# 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
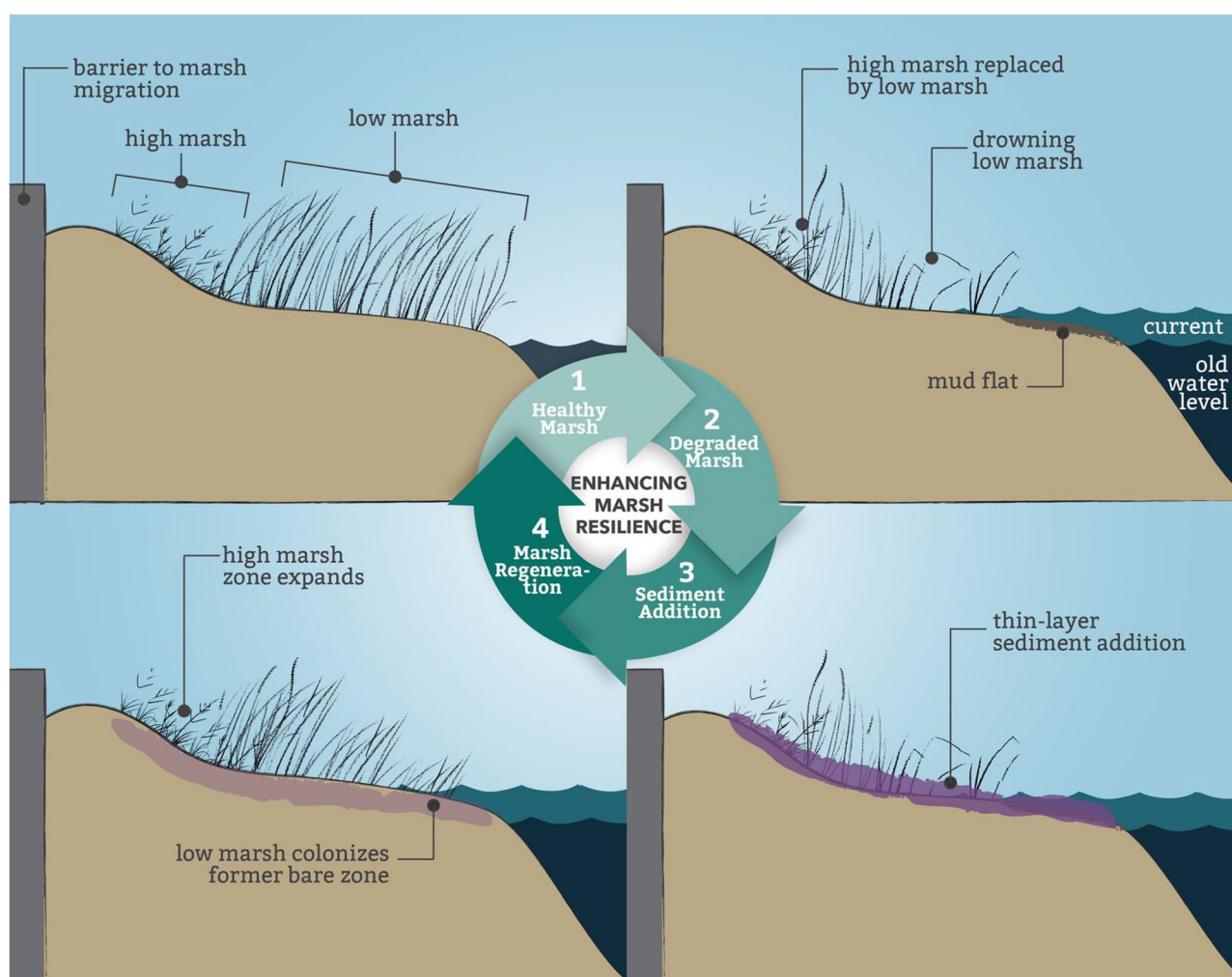


**Fig. 1** Conceptual diagram illustrating effects of sea-level rise on high and low salt marsh habitats and the use of sediment addition as a restoration tool to increase resilience of both these habitats. At time 1 (upper left), there is an extensive low marsh, dominated by a single species, and landward 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
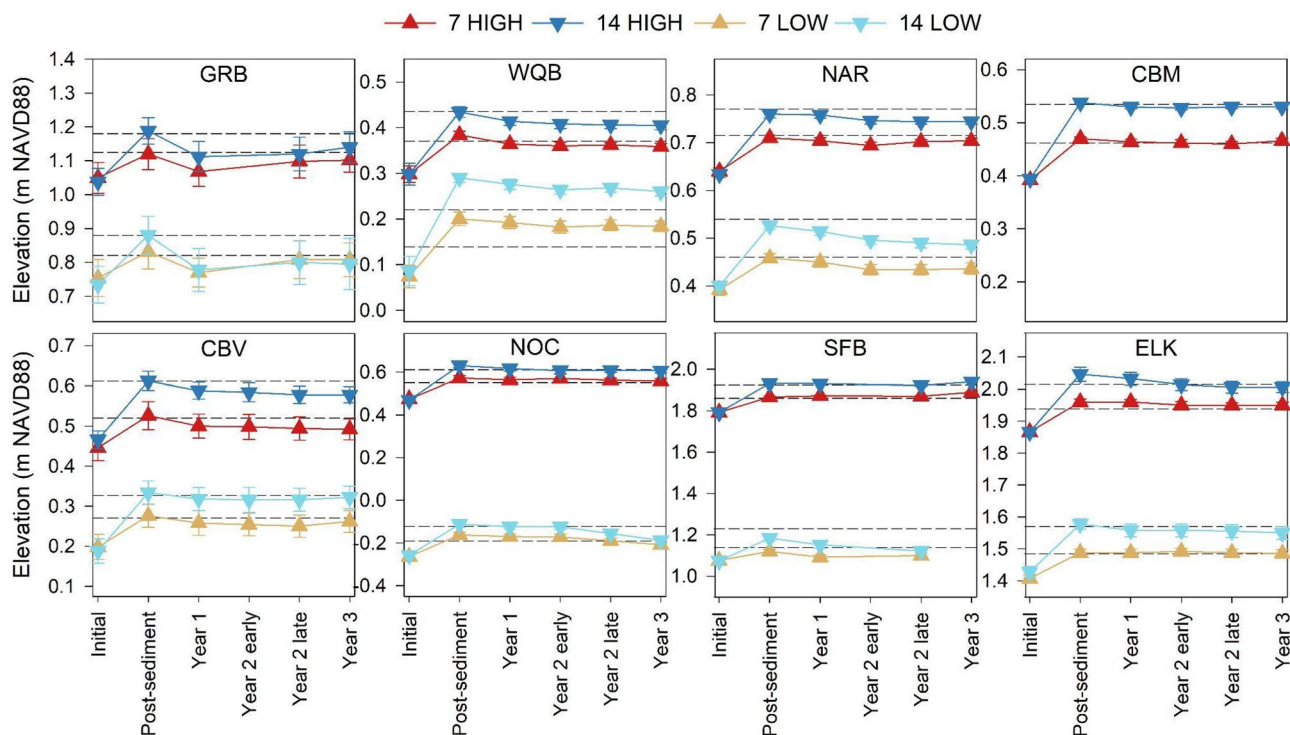


**Fig. 3** Plot elevations over the duration of the study at each NERR. From left to right and top row to bottom row, sites are arranged north to south, starting with east coast, then west coast. Treatments shown include 7 cm and 14 cm additions in low and high marsh. Error bars are ± 1 SE. In each plot, 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
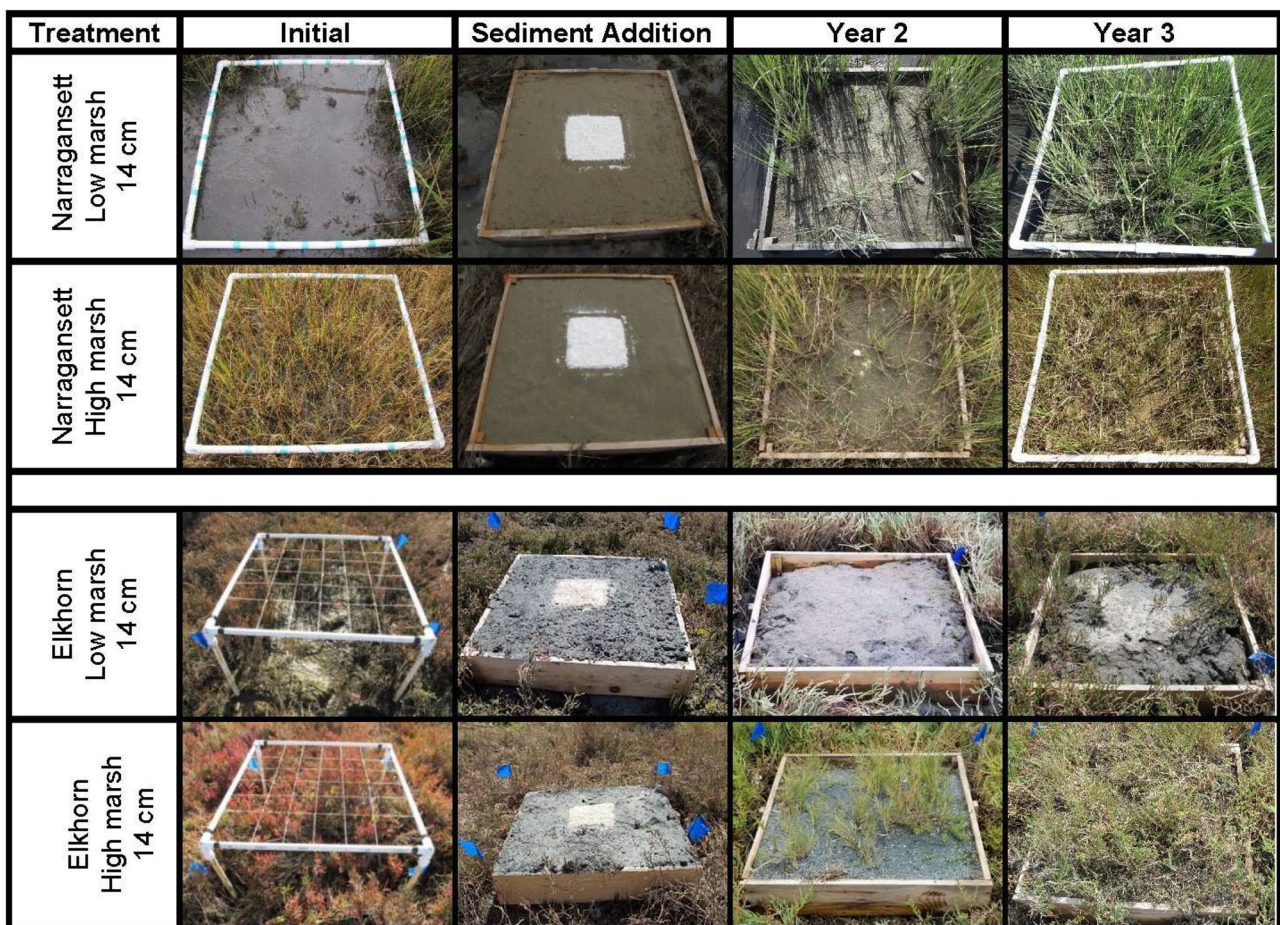


**Fig. 4** Contrasts in recovery by site and elevation. Comparison of time-series photographs of one treatment (14 cm sediment addition) in low and high marsh at Narragansett Bay, RI, and Elkhorn Slough, CA. Time periods shown include initial conditions, immediately after sediment addition and at the 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
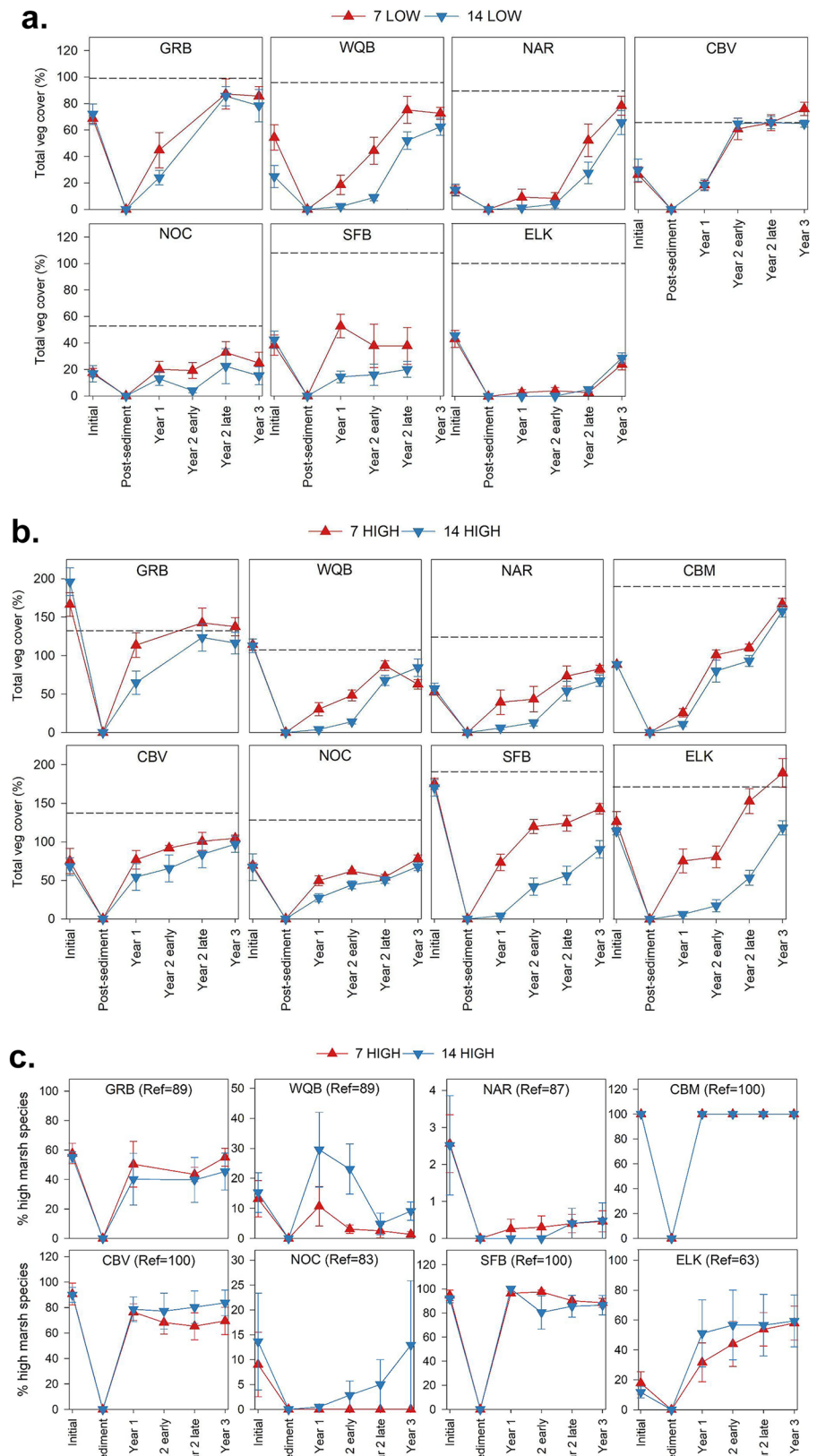
**Table 2** Global model summaries for vegetation cover, RPI, and crab burrow density. Model effects are shown in the left column, with degrees of freedom (Df), statistical test values (*F* value and chi-square), and *p* values (*p*) shown for each response variable in subsequent columns

| | 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

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**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)

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**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 / Controls | Reference / Controls | Reference / Sediment addition | Thin / Thick | Biochar amended / Unamended quarry | Unamended quarry / Dredged | Unframed control / 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 / Controls | Thin / Thick | Biochar amended / Unamended quarry | Unamended quarry / Dredged | Unframed control / 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 / Controls | Reference / Controls | Reference / Sediment addition | Thin / Thick | Biochar amended / Unamended quarry | Unamended quarry / Dredged | Unframed control / 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 |
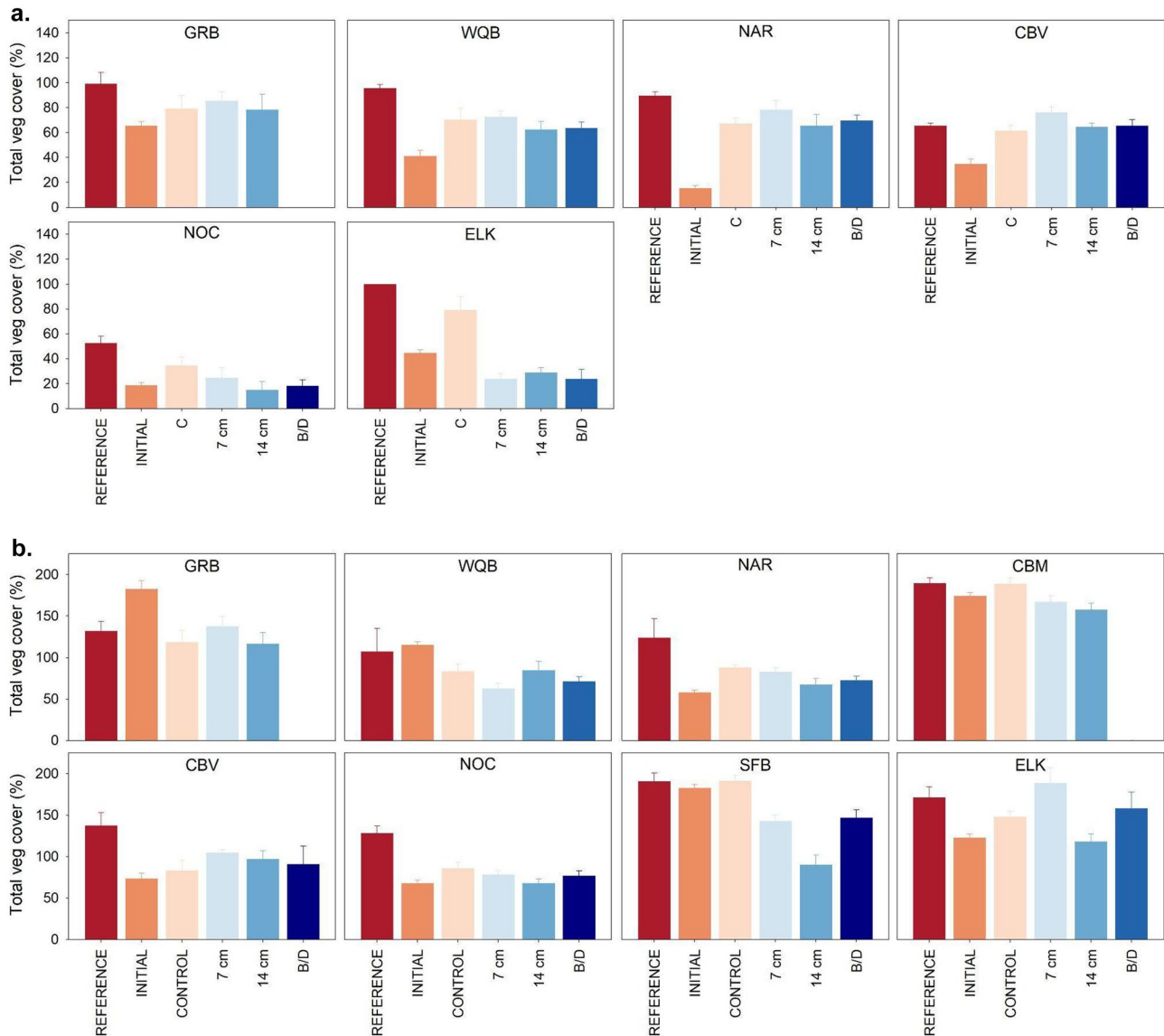
Fig. 6 Effect of treatment on vegetation cover. Total vegetation cover (all species combined) by treatment and site in low (**a**) and high (**b**) marsh. Sites are arranged north to south, east to west (CBM and SFB low marsh not shown due to lack of year three data). Reference data are from year three, 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).
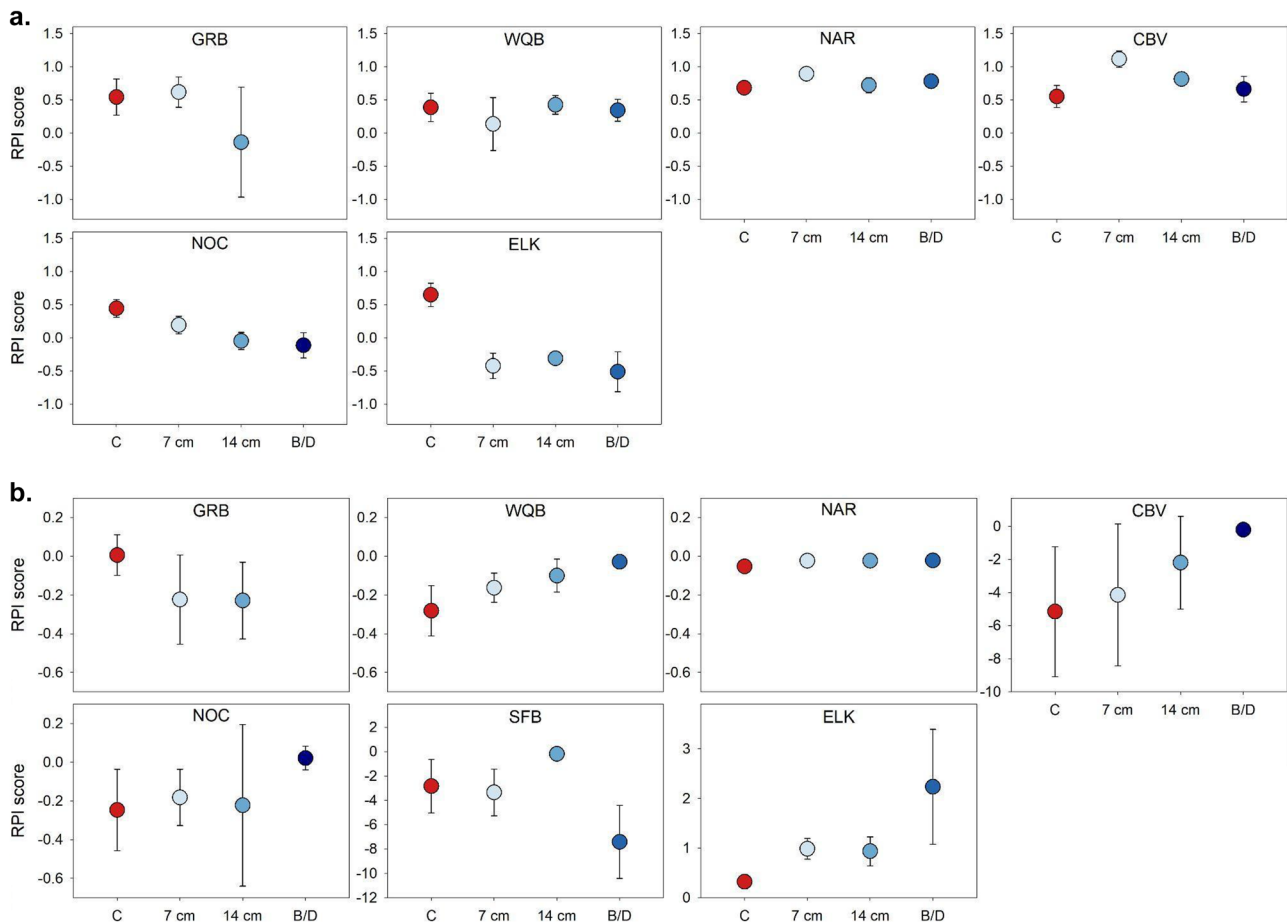
**Fig. 7** Restoration Performance Index. RPI scores for control, 7 cm, 14 cm, B, and D treatments in low (**a**) and high (**b**) marsh at each site. Symbols are means from 5 replicate plots; error bars are ±1 SE. WQB, NAR, and ELK show biochar plots (B) in medium blue, CBV and NOC show dredged plots (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 ($0.7 \times 0.7$ 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. *Adding 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.

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