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PRACTICE AND TECHNICAL ARTICLE

Sediment addition to address tidal marsh elevation deficits caused by farm impoundments: a Delaware Bay, New Jersey, United States case study

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Abstract

Introduction: Dredge material use is emerging as an important technique for restoring marshes threatened by historic mismanagement and sea-level rise, yet optimal methods to maximize ecological benefit remain under development. The Delaware Estuary is in urgent need of restoration, as historic agricultural conversion caused substantial and persistent elevation loss.

Objectives: We conducted a pilot project in a previously restored marsh where elevation deficits continued to inhibit revegetation. Using material from maintenance dredging of tidal channels, we elevated a 0.4 ha site contained with coir logs to create conditions conducive to plant recolonization and long-term recovery.

Methods: Dredging occurred from Fall 2018 through March 2019, with sediment pumped into containment to raise elevations to a target of 0.5–0.7 m NAVD88 (just below MHW). Elevation and vegetation were monitored before, immediately after, and across five growing seasons following construction.

Results: Target elevations were achieved, producing a mean post-construction elevation of 0.54 m (0.53–0.56, 95% CI), a 0.42 m increase from pre-project conditions. Vegetation cover rose from 55 to 86% by the second season and reached 100% by year 5, despite 0.1 m of settling. Areas 50–100 m outside the containment also gained elevation and vegetation, indicating localized sediment dispersal. Previously vegetated zones that received material did not settle and instead showed increasing elevation across all five seasons.

Conclusions: This project demonstrates that integrating hydrological restoration with sediment addition can restore optimal elevations for *Spartina alterniflora* and accelerate vegetation recovery in degraded mid-Atlantic marshes.

Implications for Practice: The results of this work show rapid revegetation following sediment placement is achievable in Northeast U.S. marshes when restoration targets elevations within the regularly flooded mid-range preferred by *Spartina alterniflora*. Designing for moderate post-placement settling is essential to sustaining long-term vegetation success and preventing the site from dropping below the optimal growth zone. This work highlights the importance of coordinated, cross-project data synthesis to refine elevation targets, improve containment approaches, and better predict sediment retention and settling patterns. Continued integration of monitoring data across restoration sites will strengthen designs and enhance the reliability and resilience of marsh restoration under rising sea levels.

Key words: carbon sequestration, Delaware Bay, elevational effects, marsh restoration, sea level rise

Introduction

Throughout the mid-to-late twentieth century in North America, conservation of tidal marshes was largely limited to land acquisition and regulatory control over their destruction (Tiner 2013). Restoration is now an area of increasing attention (Waltham et al. 2021), but the art and science of tidal marsh restoration is still at an early stage, with some evidence of successful methods (Cutts et al. 2019) but also an indication of the challenges in restoring ecological function on a time scale that meets the urgency of the current moment of accelerating sea level rise and marsh loss (Moreno-Mateos et al. 2012). At the same time, there is often uncertainty about what array of interventions is needed at a particular site given the broad range of conditions tidal marshes experience across gradients of environmental variability and levels of direct and indirect human impact (Thorne et al. 2015).

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Dredge material use for tidal marsh restoration is emerging as a key strategy in many parts of North America (Streever 2000), where channel maintenance is matched with sites needing restoration. This is preferable to removing sediment from the estuary because it avoids incurring a net debt to the sediment budget (Ganju 2019). Consistent and proven methods for determining where and how to apply dredged material in ways that optimize conservation benefit still need to be refined.

Global evaluations of tidal marsh restoration success indicate that there can be a long timeline to achieving project goals associated with ecosystem function (Moreno-Mateos et al. 2012). A key goal of many projects is to establish marsh vegetation cover, although a global meta-analysis found that only 53% of salt marsh restoration projects had successful plantings, with functional equivalence to reference wetlands being reached between 5 and 25 years (Liu et al. 2024). Vegetation recovery rates likewise vary widely among dredge placement projects (Streever 2000), with the determinants of rapid versus delayed achievement of ecosystem function not well understood.

The 66,000 ha Delaware Estuary is in critical restoration need, where more than half of its tidal marshes were historically managed for agriculture (Smith et al. 2017). This practice caused oxidation of peat soils and prevented the deposition of suspended sediment and nutrients from reaching the interior of the marsh, resulting in significant elevation loss (Portnoy 1999). These impacts caused at least 4000 ha of marsh loss and have left the remaining formerly-managed marshes up to 0.6 m lower in elevation than comparable marshes that were not historically managed (Smith et al. 2017). These impacts, combined with sea level rise, greatly increase the vulnerability of these marshes to complete loss (Weinstein & Weishar 2002) and have left present-day ecosystems and human communities less resilient to storms, sea level rise, and coastal erosion (Sheng et al. 2022).

In this study, we report on a restoration project intended to demonstrate how dredge material can be used to offset the dramatic elevation loss caused by past agricultural use. We show how hydrological restoration can be integrated with sediment addition to improve vegetation recovery in these degraded marshes by bringing marsh elevation closer to the optimal growth range of *Spartina alterniflora* and increasing their resilience to sea level rise. We evaluate restoration effectiveness by examining elevation and vegetation trajectories and consider refinements to restoration strategies in the future based on these results.

Methods

Study Site Description and Background

The Thompsons Beach, Maurice River Township Marsh (39.201737, −74.993275) is a 565 ha formerly farmed salt marsh that experienced levee breaches that caused its conversion to open water and mudflats (Hinkle & Mitsch 2005). In 1994, a restoration project re-created tidal channel hydrology across the farmed wetland with the intent of accumulating suspended sediment and allowing for effective flooding and drainage (Teal & Weishar 2005).

The resulting restoration produced an increase in vegetated marsh, from 10 to 70% cover in the span of 8 years (Hinkle & Mitsch 2005). However, sediment and elevation deficits that were the legacy of salt hay farming still have not been recovered across significant portions of the site, with some areas only sparsely colonized by *Spartina alterniflora*. A contemporary estimate of vegetation cover in the project area (Ganju et al. in review) shows vegetation cover remains at 70%, the same estimate for cover made in 2005 (Hinkle & Mitsch 2005).

Tidal range is approximately 1.6 m (see Supplement S1 more details) and mean suspended-sediment concentration at the site is relatively high, at 151 mg/L with daily flood-ebb suspended sediment concentration differential that was positive 85% of the time (median value +32 mg/L), indicating a dominance of sediment import (Bales et al. 2024).

Project Design

Target elevations were selected to maximize *S. alterniflora* biomass accumulation at approximately Mean High Water (MHW) (Morris & Sundberg 2024). This would allow for the site to be regularly flooded by tides (Smith et al. 2017), preventing the generation of acid sulfate soils—when sulfuric acid is created through the oxidation of sulfidic sediments (Fanning & Burch 2015). Based on estimates of tidal datums, we determined a target placement elevation of 0.61 m NAVD 88 (a conservative estimate of MHW), allowing for a range from 0.53 to 0.76 m. Based on our analysis of water level data at the site (see Supplement S1), the 0.61 m target elevation would be flooded 7.85% of the time and flooding duration across the target elevation range is 3.31–12.4%.

We defined a 0.45 ha dredge placement area within a larger permitted area of 1.5 ha. To raise the surface elevation of the 0.45 ha area from less than 0.3 m NAVD 88 to the target elevations required an estimated placement volume of up to 2217 m^3 of dredge material. This material would come from the heavily silted upper eastern creek adjacent to the placement site (Fig. 1), one of the channels previously created to restore tidal hydrology to the site (Teal & Weishar 2005). Designed channel depth is approximately −1.67 m NAVD 88, 3.0 m wide, with 4:1 sloped sides creating a 15.2 m wide hopper cut (Figs. 2 & 3).

To contain material during sediment pumping and settlement, we placed coir logs (Reddy 2019) around the 0.45 ha placement area perimeter. An existing road was used as one side of the rectangular area, with 300 coir logs placed along the remaining 185 m of the perimeter. Coir logs were placed on coir mat to help reduce settling in the soft underlying silt. The main outer wall consisted of two 0.6 m by 3.6 m coir logs stacked on top of each other with a 0.4 m overlap that were staked in and tied down with twine.

Material pumped from the dredge through a discharge pipe accessed the placement area from several points along the adjacent access road (Fig. 3). The discharge pipe split into two outflow lines with diffusers attached. Discharge lines moved within the area used a low-impact vehicle to evenly distribute sediments.

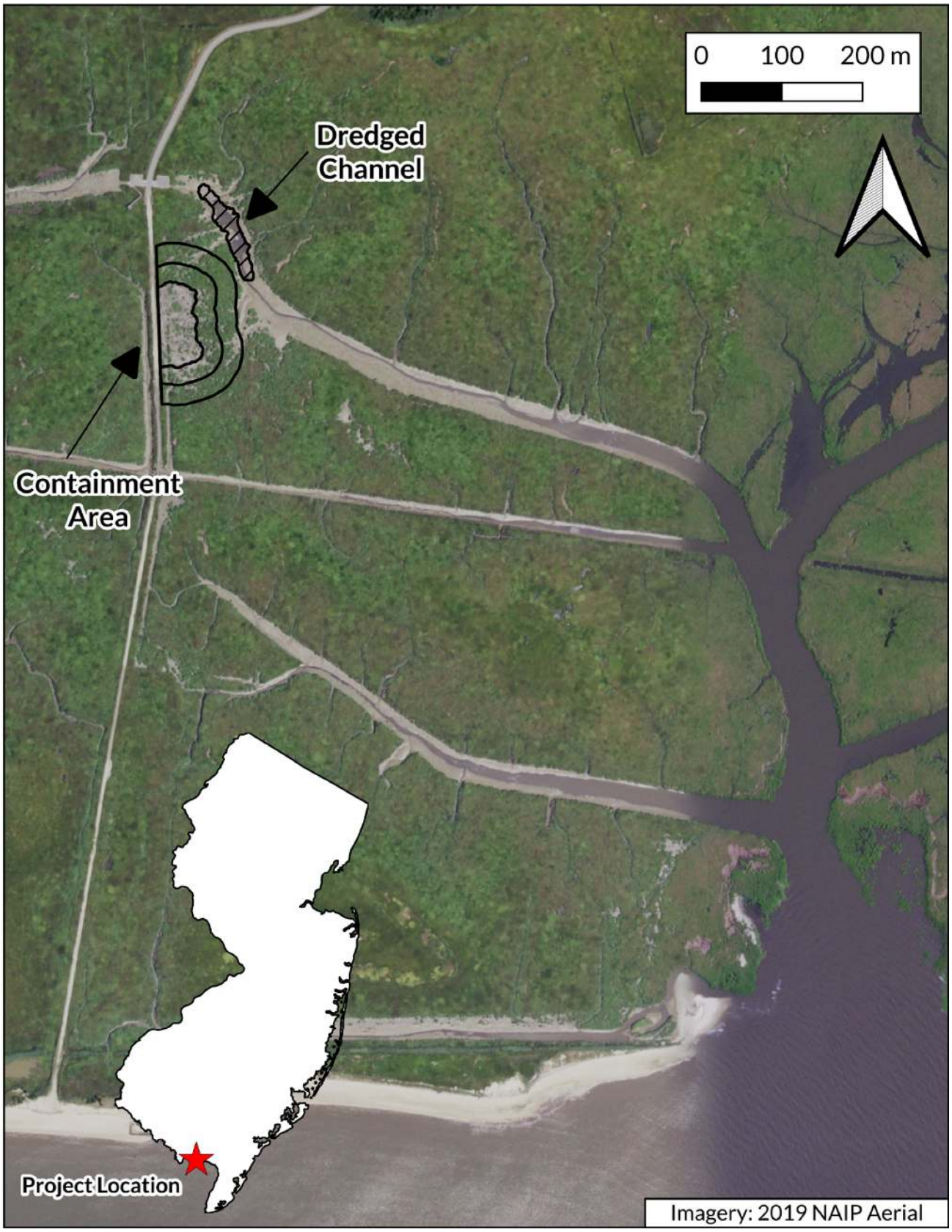


Figure 1. Thompson's Beach, New Jersey, United States with project dredging and placement areas.



Figure 2. Left, dredge operating in tidal channel with pipe entering the road and routed to the placement site; right, pipe discharging sediment slurry into the placement site with coir log containment berm surrounding the area.

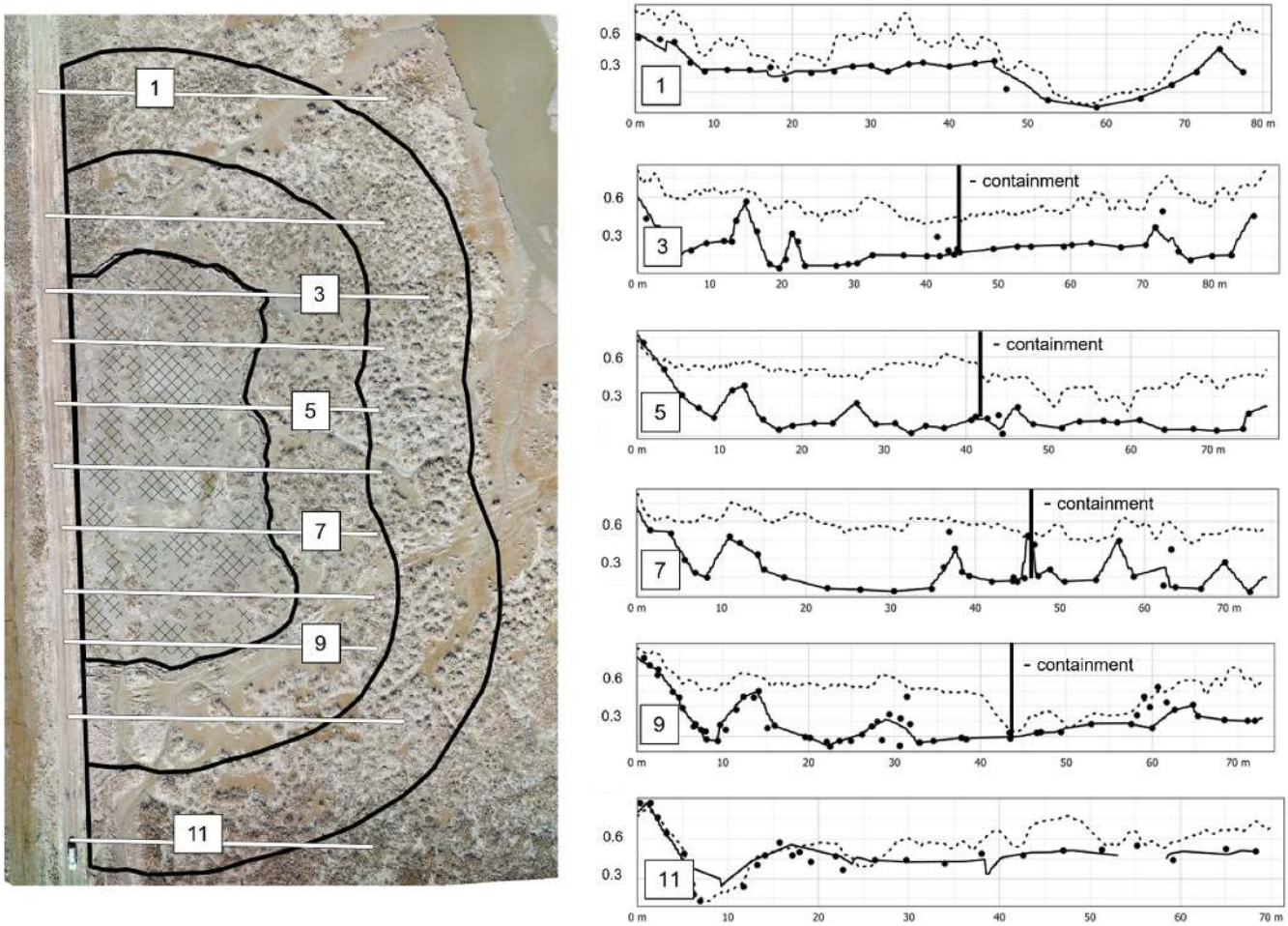


Figure 3. Drone imagery of the project area just after completion of dredge placement in March, 2019. Hatched areas indicate zones used to estimate dredge placement elevations in the core project area. White lines indicate elevation transects that were surveyed before and after dredge placement. Elevation profiles show the before (September 2017, solid line DEM; black dots RTK GPS points) and after (March 2019, dotted line DEM) elevation along a subset of these transects.

After dredging completion, the site was seeded with 113.5 L of cold stored wet *S. alterniflora* seed. Seed was sowed across 16 plots ranging from 4 to 12 sq. m in size (105 sq. m total) throughout the containment site. Seeded plots were covered with jute erosion control material to help minimize seed loss.

Elevation Surveys

Surface elevation surveys occurred along regular transect lines conducted within the placement zones occurred prior to material placement, during and after completion (Fig. 4). Surveys were supplemented with terrestrial Lidar and aerial photogrammetry to create digital elevation models (DEM). We used real-time kinematic (RTK) Global Positioning Systems (GPS) to measure cross-sections across the proposed dredged area of the channel to determine the dredging envelope and to monitor the amount of material removed from the channel. We also conducted broader RTK elevation surveys across the site to characterize vegetation zonation by elevation to inform target elevation determination.

To compare site elevations before and immediately after placement in the containment area, we delineated 50 vegetation-free polygons (Fig. 4) that comprised 35% of the placement area. This was to avoid any error induced by vegetation in the creation of digital elevation models. We present the mean value across these polygons and conduct a matched-pairs *t* test to examine statistical differences.

Follow-up surveys to determine elevation change since placement were conducted in October 2024. Elevations were collected at 20 random points within each of three zones (containment area, 0–25 m from the coir log barrier, and 25–50 m from the coir log barrier). Within the containment area, the majority of these points were unvegetated prior to project initiation (75%) whereas in the middle (86%) and outer (78%) zones, the majority of these points were vegetated. To determine trends in elevation change before, immediately after, and 5 years post-placement, we extracted elevation values to these points from the pre and post-placement digital elevation models.

Vegetation Classification

Aerial imagery of the restoration site was collected via drone over the course of the monitoring period. Drone imagery for 2018 through 2020 was planned and processed to generate orthomosaic and digital surface model (DSM) products. Vegetation coverage at the site was assessed with two drone flights each year, one each spring and one each Fall from 2018 to 2021 and then once a year in the spring of 2022 and 2023.

Drone imagery was classified using object-based image analysis (OBIA) with a support vector machine (SVM) classifier. Imagery from 2018 through 2020 was classified using the orthomosaic's red, green, and blue bands as inputs, while imagery from 2021 through 2023 included elevation data. The classification model was trained using random points manually assigned to two classes: (1) areas that were vegetated and (2) areas that were non-vegetated.

Results

Construction

Containment boundary elevations ranged from 0.66 to 1.03 m shortly after it was constructed (November 2018) but settled to 0.36–0.88 m by the time dredge placement was completed (March 2019). Dredge placement began in late Fall 2018 and was completed by March 2019. Based on volume change

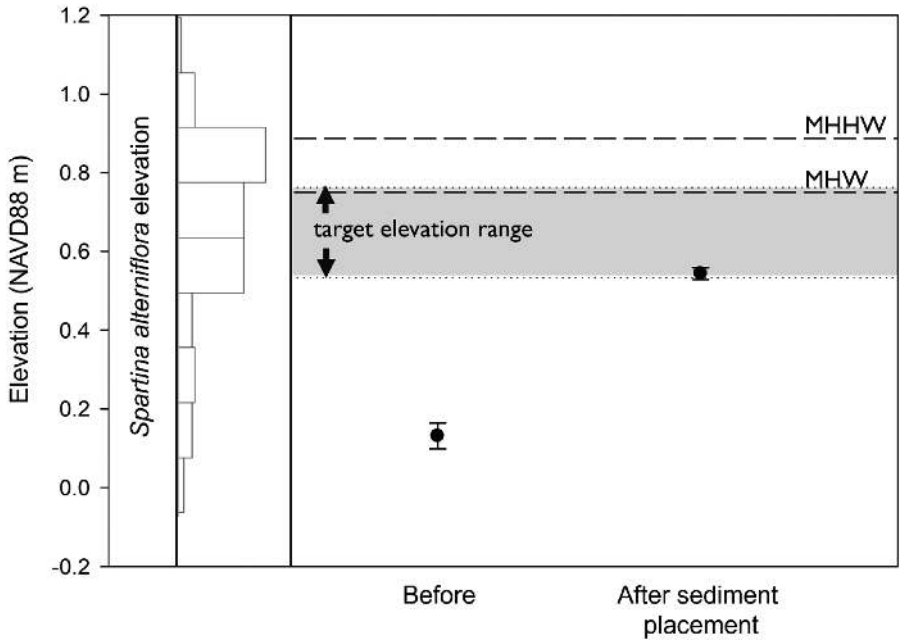


Figure 4. Elevation before and after sediment placement. The elevation distribution of *Spartina alterniflora* in the project area is displayed in the left panel. Tidal datums and the target elevation range are displayed for reference.

estimates in the placement area, approximately 1399 m^3 of 100% silt sediment slurry was deposited into the confined area.

Dredging was conducted over a 182.9-m section at the upstream portion of the creek, with maximum excavation elevations ranging from −1.5 to −1.68 m NAVD 88 (Figs. 1 & 2). The total amount of material dredged was 1903 m^3. Based on the volume remaining in the placement area versus the volume dredged, approximately 504 m^3 of material escaped from the containment area.

Elevation

The mean elevation of the project area prior to sediment placement was 0.12 m (0.093–0.15 95% CI). After placement, the mean increased to 0.54 m (0.53–0.56 95% CI), an increase of 0.42 m (Fig. 5). A matched-pairs t test comparing elevations across the 50 polygons in the placement area indicated a significant increase ($T = 32.7$, degrees of freedom [df] = 49, $p < 0.001$). Mean elevation immediately after placement reached just above the lower threshold of the target elevation range.

Matched pairs analysis of random points indicated significant elevation increases in all three zones before and immediately after sediment application (Fig. 6, inner contained area, $t = 13.3$, $df = 19$, $p < 0.001$; middle 0–25 m from contained area, $t = 6.25$, $df = 19$, $p < 0.001$; outer 25–50 m from contained area, $t = 6.65$, $df = 15$, $p < 0.001$). While the inner zone reached the lower threshold of the target elevation range (0.53–0.76 m), the middle and outer zones, which were not intentionally targeted for sediment placement, increased but did not reach the

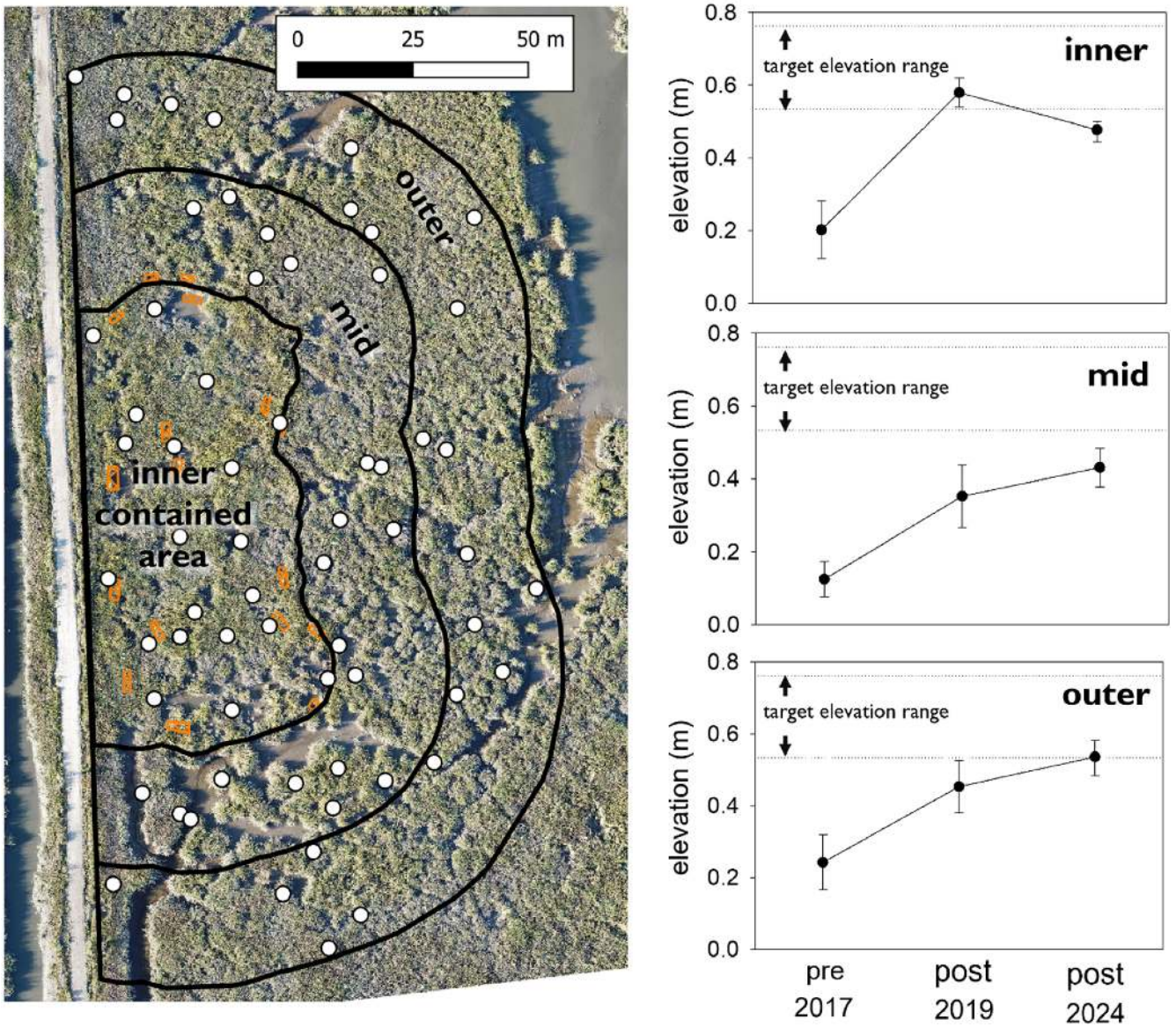


Figure 5. Elevations at random points across three zones and three time intervals (prior to restoration, immediately post sediment placement and 5 years post-placement). The aerial image is from September 2020, at the end of the second growing season showing extensive revegetation of the project area. Also indicated in orange hatched areas are 16 test plots where *Spartina alterniflora* seed was sowed.

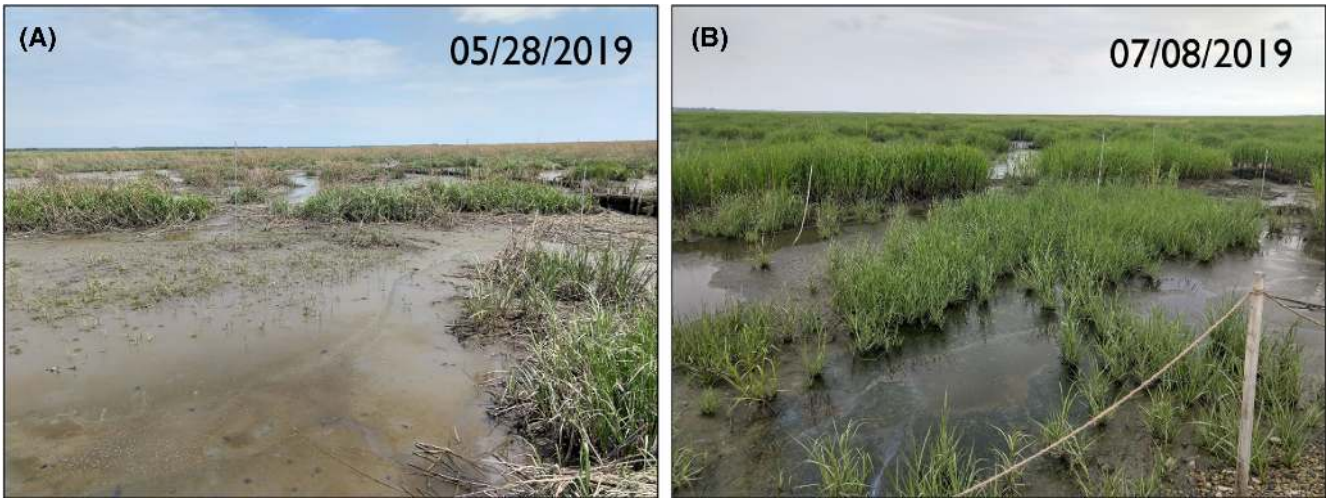


Figure 6. Progression of planted seeds in the first growing season.

target elevation threshold (middle mean = 0.35 m ± 0.27–0.45 95% CI, outer mean = 0.50 ± 0.42–0.58 95% CI). Mean elevation increase was 0.23 m for the middle zone and 0.27 m for the outer zone. These results, along with a visual inspection of elevation profiles (Fig. 4), indicate that the containment was not fully effective at retaining sediment in the project area.

Comparing elevations immediately after placement versus 5 years later, elevations in the inner contained area decreased significantly (−0.10 m, $t = -4.40$, $df = 19$, $p < 0.001$) while elevations in the middle (+0.079 m, $t = 1.62$, $df = 20$, $p = 0.11$) and outer zone held steady (+0.033 m, $t = 0.73$, $df = 22$, $p = 0.47$).

Vegetation Cover

We noticed widespread germination of both planted and wild seed in April 2019 and by late May 2019 the seedlings were 20–25 cm tall. By late July, the seedlings were well-established plants (Fig. 7). By the end of the growing season, it was difficult to discern the planted plots because natural colonization by *Spartina alterniflora* seedlings was pervasive.

Aerial imagery analysis over five growing seasons overall indicates a progression of increasing vegetation cover over the first two growing seasons after placement, followed by 2 years of stable to slightly declining cover followed by the final growing season where cover increased to its maximum level, particularly for the core placement area. Vegetation cover in the inner, contained placement area did not increase in the first growing season ($\chi^2 = 2.32$, $df = 1$, $p = 0.14$) but by the second growing season there was a significant increase in vegetation coverage (from 55 to 85%, $\chi^2 = 108.95$, $df = 1$, $p < 0.001$). Through the third and fourth growing seasons, vegetation cover in the inner area held steady. It then increased significantly in the fifth growing season (from 84 to 97%, $\chi^2 = 48.21$, $df = 1$, $p < 0.001$).

In contrast with the inner placement area, the middle (from 65 to 79%, $\chi = 27.49$, $p < 0.001$) and outer zones (from 77 to 85%, $\chi^2 = 16.11$, $df = 1$, $p < 0.001$), vegetation cover increased significantly in the first growing season following dredge material placement. There was no significant change for mid ($\chi^2 = 1.62$, $df = 1$, $p = 0.20$) or outer ($\chi^2 = 1.25$, $df = 1$, $p = 0.26$) between 2019 and 2020. Both the mid (82–70%, $\chi^2 = 22.29$, $df = 1$, $p < 0.001$) and outer zone (87–78%, $\chi^2 = 21.47$, $df = 1$, $p < 0.0001$) vegetation cover declined significantly between 2020 and 2021. Vegetation cover held steady in the following year before increasing again in 2023 (mid, 70–85%, $\chi^2 = 36.96$, $df = 1$, $p < 0.001$, outer, 75–85%, $\chi^2 = 36.23$, $df = 1$, $p < 0.0001$). Levels in 2023 were equivalent to 2020 estimates.

Discussion

This project sought to raise salt marsh elevation to enhance the extent, productivity, and accretion potential of *Spartina alterniflora* in areas where large elevation deficits persist as a legacy of salt hay farming. We achieved this objective by conducting restoration-focused dredging in an adjacent channel and strategically placing that material to raise the marsh elevation by 0.42 m. Over 5 years of monitoring, natural colonization and expansion of *S. alterniflora* proceeded rapidly, with vegetation cover increasing from 55 to 86% by year 2 and approaching 100% by year 5.

We documented significant escape of material from a containment berm into the surrounding area (26% of the volume dredged). This material undoubtedly settled in the immediate vicinity of the contained area because we documented significant elevation increases up to 50 m away from the edge of the containment berm. These outer areas also showed an increase in vegetation cover over time. Containment served a dual role of retaining sediment and creating a settling basin during dredge slurry pumping so that water levels could be held somewhat higher than the surroundings and thus allow silty sediment to accumulate elevation. Building elevation with silty material is a challenging task since it can only accumulate as high as the level of the water. This challenge was encountered while pumping material, as it became difficult to build to the higher ends of the target elevation given

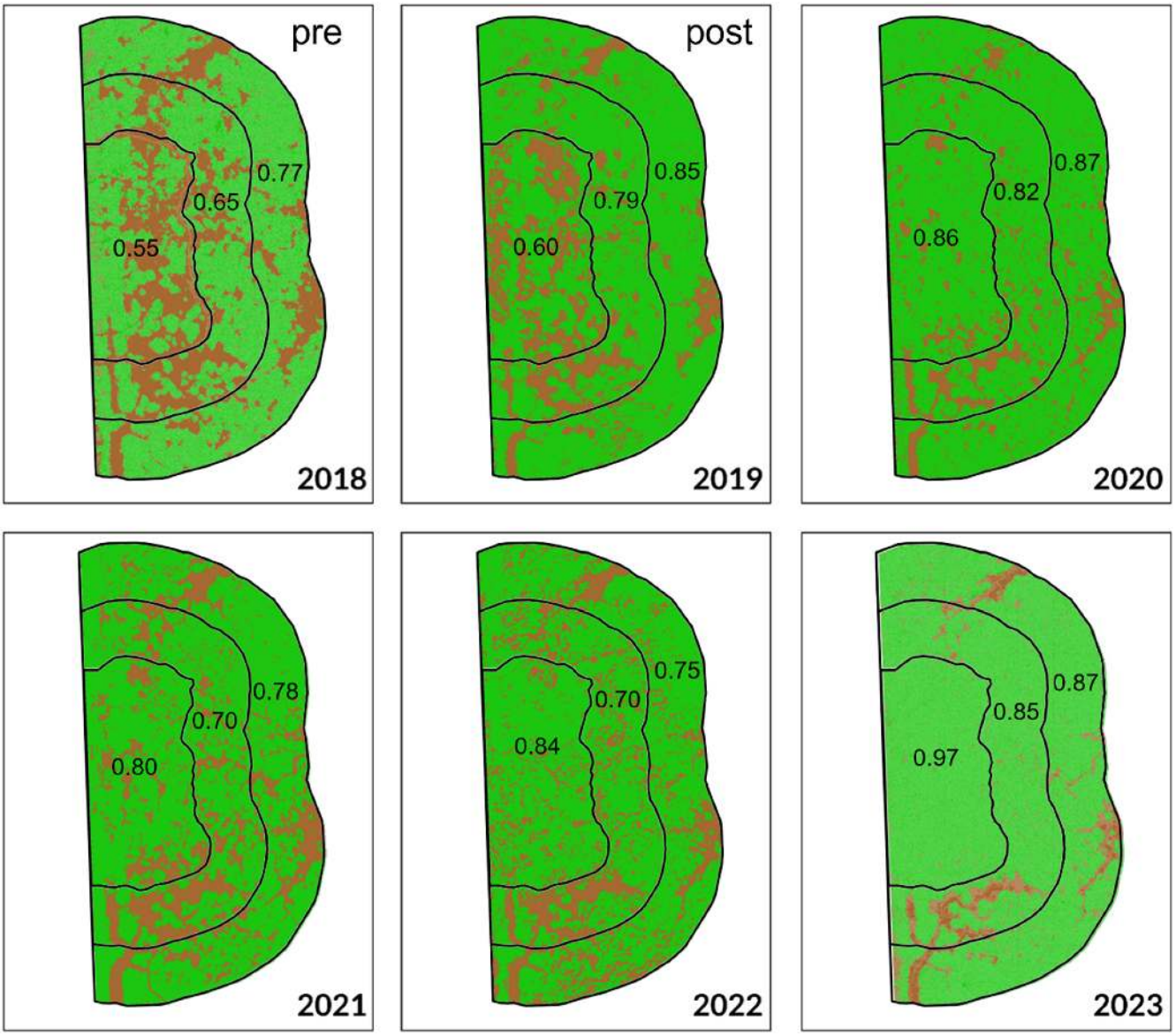


Figure 7. Aerial image classification of vegetation cover prior to and for five growing seasons after sediment placement. Inner (contained placement area), mid, and outer zones are delineated, and percent cover for each zone/year is displayed.

the limited time that water levels reached those elevations. Sandy dredged material is more amenable to building elevation. Settling rates of silty material post-placement are also more difficult to predict compared with sand (Chabreck 1990).

We also documented significant settling of material (−0.10 m) in the target area which comprised ¼ of the initial elevation increase. This rate of settling is similar to that observed at a recent project in New Jersey (Harris et al. 2025) where the settlement was attributable to consolidation of the dredged material along with the underlying material. Interpretation of results in the middle and outer areas is more difficult because, unlike the inner zone, the elevation monitoring points were vegetated prior to project initiation that remained alive and not fully buried by sediment. These areas show a non-significant upward trend in elevation, potentially indicating that settling is offset by the sediment trapping and organic accretion capacity of the living vegetation.

Vegetation coverage increases were rapid, with significant increases after the second growing season for the placement area and the first growing season in the mid and outer zones. This difference may be due to the lighter impact (no construction vehicle activity) and lesser amount of sediment reaching these outer areas that allowed existing vegetation to respond immediately to the flush of new sediment and increased elevation. There was a 2-year stall in vegetation cover increase that we cannot readily explain. One possibility is that water levels may have been higher in those years during the growing season. By year

5, the core placement area had nearly 100% vegetation cover while the outer two areas were approaching 90% cover.

In the Northeast United States, the majority of restoration projects have occurred within the last 10 years and have placed material on vegetated marsh to achieve elevations at or above Mean Higher-High Water (Raposa et al. 2022; New Jersey Department of Environmental Protection et al. 2023) for the dual purpose of creating marshes that are resistant to the effects of sea level rise and to create habitat for nesting birds that use the highest parts of the marsh. Some of these projects, however, have seen low success in restoring habitat and marsh function, with vegetation recovery that had still not returned to baseline conditions 6–7 years post-placement (New Jersey Department of Environmental Protection et al. 2023).

Stagg and Mendelssohn (2011) demonstrated that resilience and stability of a sediment-subsidized marsh is highest when the target elevations are near MHW because at higher elevations vegetation recovery was much slower, attributed to dry, infrequently flooded conditions. The authors cautioned that elevation targets intended to offset future sea level rise induced a 15-year lag in the recovery of marsh function, while placing at optimal current elevations produced a "resilient system almost immediately." This insight may explain the rapid expansion of vegetation in our project as our final elevations fell just below MHW within the growth range of *S. alterniflora*. Another recent project that achieved dredge placement elevations at approximately MHW also observed relatively rapid reestablishment of *S. alterniflora* (Harris et al. 2025).

More work is needed to understand the influence of target elevation, depth of placement, and patchiness of placement on measures of restoration success across a range of geographies and physical settings. Critical to meeting these needs is consistent reporting of project outcomes that can inform broader-scale insights into patterns of restoration success and failure (Moreno-Mateos et al. 2012; Liu et al. 2024). This project highlights opportunities for improving resilience of tidal marshes through restoration and also highlights some important limitations and tradeoffs. Advancing restoration practice at a large scale depends on the integration of ecological restoration into dredging programs to yield benefits that are critically needed to offset the impacts of climate change and the heavy human use of our seascapes.

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Supporting Information

The following information may be found in the online version of this article:

Supplement S1. Tidal datum derivation and flooding duration analysis for the sediment placement target elevation.

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