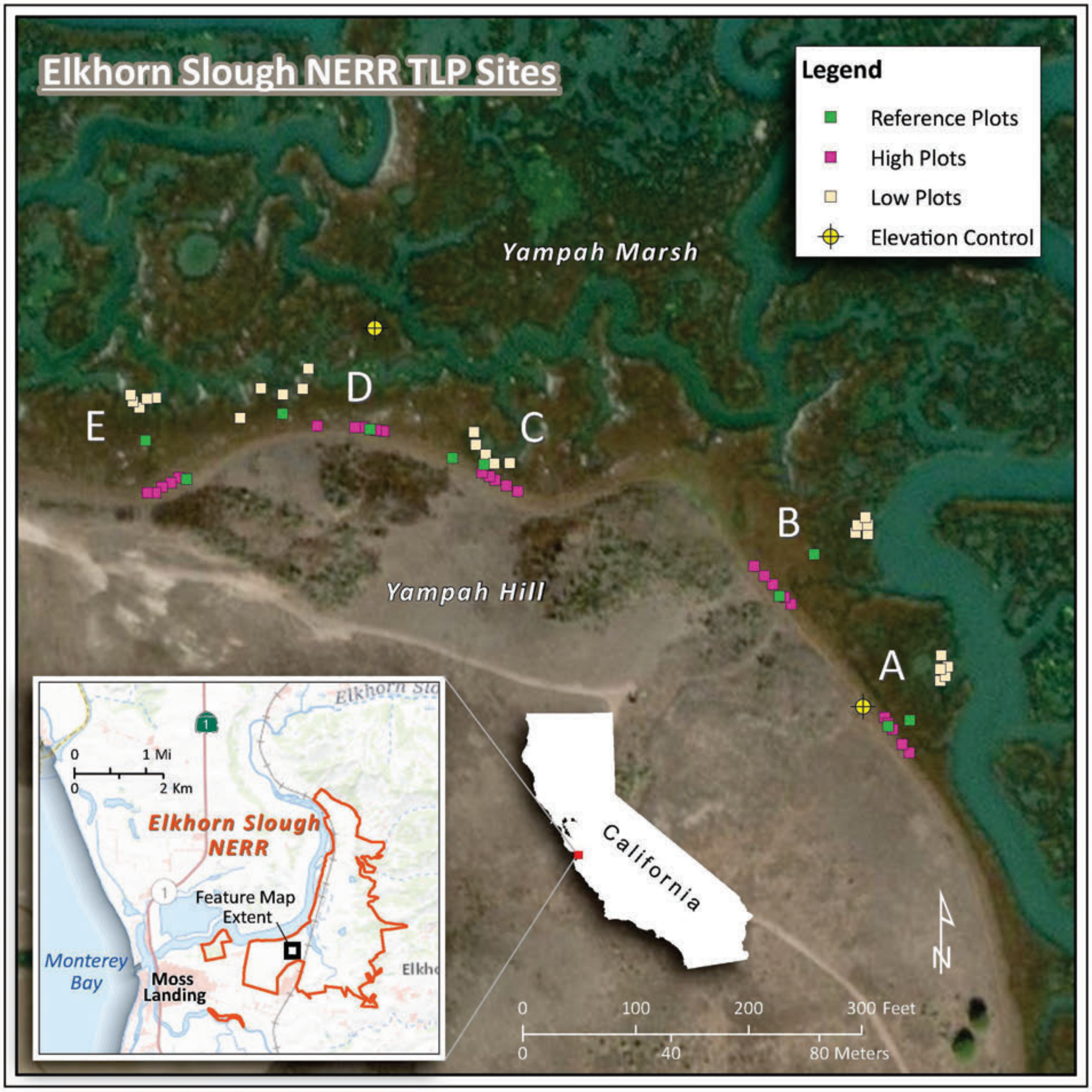
Manzanita marsh is a small tidal salt marsh in the saline portion of the San Francisco Estuary, located along the western shore of Richardson Bay just north of the Golden Gate. The high marsh is bounded by paved parking lots and an office building, and a freeway bridge passes over the western edge of the site. Historic tidal wetlands in this estuary are dominated by high marsh platforms that are thus far keeping pace with contemporary rates of sea-level rise. Small, flat and poorly drained fringing wetlands like Manzanita marsh mostly have formed within the past 100-200 years and may be more vulnerable to increasing inundation. The central platform of Manzanita marsh is poorly drained with almost no small channel development other than a drainage ditch along one side, and thus may be a good model for other fringing marshes with limited drainage. The lower marsh at this site is exposed to periodic waves from recreational boats and a nearby seaplane tour operator, and is dominated by a narrow band of California cordgrass (*Spartina foliosa*). Above this zone the cordgrass gently grades into pickleweed (*Salicornia pacifica*) and then the higher marsh plain, which is dominated by a mix of locally common species including pickleweed, salt grass (*Distichlis spicata*), and fleshy jaumea (*Jaumea carnosa*). Compared with experimental plots in low marsh areas of cordgrass and bare ground, the slightly higher elevation "Low" reference plots included less bare ground, higher density of cordgrass, and some pickleweed. High marsh experimental plots are dominated by salt grass and fleshy jaumea, with pickleweed, arrowgrass (*Triglochin maritima*), California sea lavender (*Limonium californicum*), and alkali heath (*Frankenia salina*) present at lower density. In comparison, "High" reference plots are dominated by a mix of salt grass and alkali heath.


122°30'55"W
San Francisco Bay NERR
Legend
Reference Plots
High Plots
Low Plots
Elevation Control
37°52'55"N
Low Plots
A
B
C
D
E
122°31'0"W
California
Manzanita Marsh
D
E
C
High Plots
A
B
37°52'55"N
122°30'55"W
Strawberry
Tiburon
Strawberry Point
Feature Map
Extent
Belvedere
Marin City
Sausalito
0
60
120 Feet
0
20
40 Meters
122°31'0"W

Elkhorn Slough NERR, CA

Elkhorn Slough is a small estuary in the middle of the Monterey Bay, 120 km south of San Francisco. It hosts the most extensive salt marshes in the state south of the Bay area. Substantial marsh loss has occurred due to diking (Van Dyke and Wasson 2005). However, even undiked salt marshes have undergone dieback over the past 50 years, in patterns consistent with excessive inundation. Elkhorn Slough NERR Sentinel Site data from surface elevation tables reveal that marsh elevation gain is less than accretion, indicating shallow subsidence is occurring. Data from repeat surveys of benchmarks suggests deep subsidence is also occurring. Elkhorn Slough lies in a very productive agricultural watershed and subsidence may be driven by groundwater overdraft and/or eutrophication-fueled decomposition. Elkhorn Slough's marshes are dominated by pickleweed (*Salicornia pacifica*), with increasing proportions of ecotone specialist species above MHHW (1.76 m NAVD88), including alkali heath (*Frankenia salina*), salt grass (*Distichlis spicata*), fleshy jaumea (*Jaumea carnosa*), and spearscale (*Atriplex triangularis*). Yampah Marsh, the site of the TLP experiments, could be a good candidate marsh for future broad-scale thin-layer placement based on its low to moderate elevation range (1.4 – 1.65 m NAVD88) and recent marsh dieback. At the experimental site, our "Low" reference plots included a higher density of pickleweed (compared with our control plots), while our "High" reference plots included a higher proportion of non-pickleweed species, as described above.

Van Dyke, E., Wasson, K., 2005. Historical ecology of a central california estuary: 150 Years of habitat change. Estuaries 28, 173–189. https://doi.org/10.1007/BF02732853.

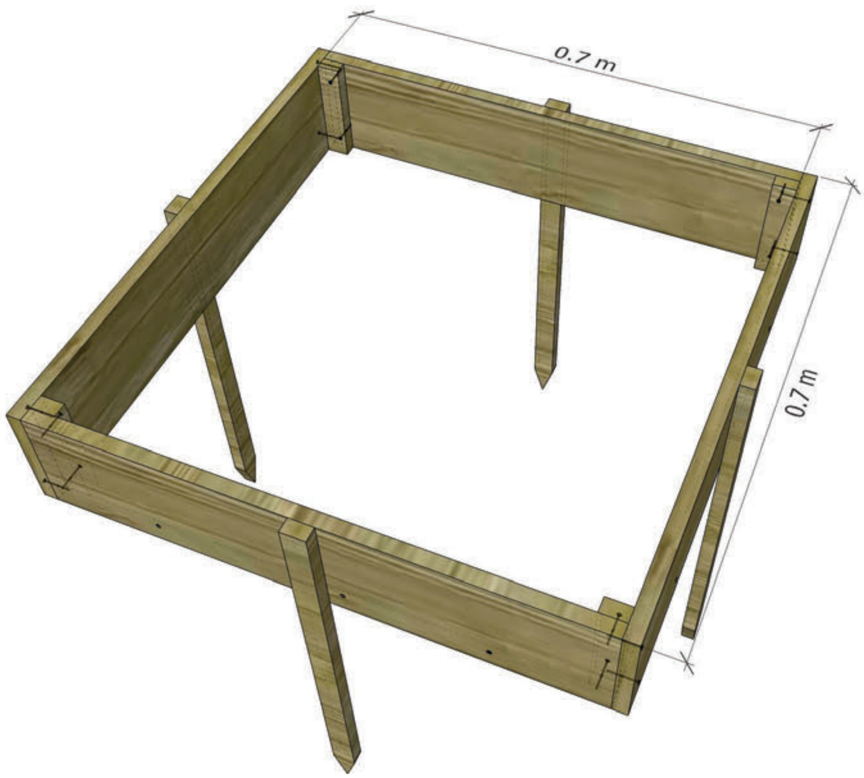


Elkhorn Slough NERR TLP Sites
Legend
Reference Plots
High Plots
Low Plots
Elevation Control
Yampah Marsh
Yampah Hill
A
B
C
D
E
California
0 100 200 300 Feet
0 40 80 Meters
N
0 1 Mi
0 2 Km
Elkhorn Slough NERR
Feature Map Extent
Monterey Bay
Moss Landing
1

Study design

In this section, we provide diagrams highlighting aspects of study design and monitoring, including a brief sub-section on an additional root sever treatment conducted at Waquoit Bay NERR.

Fig. S1 Diagram of the 0.7 m x 0.7 m wooden frame used in sediment addition plots in this study. Note the drainage holes and stakes used to secure the frame into the sediment



ADDITIONAL ROOT SEVER TREATMENT AT WAQUOIT BAY NERR

The design of the TLP experiment included root severing for all manipulated plots (sediment addition, biochar/dredge, procedural control) to decrease the likelihood of rhizomes from plants surrounding the plots subsidizing recolonization after sediment addition or procedural controls were implemented. Waquoit Bay therefore added a sever treatment (no frame) to examine the effect of severing plant roots. Severing methods were identical for all treatments where isolation of the roots within the frame (7 cm, 14 cm, biochar/dredged) or marked plot with no frame (sever treatment) was the objective. Effects of the sever treatment on plot vegetation were compared with unframed controls using a t-test on year 3 vegetation data. A one-tailed probability distribution was chosen *a priori* for comparison between groups because the root severing was hypothesized to be stressful for plants.

The effect of severing was different in high and low marsh. Total vegetation cover in high marsh was similar between sever (78.6 ± 7.79 cm SE) and control treatments (82.2 ± 8.90 cm SE) (**Fig. S2**), but in low marsh final vegetation cover was significantly lower in the sever treatment (34.0 ± 12.83 cm SE) than in the controls (70.4 ± 9.09 cm SE), ($t=2.31$, $df=8$, $p<0.03$). Mean plant canopy height was also affected by severing, but only in low marsh (**Fig. S3**). In high marsh, canopy height of *S. alterniflora* in the sever treatment (35.98 ± 1.76 cm SE) was not significantly different from heights in the controls (36.98 ± 0.82 cm SE). In contrast, *S. alterniflora* canopy height in low marsh was significantly lower in the sever treatment (27.85 ± 3.14 cm SE) compared to controls (44.70 ± 7.44 cm SE), ($t=2.09$, $df=8$, $p<0.03$).

The Waquoit Bay sever treatment was added while exploring the high and low marsh zones where the full experiment was to be conducted. The peat in the high marsh was firm and it was easy to walk. Walking in low marsh was much more difficult; the low marsh plots were at the upper edge of an unvegetated area and the peat was considerably softer and under several inches under thick mud. The result that root severing was a significant stress that affected both total vegetation cover and canopy height at the end of the experiment in low marsh was not a surprise. Similar to many of the other sites in this experiment, there was substantial vegetation cover in former bare areas of the low zone by year three of the experiment. Nevertheless, the plants that had undergone the stress of severing three years prior still showed indications of that event. The root severing was performed to more fully mimic the conditions that would be encountered by early colonizing plants in a full-scale restoration. Waquoit Bay's results that low zone recovery was significantly affected by this experimental manipulation should be interpreted in the context of using small plots and are not necessarily applicable to sediment placement that is conducted at a full restoration scale.

Fig. S2 Effects of root severing on total vegetation cover in low (A.) and high (B.) marsh

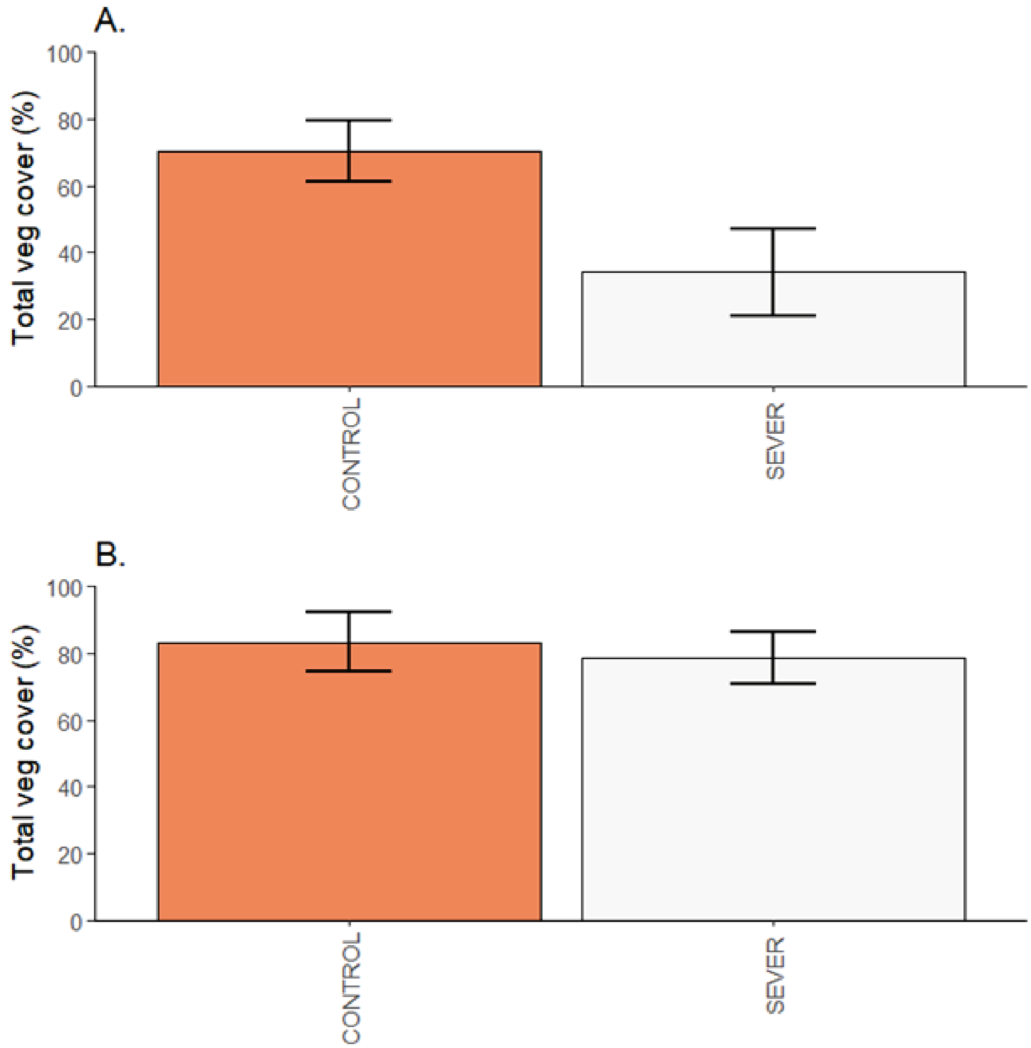


Fig. S3 Effects of root severing on *Spartina alterniflora* canopy height in low (A.) and high (B.) marsh

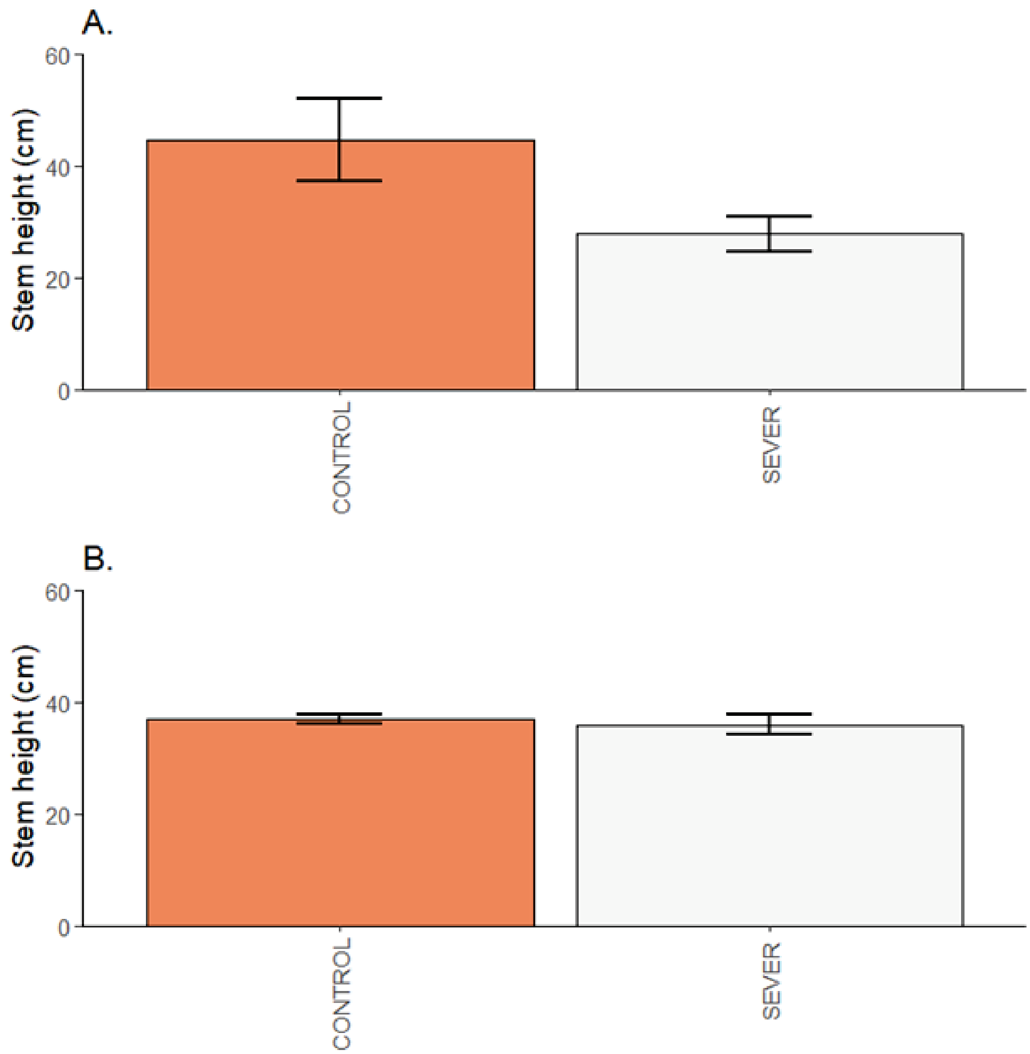


Fig. S4 Example of the blocked design from Elkhorn Slough, CA. Here two complete blocks with paired high marsh and low marsh treatments are shown. The order of plots within blocks was randomized. Reference plots (red squares) for low marsh treatments were placed in the mid-marsh zone. Reference sites for high marsh plots were placed at the upper edge of the high marsh

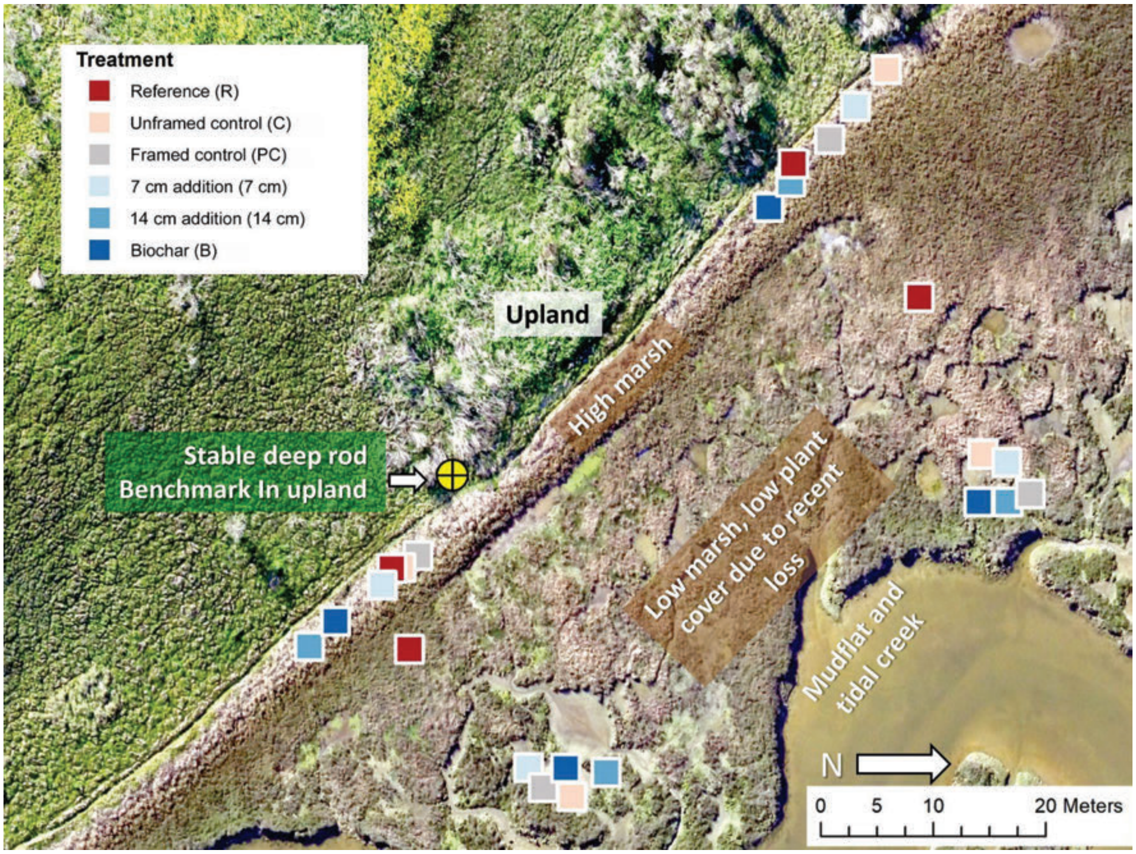
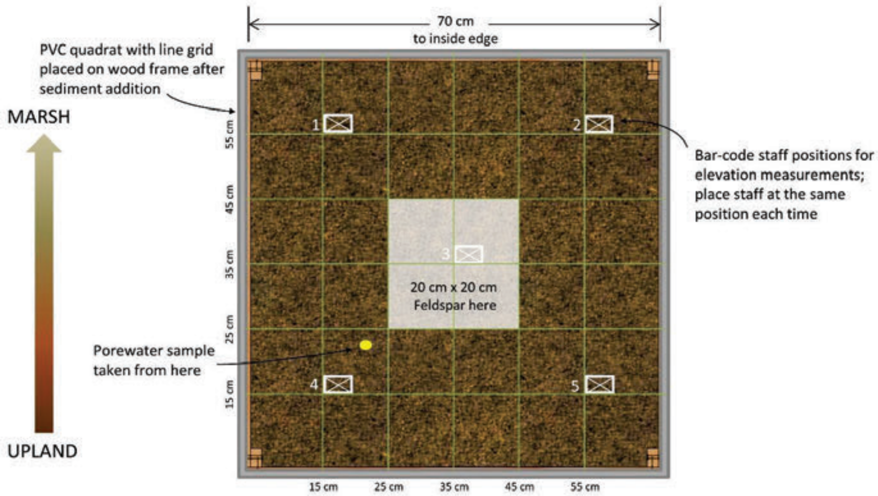
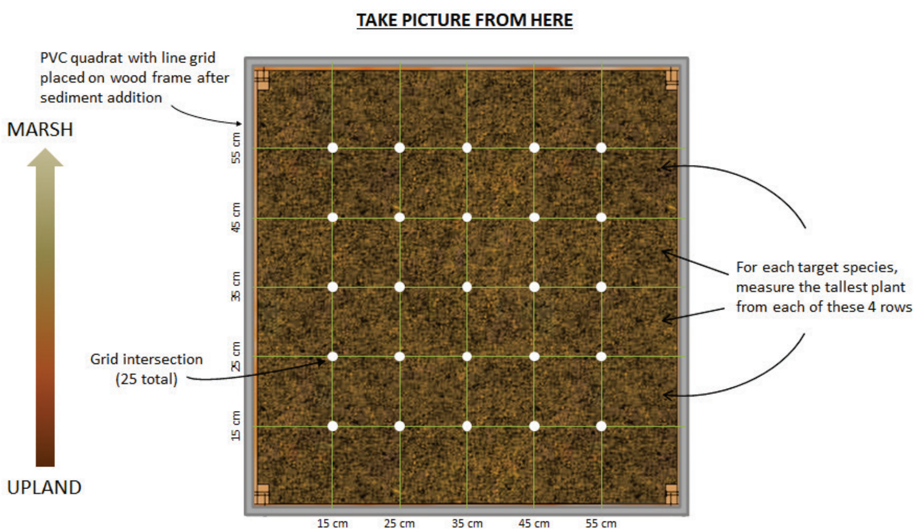


Fig. S5 Diagrams extracted from the field monitoring protocol used by all sites in this study. Top: locations of feldspar marker horizons and elevation collection points in study plots. Bottom: instructions for collecting vegetation monitoring data and taking plot photographs



<u>After sediment addition</u>: Place PVC quadrat with line grid directly on top of wood frame. Use grid to align feldspar, bar-code staff positions, and porewater sample locations.



Sediments

Sediment conditions were evaluated at the beginning of the experiment and one year after sediment addition. Below, we review the methods and results and discuss their significance.

METHODS

Initial characteristics of added vs. ambient sediments

Sediment properties were evaluated to characterize differences among ambient sediment, the sediment added into our experimental TLP plots, and *in situ* dredge and TLP projects near the sites (**Table S1**). Sediment samples (10-20 cm^3) were collected near the beginning of the study to quantify parameters reflecting sediment type, including percent water, percent organic matter, bulk density, and particle size distribution. Samples were collected from within the top 5 cm of 1) ambient low and high marsh areas within each study marsh, 2) dredged sediments from *in situ* operations and TLP projects, and dredged plots used in this study, when available, and 3) quarry sediments from local TLP projects and the quarry/mud plots used in this study, when available. Three replicate samples were collected from each source at each site. In the lab, particle size distribution was measured on sediment samples pre-treated with H_2O_2 to remove organic material (Gray et al. 2010), then introduced into a Beckman Coulter LS-13-320 system recording particle size distributions from 0.04-2000 µm with 117 bins, and run in triplicate. Average particle size distributions were post-processed with Gradistat.v8 software (Blott and Pye 2001), including bin aggregation to texture classes, and statistical description. Sediment textures were defined per Friedman and Sanders (1978). Particle size (diameter, *d*) values were converted to phi (ϕ) units using the formula $\phi = -\log_2 d$, and the full logarithmic method of moments was used to calculate particle size mean, sorting, skewness and kurtosis. Sediment samples were processed for bulk density, water content, and organic content by drying a known volume of sediment to constant weight and combusting for 4 hours at a temperature of 550°C (Heiri et al. 2001).

Sediment conditions in experimental plots after one year

Sediment conditions were also characterized in spring of the second year after TLP to determine how experimental treatment plots differed after exposure to tidal inundation and weather, since sediment conditions can affect plant growth. Sediment samples (60 cm^3 from 0-5 cm of depth) were collected in March of 2019, one year after sediment addition, from low and high marsh plots in the C, 7 cm, 14 cm, B, D, and R treatments. Each sediment sample was then placed into a labeled bag and frozen for later analysis. Parameters analyzed included bulk density (g cc^{-1}), percent water, redox potential (ORP; mV), pH, adsorbed NH_4^+ (uM g^{-1}), and porewater salinity.

Sediment water weight and bulk density were measured by drying a known volume of wet sediment (2.5 cc) to constant weight at 60°C. Sediment pH was measured using a 1:1 solution of sediment to water (soil dry weight:water weight) (NRCS 2004) using a Thermo Scientific Orion Star A211 pH meter calibrated with reference solutions. Dry weights were used to calculate the amount of water to be added. These weights were calculated based on a separately dried subsample, and sediments were not dried prior to analysis. Some samples (31 %, mostly control and reference samples collected from the low marsh zone) exceeded a 1:1 ratio of soil dry weight to water weight upon collection and were dried slightly to reduce water content instead of receiving water additions. Sediment redox was measured directly using an ORP probe (Thomas Scientific, bench-top pH/mV meter; Marvin-DiPasquale et al. 2008). Sediment porewater salinity was measured using the dilution method (USSL 1954; Watson and Byrne 2009). Fifteen mL of reverse osmosis water was added to eight grams of wet sediment, which was mixed on a vortex mixer and allowed to equilibrate at least one hour, followed by 10 minutes of centrifugation at 2500 rpm. Analysis of the supernatant for salinity and conductivity was performed using a YSI Professional plus multiparameter meter, calibrated daily. Porewater salinity was back-calculated based on a dilution factor for each sample based on the sample specific wet-weight and measured water content. To measure sediment nutrients, sediments (8.0 g wet weight) were extracted with 40 mL of 1.0 M KCl, shaken for one hour on an orbital shaker table. Samples were centrifuged (15 minutes at 2500 rpm), filtered through a Glass Fiber Filter, and analyzed for ammonium concentration using EPA Method 4500-NH3F, the Manual Phenate Method, using a Shimadzu UV-1601 UV-visible spectrophotometer. We focused on nitrogen rather than phosphorus because nitrogen tends to be the limiting nutrient where salinity exceeds 15‰. We measured ammonium because nitrate levels tend to be low in wetland soils due to low oxygen concentrations.

DATA ANALYSIS

We used non-metric multidimensional scaling (nMDS; PRIMER version 7.0.13; Clarke and Gorley 2015) to examine variability in structure among sediment sources based on similarity of sediment composition parameters (% organic matter, bulk density, mean grain size, % sand, and % silt+clay) among 1) the initial samples in TLP plots, 2) ambient marsh peat, and 3) quarry/dredged sediments from local dredge operations or local TLP projects. We also used nMDS to examine variability in sediment conditions among treatments based on similarity of parameters (bulk density, percent water, redox potential, pH, NH_4^+, and salinity) in samples collected approximately one year after sediment addition in 7 cm, 14 cm, C, and R plots (control samples not collected at WQB). Data were normalized prior to each analysis to account for different parameter units, and resemblance matrices were developed based on Euclidean distance among samples. To complement ordination, we conducted a two-way Analysis of Similarity (ANOSIM, with site and treatment factors, using individual plots as replicates) to compare 7 cm, 14 cm, C, and R treatments. We also separately conducted a similar ANOSIM to directly compare 14 cm and biochar plots. All ANOSIM tests were run separately for low and high marsh.

RESULTS

Initial characteristics of added vs. ambient sediments

All sites attempted to apply a standardized sediment grain size mixture from local quarried sources; nevertheless sediment composition varied among sites. Relative proportion of clay was similar among all sites (<10% clay) and most sites approximated the target of 75% sand (i.e., WQB, NAR, CBM, SFB, and ELK were all ~60-80% sand), but three sites added relatively more silt than targeted (GRB sediments were ~30% sand; CBV and NOC ~50% sand) (**Fig. S6**).

There was a significant global difference among all sediment types (two-way crossed ANOSIM with site and treatment factors, R=0.64, p=0.01) and pairwise differences between added quarry sediments and high ambient (R=0.99, p=0.001) and low ambient (R=0.88, p=0.001), but no difference between added quarry and sediments from local sources and local TLP projects (R=0.59, p=0.1; visualized with nMDS, **Fig. S7**). Sediments also differed among the 8 sites (R=0.65, p=0.01 across all treatments), with significant differences (p<0.05) for 26 of 28 possible pairwise comparisons. Thus, despite site-specific differences, sediments added to study plots were generally similar to those used in local restoration projects, but very different from ambient marsh sediments (**Table S2**). Ambient sediments had much less sand (~30%) than TLP sediments (~65% for TLP plots and 85% for local TLP projects), and more organic matter (~30%) than TLP (<2% for sediment addition plots and local TLP)**.**

Sediment conditions in experimental plots after one year

We anticipated that adding sediments to plots would alter attributes such as moisture content and porewater nutrient concentrations. After one year, at the site level in low and high marsh, 7 cm and 14 cm plots strongly separated from both controls and reference plots based on sediment conditions (nMDS, **Fig. S8**). Using individual plots as replicates, 7 cm, 14 cm, control, and reference were all significantly different from each other in low and high marsh (two-way ANOSIM with site and treatment factors; low marsh global *R*=0.56, *p*=0.001, all pairwise comparisons *p*<0.001; high marsh global *R*=0.67, *p*=0.001, all pairwise comparisons *p*<0.001). This was driven by consistent differences in individual parameters between added sediments, regardless of type (i.e., quarry+mud, B, D), and ambient marsh sediments. Specifically, all types of added sediment had lower water content and ammonium concentrations but higher bulk density, ORP (except dredged in low marsh) and pH than ambient sediments in both low and high marsh (**Table S3**). Simply put, TLP sediments, whether quarry, dredged or biochar-amended, were typically drier, sandier, more oxygenated, and nutrient poor compared to ambient marsh sediments.

We also anticipated that adding biochar to quarry sediment would alter conditions, but instead found no significant difference between 14 cm and biochar treatments at either elevation (two-way ANOSIM with site and treatment factors; low marsh global *R*=0.03, *p*=0.32; high marsh global *R*=0.12, *p*=0.10).

DISCUSSION

The sediment we used in the coordinated experiment was obtained from local quarries, supplemented by a small amount (10% by volume) of local marsh mud, in order to provide similar sediment grain size composition across the eight estuaries. Our analysis revealed that the sediment used for our TLP experiments resembled the physical properties of dredged sediment and sediment used in local TLP projects, but differed from ambient marsh sediment, mostly in being much sandier. The sandy sediments in the TLP plots likely explains their lower moisture, higher oxygenation, and lower nutrient concentrations relative to ambient marsh sediments. Croft et al. (2006) reported more oxygenated sediments in sediment addition plots, likely due to decreased waterlogging. Wigand et al. (2016) found sand-amendment of marshes altered porewater chemistry (lower pH, sulfides, phosphates, ammonium), but by the end of the growing season, plants grown in natural vs. sand-amended soils had similar belowground productivity and total biomass. Overall, it is important to remember that while the focus of TLP is to raise elevation, in our experiment and in large-scale restoration projects, elevation is not the only factor affecting marsh vegetation that is altered by sediment addition -- belowground biogeochemistry is altered as well.

Although there were no consistent differences in vegetation cover between TLP applications of the sand dominant mixture, sand amended with biochar amendments, or dredged sediments, there were notable differences in sediment conditions. Biochar amended and sandy sediments had water content 35% less than dredged sediments, and biochar amended and sandy sediments had ORP values that indicated oxygenated conditions (biochar = 90.5mV vs. sandy mix = 72.3mV) versus reduced conditions for dredged sediments (dredged = -34.7 mV). Considering that TLP is being utilized to counteract current or future flooding, increasing drainage and soil oxygenation through addition of sandier or biochar-amended sediments, which should be expected to increase soil drainage (e.g., Trifunovic et al. 2018), may be beneficial. While no differences in soil salinity or pH between soil treatments were found that could be expected to have important effects on plant growth (there were slightly higher pH values in biochar amended soils, in accordance with the known loss of acid functional groups during carbonization; Singh et al. 2017), there were however higher levels of soil ammonium levels found in dredged sediments, compared with sandy and biochar-amended sands. These higher levels of nutrients may promote more rapid re-establishment of vegetation, as has been observed previously in greenhouse studies (e.g., Feher and Hester 2018).

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Table S1 Dredged sediments analyzed for particle size distribution for comparison with sediments used in marsh TLP plots.

Nearby NERR	State	Project Description	Coordinates	Date	Samples
CBV	VA	Wormley Creek federal navigation project from Yorktown shoreline.	37.2361° -76.5056°	Nov-17	4
ELK	CA	Samples dredged from Pajaro River bench excavation project and stockpiled	36.8103° -121.7570°	Nov-17	3
NAR	RI	Samples dredged from a marina and used as part of the Sachuest Point Landfill Remediation and Saltmarsh Restoration Project	41.4849° -71.2451°	Oct-17	3
NAR	RI	Beneficial use of dredged sediment to build marsh elevation at Ninigret Pond.	41.3581° -71.6419°	Oct-17	3
NAR	RI	Beneficial reuse of dredged sediment to build marsh elevation at the Narrow River Estuary, RI	41.4559° -71.4500°	Oct-17	3
NOC	NC	Dredged spoil disposal area near the NERR from dredging of the intercoastal waterway. Three finer samples collected in 2015 were analyzed as well as three coarser samples collected in 2017.	34.1928° -77.8225	2015/ 2017	6
SFB	CA	Dredged sediments from the Montezuma Wetlands restoration project (sediments sourced from various dredging projects)	38.0996° -121.8859°	Apr-19	3
USDA NRCS*	NJ	Sediment dredged from Shark River and deposited on Shark River Island.	40.1867° -74.0292°	Nov-17	4
WQB	MA	Collected from intersection of Great and Little River, Waquoit Bay. Sediment dredged from Great River.	41.5617° -70.5139°	Oct-17	3

*contributed by advisory committee member

Fig. S6 Initial grain size composition of the sediment mixtures (local quarry plus 10% mud) added to experimental TLP plots across the eight sites. Red = % sand; tan = % silt; blue = % clay. Dashed reference line indicates the target % sand contribution. Labels are 3-letter codes for each site

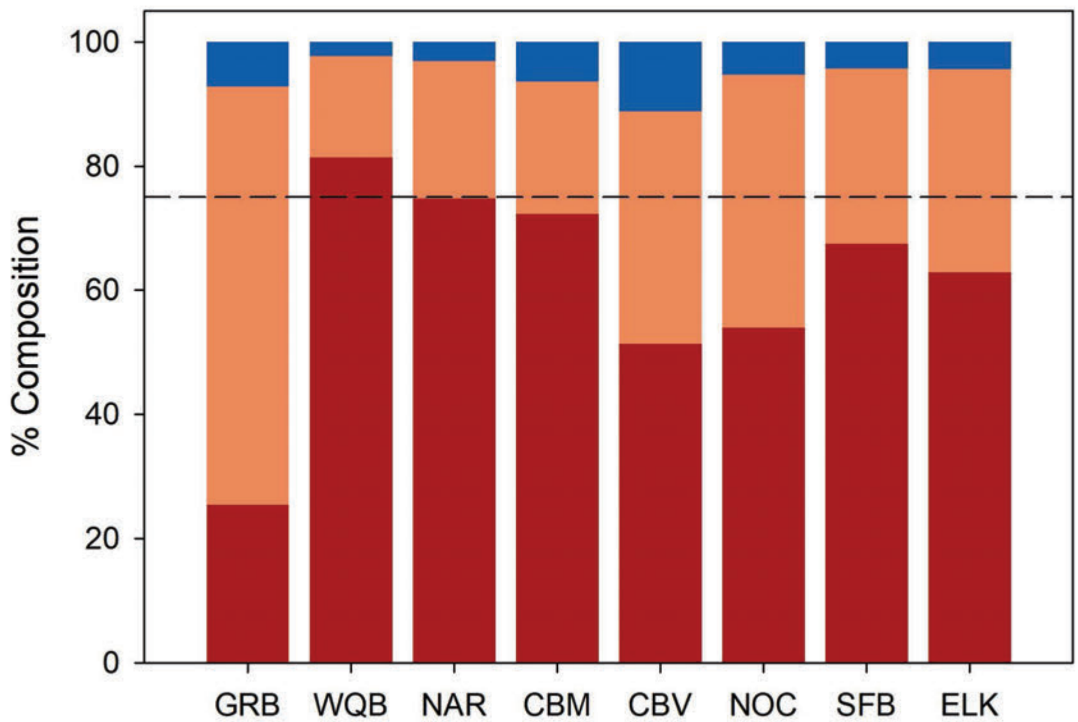


Fig. S7 Characterization of initial sediment properties. nMDS ordination of quarry sediment added to TLP plots and other sediment types (normalized data and Euclidean distance resemblance matrix using five sediment parameters from each sample: % organic matter, bulk density, mean grain size, % sand, and % silt+clay). Ambient low and high = natural marsh sediment from project sites collected from low and high marsh zones; Q/M and D (TLP plots) = the quarry/mud mixtures added to low and high plots at all 8 sites and dredged sediments added at three sites, respectively; D and Q (local TLP) = dredged and quarry sediments from local sources or local TLP projects near focal NERRS, respectively. Labels are 3-letter codes for each site. The ordination makes clear that ambient marsh sediments differ significantly from sediments added by TLP (experimental plots and local restoration projects)

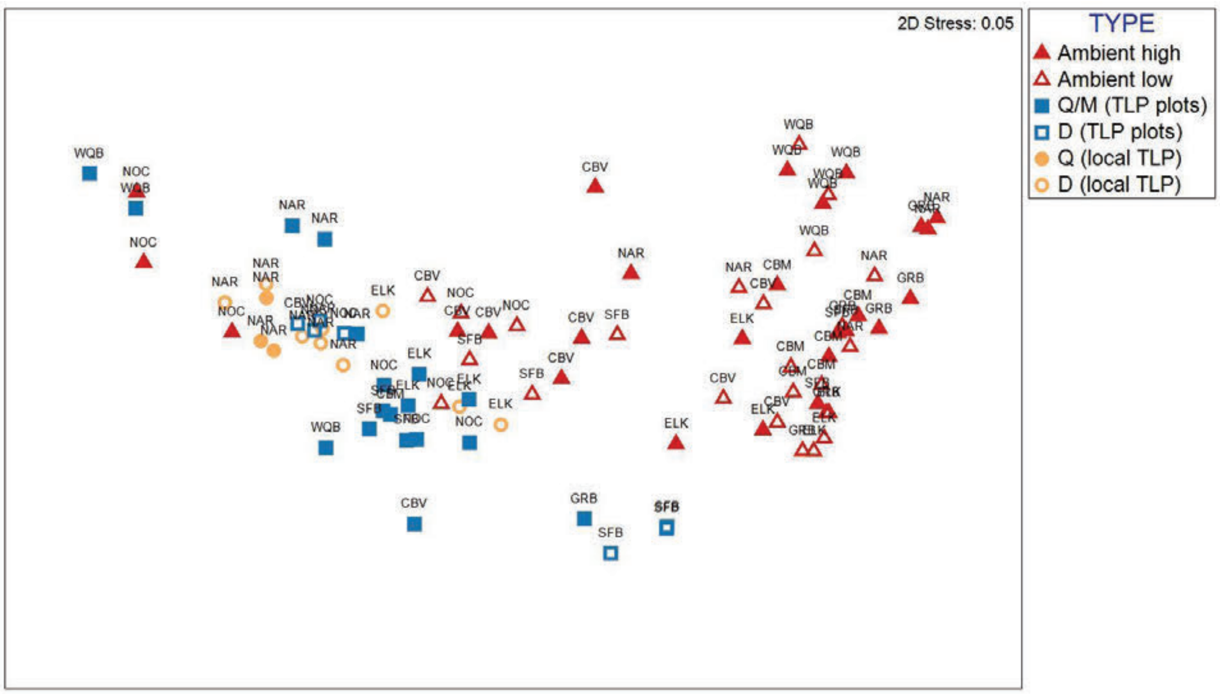
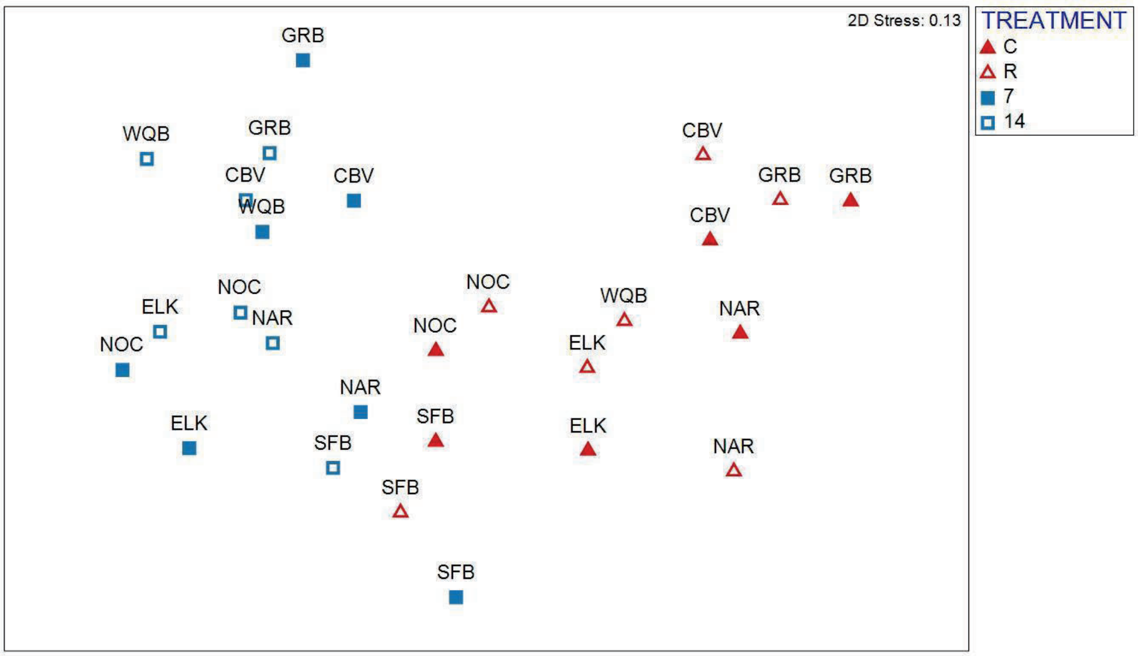


Fig. S8 Variation in sediment properties in experimental plots after one year. Comparison of 7 cm, 14 cm, control and reference treatments (mean of five plots per treatment per site) in low (a.) and high (b.) marsh based on sediment properties (nMDS using normalized data and Euclidean distance resemblance matrices). Control samples not collected at WQB. Parameters include bulk density ($g\ cc^{-1}$), percent water, redox potential (ORP; mV), pH, NH_4^+ ($uM\ g^{-1}$), and salinity. For both low and high marsh, it is clear that control and reference plots (with ambient sediments) differ significantly from the sediment addition plots (with quarried sediments)

a.



b.

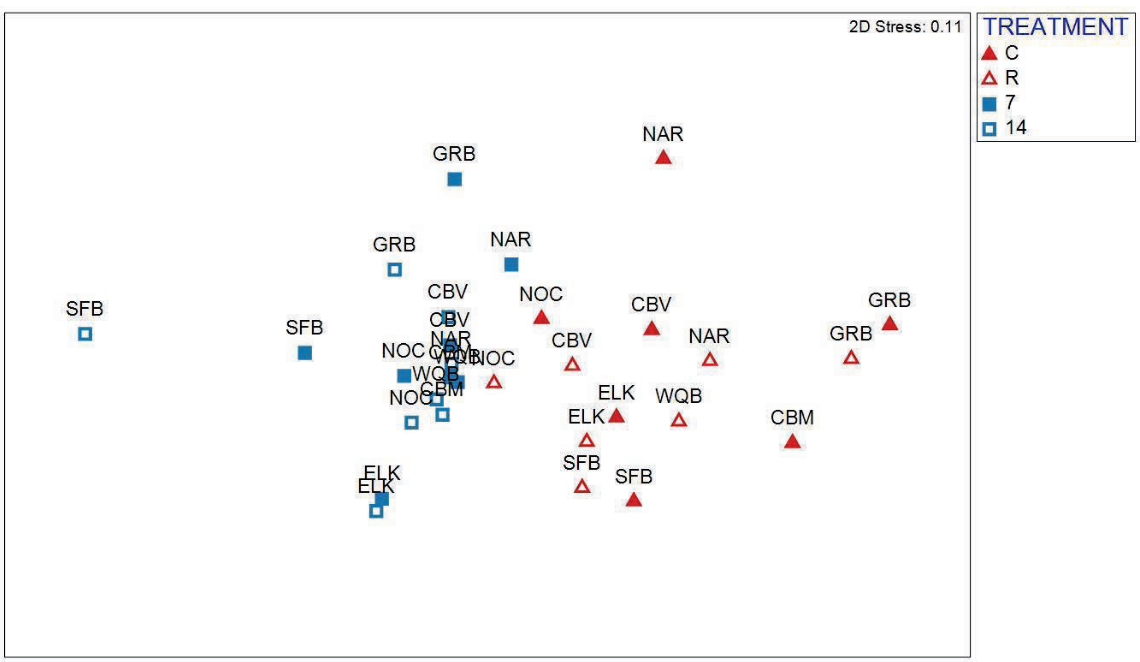


Table S2 Initial sediment characteristics (% organic content, bulk density, and % sand; all mean values) from the eight NERR sites. Samples were collected from natural marsh sediment (i.e., ambient) in low marsh and high marsh zones at each site and from the quarry/mud mixture added to TLP plots. A subset of sites also collected samples from dredged sediments (from local *in situ* sources, local TLP projects, and from the dredged sediments added to TLP plots), and quarry sediments (from local TLP projects and from the quarry/mud mixtures added to TLP plots). Grand totals are means across all sites. Conditional formatting was applied separately to each parameter, with darker green indicating relatively high values and darker red lower values

% ORGANIC		GRB	WQB	NAR	CBM	CBV	NOC	SFB	ELK	Grand Total
	AMBIENT - HIGH	53.95	61.29	53.96	37.10	14.05	1.63	34.57	22.38	33.26
	AMBIENT - LOW	26.34	58.11	41.11	26.20	20.38	5.54	11.45	18.92	25.78
	DREDGED (LOCAL SOURCE)		0.93			0.39	5.38			3.02
	DREDGED (LOCAL TLP PROJECT)			0.96					2.48	1.47
	DREDGED (TLP PLOTS)					0.23	1.16	3.40		1.99
	QUARRY (LOCAL TLP PROJECT)			1.31						1.31
	QUARRY + MUD (TLP PLOTS)	3.77	0.71	3.95	1.14	0.82	0.41	1.44	2.03	1.74

BULK DENSITY		GRB	WQB	NAR	CBM	CBV	NOC	SFB	ELK	Grand Total
	AMBIENT - HIGH	0.19	0.17	0.26	0.25	0.75	1.66	0.28	0.71	0.55
	AMBIENT - LOW	0.31	0.16	0.20	0.29	0.57	1.01	0.95	0.29	0.48
	DREDGED (LOCAL SOURCE)		1.62			1.35	1.12			1.30
	DREDGED (LOCAL TLP PROJECT)			1.36					1.25	1.32
	DREDGED (TLP PLOTS)					1.29	1.29	1.28		1.29
	QUARRY (LOCAL TLP PROJECT)			1.53						1.53
	QUARRY + MUD (TLP PLOTS)	1.45	1.74	1.35	1.54	1.99	1.48	1.64	1.35	1.54

% SAND		GRB	WQB	NAR	CBM	CBV	NOC	SFB	ELK	Grand Total
	AMBIENT - HIGH	4.09	28.86	20.86	7.56	60.06	94.78	7.00	16.53	33.27
	AMBIENT - LOW	4.35	26.86	15.25	9.92	32.86	64.82	52.88	1.68	26.35
	DREDGED (LOCAL SOURCE)		98.08			95.96	62.35			79.69
	DREDGED (LOCAL TLP PROJECT)			93.27					61.80	82.78
	DREDGED (TLP PLOTS)					96.88	90.95	13.21		58.48
	QUARRY (LOCAL TLP PROJECT)			88.60						88.60
	QUARRY + MUD (TLP PLOTS)	25.43	81.47	74.83	72.29	51.43	54.00	67.49	62.88	65.06

Table S3 Sediment conditions (bulk density, water fraction, salinity, oxygen redox potential [ORP], pH and ammonium [NH_4^+]) from eight NERR sites one year after the experiment was initiated. Mean values for each parameter are shown for the 7 cm addition, 14 cm addition, biochar, dredged, unframed control, and reference treatments, and for low marsh (top) and high marsh (bottom). Blanks indicate no data. Grand totals are means across all sites. Conditional formatting was applied separately to each parameter, with darker green indicating relatively high values and darker red lower values

LOW MARSH

Bulk density	GRB	WQB	NAR	CBM	CBV	NOC	SFB	ELK	Grand Total
7-cm	2.69	1.37	1.38		1.66	1.22	1.29	1.62	1.60
14-cm	2.49	1.28	1.56		1.60	1.33	1.46	1.47	1.60
Biochar		1.29	1.48					1.34	1.37
Dredged		1.46			1.27	1.06	1.08		1.22
Control	0.64		0.28		0.51	0.79	1.05	0.35	0.60
Reference	0.58	0.21	0.23		0.41	0.61	1.05	0.23	0.47

ORP	GRB	WQB	NAR	CBM	CBV	NOC	SFB	ELK	Grand Total
7-cm	-117.92	-3.50	-100.24		-167.20	136.06	-228.56	-116.18	-85.36
14-cm	-71.98	105.56	-13.72		24.88	31.64	-104.24	18.76	-1.30
Biochar		136.18	62.02					-25.28	57.64
Dredged					-212.42	-62.16	-175.38		-149.99
Control	-201.26		-94.96		-215.56	-138.46	-196.44	-231.60	-179.71
Reference	-199.68	-119.16	-135.08		-37.50	-51.94	-127.30	-121.30	-113.14

Water fraction	GRB	WQB	NAR	CBM	CBV	NOC	SFB	ELK	Grand Total
7-cm	0.28	0.17	0.26		0.18	0.27	0.37	0.17	0.24
14-cm	0.24	0.14	0.19		0.20	0.26	0.28	0.18	0.21
Biochar		0.15	0.24					0.21	0.20
Dredged					0.29	0.27	0.39		0.32
Control	0.72		0.80		0.69	0.42	0.47	0.73	0.64
Reference	0.79	0.83	0.82		0.70	0.53	0.44	0.80	0.70

pH	GRB	WQB	NAR	CBM	CBV	NOC	SFB	ELK	Grand Total
7-cm	6.50	7.37	6.19		7.16	7.55	5.70	8.16	6.94
14-cm	6.97	7.44	7.00		7.24	7.71	6.43	8.07	7.27
Biochar		7.67	7.25					8.03	7.65
Dredged					7.85	7.51	6.54		7.30
Control	6.20		5.88		6.49	7.30	6.91	7.34	6.69
Reference	6.71	7.29	5.44		6.09	7.24	6.41	6.89	6.58

Salinity	GRB	WQB	NAR	CBM	CBV	NOC	SFB	ELK	Grand Total
7-cm	18.95	18.87	38.90		19.32	42.78	45.51	44.83	32.74
14-cm	22.90	14.30	37.39		16.78	33.35	47.69	38.04	30.06
Biochar		16.33	32.42					49.44	32.73
Dredged					19.70	50.77	45.25		38.57
Control	18.55		28.39		16.23	35.71	41.84	35.80	29.42
Reference	15.63	28.65	23.95		14.05	35.32	51.55	30.35	28.50

NH_4	GRB	WQB	NAR	CBM	CBV	NOC	SFB	ELK	Grand Total
7-cm	0.23	0.11	0.11		0.21	0.43	0.02	0.34	0.21
14-cm	0.17	0.09	0.03		0.17	0.35	0.05	0.19	0.15
Biochar		0.16	0.06					0.18	0.13
Dredged					0.78	0.34	0.05		0.39
Control	2.75		1.68		1.69	0.54	0.03	0.51	1.20
Reference	2.32	1.03	0.29		1.86	1.16	0.06	0.43	1.02

HIGH MARSH

Bulk density	GRB	WQB	NAR	CBM	CBV	NOC	SFB	ELK	Grand Total
7-cm	2.72	1.32	1.55	1.39	1.72	1.86	1.88	1.37	1.78
14-cm	2.71	1.47	1.55	1.34	1.75	1.55	2.04	1.27	1.76
Biochar		1.44	1.68					1.22	1.45
Dredged					1.36	1.34	1.46		1.38
Control	0.42		0.81	0.29	0.68	1.22	0.37	0.45	0.66
Reference	0.37	0.27	0.28		0.82	1.33	0.38	0.42	0.55

ORP	GRB	WQB	NAR	CBM	CBV	NOC	SFB	ELK	Grand Total
7-cm	-179.42	111.28	18.32	85.74	81.90	69.36	157.62	299.80	79.84
14-cm	93.02	119.78	112.24	198.86	113.62	122.86	196.12	264.04	145.95
Biochar		144.10	60.92					164.94	123.32
Dredged					-11.50	82.90	170.26		80.55
Control	-269.00		-77.56	116.44	-166.84	-177.16	-97.16	109.98	-112.96
Reference	-248.60	114.84	-102.16		-18.40	-59.98	38.52	225.80	-7.14

Water fraction	GRB	WQB	NAR	CBM	CBV	NOC	SFB	ELK	Grand Total
7-cm	0.26	0.15	0.22	0.10	0.16	0.13	0.14	0.12	0.17
14-cm	0.20	0.13	0.18	0.20	0.15	0.13	0.12	0.11	0.15
Biochar		0.15	0.20					0.11	0.15
Dredged					0.25	0.18	0.24		0.22
Control	0.82		0.54	0.81	0.58	0.30	0.78	0.58	0.60
Reference	0.84	0.79	0.82		0.44	0.21	0.71	0.53	0.62

pH	GRB	WQB	NAR	CBM	CBV	NOC	SFB	ELK	Grand Total
7-cm	6.55	7.38	5.91	7.40	7.04	7.94	7.37	8.54	7.25
14-cm	6.92	7.70	7.20	7.44	6.56	8.22	7.49	8.89	7.57
Biochar		7.75	7.46					8.49	7.90
Dredged					7.90	7.70	7.95		7.85
Control	6.22		4.54	6.24	6.61	7.78	7.46	7.12	6.62
Reference	6.96	6.46	6.59		7.09	7.94	7.59	6.80	7.06

Salinity	GRB	WQB	NAR	CBM	CBV	NOC	SFB	ELK	Grand Total
7-cm	11.41	9.31	24.42	23.82	15.38	30.28	132.45	5.20	32.63
14-cm	13.58	8.94	23.49	16.68	14.42	24.50	234.59	4.98	46.36
Biochar		7.54	23.03					5.29	11.95
Dredged					16.39	21.19	110.27		49.28
Control	13.37		40.77	6.97	13.90	28.43	81.25	6.09	30.64
Reference	11.97	13.40	9.67		4.28	26.26	63.00	2.28	18.69

NH_4	GRB	WQB	NAR	CBM	CBV	NOC	SFB	ELK	Grand Total
7-cm	0.07	0.04	0.02	0.06	0.07	0.06	0.01	0.11	0.06
14-cm	0.18	0.04	0.02	0.06	0.02	0.09	0.02	0.03	0.06
Biochar		0.08	0.01					0.04	0.05
Dredged					0.21	0.06	0.04		0.10
Control	5.78		0.09	4.92	1.70	0.84	0.32	2.40	1.86
Reference	5.06	1.86	2.01		1.22	0.53	0.27	1.10	1.72

Elevation and accretion

Supplementary information on elevation and accretion rate monitoring

Table S4 Mean increase in plot elevation (cm) from pre-sediment addition to post-sediment addition conditions ('Post') and late in the growing season of years two and three after sediment addition ('Year 2' and 'Year 3'). Treatments shown include 7 cm sediment addition, 14 cm addition, and biochar/dredged in low and high marsh

	LOW MARSH									HIGH MARSH								
	7 cm			14 cm			B/D			7 cm			14 cm			B/D		
	Post	Year 2	Year 3	Post	Year 2	Year 3	Post	Year 2	Year 3	Post	Year 2	Year 3	Post	Year 2	Year 3	Post	Year 2	Year 3
GRB	7.9	5.6	5.4	14.5	6.4	6.0				7.1	4.9	5.3	14.9	8.2	10.2			
WQB	12.5	11.2	11.0	20.4	18.1	17.8	20.2	17.4	17.2	8.5	6.3	6.1	13.5	10.6	10.8	15.4	11.5	11.3
NAR	6.6	4.2	4.2	12.2	8.9	8.5	12.1	9.0	7.8	6.7	6.1	6.3	12.9	11.4	11.2	13.1	11.3	11.4
CBM										7.7	7.0	7.3	14.7	13.6	13.7			
CBV	7.9	5.2	6.3	14.6	12.7	13.4	15.4	12.5	13.3	7.7	4.8	4.6	14.7	11.4	11.4	14.2	10.2	9.6
NOC	10.1	7.3	5.7	14.5	10.2	7.0	15.2	8.0	4.2	9.9	9.1	8.7	15.9	14.0	13.4	15.9	13.8	13.4
SFB	4.4	2.2		10.8	4.8		13.7	2.9		7.4	7.7	9.7	13.8	12.9	14.7	15.0	14.0	16.1
ELK	8.1	7.9	7.4	15.2	12.8	12.1	14.7	12.5	11.7	9.4	8.4	8.4	17.9	14.0	13.9	18.9	15.2	15.0
mean	8.2	6.2	6.7	14.6	10.5	10.8	15.2	10.4	10.8	8.1	6.8	7.1	14.8	12.0	12.4	15.4	12.7	12.8

ACCRETION RATE MONITORING

To quantify accretion rates, we installed feldspar marker horizons in the center of each sediment addition and control plot immediately after sediment addition at all sites. We estimated the thickness of the sediment layer above this horizon one and two years following sediment addition. At some sites, most feldspar was lost by year one and so no second survey was conducted; rates were annualized to allow for comparisons among sites with one vs. two years of data.

Feldspar marker horizons that had been placed at the time of sediment addition apparently washed away from many plots (**Fig. 3** in the main paper). This appeared to occur especially often where feldspar was placed in unvegetated areas, whether on the added sediment or in the bare pannes at the center of the low control plots. At four sites (GRB, WQB, CBM, SFB) most or all plots lost feldspar in low and high marsh, so patterns could not be evaluated by treatment. At most of the remaining sites, missing data precluded thorough statistical analyses. However, a strong elevational trend was evident in the data that were available; low marsh had higher accretion than high marsh (**Table S5**). Comparing treatments within a marsh elevation zone, there was a decrease in accretion rates from plots with 0 to 7 to 14 cm of sediment addition. Sites also varied greatly in accretion rates, with a five-fold difference between the lowest (ELK) and highest (NOC) accretion sites.

Table S5 Sediment accretion rates in control and sediment addition plots across sites. Treatments are presented in order of sediment addition (from 0 cm to 7 cm to 14 cm); high and low elevations are presented separately. Number of plots where feldspar marker horizon was refound and average accretion rate for those is shown for each site. The initial sample size was n=5 per treatment, but at many sites, the sample size of feldspar horizons that were refound was much lower. Three sites are omitted because no feldspar was refound (GRB, WQB, SFB). Mean accretion rate per treatment across sites was calculated without CBM because of too much missing data there. Conditional formatting is applied within each column to help with visualization of accretion rates, which generally decreases with sediment addition amount

Accretion rates (mm yr^{-1}) across sites

TREATMENT	*sediment added (cm)*	Average	NAR *n*	NAR rate	CBM *n*	CBM rate	CBV *n*	CBV rate	NOC *n*	NOC rate	ELK *n*	ELK rate
High Elevation												
C	*0*	**3.1**	*1*	2.9	*5*	0.6	*3*	4.4	*5*	4.4	*5*	0.8
PC	*0*	**2.1**	*3*	3.3	*5*	1.4	*4*	1.4	*5*	2.9	*5*	0.8
7	*7*	**2.3**	*0*		*0*		*5*	5.0	*5*	1.6	*5*	0.3
14	*14*	**2.3**	*2*	0.0	*0*		*5*	3.1	*2*	3.9	*0*	
B	*14*	**0.4**	*0*		*n/a*		*n/a*		*n/a*		*1*	0.4
D	*14*	**0.3**	*n/a*		*n/a*		*5*	0.3	*n/a*		*n/a*	
Low Elevation												
C	*0*	**8.9**	*0*		*n/a*		*4*	7.3	*1*	10.6	*0*	
PC	*0*	**6.0**	*0*		*n/a*		*5*	6.0			*0*	
7	*7*	**5.0**	*1*	7.1	*n/a*		*3*	4.1	*4*	7.8	*4*	1.0
14	*14*	**2.3**	*4*	1.8	*n/a*		*5*	2.9	*1*	4.0	*5*	0.6
B	*14*	**1.1**	*1*	1.4	*n/a*		*n/a*		*n/a*		*5*	0.7
D	*14*	**2.6**	*n/a*		*n/a*		*5*	0.8	*1*	4.3	*n/a*	
SITE TOTAL			*12*	**2.4**	*10*	**1.0**	*44*	**3.4**	*24*	**4.0**	*30*	**0.7**

Vegetation

The primary focus of our paper is on vegetation cover responses to sediment addition, which is included in the main paper. Below we provide additional information on vegetation responses, including methods and results for vegetation canopy height, frame edge effects, and sources of vegetation recovery.

METHODS

After point-intercept, we measured the maximum height of up to four plants of each species of interest (*Spartina alterniflora*, *Spartina patens*, *Distichlis spicata*, *Salicornia pacifica* and *Spartina foliosa*), one plant from each internal grid row in a plot (**Fig. S5**). The first year after sediment addition, we also 1) estimated how much revegetation in each sediment addition plot was from recovery of existing vegetation through the added sediment vs. from seed germination (i.e., using simple visual observations of each plot to estimate percent of revegetation from recovery of existing plants vs. from seeding), and 2) separated point-intercept data in the inner plot (innermost nine intercepts) from along the edge (outermost 16 intercepts) in each plot to explore frame edge effects on cover and revegetation.

DATA ANALYSIS

To examine potential edge effects of frames on vegetation recovery, we calculated the difference in percent cover between outer 16 and inner 9 intercepts in the first fall after sediment addition, and conducted analysis of variance (ANOVAs) for each site and elevation to determine whether C, 7 cm and 14 cm treatments differed.

Analyzing canopy height responses to TLP treatments required a different approach than used for vegetation cover, as the focal plant species differ in their average canopy heights, and not all focal species were found at all sites. Therefore, we could not use a global model to explore generalities across sites, but we did perform separate GLMM analyses for low and high marsh at each site, using the same custom contrasts as described for vegetation recovery (**Table 3** in the main paper). For focal species canopy height analyses, we only included sites where the species was present in at least two plots per treatment. Prior to canopy height analyses, we assessed appropriate distributions for each response variable using Anderson-Darling goodness-of-fit tests, and residual plots were further used for each model to verify the appropriateness of distribution and link functions used. Canopy height data were normally distributed. We also plotted canopy height over time over time to visualize temporal trajectories and variability among treatments and sites.

RESULTS

Source of vegetation colonization in sediment addition plots

Recovery of vegetation cover was mostly from regrowth of existing vegetation through both depths of added sediments and not from seed germination. In the year one survey, about five months after sediment addition, four sites (NAR, NOC, SFB, ELK) estimated that 100% of vegetation in sediment addition plots was from regrowth of buried vegetation. The other sites that estimated vegetation sources in this period also indicated that most vegetation was from regrowth (averaged across all sediment addition plots, 96% at GRB, 95% at CBM, 90% at WQB, 81% at CBV).

Edge effects

In general, initial recovery in the first year after sediment addition occurred a bit more frequently in the outer 16 intercepts than the inner 9, especially in high marsh, suggesting a role for some edge effect such as looser sediments near the frame edge allowing for underlying plants to grow up through the sediment more readily. However, this contrast between outer and inner intercepts was only significantly different among sediment addition and control plots at a minority of sites (just CBV for low marsh; WQB, CBM and SFB in high marsh, **Fig. S10**). Typically, this effect of higher cover in the outer vs. inner portion was more pronounced in the 7 cm vs. 14 cm treatment, again suggesting that recovery was due to existing vegetation pushing through the sediment layer rather than germination of new plants.

<u>Canopy height</u>

Sediment addition vs. control: After three years, low marsh canopy height was higher than initial in sediment addition plots at four of six sites, but also in controls demonstrating broad natural recovery during this time even without sediment addition. The only significant difference in final low marsh height was at ELK where controls were higher (t=6.99, p<0.0001), suggesting a negative effect of sediment addition on height at that site (**Fig. S11, Table S6**). In high marsh, final height in sediment addition plots was higher than initial at three of six sites, but also higher in controls at all but one site, again suggesting broad natural recovery. Final height was similar in controls and sediment addition plots at all sites except SFB, where controls were significantly higher (t=2.33, p=0.0288), suggesting a negative effect of sediment addition on height at that site.

Reference vs. control: In every case except NAR low marsh, final canopy height was higher in reference compared to controls, significantly so at four of six low marsh sites and half the high marsh sites (**Fig. S11, Table S6**).

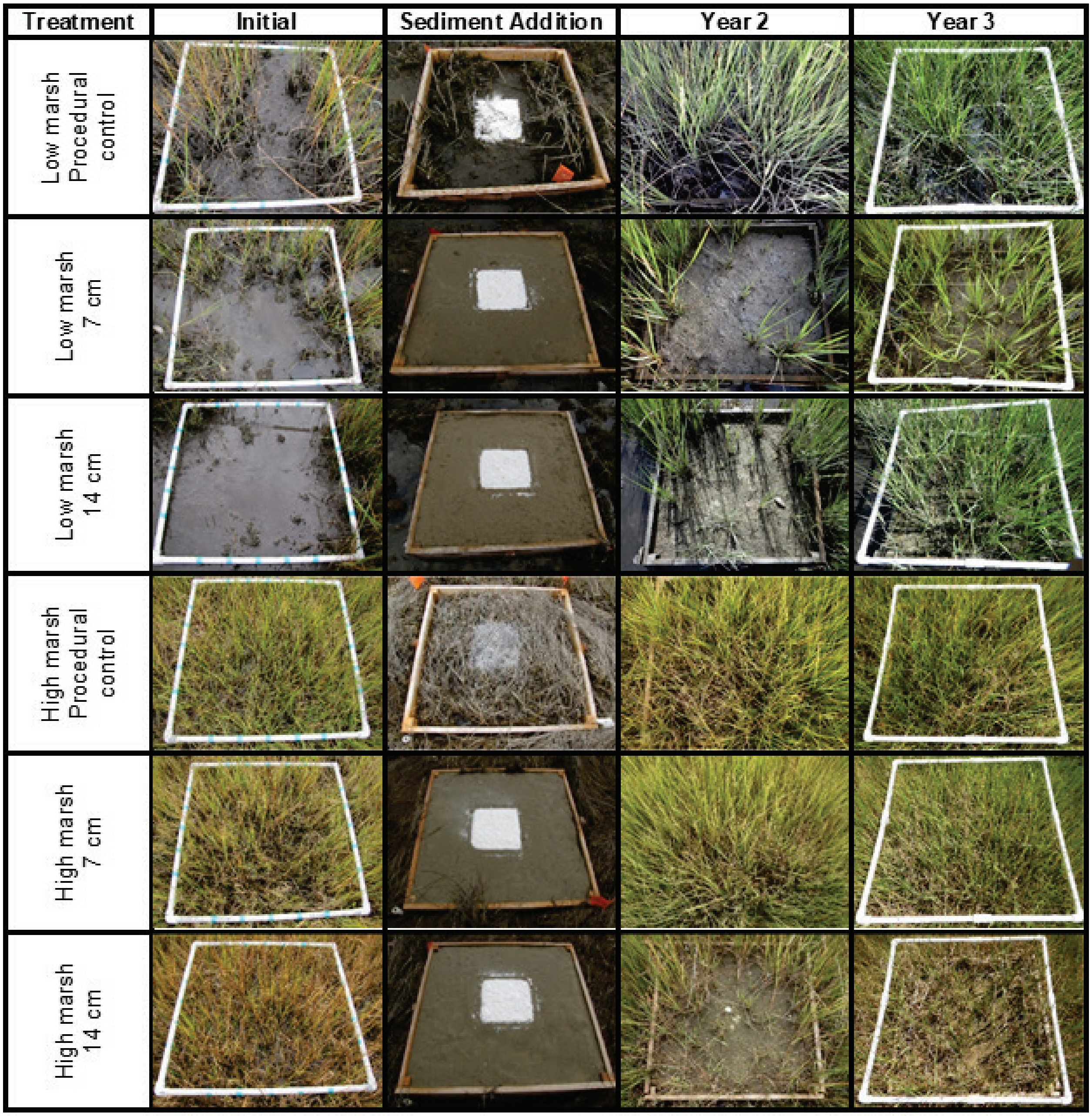
Sediment addition vs. reference: Final low marsh canopy height was lower in sediment addition plots than reference at all sites (significantly so at four) except NAR where it was significantly higher than reference (t=-5.88, p<0.0001) (**Figs. S11-12, Table S6**). Final high marsh canopy height was lower than reference levels at all sites and significantly lower than reference at half the sites (WQB, CBM, SFB).

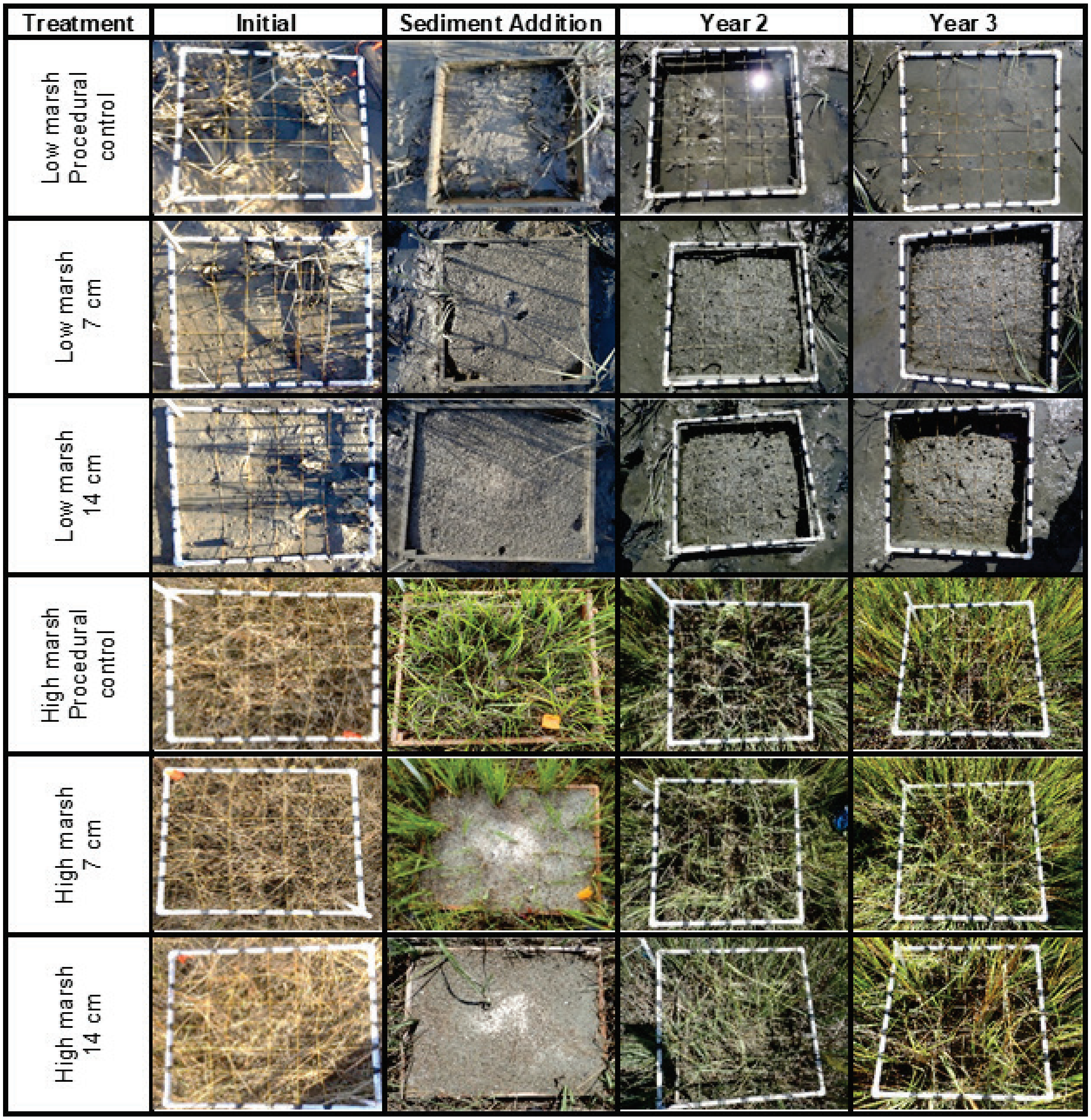
Thin vs. thick sediment addition: Low marsh canopy height typically recovered more rapidly in 7 cm vs. 14 cm, but by year three heights were similar in both treatments at all sites except NAR, where *S. alterniflora* was significantly higher in 7 cm (t=-2.44, p=0.0242) (**Figs. S11-12, Table S6**). In high marsh, height in 7 cm plots was initially higher than 14 cm at every site except ELK and it remained higher at five of six sites after three years, significantly at both west coast sites (SFB t=-2.50, p=0.0195; ELK t=-2.14, p=0.0479)**.**

Sediment type comparisons: There were no significant differences in canopy height between sediment types at any site, in low or high marsh plots (**Fig. S11, Table S6**), although height was slightly higher in quarry vs dredged in all cases, while results were mixed for quarry vs biochar.

Control comparisons: Final canopy height in framed and unframed controls was not significantly different at any site in low or high marsh except GRB high (t=-2.33, p=0.0349) (**Table S6**).

Fig. S9 Time-series photographs from NAR (top set), NOC (middle), and ELK (bottom). For each site, photographs are shown from the procedural control, 7 cm and 14 cm addition treatments in both low and high marsh from initial conditions, immediately after sediment addition and at the end of the growing season in years two and three. In addition to vegetation change, these figures illustrate the loss of feldspar marker horizons that occurred in many plots




Treatment
Initial
Sediment Addition
Year 2
Year 3
Low marsh Procedural control
Low marsh 7 cm
Low marsh 14 cm
High marsh Procedural control
High marsh 7 cm
High marsh 14 cm

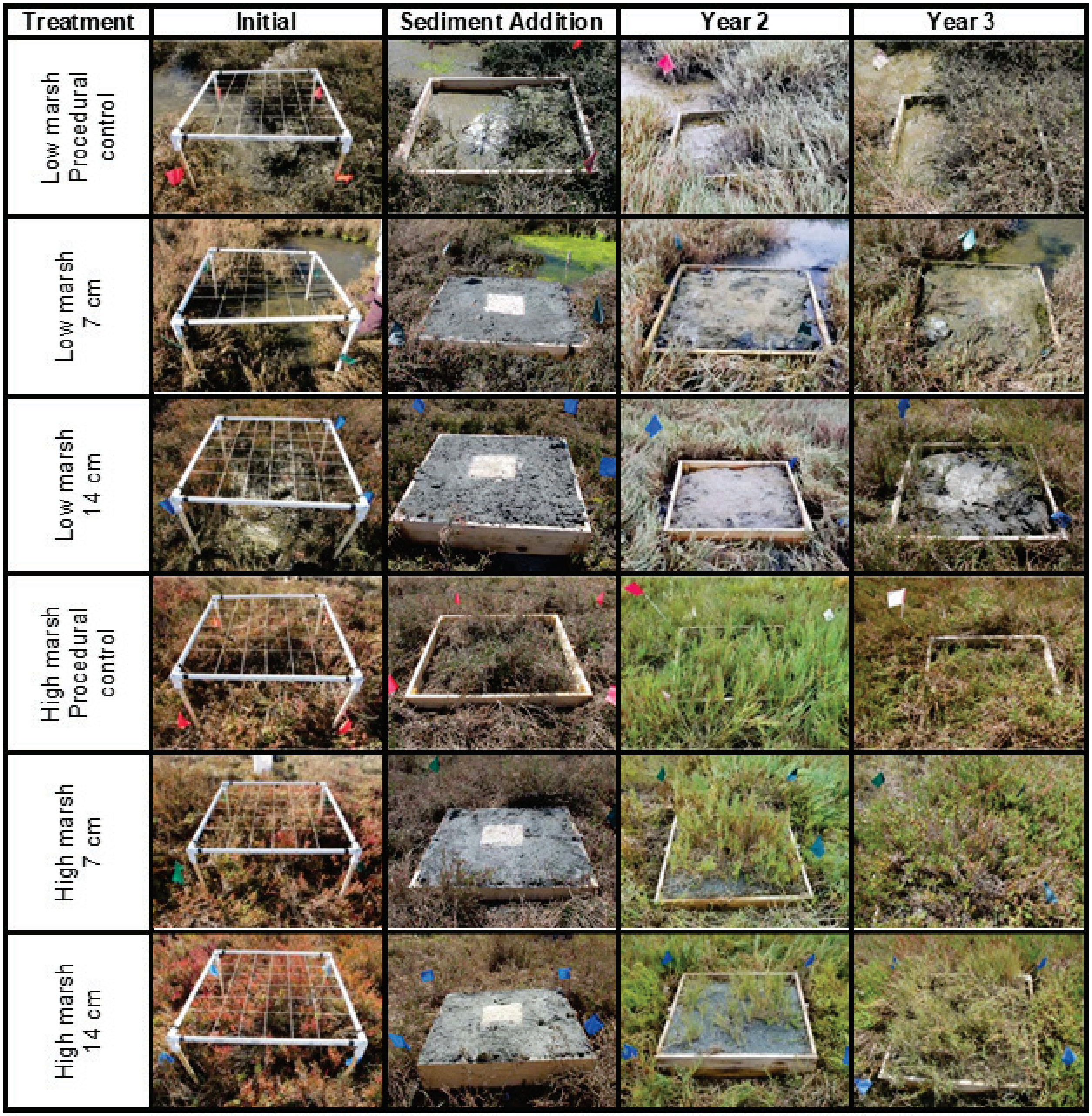
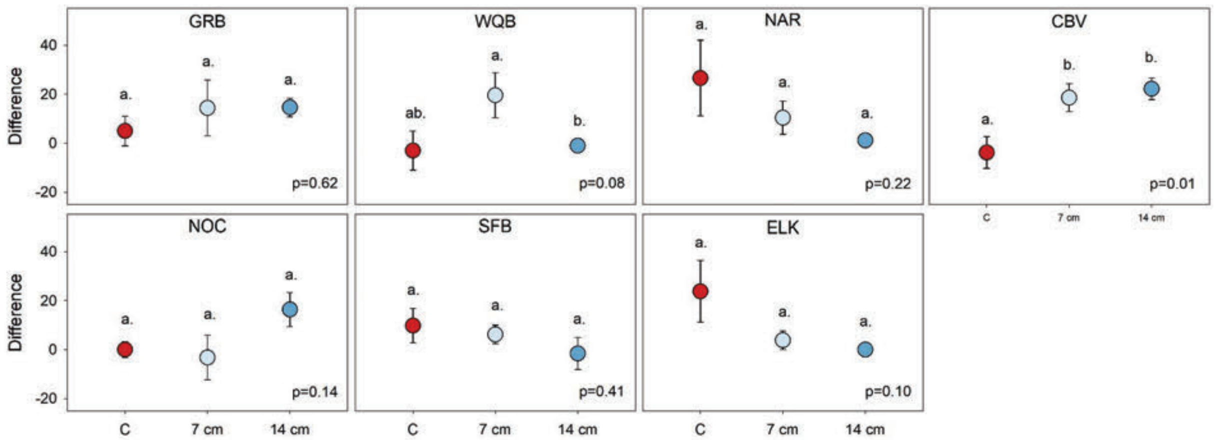

Treatment
Initial
Sediment Addition
Year 2
Year 3
Low marsh Procedural control
Low marsh 7 cm
Low marsh 14 cm
High marsh Procedural control
High marsh 7 cm
High marsh 14 cm

Fig. S10 The difference between percent cover in the outer 16 point intercepts (potentially influenced by edge effects) vs. the inner 9 intercepts is shown at all participating sites in low (a.) and high (b.) marsh; if percent cover is same in both areas the value is 0, if cover is higher in the outer zone the number is positive

a.



b.

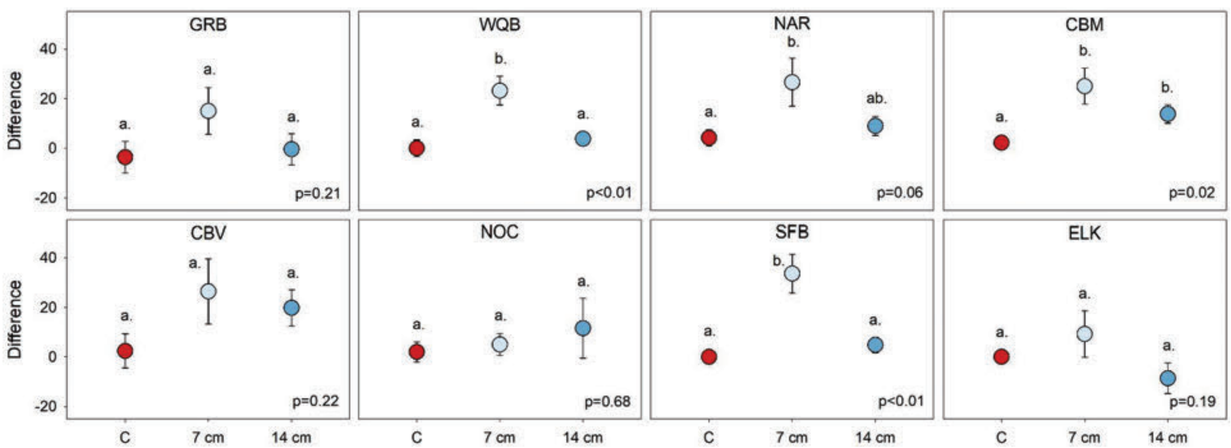
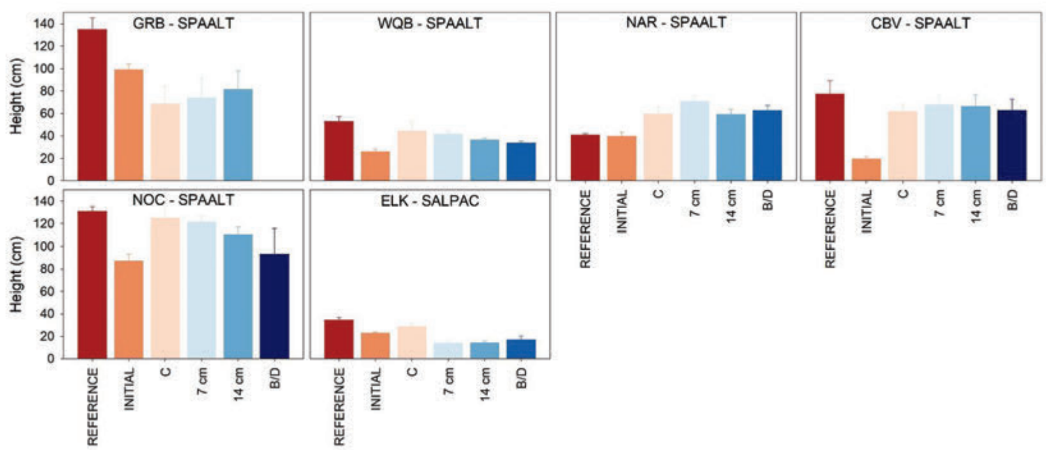


Fig. S11 Canopy height of dominant low marsh species (a.) and desired high marsh species (b.) after TLP at each site by treatment. Sites are arranged north to south, east to west (CBM and SFB low marsh not shown due to lack of year three data, and NAR and NOC high marsh not shown due to very limited recovery of high marsh species). Reference data are from year three, except SFB which is year two. Initial data are combined across all other treatments and all remaining data are year three. Error bars are ±1 SE. SPAALT=*Spartina alterniflora*, SALPAC=*Salicornia pacifica*, SPAPAT=*Spartina patens*, DISSPI=*Distichlis spicata*. WQB, NAR and ELK show biochar plots (B) in medium blue, CBV and NOC show dredged plots (D) in dark blue

a.



b.

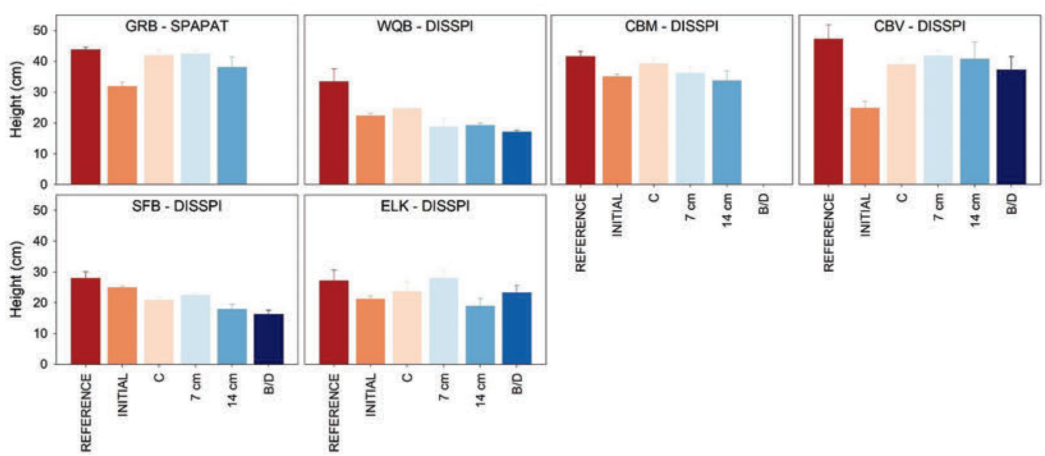
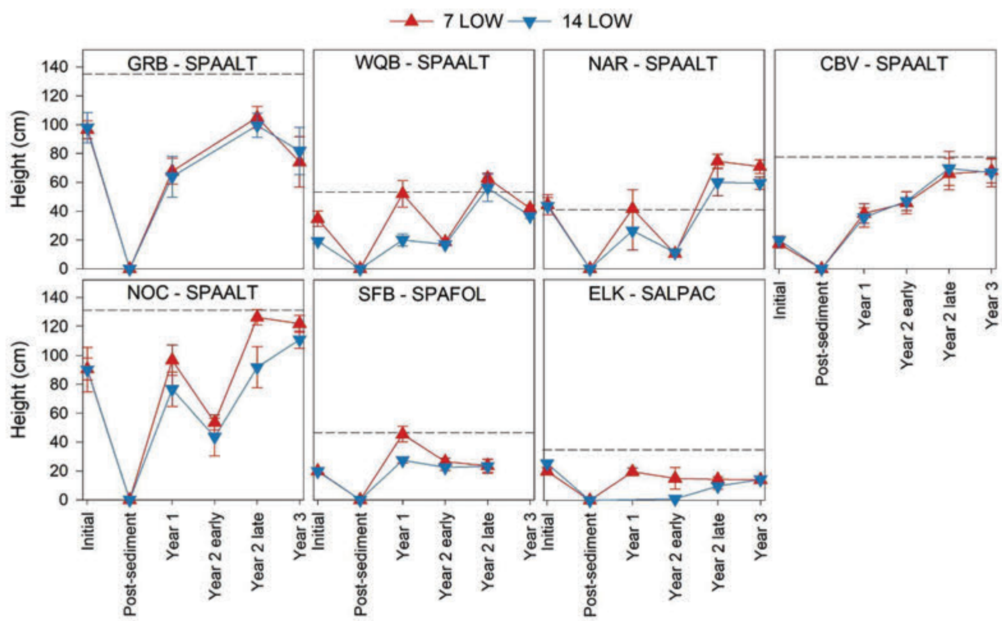


Table S6 Summary of GLMM custom contrast test results between select treatments at each site and elevation from GLMM analyses for vegetation canopy height (t-values). Light blue cells indicate that height was higher in the first treatment within each custom contrast pair; brown cells indicate it was higher in the second treatment. Significant differences are indicated with asterisks (* p<0.05; ** p<0.01; *** p<0.001). For example, in WQB low marsh, canopy height was significantly higher in reference plots compared to controls (t-value = -2.96). Treatment groups are defined in **Table 3** in the main paper

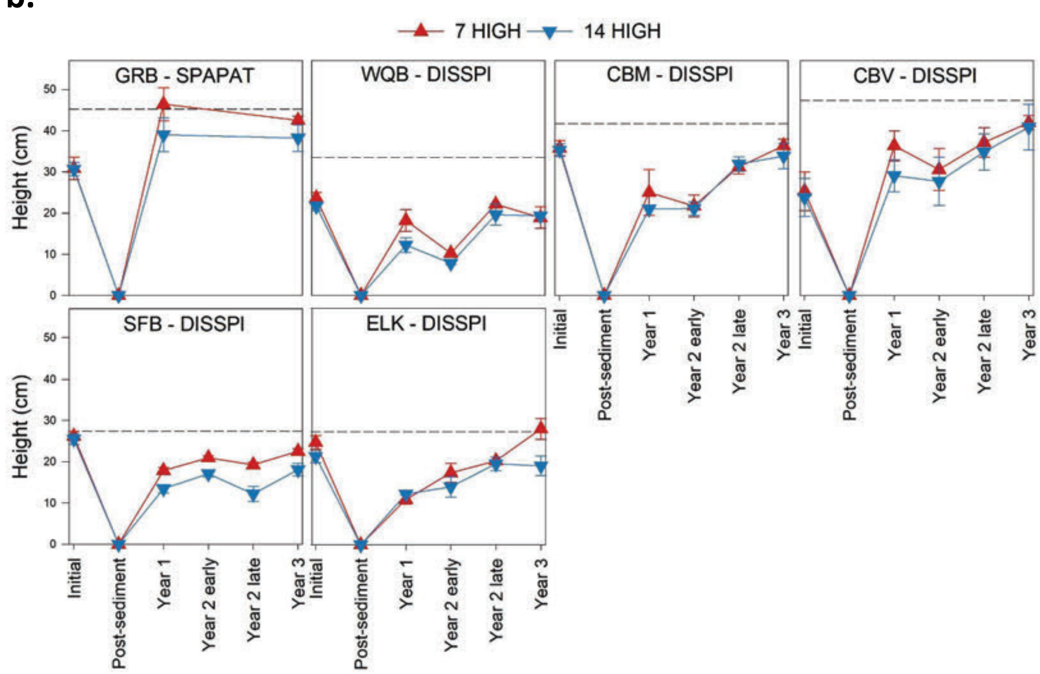
CANOPY HEIGHT								
CONTRAST		**Sediment addition**	**Reference**	**Reference**	**Thin**	**Biochar amended**	**Unamended quarry**	**Unframed control**
		Controls	**Controls**	**Sediment addition**	**Thick**	**Unamended quarry**	**Dredged**	**Framed control**
LOW MARSH	GRB	0.15	**-5.23** ***	**-5.35** ***	0.62			1.67
	WQB	0.68	**-2.96** **	**-3.66** **	-0.99	0.47		-1.93
	NAR	-0.24	**5.35** ***	**5.88** ***	**-2.44** *	-0.75		1.33
	CBV	-0.34	**-2.23** *	**-2.10** *	-0.16		-0.54	0.42
	NOC	0.17	-1.38	-1.54	-0.64		-0.42	-1.80
	ELK	**6.99** ***	**-2.74** *	**-8.44** ***	0.09	-0.92		-0.66
HIGH MARSH	GRB	-0.63	**-2.29** *	-1.75	-1.77			**-2.33** *
	WQB	2.57	**-6.13** ***	**-11.78** ***	0.19	1.06		0.53
	CBM	1.91	-0.84	**-2.40** *	-0.81			0.00
	CBV	-0.66	-2.07	-1.73	-0.22		-0.85	-0.36
	SFB	**2.33** *	**-3.86** ***	**-5.94** ***	**-2.50** *		-0.99	0.51
	ELK	0.84	-0.45	-1.27	**-2.14** *	-1.01		0.75

Fig. S12 Temporal trajectory of canopy height. Mean canopy height over time in 7 cm and 14 cm treatments for typical low marsh plant species in low sediment addition plots (a.) and high marsh plant species desired after TLP in high sediment addition plots (b.). Error bars are ±1 SE and the dashed lines indicate reference levels from year three, except SFB which is year two. Figures are labeled on top by site abbreviation (Table 1) and marsh species. SPAALT=*Spartina alterniflora*, SPAFOL=*Spartina foliosa*, SALPAC=*Salicornia pacifica*, SPAPAT=*Spartina patens*, DISSPI=*Distichlis spicata*. Recovery was fast in most cases; in some cases 7 cm recovered more quickly than 14 cm

a.



b.



Crabs

The main paper provides information on crab burrowing during your experiment, but below we provide additional tables for crab species abundance across sites, treatments and years, and additional complementary information on burrowing.

Table S7 Percent of plots where each crab species was observed across all plots and sampling periods at each site (e.g., of 280 total plots sampled, at least one crab was observed at 29% of all plots in NAR). Note that more than one crab may have been observed in a plot at a time

	GRB	WQB	NAR	CBM	CBV	NOC	SFB	ELK
Armases cinereum	0.00	0.00	0.00	0.00	0.00	2.01	0.00	0.00
Callinectes sapidus	0.00	0.00	0.36	0.00	0.00	0.00	0.00	0.00
Carcinus maenas	0.00	0.97	0.00	0.00	0.00	0.00	0.00	0.00
Pachygrapsus crassipes	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.30
Sesarma reticulatum	0.00	0.00	0.36	0.00	0.74	0.00	0.00	0.00
Uca minax	0.00	0.00	0.00	0.00	2.96	0.00	0.00	0.00
Uca pugilator	0.00	2.90	0.00	0.00	0.00	0.00	0.00	0.00
Uca pugnax	0.00	0.97	28.57	0.00	4.81	4.01	0.00	0.00
Uca spp.	0.00	19.35	0.00	0.00	1.85	0.29	0.00	0.00
Unidentified	0.00	0.00	0.00	0.69	0.00	16.33	0.00	0.00
Total	0.00	24.19	29.29	0.69	10.37	22.64	0.00	6.30

Table S8 Percentage of plots (across all sites) with crabs present during initial sampling and each year after sediment addition in 7 cm, 14 cm, biochar/dredged, and unframed control treatments in low and high marsh

LOW MARSH		Initial	Year 1	Year 2 late	Year 3
	7	2.86	25.71	40.00	40.00
	14	2.86	25.71	25.71	20.00
	B	6.67	26.67	46.67	53.33
	D	6.67	33.33	0.00	0.00
	C	0.00	11.43	11.43	16.67

HIGH MARSH		Initial	Year 1	Year 2 late	Year 3
	7	0.00	25.00	10.00	12.50
	14	7.50	22.50	7.50	7.50
	B	0.00	20.00	20.00	26.67
	D	6.67	33.33	6.67	6.67
	C	5.00	17.50	7.50	7.50

Table S9 Burrow density (total number of burrows per plot) over time at each site in high marsh and low marsh. Data are means, shown for 7 cm, 14 cm, biochar/dredged, and control plots during initial conditions before sediment was added and each year thereafter. Conditional formatting was applied so that the lowest and highest burrow densities are shown in dark green and red, respectively, with intermediate densities in yellows

		LOW MARSH				HIGH MARSH			
		Initial	Year 1	Year 2 late	Year 3	Initial	Year 1	Year 2 late	Year 3
GRB	7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WQB	7	0.00	29.80	24.75	65.60	0.80	18.00	15.60	21.60
	14	0.00	9.20	18.60	82.80	0.20	14.40	10.00	31.00
	B	0.00	5.40	16.80	74.80	0.80	17.40	11.80	30.40
	C	0.00	0.60	1.20	6.20	0.40	0.20	1.80	3.80
NAR	7	3.40	39.40	21.80	37.60	0.60	11.80	3.80	3.20
	14	5.80	10.80	17.20	34.00	0.00	3.20	2.20	0.20
	B	2.00	18.60	31.20	15.00	0.20	4.40	4.80	2.20
	C	2.00	4.40	2.60	1.00	0.80	0.00	2.60	1.00
CBM	7					0.00	0.00	0.00	0.00
	14					0.00	0.00	0.20	0.60
	C					0.00	0.00	0.00	0.20
CBV	7	1.20	4.20	44.60	27.40	5.20	12.20	14.20	20.80
	14	0.60	5.00	21.20	26.60	9.00	5.20	7.20	17.40
	D	1.40	0.20	3.40	8.60	5.40	3.00	5.40	18.00
	C	1.80	2.00	2.00	5.80	3.60	5.00	11.40	10.20
NOC	7	2.20	55.20	72.80	49.80	4.60	9.20	34.00	31.80
	14	1.00	36.40	65.20	51.60	5.80	6.00	20.20	37.60
	D	0.40	84.60	70.20	47.60	3.40	23.00	44.20	29.20
	C	0.80	0.60	12.20	16.80	4.60	5.00	12.00	15.60
SFB	7	0.00	0.00	0.00		0.00	0.00	0.00	0.00
	14	0.00	0.00	0.00		0.00	0.00	0.00	0.00
	D	0.00	2.20	0.00		0.00	0.00	0.00	0.00
	C	0.00	0.00	0.00		0.00	0.00	0.00	0.00
ELK	7	0.80	2.80	10.00	5.40	0.00	0.00	1.00	0.20
	14	2.00	1.00	10.40	6.40	0.00	0.00	2.00	0.00
	B	3.00	0.00	10.00	5.20	0.00	0.00	0.80	0.60
	C	1.00	0.20	0.60	0.80	0.00	0.00	2.00	0.40