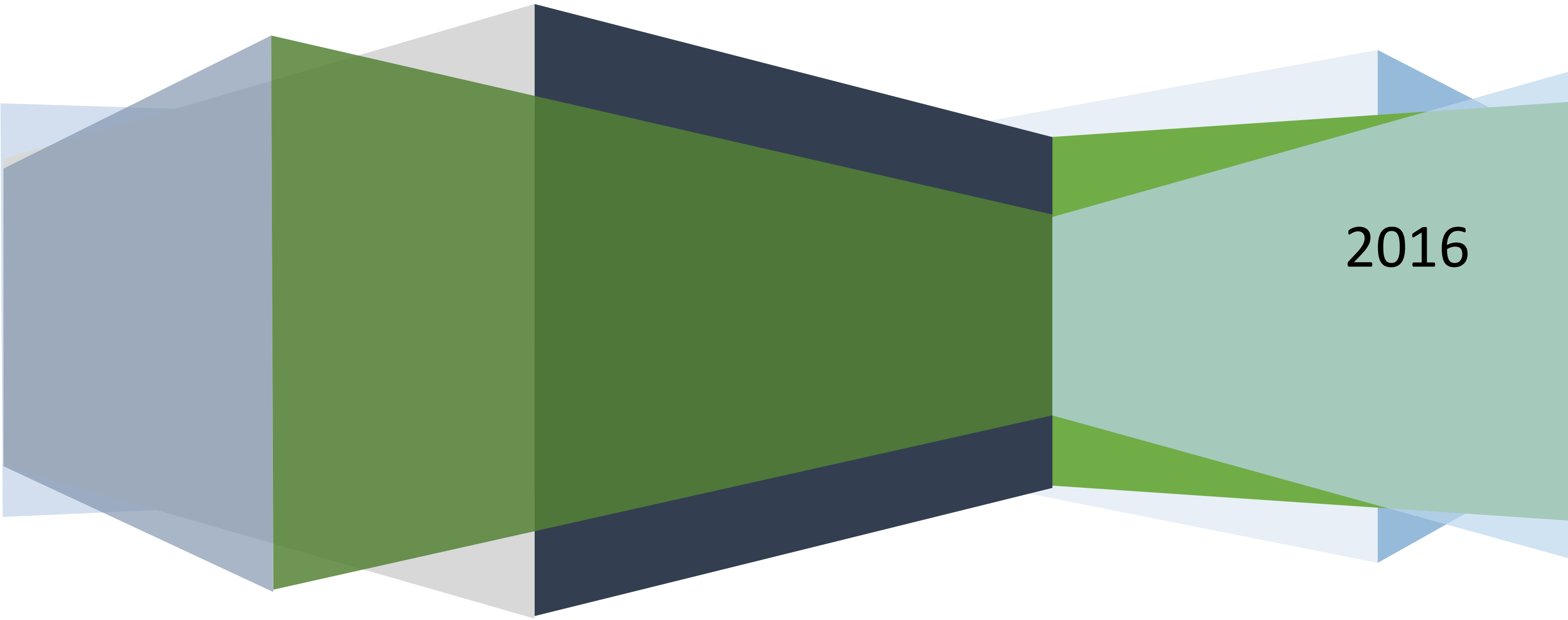
Partnership for the Delaware Estuary

Design, Implementation, and Evaluation of Three Living Shoreline Treatments in Lewes and Inland Bays, DE

A technical report submitted to Delaware Department of Natural Resources and Environmental Control in partial fulfillment of Contract No. 12404-Monitoring: Coastal Wetland Monitoring Stations and Living Shoreline



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Design, Implementation, and Evaluation of Three Living Shoreline Treatments in Lewes and Inland Bays, DE

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Executive Summary

Living shorelines are an example of erosion control tactics that seek to stem the landward retreat of tidal marshes while also enhancing the resilience and ecological health along the seaward edge. As part of PDE's recent efforts to increase the number of living shoreline demonstration and research study sites, in 2013, we partnered with Delaware Department of Natural Resources and Environmental Control (DNREC) to identify new areas suitable for living shorelines, and to implement projects in two locations: along the Lewes-Rehoboth canal in Lewes, DE (two sites); and at Delaware Seashore State Park in the Inland Bays, DE (one site). Explicit goals were set for each project, and preliminary RTK-GPS and biological surveys were conducted to collect accurate baseline data needed for treatment design.

Based on site characterization data and best scientific judgment, a bio-based living shoreline design, consisting of coir logs, mats, and twine, wooden stakes, and oyster shellbags was selected as the most appropriate alternative for all three treatment areas. Additional high resolution elevation measurements were gathered at each site to denote the placement of materials within the local tidal spectrum. Living shoreline treatments were installed at both locations in April 2014, with additional materials installed at the Lewes AOI in October, 2014. Purchased plugs and salvaged clumps of *Spartina alterniflora* from intertidal areas in close proximity to each site were planted in the living shoreline treatments at both locations in summers 2014 and 2015, with an additional effort in the Inlands Bays in 2016.

A goal-based monitoring plan was developed to evaluate the ability of each living shoreline to meet its objectives and to persist at a site. Metrics relevant to each goal were chosen based on their ability to produce a meaningful result regarding treatment effects, and included: shoreline position; platform elevation; vegetation robustness; shellfish density; accretion rates; bearing capacity; and material structural integrity. Methods appropriate for the collection of data required for statistical analysis were selected. The monitoring approach for the two living shoreline installations followed a Before-After-Control-Impact paired design (BACI). Each installation, or impact area, was paired with an untreated but similar control area, within which identical spatial and temporal data collection occurred. Two-way ANOVA of BACI data were used to identify significant differences in metric values between the treatments and controls over time. The USGS Digital Shoreline Analysis Software (DSAS) and ArcGIS Geostatistical and 3D Analyst extensions were employed to measure lateral and vertical marsh movement.

Overall, the Lewes Marsh treatment area gained 83.39m^2 of salt marsh habitat, whereas the control area lost 22.10m^2. At the Inland Bays location, the Rip Rap site treatment area built 146.83m^2 and lost 14.95m^2 at the control, and the Marsh site gained 63.87m^2 at the treatment and lost 7.20m^2 to erosion at the control. All three living shoreline treatments met their stated goals of shoreline stabilization and ecological enhancement. Shoreline position at all three treatment areas was moved waterward and appears to be stable. In contrast, the vegetated marsh edge in all control areas (untreated areas) continued to erode landward. Ecological enhancement was also substantiated in the new living shoreline treatments, evidenced by robust new vegetation positioned within optimal vertical growth ranges. Many of the currently vegetated areas were unvegetated prior to living shoreline installation. The vertical position of the new marsh with the treatment impact areas is within the proper elevation range relative to the local tidal datum for the development and persistence of the dominant marsh vegetation, *S. alterniflora*.

Even though areas with low TSS, like the Inland Bays, can be difficult for living shorelines to naturally trap sediments, once filled, they may still be able to keep pace with larger scale processes, such as sea level rise, due to periodic inputs of sediment. Vegetation robustness increased within all living shoreline impact areas, indicating that the elevation targets were appropriate and were met. Shellfish communities have not yet shown a significant response, but as the living shorelines are young, more time may be needed for bivalves to recruit and colonize. These data set the stage for tracking the health of the salvaged material over time when positioned properly in the tidal prism. Coir-fiber materials have been shown to be adequate in low energy environments, although impacts of faunal usage (HSCs) can affect the durability, and lifespan, of degradable materials. Shellbags displayed greater resistance to degradation and were successful in trapping and retaining sediments.

As a next step, monitoring should be continued to document changes in the physical attributes and biological community within and around the living shorelines. These demonstration projects provide valuable baseline and early-stage data regarding the trajectories and persistence of natural and nature-based infrastructure. A living shoreline is more than a sum of its structural components; it is the successful functionality of the biological components over time. The rigorous monitoring design has allowed for the quantitative evaluation of this functionality, and has been crucial for attending to the periodic needs of the treatments. As these shorelines continue to mature, long-term data will help inform design, adaptive management, and temporal expectations of living shorelines in our area.

Introduction

Tidal wetlands are the most productive habitat in the Delaware Estuary system, performing many vital services including: protection of inland areas from tidal and storm damage; water storage and flood protection during large scale storm events; providing important habitat for a wide variety of fish and wildlife; water quality enhancement through contaminant removal and carbon sequestration; providing spawning and nursery habitat for commercial fisheries; recreation; and aesthetic value (PDE, 2009 and 2012) . Currently however, coastal wetlands are being lost in the Delaware Estuary at a rate of about an acre per day (PDE, 2012). For these reasons, protection of coastal salt marsh habitats has become a key focus of many coastal resource management organizations, especially considering their high vulnerability to climate change and sea level rise (Kreeger et al. 2010).

Figure 1 Location of two living shoreline: green star denotes Lewes, and pink star indicats Inland Bays.

Traditionally, salt marsh protection consisted of hardened structures, such as seawalls and bulkheads that separated the marsh and subtidal ecosystems. This separation can disengage many important biogeochemical interactions, which are reflected in biotic use of waters around bulkheads compared to salt marshes (Seitz et al., 2006; Bilkovic and Roggero, 2008; Partyka and Peterson, 2008; Currin et al. 2010; Balouskus and Targett, 2016; Gitman et al., 2016a; Torre and Targett, 2016. Additionally, hardened structures reflect wave energy, scouring the substrate waterward of the structure and creating impact zones for waves and debris behind the structures (Pilkey and Wright, 1989; Pilkey et al., 1998, Rogers and Skrabal, 2001; Bozek and Burdick, 2005; National Research Council, 2007; Currin et al. 2010; Gitman et al. 2016b). Recent research has indicated that stabilizing degraded marshes with natural, softer materials can provide stabilization and sediment capture services, facilitating marsh regeneration, while absorbing, rather than reflecting, wave energy and retaining connectivity of the terrestrial and aquatic environments. Many of the benefits conveyed by coastal marshes and soft armoring techniques were witnessed during and after Hurricane Sandy, which caused tremendous damage to both built and natural infrastructure in the upper mid-Atlantic region in late October 2012.

Living shorelines are an example of erosion control tactics that seek to stem the landward retreat of tidal marshes while also enhancing the resilience and ecological health along the seaward edge. Typical goals of living shorelines are to maintain tidal interaction and to utilize materials that facilitate natural marsh and subtidal processes, such as sedimentation, shellfish recruitment, and vegetation stabilization that allow for the growth and development of resilient marsh ecosystems. There is a diverse array of living shoreline methods, ranging from biological-based designs suitable mainly for low energy locations to complex hybrid designs that are more appropriate in higher energy areas. Since 2007, PDE has worked with the Rutgers University Haskins Shellfish Laboratory and other partners to develop, test and implement bio-based living shorelines that are comprised of fiber logs, paired with a variety of other natural materials. These research and development efforts have been a key element of the Delaware Estuary Living Shoreline Initiative (DELSI), and the fiber log approach has also been coined the "DELSI Method," although the program now is testing a variety of other tactics as well.

Locations

As part of our recent efforts to increase the number of living shoreline demonstration and research study sites, in 2013, PDE partnered with Delaware Department of Natural Resources and Environmental Control (DNREC) to identify new areas suitable for living shorelines, and to implement projects in two locations. One of the selected locations was along the Lewes Rehoboth Canal behind the baseball fields in Lewes, DE containing one paired treatment/control site. The other location was at the DNREC marina at Delaware Seashore Park across the inlet from the Burton Island Nature Preserve containing two paired treatment/control sites (Fig 1). These locations were chosen to address salt marsh erosion in low to moderate energy environments in areas near public access to maximize potential outreach outcomes once living shorelines were installed. Physical and biological conditions at both locations were similar to baseline conditions at sites where PDE had previously installed bio-based living shorelines including: erosion along a predominantly salt marsh habitat; vegetation community dominated by *Spartina alterniflora*; low slope along the foreshore; moderate protection from large scale fetch; and meso- or euhaline conditions.

Lewes

The Lewes location is along the Lewes and Rehoboth Canal, directly behind the baseball fields west of the public boat ramps on Main Street at a newly renovated waterfront park in Lewes, DE. The park is a central gathering spot for local residents and, recently, the city has been updating park amenities including sports facilities, playground equipment, and public gathering areas. A protective fringe of salt marsh positioned between the baseball fields and canal along the park's north margin had been experiencing erosion, which the city wanted to address. A living shoreline was selected as an appropriate treatment as it was congruent with the other nature-based uplift projects in the park.


Figure 2 Eroding marsh edge in the Lewes Marsh site treatment area. The large cusp behind the white arrow is located directly across the canal from a marina boat ramp.

The Lewes location consisted of one living shoreline site (Marsh) for which a paired treatment and control, ~26m in length, were selected and delineated (Fig. 3). The paired treatment and control are separated by a small drainage creek that bisects the AOI. The existing vegetation community consisted of a ~2m band of tall-form *Spartina alterniflora* along the waterward margin, grading to short and mid-form *S. alterniflora* moving inland to the upland vegetation boarder. The treatment area exhibited a large, landward indentation along the contiguous vegetated edge located directly across the canal from the boat ramp at the Lewes Harbor Marina (Figs. 2 and 3). The width of the tall form *S. alterniflora* band decreased along the indentation from the outward extent and was completely absent at the cusp's center-replaced by short form *S. alterniflora.* This eroding shoreline was beginning to

Figure 3 Overview of the living shoreline site (Marsh) in Lewes. The site consists of a paired treatment and control along an eroding stretch of salt marsh.

encroach on the little league baseball fields directly upland of the fringing marsh. The vegetated edge along paired control was located at a similar lateral extent as the treatment area, but did not exhibit a cusping morphology.

Inland Bays

The Inland Bays location was at the DNREC Indian River Marina on the eastern shore of Balders Pond. The location included two paired treatment and control areas: Rip Rap and Marsh (Fig. 4). Located in Delaware Seashore Park, the marina is just north of the Indian River Inlet and has a public boat launch and facilities for long-term boat housing and maintenance. The location is adjacent to the marina's main facilities to the south. A public access walkway to the Burton Island Nature Preserve is located to the north, providing additional viewing opportunities for the general public.

Rip-Rap

The Rip Rap site was situated at the southern end of the west-facing shoreline in an area where rip rap had been previously placed to stabilize the tall bank between the sandy intertidal and the office lawn (Fig 5a). The rip rap extended 13.75m north along the sandy intertidal zone from the southern end of the treatment area where the slope grade decreases and upland vegetation is present (Fig 5b). The vegetated upland portion of the site extended an additional 10.61m north to a *Phragmites* band situated behind the existing salt marsh. The width of the sandy intertidal flat expands from 3.05m at the southern end to 9.14m at the northern end of the rip-rap treatment area, and finally to 13.72m at the southern boundary of the existing salt marsh. The Rip Rap site control area was located on the salt marsh adjacent to the Rip Rap treatment area, approximately 12.19m north of the boundary. The vegetation community consisted of a ~5m band of tall form *S. alterniflora*, gradually shifting to mid-form heights moving into the back marsh. Although the Rip Rap control area does not contain rip rap, this area was chosen as the best possible reference for the marsh habitat intended to be established in the treatment area. Specifically, the control area would provide information regarding current lateral marsh movement, biological health, and elevation profiles in a natural marsh experiencing the same chemical and physical conditions with the same aspect and foreshore slope against which the living shoreline could be compared.

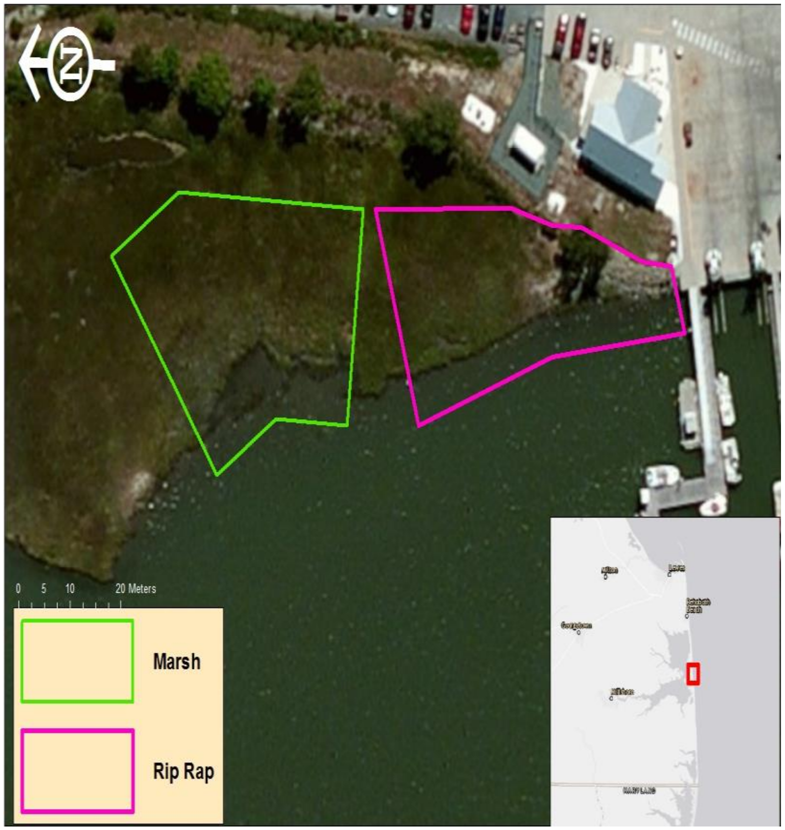


Figure 4 Overview of two living shoreline sites at the Inland Bays location. The Marsh site, located to the north, consists of a paired treatment and control along an eroding stretch of salt marsh. The Rip Rap site, located to the south, consists of a treatment area in front of a Rip Rapped shoreline and a control of eroding salt marsh.

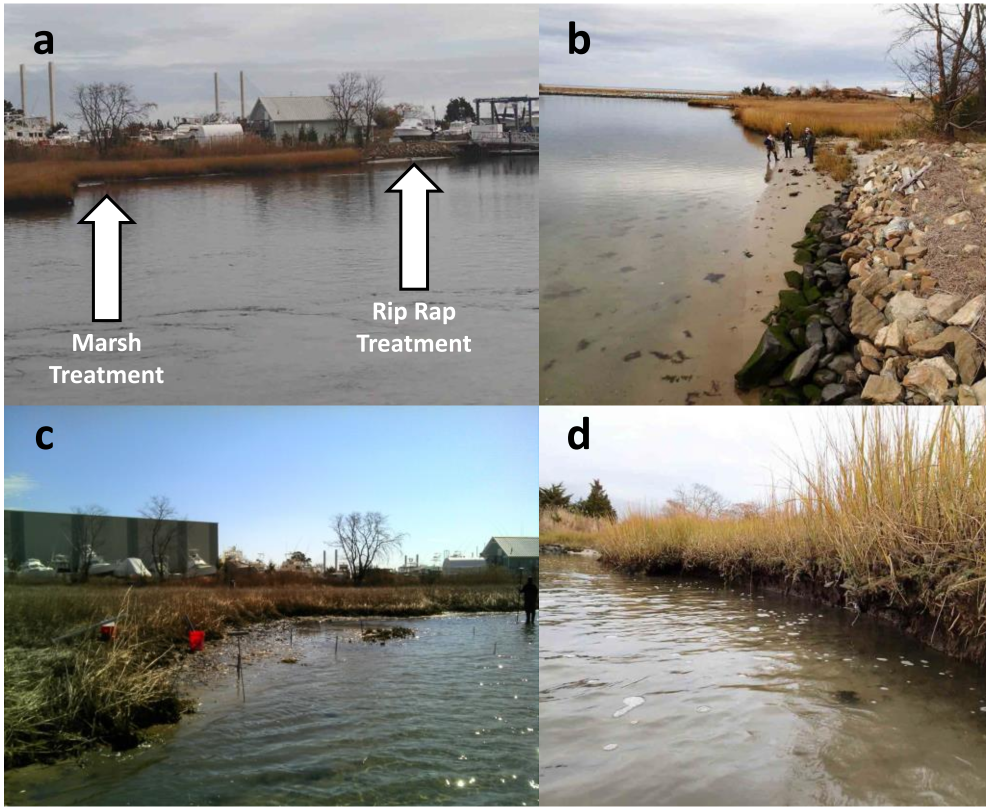


Figure 5 Pre-existing conditions at the Inland Bays location. a) North end was a fringing salt mash that ended at the marina to the south, which was rip raped along its waterward margin. b) Rip rap behind the marina at the Rip Rap site. Note the non-vegetated foreshore. c) Eroding portion of salt marsh at the Marsh Site. d) Undercutting along the marsh edge between the Marsh and Rip Rap sites.

Marsh

The Marsh site was located at the northern end of the Inland Bays location in the existing salt marsh, between the marina and the causeway to the Burton Island Nature Preserve. The treatment and control areas were comprised entirely of salt marsh habitat between Balder's Pond and the marina facilities (Fig 4). The treatment and control areas were ~15.6m in length and were separated by a marsh drainage creek that extended into the high marsh interior. The vegetation community in the treatment and control areas consisted of a ~2m band of sparse tall form *S. alterniflora*, gradually shifting to mid-form and short form *S. alterniflora* in the back marsh. There was an area of pooling water just behind the existing vegetated edge containing a high density of ribbed mussels, but sparse and leggy vegetation. The foreshore substrate was sand covered in a thin layer of fine sediments. The treatment area exhibited signs of lateral marsh retreat possibly due to orientation (facing largest fetch to the southwest; Fig. 5c) or vegetation health decline in areas of pooling water. Although the control area also showed signs of vegetative health decline in the area just landward of the foreshore levee, additional undercutting was observed along the contiguous vegetated edge (Fig. 5d).

Project Goals

Clear identification of project goals, explicit for every site, are important because they guide project design and performance monitoring. In order to properly gauge if a living shoreline is having an impact on the environment where it is installed, there must be standards to evaluate performance against. The selection of relevant metrics and appropriate methods will be discussed below in the Monitoring section.

Lewes

The primary goal of the living shoreline at the Lewes Marsh site was shoreline stabilization, specifically stemming the lateral landward migration of the salt marsh. This primary goal was augmented by the secondary goal of ecological enhancement upon which the primary goal is partially dependent. Ecological enhancement refers to the promotion of positive health and stable ecological conditions (e.g. community complexity, structure, and composition) in the habitat targeted by the living shoreline. To successfully achieve long-term shoreline stabilization using a living shoreline, an ecologically sound habitat must be created, or fostered, by the installation materials.

At this location, the foreshore environment was situated at an elevation below the optimum growth range (mean water to mean high water) for the dominant vegetation at the site, *S. alterniflora*, which would preclude the development of healthy salt marsh along the foreshore. Shoreline stabilization in isolation along the existing marsh edge may prevent the lateral retreat of the marsh, but would not cultivate the long-term resiliency of a healthy salt marsh within the current non-vegetated eroded cusp. Therefore, a synergistic coupling of shoreline stabilization and ecological enhancement goals were selected to address current conditions and promote ecological resiliency.

Primary Goal: Shoreline Stabilization

Secondary Goal: Ecological Enhancement

Inland Bays

Rip-Rap

The living shoreline installed at the Rip Rap site had two goals. The primary goal was ecological enhancement, and the secondary goal was shoreline stabilization. Ecological enhancement was sought by re-vegetating the foreshore in front of the site, one area in which historical aerial images showed was once salt marsh. This would provide a buffer and "green-up" the rip rap and exposed interface between the intertidal and upland areas. The extension of the marsh along this area required that the living shoreline design address all the proper ecological/physical conditions for a resilient marsh (e.g. proper elevation, drainage, community structure, etc.). The secondary goal was shoreline stabilization, which would be shown if the created marsh retained its horizontal position over time.

Primary Goal: Ecological Enhancement

Secondary Goal: Shoreline Stabilization

Marsh

The goals of the living shoreline at the Inland Bays Marsh site were similar to the Lewes Marsh site, consisting of a primary goal of shoreline stabilization and a secondary goal of ecological enhancement. The primary goal of shoreline stabilization, like Lewes, was to halt the lateral landward migration, and to build the cusping marsh back out to the extent of the surrounding marsh. As noted above, the existing marsh was experiencing water retention in the area just behind the existing edge, where vegetation was sparse. The secondary goal of ecological enhancement was chosen to ensure that the living shoreline promoted the proper physical conditions (e.g., elevation, drainage contours, etc.) for a healthy biological community, including native marsh grasses and ribbed mussels.

Primary Goal: Shoreline Stabilization

Secondary Goal: Ecological Enhancement

Site Characterization

Once the sites were identified and goals were established, preliminary RTK-GPS and biological surveys were conducted to collect accurate baseline data needed for designing living shoreline projects. As all living shoreline designs are tailored to local conditions, slope, gradient, aspect, substrate type, and community structure (flora and fauna) were documented.

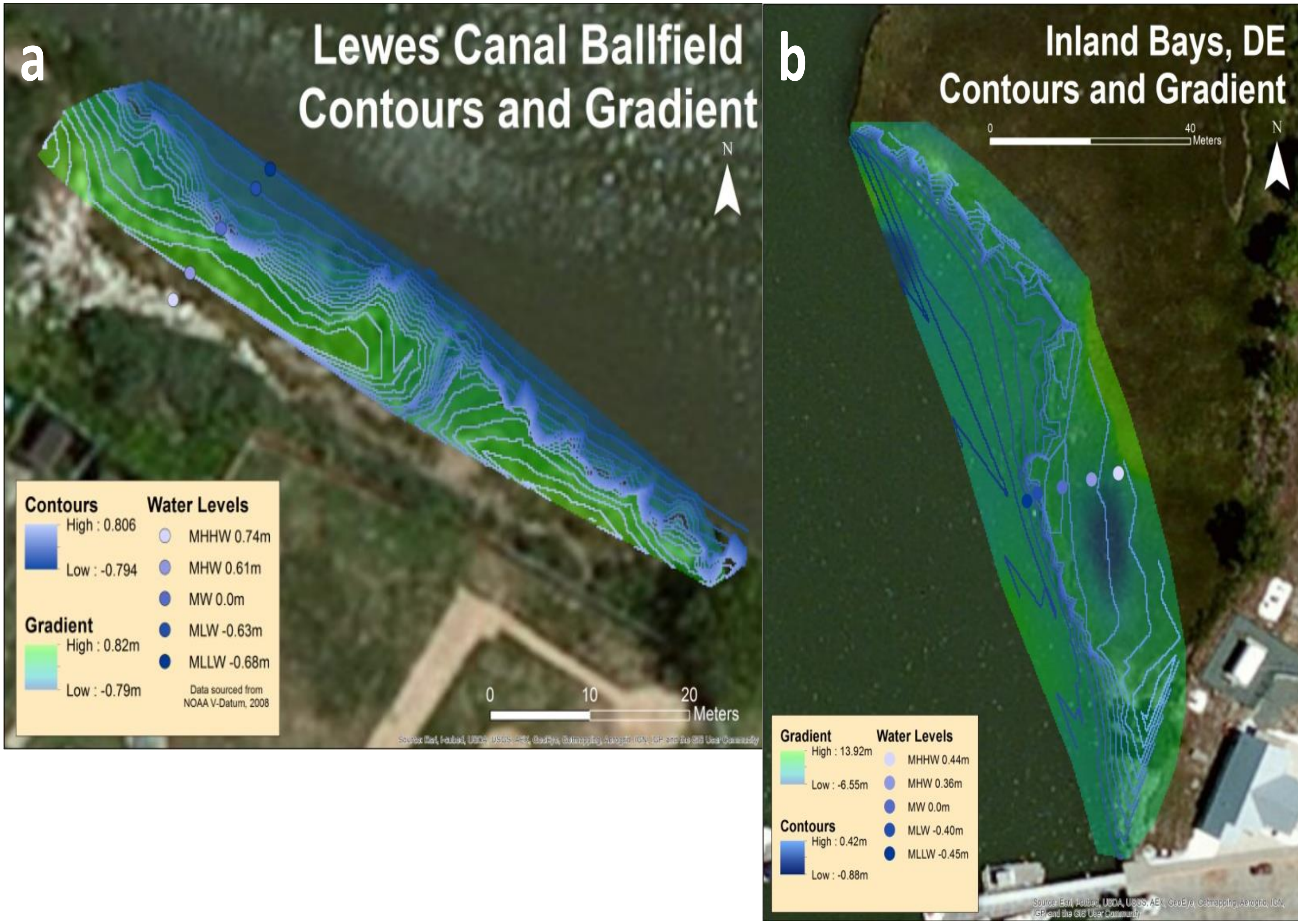


Figure 6 Contour and gradient profiles along the Lewes (a) and Inland Bays (b) locations. Contour lines and gradient polygon spanned the area between mean lower low water and mean higher high water. Local tidal datum elevation represented as points.

Physical Data: To determine the appropriate placement of materials within the local tidal prism to facilitate marsh enhancement, physical data concerning marsh platform elevation and topography were collected using Trimble R6 Real-Time Kinematic GPS (RTK) and analyzed using the Geospatial Analyst Tool extension in ArcGIS 10.2. The RTK unit uses a global navigation satellite system (GNSS) to measure latitudinal/longitudinal and vertical (elevation) position with an accuracy of 8mm +1ppm RMS and 15mm + 1ppm RMS respectively. The additional error attached to each measurement reflects the distance of the unit from the base station; for every 1km of distance an additional 1mm of potential error measurement is added. The average accuracy, including error, is within 16mm horizontal and 30mm vertical error.

Biological Data: In addition to horizontal and vertical positioning of the salt marsh within the local tidal prism, data concerning the vegetation type present and substrate at each point were also collected. These data were used to assess the spatial variation in vegetative communities, and their elevation ranges across the marsh platform.

The following site characterizations discuss relative positions of site-specific features of each location. Quantitative elevation positions of these features and their relationship to living shoreline materials is discussed below in the Design and Implementation section.

Lewes

The marsh at this location exhibited a vertical drop-off of 1.2m from the marsh platform to the surface of the sloping mud flat at its waterward most point. The mudflat was fairly uniform in elevation, only dropping below this elevation past the waterward most extension of the existing salt marsh (Fig 6a).

Between mean low water and the current vegetated edge that the mudflat marsh edge interface, a steeper slope and higher elevations were present, likely formed by deposition of eroding material from the marsh. The entire area waterward of the current vegetated edge was below mean water. Hence, a living shoreline required extensive elevation gains to establish proper position within the tidal datum (Fig 6a).

The non-vegetated area consisted primarily of fine sediments with low bulk density, resulting in soft, deep mud. Clumps of oysters were present along the foreshore in the intertidal zone and ribbed mussels existed in dense patches along portions of the vegetated edge. The ribbed mussel population was patchy with areas of high density interspersed among areas of very low density.

Inland Bays

Rip-Rap

The sandy intertidal area along the Rip Rap treatment area was positioned primarily below mean water. The area exhibited a fairly uniform grade waterward of the rip rap. The sandy sediments were firm and suspended sediment concentration in the water column appeared to be low. No shellfish were present, but remnants of previously existing salt marsh vegetation existed at approximately mean low water as relic peat mats, with a sprig or two of emergent vegetation still growing.

At the Rip Rap control area, a sharp increase in elevation was present at the existing salt marsh edge, increasing to a levee directly behind the edge (light green area directly behind clustered contours) (Fig 6b) and transitioning into a plateau in the high marsh area (dark blue area to right of tidal datum points). Ribbed mussels were present in the substrate landward of the marsh edge in highly variable densities. The substrate appeared to have high water retention along the waterward margin, which became more firm moving landward. The foreshore substrate contained a mix of sand and fine material, and this zone was not vegetated or populated with shellfish.

Marsh

The vegetative extent at the northern portion of the treatment area was positioned approximately at mean water, and decreased to a position at mean low water at the southern end. The grade and contour were uniform across the site with an area of slightly higher grade centrally located behind marsh edge (depressional area behind clustered contours, depicted as bright green in Figure 6b). The non-vegetated area within the eroding cusp was positioned below the mean water contour and had trapped ~5cm of fine material above a sand lens. The control area shared a similar grade and contour, but exhibited undercutting along the marsh face.

Living Shoreline Design and Implementation

PDE, with technical assistance from Rutgers University Haskin Shellfish Research Laboratory, designed living shoreline treatments that followed design standards and material components of previous installed projects. Based on site characterization data and best scientific judgment, a bio-based living shoreline design was selected as the most appropriate alternative for all three treatment areas, consisting of coir logs, mats, and twine, wooden stakes, and oyster shellbags.

Parallel placement of materials relative to the existing shoreline was selected as the waterward-most extent of the treatment. The configuration of materials was determined to meet the site-specific goal of shoreline stabilization. The materials were selected and configured to create a stable refuge for the development of a resilient ecological community.

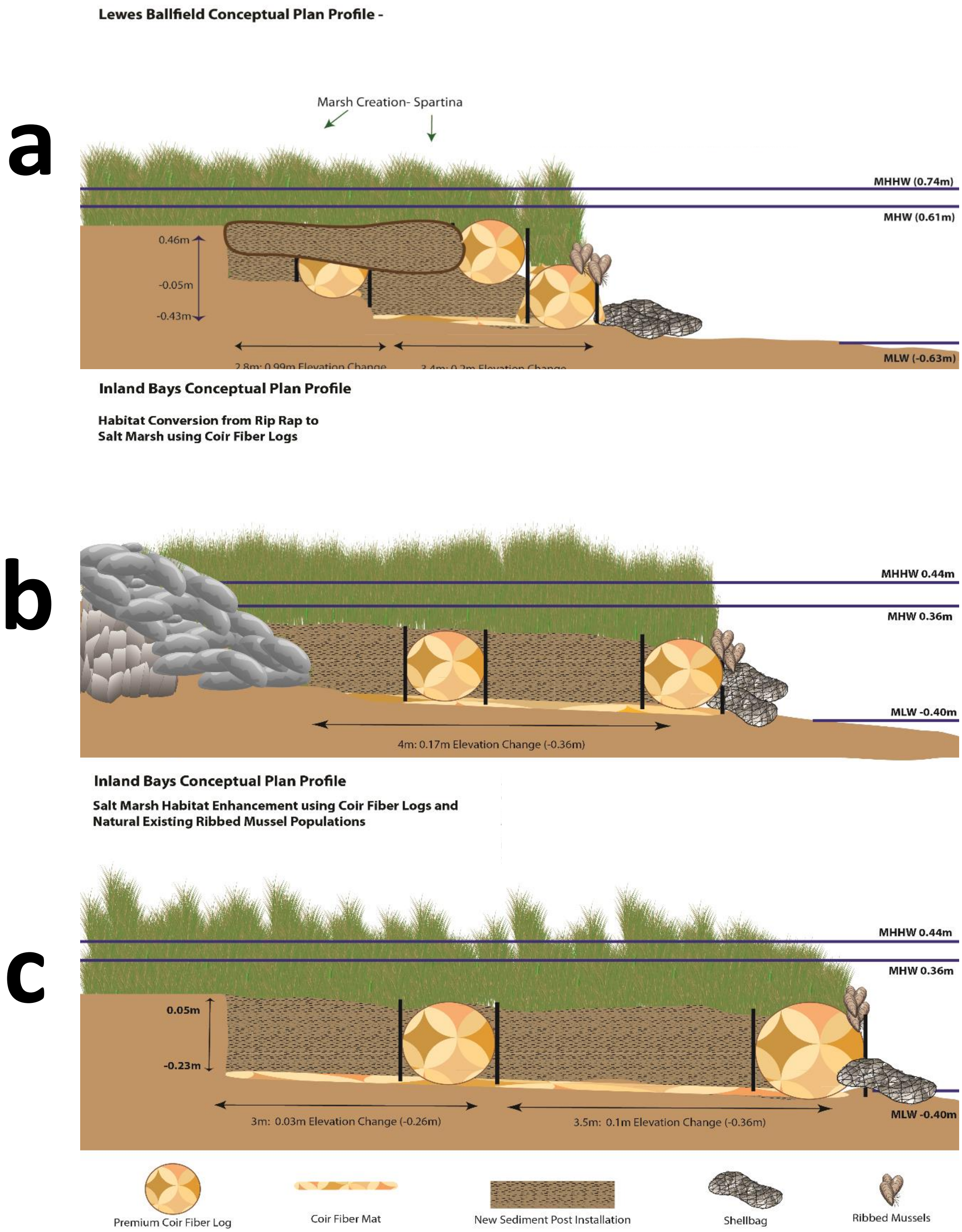


Figure 7 Profile sections of treatment designs for Lewes (a), Inland Bays Rip Rap (b), and Inland Bays Marsh (c) sites. Each site design was vertically positioned within the local tidal prism as delineated by the mean low water (MLW), mean high water (MHW), and mean higher high water (MHHW) lines.

Placement of materials along the elevation gradient was situated to meet the site-specific goal of ecological enhancement. The materials were positioned in the treatment impact area (area encompassed by the treatment materials) between mean water and mean high water, targeting the proper growth range of *S. alterniflora*.

Based on initial measurements and site characterizations, conceptual designs were composed in Adobe Illustrator. Upon approval, additional high resolution elevation measurements were gathered at each site to denote the placement of materials within the local tidal spectrum during installation (Fig. 7).

At all sites, installation began by rolling coir matting along the mudflat across the entire treatment area. The mat acted as a secure base for the coir fiber logs, prevented sinking, and protected the logs against sharp shells and/or rock buried in the mud.

Coir fiber logs were then positioned, end to end, and were tied tightly together using coir twine. Stakes (with pre-drilled 5/8" holes) were then positioned along the logs, one pair every two feet (n=12, stakes per 12' log). Stakes were hammered into the substrate at a slight angle to create an "A" formation until the top of the stake was uniform with the top of the logs.

Coir twine was threaded through the logs and stakes to connect them. Stakes were then hammered further down so that the twine cinched the log down, providing additional security. Shellbags were then placed against the outer face of the waterward cusp and on the landward side at joints. Additional bags were placed at the ends of each cusp to armor the ends and prevent movement.

Specific design considerations for each location and treatment are described below.

Lewes

The waterward cusp was 84’ long. Because of a large elevation drop, a double log treatment was needed to elevate the created marsh to meet minimal vertical requirements for target vegetation, i.e., an elevation no lower than mean water and comprised of a double stack of seven 12’ x 16” coir fiber logs. The first tier of 16” coir fiber logs was placed at ~-0.6m elevation, allowed to settle and backfill, with a final target elevation of ~-0.3m. This cusp was placed 6.2m from the existing marsh edge, with a total elevation change of ~1.2m.

At the eastern end of the treatment area, the coir fiber logs extended between two already existing pilings (which provided additional stability) before tying into the existing marsh edge. Shellbags were placed between the pilings and logs to prevent wear on the logs due to rubbing against the pilings. The second tier of coir fiber logs was placed on top to bring the final elevation of the treatment to ~MW.

The landward tier was ~ 60’ long installed at an elevation of -0.2m to bring the final elevation to just above MW. The landward tier log was attached to the waterward tier at the western end of the treatments area. At this location a stack of 6 shellbags wrapped in coir matting was secured to the marsh slope using wooden wedges to provide extra stabilization at the end of the treatment as well as to hold back-filled sediment in the treatment area. Due to the steep slope within the treatment area, the internal, landward cusp only required a single coir fiber log to reach a similar elevation (Fig 7a).

The first tier of coir fiber logs in the front cusp and the single back cusp tier were installed 04/17-18/2014, and the second tier of the front cusp was installed 10/20/2014 to collect sediment over the 2014/2015 winter. Sedimentation occurred rapidly at this site, with trapped sediment filling ~3/4 of the treatment area by spring 2015. Planting efforts helped the treatment trap additional sediment, and consisted of salvaged eroded *S. alterniflora* mussel clumps and purchased plugs 6/27/2014, 04/02/2015, and 06/29/2015 (Table 1).

Inland Bays

Rip-Rap

The waterward portion of the rip rap installation measured 25m long and extended from the end of the existing salt marsh, arching out in front of the non-vegetated peat mat, and tucking behind the rip rap at the marina end of the treatment. The waterward portion of the installation contained a single tier cusp of seven 16” x 12' coir fiber logs, installed at -0.33m. This cusp began at the eastern end of the existing salt marsh and extended to approximately the middle of the rip rap area. The landward cusp of five 16" x 12' logs installed at -0.2m followed the visible non-vegetated peat mat, extending from the existing marsh edge to the west to the edge of the rip rap to the east.

These treatment configurations resulted in a final elevation of both cusps in each treatment to be between MW and 0.1m, post settlement (Fig. 7b). Materials were installed 04/14-15/2014, and sediment trapping was virtually non-existent. Salvage occurred on 04/01/2014, 06/30/2015, and 07/15/2016, and purchased plugs were installed on 2014 date (Table 1).

Spring horseshoe crab (HSC) spawning in the area resulted in many crabs actively using the treatment area. Although not a risk to the HSCs, they were periodically removed from the immediate treatment to avoid potential public perception regarding (false) entrapment. To prevent the need for constant HSC maintenance during the spawning season, and due to a lack of significant natural sedimentation, a decision was made to back-fill the treatment areas with sand from a local dredge project on 07/16/2014. Forty-five cubic yards of sand were split between the two sites at the Inland Bays location. Sand was moved by wheelbarrow and shoveled into each treatment. Once the treatments were filled, HSCs more easily navigated the terrain and readily moved into and out of the treatment areas.

Table 1 Materials used to construct and maintain living shoreline treatments at each site. Material installation are delineated by year. A “Yes” denotation in the Salvaged Plants column indicates that local, eroded material was salvaged and planted into a living shoreline treatment. An ”X” denotation indicates that no material specified in the column header was installed in that time period.

Location	Site	Date	Coir Logs	Coir Mat	Wooden Stakes	Oyster Shellbags	Salvaged Plants	Purchased Plugs
Lewes	Marsh	2014	19	2	144	135	Yes	550
Lewes	Marsh	2015	X	X	84	X	Yes	X
Inland Bays	Rip Rap	2014	12	1	144	130	X	600
Inland Bays	Rip Rap	2015	X	X	X	X	Yes	X
Inland Bays	Rip Rap	2016	X	X	X	X	Yes	X
Inland Bays	Marsh	2014	8	1	96	65	X	400
Inland Bays	Marsh	2015	X	X	X	50	Yes	X
Inland Bays	Marsh	2016	X	X	x	12	Yes	X

An unexpected result of the HSC activity was that their movement across the coir fiber logs facilitated deterioration. The sharp pincers on the HSC legs tore the coir fiber netting and exposed the inner coir fill material. This resulted in some isolated loss in elevation along the foreshore, but sand movement across the coir fiber logs helped to retain partial logs along the front and sealed in most of the exposed logs on the second, landward, tier. The HSCs were able to navigate successfully around the salvaged plant material, resulting in little disruption of vegetation community. Additional shellbags were placed along the front at the waterward log tier to provide enhanced armoring as well.

Marsh

The waterward portion of the installation was 15.6m wide and consisted of a single tier of five, 16" x 12' coir fiber logs placed at -0.3m elevation. After backfilling of sediment, the final elevation was just above MW at ~0.1m. A second cusp of three 16" x 12' logs was installed behind the waterward cusp at -0.2m elevation. After backfilling, the final elevation of the marshward cusp was ~0.2m above MW.

See above regarding HSCs and backfilling of sand. Although not in direct view of the public, the marsh treatment area was backfilled for consistency across treatments and to preemptively address the lack of waterborne sediment. These elevations allowed for the newly produced marsh to be within the optimal growing range for *S. alterniflora* (Fig. 7c). Salvage and planting occurred in tandem with the Rip Rap treatment in 2014, 2015, and 2016 (Table 1).

Monitoring

A goal-based monitoring plan was developed to evaluate the ability of each living shoreline to meet its objectives and to persist at a site. Metrics relevant to each goal were chosen based on their ability to produce a meaningful result regarding treatment effects. Methods appropriate for the collection of data required for statistical analysis (see next section) were used. The monitoring approach for the two living shoreline installations followed a Before-After-Control-Impact paired design (BACI). Each installation, or impact area, was paired with an untreated but similar control area, within which identical spatial and temporal data collection occurred.

Data were collected at two resolutions: feature-based and replicate-based. Feature-based data collection occurred along a feature of interest, and was not necessarily collected at equal intervals or in replicate. At the sites, shoreline position was considered a feature of interest and its position was surveyed twice a year, using an RTK-GPS. Replicate-based data collection occurred in replicated plots situated at specific positions relative to the sites. At the sites, metrics regarding marsh platform elevation, sediment accretion, substrate firmness, vegetation robustness, and the extent of the bivalve community were evaluated in replicate plots at specific positions relative to the treatment and control areas.

Five transects, oriented perpendicular to the existing vegetated edge, were established at each treatment and control prior to the installation of each living shoreline in 2014. Transects 1 and 5 delineated the outer bounds of the treatment and control areas. Transects two, three, and four contained sampling plots within which data were collected. Five sampling plots were positioned along transects 2-4, at the following locations. These are also schematically depicted in Fig. 8 and mapped for each treatment and control in Figs. 9 and 10.

- Plot 1: positioned at approximately mean low water. This area was considered the foreshore as it was located waterward of the living shoreline.

- Plot 2: positioned between the two locations of coir fiber log cusps. This was considered the impact area as it was located within the area between living shoreline materials and the pre-existing marsh edge.
- Plot 3: positioned behind the landward coir fiber log cusp and the existing 2014 contiguous vegetated edge. This was considered the impact area as it was located within the area between living shoreline materials and the pre-existing marsh edge.
- Plot 4: positioned on the marsh levee between 1-2m landward of the 2014 contiguous vegetated edge. This was considered the marsh platform as it was located landward of the treatment area on the pre-existing marsh platform.
- Plot 5: positioned approximately 1m landward of the low marsh/high marsh boundary in high marsh vegetation. This was considered the high marsh as it was located landward of the treatment area, in high marsh vegetation on the pre-existing marsh platform.

At each treatment's paired control, plots 1-3 were installed at a similar lateral position from the existing marsh edge. Monitoring was performed by PDE and DNREC staff. A description of each metric and method is given below with their associated goal, spatial and temporal sampling resolution, and analysis question to evaluate treatment impacts (also summarized in Table 2).

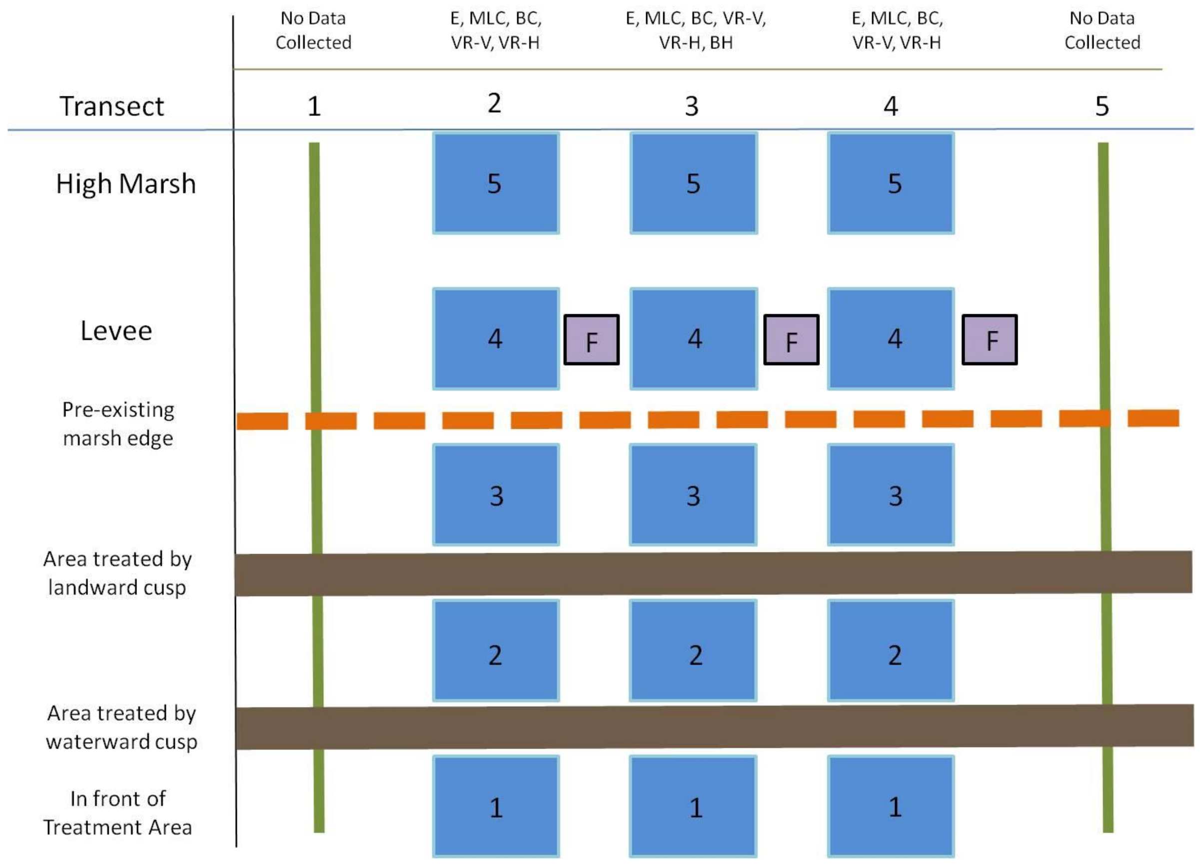


Figure 8 Monitoring plot layout for all three sites. The top of the schematic denotes metrics collected in each plot: E= elevation; MLC=ribbed mussel lip counts; BC=bearing capacity; VR-V= vegetation robustness vertical density; VR-H=vegetation robustness horizontal density; BH=blade height. The purple box with an "F" denotes the placement of the feldspar marker horizon plots. No data were collected along transects 1 and 5 which delineated the end of paired treatments and controls. Locations of prominent features are denoted on the left of the schematic.

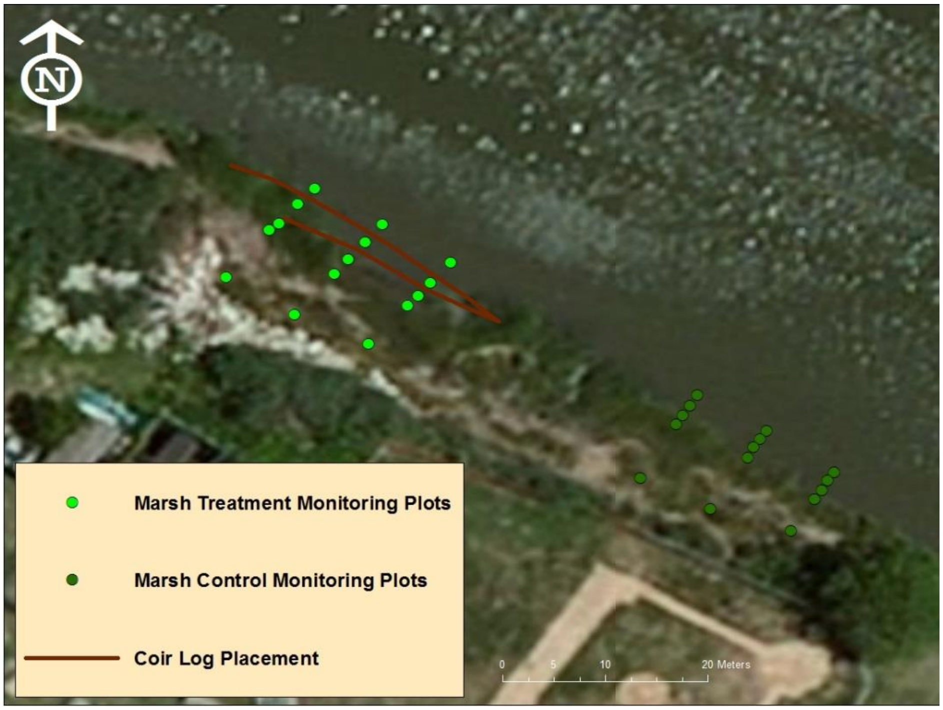


Figure 9 Position of monitoring plots and coir log treatments within the paired treatment and control areas at the Lewes living shoreline location. Monitoring plot locations and log positions collected using RTK-GPS.

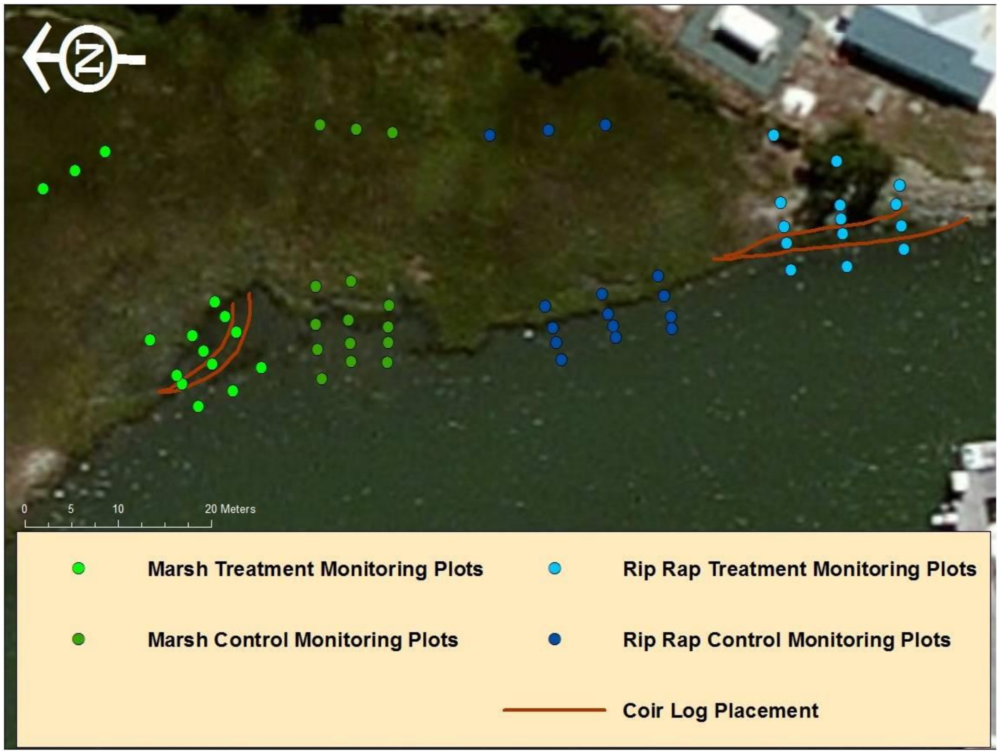


Figure 10 Position of monitoring plots and coir log treatments within the paired treatment and control areas at the Inland Bays living shoreline location. Monitoring plot locations and log positions collected using RTK-GPS.

- Horizontal Position of the Vegetated Edge: measured the geospatial position of the vegetated marsh edge as surveyed using an RTK-GPS over time. Data collected twice annually at a minimum resolution of ~3m intervals.
- Vertical Position of the Marsh: measured the vertical position of the marsh platform as surveyed using an RTK-GPS over time. Data collected twice annually in each monitoring plot.
- Sediment Accretion: measured the sediment deposited on the marsh surface as measured above a feldspar marker horizon. Feldspar was deposited on the marsh surface in 0.5m^2 plot in 2014. During spring monitoring in 2015 and 2016 a 3in^2 plug of marsh was removed from the plot and accretion above the marker horizon was measured using calipers. Three replicate measurements were taken per plot/year in each treatment and control.
- Substrate Firmness: measured substrate firmness as penetrative capacity of a slide hammer after 5 blows. Three replicate measurements were taken per plot/year in each treatment and control.
- Vegetation Robustness: vegetation robustness is a unitless index that integrated the vertical and horizontal density of vegetation within a plot, normalized for vegetation height. The formula for calculation was:

$$Vegetation\ Robustness = \frac{Horizontal\ Vegetation\ Density + Vertical\ Vegetation\ Density}{2}$$

Three replicate measurements were taken per plot/year in each treatment and control. The following three metrics were used to calculate the above percentages:

  - Horizontal Vegetation Density: measured horizontal density by counting the number of bars visible (out of 10; 10cm width each) on a 1m obstruction board from 3m away within the same band of vegetation. The count was conducted at three heights: 0.25m; 0.50m; 0.75m. The height to which data was used for calculations (number of bars available; max=30, 10 at each height) was determined by the max vegetation height as measured by Blade Height below. Calculations were as follows:

$$Horizontal\ Vegetation\ Density = \frac{number\ of\ bars\ available - number\ of\ bars\ visible}{numberof\ bars\ available}$$

  - Blade Height: Twenty-five stems were measured, moving from the waterward corner towards the interior. Max blade height was used for the Vegetation Robustness calculation.
  - Vertical Vegetation Density (Canopy Cover): Five measurements of ambient light were taken above each plot (corners and center) and at the ground level (penetrative light) beneath canopy using a light meter. Calculations were as follows:

$$Vertical\ Vegetation\ Density = 1 - (\text{ratio of penetrative light: ambient light})$$

- Extent of Bivalve Community: measured the number of ribbed mussels and oysters in each plot by counting the number visible. Three replicate measurements were taken per plot/year in each treatment and control.

Each metric was collected once annually (Table 2), either in the spring or in late summer after the peak growing season for vegetation. RTK data were collected at each monitoring event in spring and later summer. Sampling of each metric began in 2014 (spring collection of Extent of Bivalve Community was conducted prior to installation), and was considered to reflect the pre-existing conditions at the site for each metric. Vegetation robustness data could not be collected until after installation in late summer 2014, but these data were still considered to be representative of the pre-existing site conditions as the living shoreline infrastructure had not been present at the site long enough to affect growth and health.

Data Analysis

Shoreline Position Change

The Digital Shoreline Analysis Software (DSAS) was used to calculate the rate and distance of lateral marsh movement at each treatment and control area. Using these shoreline databases the basic instructions found in the DSAS instruction manual were used (see: http://woodshole.er.usgs.gov/project-pages/DSAS/version4/index.html). Geodatabases that contained all shorelines were constructed in ArcGIS 10.2 using point data collected with the RTK-GPS. ArcGIS 10.2 was used as the primary software interface, and all DSAS utilities were downloaded and installed.

Table 2 Goal-based metrics and methods applied to all three living shoreline treatments and controls at both study locations. Included are the spatial and temporal resolution at which the metrics were collected, and the analysis question asked to gauge differences between the treatment and control over time. These metrics were collected at all three sites among both AOIs

Goal	Metric	Methods	Temporal Resolution	Spatial Resolution	Analysis Question	Analysis Method
Shoreline Stabilization	Horizontal Position of Vegetated Edge	RTK-GPS Survey	Spring and Late Summer/Fall	Collected along the contiguous vegetated edge (~1m)	Did the horizontal position of the marsh change; in what direction?	DSAS ArcGIS 3D Analyst
Ecological Enhancement	Vertical Position of Marsh	RTK-GPS Survey	Spring and Late Summer/Fall	Collected along each transect (~1m) and in each monitoring plot (n=15)	Is the vertical position of the marsh appropriate for marsh vegetation?	BACI ArcGIS 3D Analyst
Ecological Enhancement	Sediment Accretion	Feldspar Marker Horizon	Spring: Prior to Vegetation Emergence	Placed in triplicate at each treatment and control adjacent to plot 4.	Did sediment accrete on the marsh surface?	BACI
Ecological Enhancement	Substrate Firmness	Slide Hammer Bearing Capacity	Late Summer/Fall: Peak Vegetation Growing Season	Collected in each monitoring plot (n=15)	Did the marsh substrate become more or less firm?	BACI
Ecological Enhancement	Vegetation Robustness: Horizontal Vegetation Density	Vegetation Obstruction Board	Late Summer/Fall: Peak Vegetation Growing Season	Collected in each monitoring plot (n=15)	Did vegetation robustness change?	BACI
Ecological Enhancement	Vegetation Robustness: Vertical Vegetation Density (Canopy Cover)	Light Meter	Late Summer/Fall: Peak Vegetation Growing Season	Collected in each monitoring plot (n=15)		
Ecological Enhancement	Vegetation Robustness: Vegetation Height	Replicate Blade Measurement	Late Summer/Fall: Peak Vegetation Growing Season	Collected in each monitoring plot along transect 3 (n=15)		
Ecological Enhancement	Extent of Bivalve Communities	Lip Counts	Spring: Prior to Vegetation Emergence	Collected in each monitoring plot (n=15)	Did shellfish community density change?	BACI
Photo Documentation		Camera	Spring and Late Summer/Fall	At each end, in front of, and behind each		

An offshore baseline shapefile was created for each site treatment (and saved to the created geodatabase). The baseline was designated based on information found in DSAS instruction manual, and is used as a location for DSAS to base subsequent shoreline measurements. Attribute tables for both the baseline file and the shoreline file were organized per the DSAS instructions, included adding a Date and ID field. For each site, DSAS "Default Parameters" were established. The created baseline was selected as "offshore."

Transect Spacing was set to 1m. The shorelines in this data set were not of great length. Use of a 1m transect spacing was selected as it provided the most data and yielded the most useful graphical information. Transect length was 15m, ensuring that each passed the end of the farthest shoreline. Cast Direction was set to LEFT (default). The shoreline shapefiles for the site were entered, and the Date field selected. Shoreline uncertainty was set to 4.4 meters, which is the default. "Closest Intersection" was selected for intersection parameters. All Metadata fields were completed. "Smoothed Baseline Cast" was selected for "Set Casting Method." Transects were then Cast.

Using the casted transects layer, statistics were then calculated. Net Shoreline Movement (NSM) and End Point Rate (EPR) were both selected and a 95% confidence interval was used (default). An "intersect" and a "rates" database were created as a product.

Transects were then clipped to fit within the boundaries of the existing shorelines. This required entering the transect layer and the "intersect" database created via the statistical calculations. The "rates" database was joined to the clipped transect file to spatially see which NSM and EPR applied to which transects. The "rates" data was added into Excel and the NSM and EPR among both Lewes and Inland Bays were examined together.

Creating histograms of these data to see what best would represent the data, thresholds were created to visually separate the data. For Net Shoreline Movement (NSM): RED-high negative shoreline movement= -1.71m to -0.865m; Yellow-negative shoreline movement = -0.864m to 0m; Green-positive shoreline movement = 0.01m to Max. Quantitative symbology was then applied based on these thresholds (NSM and EPR separately) to the clipped transects file (joined to the "rates" database) for each location. For NSM, the clipped transects file with applied symbology was used to draw a smoothed line along the 2016 shoreline. Transects were then removed.

Additionally, a side-view cross section was created to visualize the horizontal and vertical change over time along the center transects at each paired treatment and control. These visuals were created in ArcGIS 10.2 using the Geostatistical and 3D Analyst tools. The high resolution RTK data was used to create a Digital Elevation Model (DEM) of each treatment and control area in spring 2014 (pre-existing conditions) and in late summer 2016 (most recent survey). The DEM was created using the Empirical Bayesian Kriging method (EBK-default parameters used) in the Geostatistical Analyst tool extension. A new shapefile representing transect 3 (center transect) at each site was created using the survey data, and the elevations from the DEM were interpolated into the shapefile along its length using the Interpolate Shape tool (DEM was set as the input surface and transect line as the feature class) located in the 3D Analyst toolbox. The transects containing the spatial elevation values were selected and displayed graphically using the Profile Graph toll on the 3D Analyst toolbar.

BACI Analysis

A Before-After-Control-Impact (BACI) statistical design was employed to ascertain significant treatment effects of the living shoreline relative to the paired control over time. The temporal component (BA) of the model considered 2014 to be the "before time" point and 2015 and 2016 the "after time" points. The paired control area (C) was differentiated from the area of impact (I).

Subsamples collected in each plot (n=3/metric/control or impact/year) were used to calculate temporal and spatial variance of each metric (response variable). A full factorial linear model was then constructed. Differences in variance were analyzed as a two-way ANOVA test to assess the effects of Time and Location on each metric. An alpha threshold of 0.05 was set to detect significant differences. An interactive effect between Time and Location indicated a significant effect as a result of the living shoreline. For example, if there was a difference in the level of a metric between the treatment area and the control area, and that difference was not the same before and after the installation, it was likely that the change in relative difference of the metric between the two locations over time was a result of the only other documented difference, the installation of the living shoreline at the treatment area.

All analyses were conducted using R version 3.0.3 (2014-03-06) -- "Warm Puppy." The linear model was constructed using the "lm()" function and variance analysis using the "anova()" function (design was balanced). BACI plot graphics were created using the gplots package and the barplot2 command. All R code was delivered with the report.

Results and Discussion

All two-way ANOVA results are located in Appendix A. Means and associated standard errors are furnished for all metrics by plot and year in Appendix B.

Lewes

The Lewes Marsh treatment area built 83.39m^2 of salt marsh and the control area lost 22.10m^2 between 2014-2016.

During the two-year assessment period, the contiguous vegetated shoreline at the Lewes Marsh treatment area was moved waterward an average of 2.24+/-1.46m. The maximum waterward movement was 4.62m, although some landward movement occurred on the western end of -0.59m (Table 3 and Fig. 11). Averaged over time among all transects, this translated to waterward lateral marsh movement rate (end point rate in table) of 0.96+/-0.62m/yr (Table 3).

This movement was a direct result of the installation of living shoreline materials, allowing for the natural/salvaged/purchased vegetation to grow waterward to this extent. Installation materials also maintained their lateral position over time, and no materials failure or event-based damage has been documented to date.

Marsh edge movement along the control site was not spatially consistent. The central vegetated edge moved landward at a greater rate that the vegetated edge at the east and western ends (Fig. 11). The average landward retreat was -0.60+/-0.57 at an average rate of -0.28+/-0.28 m/yr, indicating that the landward movement was not consistent over space and time at the site, that there were areas and times of stability, but these were not representative of the lateral movement overall (Table 3). One transect located at the eastern most extent of the control area moved waterward 1.50m, but at this location the shoreline was oriented perpendicular to the rest of the vegetated edge, which resulted in DSAS model transects intersecting and possible model error.

For both the treatment and control areas, there greatest lateral movement was in the middle, at transect 3, but the net movement was in opposite directions: waterward in the treatment and landward in the control (Fig 12). The distance between the 2014 and 2016 vegetated edge in the treatment area (denoted at blue star and peak of solid blue line slope toward the left of the graph in Fig. 12 respectively) is approximately the max waterward shoreline movement (4.62m, Table 3). Although positioned higher in the tidal datum relative to the treatment area, the movement of the contiguous vegetated edge in the control area

Table 3 Lateral marsh movement and rate for Lewes Marsh site. Negative values indicates landward marsh movement and positive values indicates waterward marsh movement. End Point Rate is the distance of shoreline movement by the time elapsed from the oldest and youngest shoreline, measured in meters per year. Net Shoreline Movement is the distance between the oldest (Spring 2014) and youngest shorelines (late summer 2016). These data are based on 1m transects along the length of the shoreline using DSAS analysis. The control consists of 41 transects, and the treatment consists of 36 transects. * indicates that there was one greater measurement of 1.59, but was considered an outlier, not representative of the site as a whole.

Site	Mean End Point Rate (m/yr)	Mean Net Shoreline Movement (m)	Min Net Shoreline Movement (m)	Max Net Shoreline Movement (m)
Control	-0.28 ± 0.28	-0.60 ± 0.57	-1.71	0.18*
Treatment	0.96 ± 0.62	2.24 ± 1.46	-0.59	4.62

Figure 11 Net Shoreline Movement is overall movement of the shoreline between the oldest shoreline measurement and the most recent shoreline measurement. Areas in green reflect a net waterward shoreline movement (i.e. gain of marsh area). Red and yellow represent areas where there was net landward shoreline movement (i.e. loss of marsh area). The difference in red and yellow was based on the mean of the overall net shoreline movements across all sites. The area at the end of the control shoreline, although showing positive movement, upon closer inspection, was most likely caused by a mis-measurement by DSAS transects around a curve.

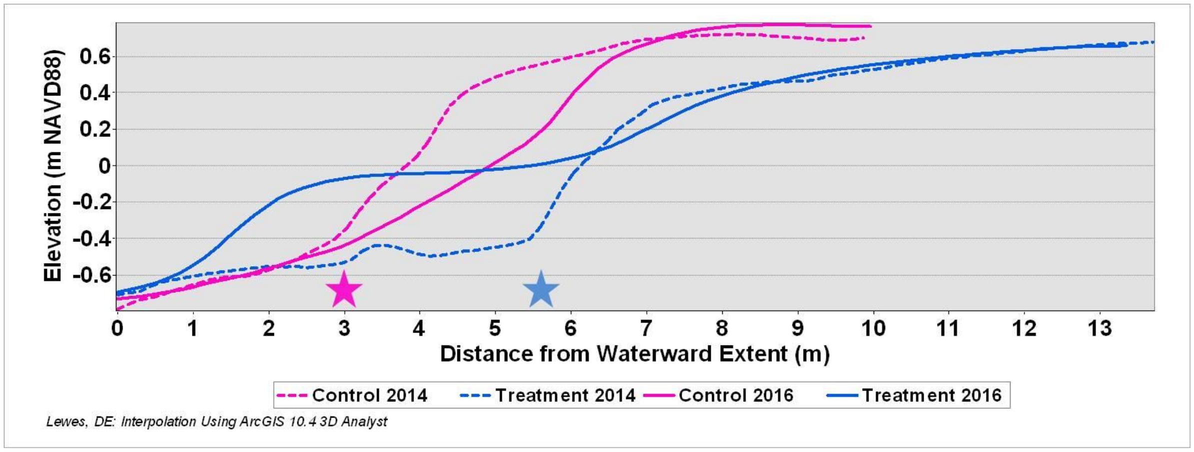


Figure 12 Elevation profile of the Lewes Marsh site along Transect 3. The control is denoted by pink lines and treatment is denoted by blue lines. Dashed lines indicate elevations and positions that were measured in 2014, and solid lines denote measurements from 2016. Stars denote the lateral position of the contiguous vegetated shoreline in 2014, color coded as noted above. All measurements were taken with a Trimble R6 RTK-GPS unit.

along transect 3 between 2014-2016 (pink star and peak of solid pink line respectively) reflects the max landward marsh movement (-1.71m, Table 3). The convergence of the dashed and solid blue lines on the marsh platform and in the high marsh (7.5-13m along x-axis; plots 4 and 5) and foreshore (0-1m along x-axis; plot 1) indicated that the living shoreline had little effect on the elevation at these locations.

In contrast to the control area, elevation significantly increased in the treatment impact area (plots 2 and 3). On average, between 2014-2016, 46cm of elevation were gained in plot 2 and 36cm were gained in plot 3. There was a significant interaction in plot 2 ($p<0.001$; Fig 13a), indicating that the change was a result of the living shoreline. Although the difference in elevation between the treatment and control in plot 3 was significant ($p<0.02$; Fig. 13a), it was attributed to a non-interactive treatment effect. These data identify preexisting differences between the treatment and control that may have overshadowed the temporal effect.

Delving deeper into the data, there also was a significant difference in elevation between the treatment and control during each year ($p<0.05$ between Treatment and Control for each year; means+/-sem located in Appendix B1), which precludes the possibility of an interactive effect. Post-hoc analysis of elevation within plot 3 of the treatment area over time, showed a significant increase in elevation between 2014 and 2016 (Tukey HSD test, $p<0.04$), which can be attributed to the living shoreline treatment. Most important, the treatment impact area (plots 2 and 3) was positioned below the lower threshold for tidal inundation required for healthy *S. alterniflora* growth (mean water, indicated as red line in Fig. 13a) prior to installation in 2014, but as a result of the treatment, the treatment area is now elevated to be within the optimum growth rage (mean water-mean high water).

Two 16" (40.6cm) diameter coir fiber log tiers were stacked along the front of the treatment (cusp 1) for a maximum potential elevation gain of 81.2cm. As described above, the second tier of cusp 1 was placed on top of sediment trapped by tier 1 between spring and late summer 2014, landward of the tier 1 logs. An elevation change of 46+/-0.02cm was measured at this location showing minimal elevation gain above the height of tier 1. The difference in the measured and expected gain was likely due to compaction of sediments trapped by tier 1 from the weight of the materials and sediment from tier 2. At plot 3, a single tier cusp (40.6cm), 36cm of elevation were gained, a greater percentage of the gain available. These data emphasize the importance of accounting for material settlement and sediment compaction when designing for target elevations, especially when stacking material.

There were no significant differences in elevation along the foreshore (Fig. 13a; plot 1), on the marsh platform (Fig. 13a; plot 4), or in the high marsh (Fig. 13a; plot 5) between the treatment and control over time. The foreshore (plot 1) result addresses concerns regarding energy reflection in front of living shorelines, as is common with hard structures. These data show that any changes that occurred waterward of the treatment area did not differ from changes at the same location in the control area, and are independent of the living shoreline.

Accretion in the high marsh (feldspar plot adjacent to plot 4) was highly variable within the treatment and control in 2015 and 2016 (Fig. 14). In 2015, similar accretion of 6.82+/-4.60mm and 6.51+/-2.13mm were measured at the treatment and control respectively. In 2016, 40.22+/-22.31mm and 11.01+/-8.56mm were measured, showing addition sediment capture at both sites, but a potentially greater gain at the treatment area. These data highlight the spatial and temporal variability in sedimentation at the site, and although they are not significant in terms of identifiable differences due to variability, they are an indication of the availability of sediment for capture. Living shorelines in locations with low sediment availability may require manual filling (see Inland Bays section below) which requires additional time and financial resource investment. Areas exhibiting sediment availability and depositional capacity are ideal sites for living shorelines designed to build marsh waterward of the existing vegetated edge and vertically into the proper inundation range.

Bearing capacity within the treatment impact area increased from 2014 in 2015 and 2016 (plot 2: 4.95+/-0.91, 10.17+/-1.59, and 9.00+/-2.74; plot 3: 6.67+/-1.61, 11.67+/-1.74, and 11.17+/-3.63; Table in Appendix B4), showing the trapping of the soft sediment behind the logs. The bearing capacity is expected to decline overtime as below ground root structure develops. These data provide the basis for tracking the trajectory of below ground living shoreline development- an area of interest for coastal resource managers with implication regarding shoreline stability, carbon sequestration, and nutrient uptake.

Proper positioning within the local tidal datum is a requirement for a healthy, resilient marsh. The Lewes living shoreline treatment was able to build and sustain this elevation within the treatment impact area. The vegetation also exhibited a positive response to the living shoreline treatment, showing significantly greater robustness over time compared to the control (Fig. 13b; plot 2 $p<0.001$ and plot 3 $p<0.02$; means+/-SEM located in Appendix B2). The greatest increase in robustness occurred between 2015-2016, when the elevation moved into the proper growth range above mean water (Fig. 13a plots 2 and 3). Although this vegetation was mostly salvaged and planted material, the 2016 measurements were taken one year post-planting, after senescence, and reflected *in situ* plant growth. The increase in response when the elevation was above mean water highlights the importance of proper elevation targets, and sets a future goal of maintaining them. High marsh vegetation robustness also increased over time relative to the control ($p<0.01$; Fig. 13b plot 5). It is difficult to say if the effect was a result of the treatment or of other upland processes, as no effect was measured in plot 4. Continued monitoring may shed more light on this difference.

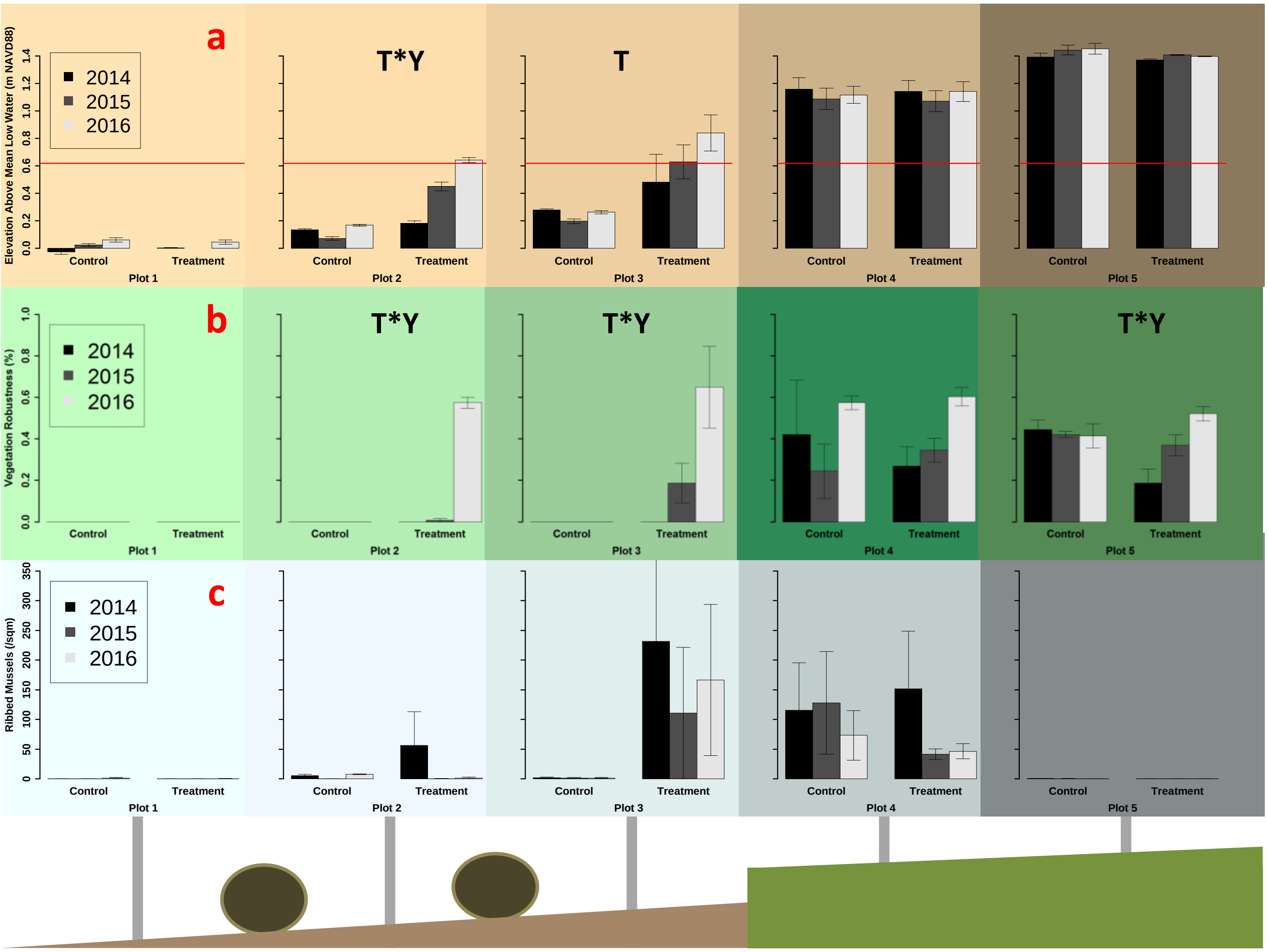


Figure 13 Barplot representation for the Lewes Marsh site of Before-After-Control-Impact (BACI) two-way ANOVA tests for three metrics: Elevation Above Mean Low Water (a); Vegetation Robustness (b); Ribbed Mussel Density (c). Each row (a,b, and c) contains five plots beginning with plot 1 on the left moving to plot 5 on the right. The increase in plot number corresponds to the plot position relative to the waterward extent of the treatment: plot 1 was waterward of treatment area; plot 2 between log cusps; plot 3 between landward log cusp and preexisting natural marsh edge; plot 4 on marsh platform just behind levee; plot 5 in high marsh vegetation. The schematic along the bottom of figure provides visual context for plot numbering across the site. "T "and "Y" notations indicate significant effects of two-way ANOVA test: T= treatment effect (difference in metric between treatment and control); Y= temporal effect (difference in metric between years); and T*Y=interactive treatment and temporal effect (difference in metric between treatment and control differs over time.

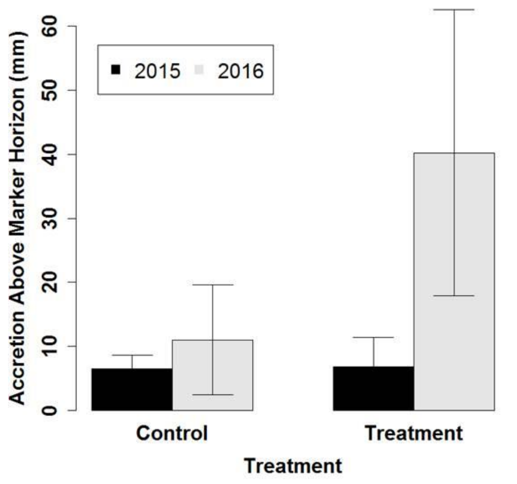


Figure 14 Accretion (mm) above the feldspar marker horizon at the Lewes AOI.

Measurements of ribbed mussel density were highly variable and differences were not significant over time in any plots. The apparent loss of mussels in plots 2, 3, and 4 between 2014-2015 (Fig. 13c) could indicate either mussel migration out of the plots or sampling error in the counts. The high level of variability (standard error of the mean) per year per plot reflects the patchy nature of ribbed mussels in the marsh; mussel density differed drastically between the replicate plots. Pooled across all plots mussel density was generally greater in the treatment area than the control, but density decreased in both areas between 2014-2016 (Table 4). This is likely the result of the erosive conditions that were present in both areas in 2014 creating an unstable environment and facilitating mortality, stress, and export with eroding material. Oyster density was low and exhibited variability between 45-80% (Table 4). It is not surprising that no significant difference was measured between 2014-2016 in regards to the faunal community, as faunal response has been shown to be a slower process in, and around, living shorelines in the south. As the living shoreline stabilizes over time, greater response may be observed, and so the weak and insignificant response in this two-year time frame is not an indicator of failure. Any change in elevation and vegetation robustness is likely setting the stage for faunal uplift to follow.

Table 4 Shellfish counts over time at each site. Ribbed mussel counts reflect pooled data across all plots, oyster counts reflect pooled data across plots 1-3.

Location	Site	2014		2015		2016	
		Ribbed Mussels	Oysters	Ribbed Mussels	Oysters	Ribbed Mussels	Oysters
Lewes	Marsh Treatment	88.00+/-41.06	7.93+/-4.33	25.93+/-19.97	0.00+/-0.00	39.92+/-26.43	1.08+/-0.92
Lewes	Marsh Control	24.73+/-18.16	4.93+/-2.16	30.53+/-22.03	2.87+/-2.27	16.93+/-10.37	4.53+/-2.07
Inland Bays	Rip Rap Treatment	0.00+/-0.00	2.26+/-1.45	0.00+/-0.00	2.00+/-2.00	49.21+/-35.91	0.07+/-0.07
Inland Bays	Rip Rap Control	0.13+/-0.13	31.53+/-15.90	0.67+/-0.67	40.67+/-21.11	45.93+/-24.39	0.07+/-0.07
Inland Bays	Marsh Treatment	0.13+/-0.13	88.87+/-42.05	0.20+/-0.14	84.40+/-43.82	144.13+/-45.15	0.27+/-0.15
Inland Bays	Marsh Control	0.13+/-0.13	31.00+/-17.12	0.07+/-0.07	33.13+/-17.07	27.60+/-15.06	0.00+/-0.00

Inland Bays

Rip-Rap

The Inland Bays Rip Rap treatment area built 146.83m^2 of salt marsh and the control area lost 14.95m^2 between 2014-2016.

The contiguous vegetated shoreline at the Inland Bays Rip Rap treatment area was moved waterward an average of 5.29+/-3.22m. The maximum waterward movement was 10.59m with no landward movement measured across the treatment (Table 5 and Fig. 15). Averaged over time among all transects, this translated to waterward lateral marsh movement rate (end point rate in table) of 0.71+/-2.34m/yr (Table 5).

Although the mean rate at this location was lower than the rate at Lewes Marsh site, the greater variability in the measurement highlights how the magnitude of the waterward movement changed across the treatment area. The deep cusp created by the vegetated edge on the northern end and the rip rapped area on the south, resulted in a larger area of created marsh in the central region of the site than along the outer margins. Although the vegetated edge is not, to date, 100% contiguous, the ecological needs of the site may preclude full vegetation from being the correct measure of success. As stated in the Design and Implementation section, HSCs rely on the site to fulfill their productive cycle, and the current, non-contiguous nature of the vegetation placement allows for free movement of HSCs among vegetated clumps. This mosaic of habitats (sandy beach paths through dense *S. alterniflora* clumps) can provide better access for the HSC breeding area while also having sufficient wave attenuation and sediment trapping potential.

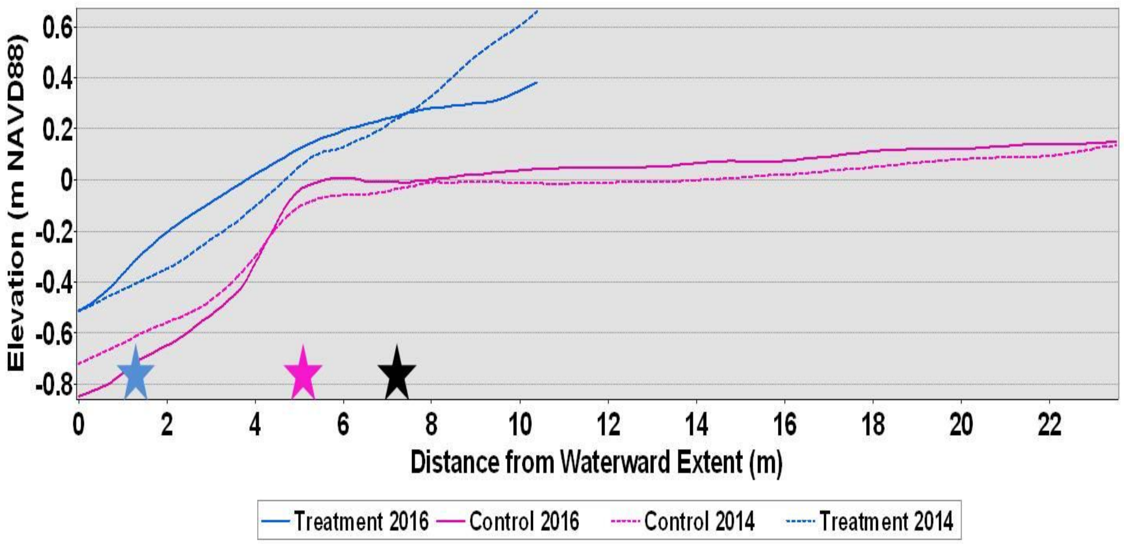
Installation materials were able to maintain their lateral position over time. Degradation of material due to HSC activity did not cause failure. In contrast to the treatment area, landward marsh movement along the control site was measured on average to be -0.63+/-0.26m at an average rate of -0.28+/-0.12 m/yr, which was similar to movement at the Lewes site. (Tables 5 and 3 respectively).

Transect 3 profiles showed the waterward movement of the treatment area from original rip rapped edge of ~6.5m between 2014-2016. Vertical elevation was also built at the waterward extent. Landward, slight elevation was built between distances 4m-7m on the x-axis, but on the rip rap area (distances 7m-11m on x-axis), elevations were lower. Since the rip rap was not altered in any way, this was likely an error in establishing plot position over time. Since the rip rap was not able to be penetrated with a marking stake, spray paint was used to demarcate the plot and transect. This marking wore off between 2014 and 2015, and an original position needed to be estimated. Therefore, 2014 measurements regarding elevation should be considered the correct elevation measurement (Fig 16). The control area showed a measured gain in platform elevation, but this gain was not reflected in the plot elevation data in Fig. 16a. This discrepancy highlights the need for replicate data points to track vertical movements.

Table 5 Lateral marsh movement and rate for Inland Bays sites. Negative values indicate landward marsh movement and positive values indicate waterward marsh movement. End Point Rate is the distance of shoreline movement by the time elapsed from the oldest and youngest shorelines, measured in meters per year. Net Shoreline Movement is the distance between the oldest (Spring 2014) and youngest shorelines (late summer 2016). These data are based on 1m transects along the length of the shorelines using DSAS analysis. The marsh-control consists of 18 transects, the marsh treatment consists of 18 transects, rip-rap-control consists of 24 transects and rip-rap treatment consists of 26 transects.

Site	Mean End Point Rate (m/yr)	Mean Net Shoreline Movement (m)	Min Net Shoreline Movement (m)	Max Net Shoreline Movement (m)
Marsh Control	-0.09 ± 0.09	-0.20 ± 0.18	-0.67	0.08
Marsh Treatment	1.26 ± 0.82	2.95±1.93	-0.05	5.62
Rip-Rap Control	-0.28 ± 0.12	-0.63 ± 0.26	-1.27	-0.23
Rip-Rap Treatment	0.71 ± 2.34	5.29 ± 3.22	0	10.59

Figure 15 Net Shoreline Movement is overall movement of the shoreline between the oldest shoreline measurement and the most recent shoreline measurement. Areas in green reflect a net waterward shoreline movement (i.e. gain of marsh area). Red and yellow represent areas where there was net landward shoreline movement (i.e. loss of marsh area). The difference in red and yellow was based on the mean of the overall net shoreline movements across all sites.



Rip Rap Treatment Inland Bays, DE: Interpolation Using ArcGIS 10.4 3D Analyst

Figure 16 Elevation profile of the Inland Bays Rip Rap site along Transect 3. The control is denoted by pink lines and treatment is denoted by blue lines. Dashed lines indicate elevations and positions that were measured in 2014, and solid lines denote measurements from 2016. Stars denote the lateral position of the contiguous vegetated shoreline in 2014, color coded as noted above. Black star denotes the position of the Rip-Rap waterward edge. All measurements were taken with a Trimble R6 RTK-GPS unit.

Elevation significantly increased in the treatment impact area (Fig 17a: plot 2 p<0.002; and plot 3 p<0.04) relative to the control. On average in the treatment impact area between 2014-2016, 13+/-3cm of elevation were gained in plot 2 and 10+/-3cm were gained in plot 3, whereas in the control area 4+/-2cm were lost in both plots (Appendix B1). The significant interactions in plots 2 and 3 regarding elevation change indicate that the change was a result of the living shoreline. As with the Lewes site, the baseline treatment impact area (plots 2 and 3) was originally positioned below the lower threshold for tidal inundation required for healthy *S. alterniflora* growth (mean water, indicated as red line in Fig. 17a) but as of 2016, it was positioned within the optimum growth rage (mean water-mean high water). Along the foreshore and on the levee (plots 1 and 4 respectively), no differences were detected, indicating no adverse treatment effects. Plot 5 exhibited a significant treatment effect (p<0.001) regarding elevation, indicating that the elevation difference between the treatment and control differed throughout the course of monitoring. Post-hoc analysis (Tukey test HSD) showed no significant differences over time between the measured elevations in the treatment and control areas.

Accretion in the high marsh (Fig. 18a, feldspar plot adjacent to plot 4) was highly variable within the treatment and control in 2015 and 2016 (Fig. 18). In 2015, accretion of 10.98+/-10.98mm and 13.48+/-2.79mm was measured at the treatment and control, respectively (Appendix B, Table B5). The degree of variability precluded any significant differences between the treatment and control. In 2016, 18.58+/-18.58mm and 27.58+/-9.17mm were measured, showing additional sediment capture at both sites, but again, these measurements were overshadowed by their inherent variability. These data suggest that sedimentation did occur each year, and that vertical marsh building was possible in each area.

Generally, bearing capacity was greater in the control area relative to the treatment (Appendix B, Table B4). As sand was used for fill at this site and is able to compact quickly and form a firm substrate, bearing capacity did not increase after placement within the treatment impact area. Bearing Capacity in the control area generally increased between 2014 and 2016 in front of the treatment (plot 1: 1.50+/-0.31 and 4.08+/-0.82; plot 2: 1.00+/-0.32 and 3.08+/-0.46; plot 3: 1.75+/-0.69 and 2.08+/-0.17), whereas bearing capacity decreased on the marsh surface (plot 4: 7.02+/-0.70 and 4.75+/-1.01; plot 5: 2.75+/-0.25 and 2.33+/-0.44). These data are confounding, as sedimentation on the marsh surface near plot 4, as indicated by the accretion rate data, would suggest an increase in bearing capacity in the newly acquired soft sediment. The accretion rate data do suggest a high rate of spatial variability, as denoted in the standard error of the means calculations, so this discrepancy may be representative of the spatial variability between correlated values of bearing capacity and sedimentation. It is likely that extended monitoring will be needed to assess trajectories of these physical processes.

Vegetation in the treatment impact area responded positively over time. Vegetation robustness increased significantly in plots 2 and 3 between 2014 (0.00+/-0.00 both plots) and 2016 (plot 2: 0.71+/-0.03, $p<0.001$; plot 3: 0.51+/-0.05, $p<0.001$ (Fig. 17b, Appendix B, Table B2). Although this vegetation was mostly salvaged and planted material, the 2016 measurements were taken one year post-planting, after senescence, and reflected *in situ* plant growth. There was also a significant vegetation robustness interactive effects in at plots 4 and 5. Along the levee (plot 4, Fig. 17b), the interactive effect was due to initial differences in vegetation (treatment was non-vegetated sand and control was vegetated salt marsh) paired with differences in trajectories over time. In the treatment area, vegetation robustness slowly increased over time, likely as a result of planting and persistence of vegetation within the proper elevations. At the control area, a significant decline (Tukey HSD post-hoc test $p<0.02$ 2015 and 2016) in vegetation robustness was observed. Although the vegetation was within the proper elevation range for growth (Fig. 17a, plot 4), additional factors such as localized pooling of water, could have affected vegetative health. A similar pattern was observed in the high marsh (Fig. 17b, plot 5), which lends credence to the hypothesis that marsh health is on the decline in landward areas.

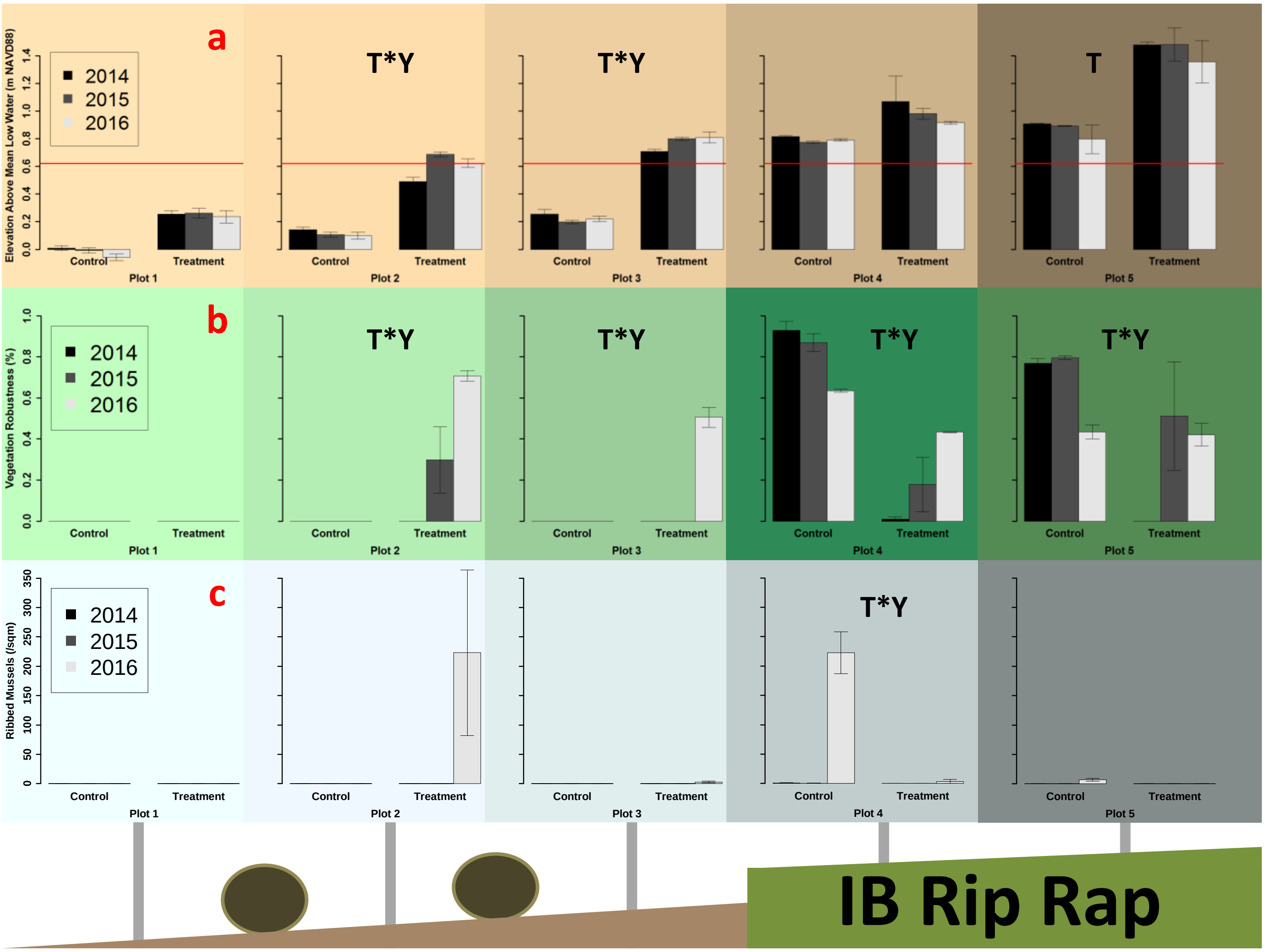


Figure 17 Barplot representation for the Inland Bays Rip Rap site of Before After Control Impact (BACI) two-way ANOVA tests for three metrics: Elevation Above Mean Low Water (a); Vegetation Robustness (b); Ribbed Mussel Density (c). Each row (a, b, and c) contains five plots beginning with plot 1 on the left moving to plot 5 on the right. The increase in plot number corresponds to the plot position relative to the waterward extent of the treatment: plot 1 was waterward of treatment area; plot 2 between log cusps; plot 3 between landward log cusp and preexisting natural marsh edge; plot 4 on marsh platform just behind levee; plot 5 in high marsh vegetation. The schematic along the bottom of figure provides visual context for plot numbering across the site. “T “ and “Y” notation indicate significant effects of two-way ANOVA test: T= treatment effect (difference in metric between treatment and control); Y= temporal effect (difference in metric between years); and T*Y=interactive treatment and temporal effect (difference in metric between treatment and control differs over time.

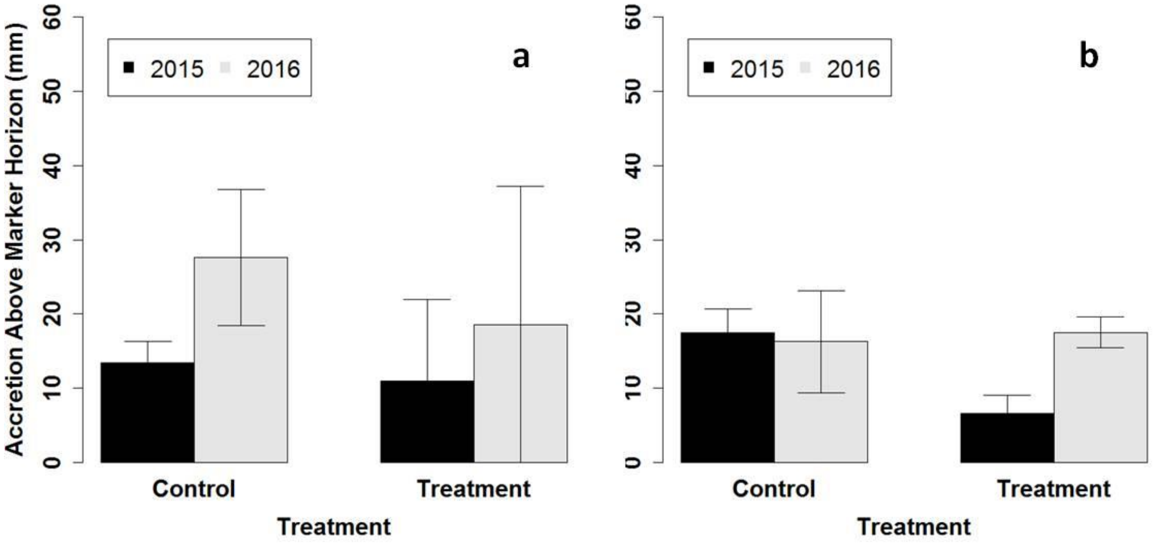


Figure 18 Accretion (mm) above the feldspar marker horizon at the Inland Bays Rip Rap (a) and Marsh (b) sites.

Ribbed mussel density increased in 2016 in plot 2 of the treatment (Fig 17c), but was not significant due to variability (Appendix B, Table B3). Pooled across all plots however, mussel and oyster density was generally greater in the control area than the treatment (Table 4). That is not unexpected because the control area was mussel habitat prior to project implementation, whereas the treatment area was not. As the treatment ages and salvaged mussels are able to better establish and propagate, it is likely that mussel density will increase. As with the Lewes site, a change in elevation and vegetation robustness should set the stage for continued shellfish recruitment and population expansion, a natural successional sequence.

Marsh

The Inland Bays Marsh treatment area built 63.87m^2 of salt marsh and the control area lost 7.20m^2 between 2014-2016.

The contiguous vegetated shoreline at the Lewes Marsh treatment area was moved waterward an average of 2.95+/-1.93m, with a maximum waterward movement of 5.62m (Table 3 and Fig. 15). Averaged over time among all transects, this translated to waterward lateral marsh movement rate (end point rate in table) of 1.26+/-0.82m/yr (Table 5). Along the treatment area, the waterward movement was positive at all locations except along the northern end, where some loss was documented (-0.5m Table 3, Fig. 15). This area appeared to be a pre-existing ponding area, and marsh break-up was apparent here in 2014. The coir fiber logs were tied into the existing marsh in this area for local sediment capture to stabilize the internal conditions. The peninsula did not erode away, but it did narrow along the waterward edge (Fig. 15). In response, shellbags were placed in front of this area in 2015 and 2016, and to date, the area appears to have stabilized.

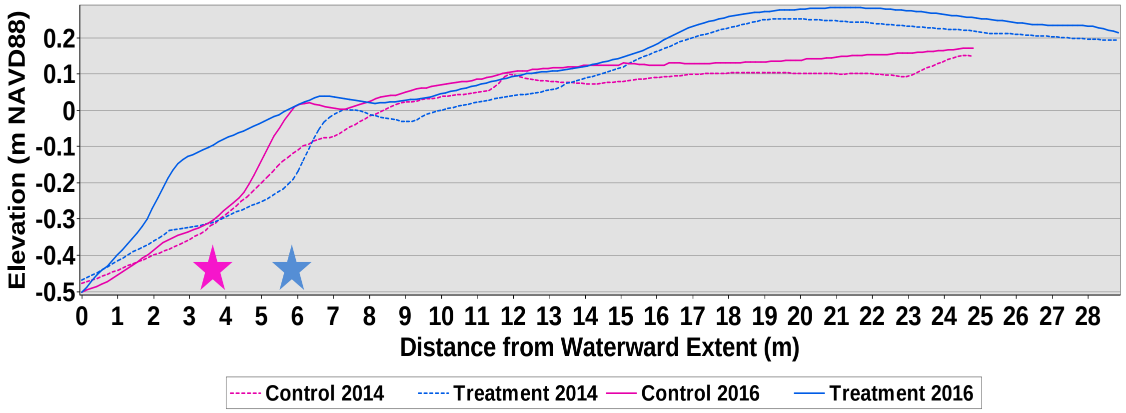
The waterward expansion of the marsh area was a direct result of the installation of living shoreline materials, allowing for the natural/salvaged/purchased vegetation to grow waterward. Installation materials maintained their lateral position over time, and material damage due to HSC activity was adaptively managed through the targeted placement of shellbags along the waterward margin. This resulted in greater stability with no detrimental loss of elevation along the front edge (Fig 20a, plot 2). Landward marsh movement occurred along the entire length of the control site (Fig 15). The average landward retreat was -0.20+/-0.18 at an average rate of -0.09+/-0.09 m/yr (Table 5). Transect 3 profiles show the waterward movement of the treatment area from ~6m in 2014 to ~2m in 2016 as measured from the waterward extent (0 on x-axis). This area also built elevation so that the newly created waterward region was at a similar vertical position as the 2014 extent. Landward, slight elevation was built, but the general morphology did not change (Fig 19). The control area exhibited a more pronounced marsh edge in 2016. This could be due to either sediment deposition between 2014 or 2016, or errors regarding the position of re-measurement with the RTK unit in 2016. Across the profile there appears to be a measured gain in platform elevation, but this gain is not reflected in the plot elevation data in Fig. 20a. This discrepancy highlights the need for replicate data points within areas of similar elevation across a site to track vertical movements.

Elevation significantly increased in the treatment impact area (plots 2 and 3) relative to the control. On average, between 2014-2016, 14+/-0.02cm of elevation were gained in plot 2 and 18+/-0.02cm were gained in plot 3 (Appendix B1). The significant interactions in plots 2 and 3 regarding elevation change indicate that the change was a result of the living shoreline. As with the Lewes and Inland Bays Marsh sites, baseline conditions (2014) in the treatment area (plots 2 and 3) were below the lower threshold for tidal inundation required for healthy *S. alterniflora* growth (mean water, indicated as red line in Fig. 20a). However, as a result of the treatment and subsequent elevation gain, plants are now (2016) positioned within the optimum growth rage (mean water-mean high water). Along the foreshore, on the levee, and in the high marsh (Fig 20a plots 1, 4, and 5 respectively), no differences were detected, indicating no adverse treatment effects.

Vegetation in plots 2 and 5 (Fig. 20b) positively responded to the change in elevation, and salvaged/planted vegetation robustness increased significantly between 2014 (0.00+/-0.00 both plots) and 2016 (plot 2: 0.41+/-0.02, $p<0.001$; plot 3: 0.51+/-0.07, $p<0.001$ (Fig. 20b, Appendix B2). Although this vegetation was mostly salvaged and planted material, the 2016 measurements were taken one year post-planting, after senescence, and reflected *in situ* plant growth. These was a significant interaction in the high marsh (Fig. 20b, plot 5) between location and time. It appears that the treatment and control exhibited different initial vegetation robustness, and that the magnitude of the changes were different over time, even though the directionality was similar. Hence, vegetation density decreased in the high marsh. This is not necessarily an indication of declining marsh health, as the vegetation is in the proper elevation range, and high marsh vegetation can exhibit highly variable growth forms. Continued monitoring of this area over time will be helpful to identify and respond to health issues, if they were to arise, before severe states of degradation are reached.

Accretion in the high marsh (Fig. 18a, feldspar plot adjacent to plot 4) was more consistent at this location than at the Rip Rap site (Fig. 18). In 2015, accretion of 6.60+/-2.48mm and 17.44+/-3.23mm, and in 2016 17.50+/-2.08 and 16.25+/-6.83 were measured at the treatment and control respectively (Appendix B, Table B5). The degree of variability precluded any significant differences, but these data do suggest that small amounts of sediment were delivered to the treatment area, while no sediment was either acquired or retained between 2015-2016 at the control area.

Bearing capacity was low in both treatment and control areas in plots 1-3 (Appendix B, Table B4). Similar to the Rip Rap site, since sand was used for fill at this site and was able to compact quickly and form a firm, stable substrate, it was not surprising that bearing capacity did not significantly change. Along the marsh levee, bearing capacity was overall greater in the treatment and control over all years (Appendix B, Table B4). The treatment area (2014: 7.16+/-0.55; 2015: 7.83+/-1.01; 2016: 8.50+/-1.32) was slightly higher than the control (2014: 6.75+/-0.48; 2015:6.83+/-0.67:2016:5.58+/-0.96), but these differences were not significant. These data suggest that the marsh is wetter in this area, and this could be associated with possible decline in marsh vegetation robustness in this area of the control site (Fig. 20b, plot 4).



Marsh Treatment Inland Bays, DE: Interpolation Using ArcGIS 10.4 3D Analyst

Figure 19 Elevation profile of the Inland Bays Marsh site along Transect 3. The control is denoted by pink lines and treatment is denoted by blue lines. Dashed lines indicate elevations and positions that were measured in 2014, and solid lines denote measurements from 2016. Stars denote the lateral position of the contiguous vegetated shoreline in 2014, color coded as noted above. All measurements were taken with a Trimble R6 RTK-GPS unit.

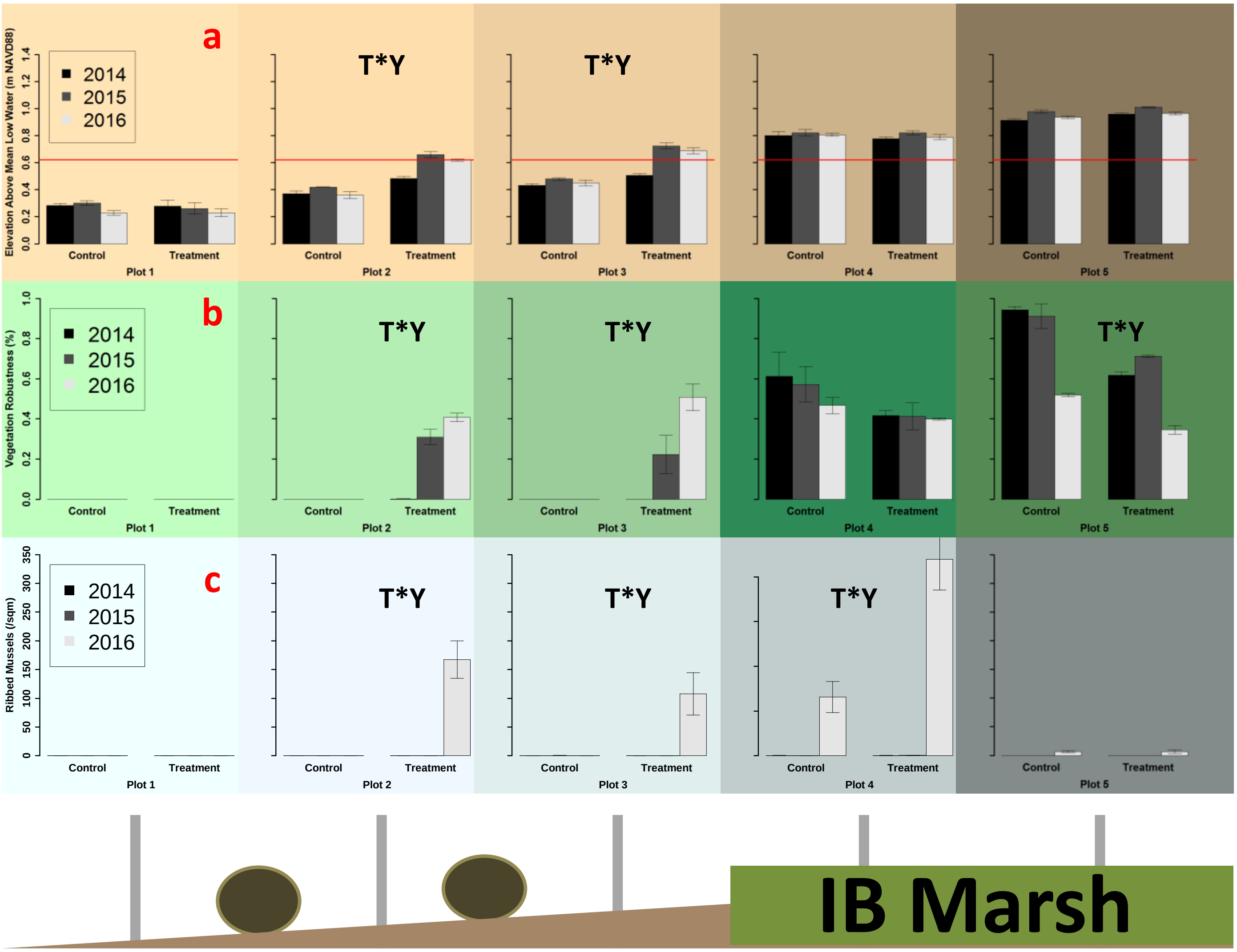


Figure 20 Barplot representation for the Inland Bays Marsh site of Before-After-Control-Impact (BACI) two-way ANOVA tests for three metrics: Elevation Above Mean Low Water (a); Vegetation Robustness (b); Ribbed Mussel Density (c). Each row (a, b, and c) contains five plots beginning with plot 1 on the left moving to plot 5 on the right. The increase in plot number corresponds to the plot position relative to the waterward extent of the treatment: plot 1 was waterward of treatment area; plot 2 between log cusps; plot 3 between landward log cusp and preexisting natural marsh edge; plot 4 on marsh platform just behind levee; plot 5 in high marsh vegetation. The schematic along the bottom of figure provides visual context for plot numbering across the site. "T" and "Y" notations indicate significant effects of two-way ANOVA test: T= treatment effect (difference in metric between treatment and control); Y= temporal effect (difference in metric between years); and T*Y=interactive treatment and temporal effect (difference in metric between treatment and control differs over time.

Ribbed mussel density was significantly higher in the treatment relative to the control between 2014-2016 in plots 2-4 (Fig. 20c; plot 2, $p<0.001$, 167.33+/-32.75/m^2; plot 3, $p<0.005$, 108.00+/-63.86/m^2; plot 4, $p<0.001$, 439.00+/-68.13/$m^{2)}$. The interaction in the two-way ANOVA BACI plot indicated that the difference was a direct result of the treatment and plantings. These data show that the transplanted mussels in plot 2-3 were able to survive, and tracking their density over time is valuable for assessing ecological enhancement. The large increase in plot 4 (Fig. 20c), could either be due to mussel migration into the high marsh, or due to survey error. The plot location was not lost between 2014 and 2016, so replacement of the plot in a different location can be ruled out as influencing the data. Ribbed mussels are capable of moving and can adjust their positions relatively quickly. Movement from newly deposited sand into their ideal niche (soft mud with *S. alterniflora*) is a distinct possibility. There was a decline in oyster populations across both treatment and control areas between 2014 and 2016. As the monitoring area is intertidal, and the presence of oysters in this habitat is a new phenomenon in this region, it is possible that severe winter icing in early 2015 caused widespread mortality of oysters in the vicinity.

Summary and Next Steps

All three living shoreline treatments met their stated goals of shoreline stabilization and ecological enhancement. To meet these goals, the following effects were documented:

- Salt Marsh Creation and Loss
    - Lewes Marsh: Treatment built 83.39m^2 of salt marsh; control lost 22.10m^2 of salt marsh
    - Inland Bays Rip Rap: Treatment built 146.83m^2 of salt marsh; control lost 14.95m^2 of salt marsh
    - Inland Bays Rip Rap: Treatment built 63.87m^2 of salt marsh; control lost 7.20m^2 of salt marsh
- Physical Effects
    - Net movement of the contiguous vegetated shoreline was waterward on all living shoreline treatments (net marsh gain), and landward for all paired controls (net erosion)
    - All living shoreline impact areas (plots 2 and 3) were vertically enhanced to be within the optimum growth range relative to the local tidal datum for *Spartina alterniflora*. Plots 2 and 3 in all control areas continue to exhibit an elevation deficit.
    - There were no adverse scouring effects on the substrate in front of living shorelines
    - Living shorelines did not have an adverse effect on sedimentation rates relative to controls
- Vegetation Response
    - Vegetation robustness increased in all living shoreline treatment impact areas (plots 2-3) relative to controls
    - Vegetation was successful in persisting in formerly unvegetated areas
    - Salvaged material was able to survive translocation and re-emerge post-senescence
- Shellfish Response
    - Shellfish communities were not adversely affected by the treatments relative to control areas
- Structural Integrity of Materials
    - Coir-fiber materials have been shown to persist and trap sediment in low energy environments

- Shellbags displayed greater resistance to degradation and were successful in trapping and retaining sediments
- Adaptive management tactics proved successful in attending to interactions with local fauna (HSCs)

Photographic time series of all living shorelines treatments is available in Appendix D.

As a next step, monitoring should be continued to document changes in the physical attributes and biological community within and around the living shorelines. These demonstration projects provide valuable baseline and early-stage data regarding the trajectories and persistence of natural and nature-based infrastructure. A living shoreline is more than a sum of its structural components- it is the successful functionality of the biological components over time. The rigorous monitoring design has allowed for the quantitative evaluation of this functionality, and has been crucial for attending to the periodic needs of the treatments. As these shorelines continue to mature, long-term data will help inform design, adaptive management, and temporal expectations of living shorelines in our area.

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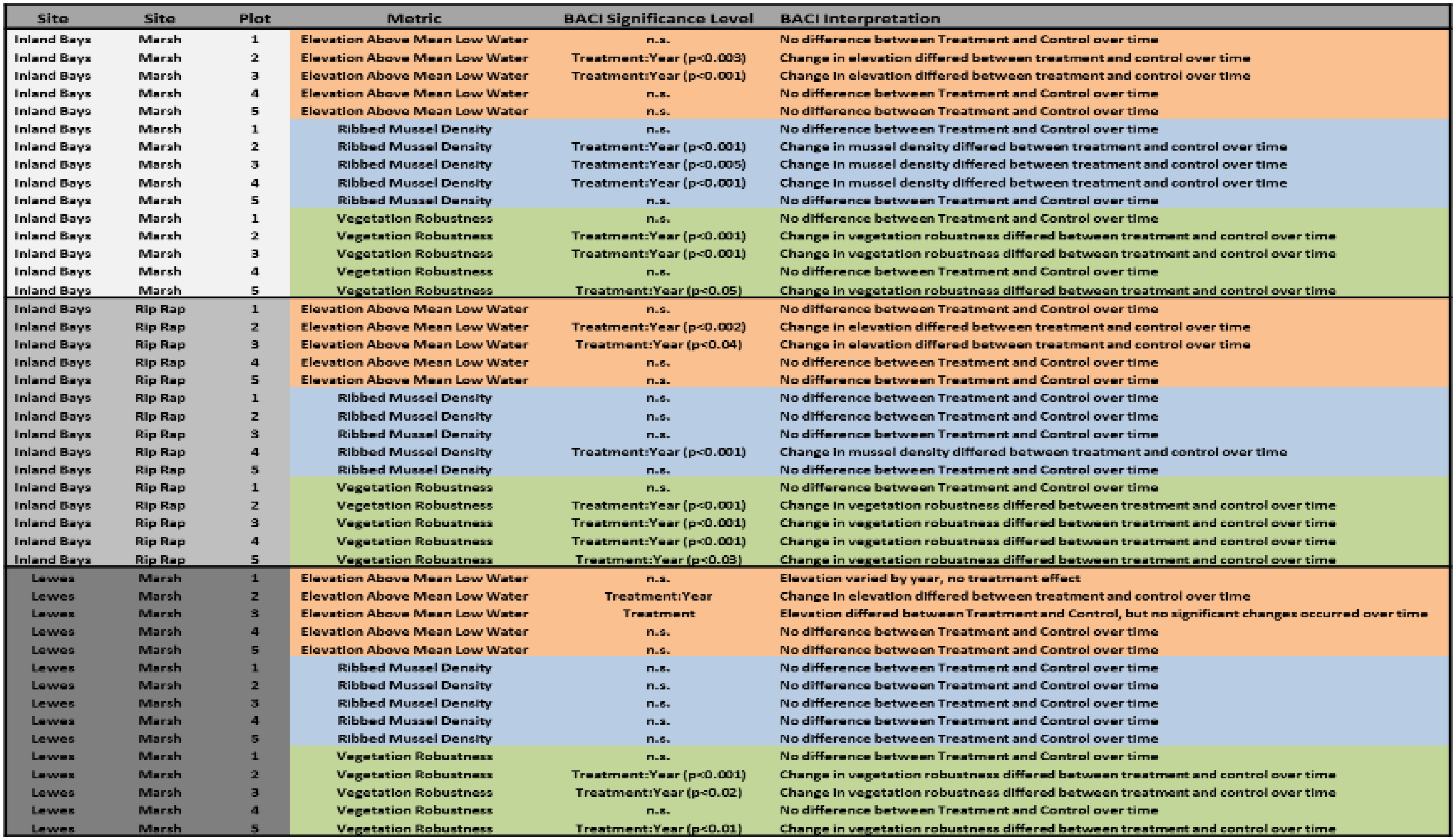
Appendices

Appendix A. BACI results

Table A1. Results of all Before-After-Control-Impact tests at both locations and all sites.



Site	Site	Plot	Metric	BACI Significance Level	BACI Interpretation
Inland Bays	Marsh	1	Elevation Above Mean Low Water	n.s.	No difference between Treatment and Control over time
Inland Bays	Marsh	2	Elevation Above Mean Low Water	Treatment:Year (p<0.003)	Change in elevation differed between treatment and control over time
Inland Bays	Marsh	3	Elevation Above Mean Low Water	Treatment:Year (p<0.001)	Change in elevation differed between treatment and control over time
Inland Bays	Marsh	4	Elevation Above Mean Low Water	n.s.	No difference between Treatment and Control over time
Inland Bays	Marsh	5	Elevation Above Mean Low Water	n.s.	No difference between Treatment and Control over time
Inland Bays	Marsh	1	Ribbed Mussel Density	n.s.	No difference between Treatment and Control over time
Inland Bays	Marsh	2	Ribbed Mussel Density	Treatment:Year (p<0.001)	Change in mussel density differed between treatment and control over time
Inland Bays	Marsh	3	Ribbed Mussel Density	Treatment:Year (p<0.005)	Change in mussel density differed between treatment and control over time
Inland Bays	Marsh	4	Ribbed Mussel Density	Treatment:Year (p<0.001)	Change in mussel density differed between treatment and control over time
Inland Bays	Marsh	5	Ribbed Mussel Density	n.s.	No difference between Treatment and Control over time
Inland Bays	Marsh	1	Vegetation Robustness	n.s.	No difference between Treatment and Control over time
Inland Bays	Marsh	2	Vegetation Robustness	Treatment:Year (p<0.001)	Change in vegetation robustness differed between treatment and control over time
Inland Bays	Marsh	3	Vegetation Robustness	Treatment:Year (p<0.001)	Change in vegetation robustness differed between treatment and control over time
Inland Bays	Marsh	4	Vegetation Robustness	n.s.	No difference between Treatment and Control over time
Inland Bays	Marsh	5	Vegetation Robustness	Treatment:Year (p<0.05)	Change in vegetation robustness differed between treatment and control over time
Inland Bays	Rip Rap	1	Elevation Above Mean Low Water	n.s.	No difference between Treatment and Control over time
Inland Bays	Rip Rap	2	Elevation Above Mean Low Water	Treatment:Year (p<0.002)	Change in elevation differed between treatment and control over time
Inland Bays	Rip Rap	3	Elevation Above Mean Low Water	Treatment:Year (p<0.04)	Change in elevation differed between treatment and control over time
Inland Bays	Rip Rap	4	Elevation Above Mean Low Water	n.s.	No difference between Treatment and Control over time
Inland Bays	Rip Rap	5	Elevation Above Mean Low Water	n.s.	No difference between Treatment and Control over time
Inland Bays	Rip Rap	1	Ribbed Mussel Density	n.s.	No difference between Treatment and Control over time
Inland Bays	Rip Rap	2	Ribbed Mussel Density	n.s.	No difference between Treatment and Control over time
Inland Bays	Rip Rap	3	Ribbed Mussel Density	n.s.	No difference between Treatment and Control over time
Inland Bays	Rip Rap	4	Ribbed Mussel Density	Treatment:Year (p<0.001)	Change in mussel density differed between treatment and control over time
Inland Bays	Rip Rap	5	Ribbed Mussel Density	n.s.	No difference between Treatment and Control over time
Inland Bays	Rip Rap	1	Vegetation Robustness	n.s.	No difference between Treatment and Control over time
Inland Bays	Rip Rap	2	Vegetation Robustness	Treatment:Year (p<0.001)	Change in vegetation robustness differed between treatment and control over time
Inland Bays	Rip Rap	3	Vegetation Robustness	Treatment:Year (p<0.001)	Change in vegetation robustness differed between treatment and control over time
Inland Bays	Rip Rap	4	Vegetation Robustness	Treatment:Year (p<0.001)	Change in vegetation robustness differed between treatment and control over time
Inland Bays	Rip Rap	5	Vegetation Robustness	Treatment:Year (p<0.03)	Change in vegetation robustness differed between treatment and control over time
Lewes	Marsh	1	Elevation Above Mean Low Water	n.s.	Elevation varied by year, no treatment effect
Lewes	Marsh	2	Elevation Above Mean Low Water	Treatment:Year	Change in elevation differed between treatment and control over time
Lewes	Marsh	3	Elevation Above Mean Low Water	Treatment	Elevation differed between Treatment and Control, but no significant changes occurred over time
Lewes	Marsh	4	Elevation Above Mean Low Water	n.s.	No difference between Treatment and Control over time
Lewes	Marsh	5	Elevation Above Mean Low Water	n.s.	No difference between Treatment and Control over time
Lewes	Marsh	1	Ribbed Mussel Density	n.s.	No difference between Treatment and Control over time
Lewes	Marsh	2	Ribbed Mussel Density	n.s.	No difference between Treatment and Control over time
Lewes	Marsh	3	Ribbed Mussel Density	n.s.	No difference between Treatment and Control over time
Lewes	Marsh	4	Ribbed Mussel Density	n.s.	No difference between Treatment and Control over time
Lewes	Marsh	5	Ribbed Mussel Density	n.s.	No difference between Treatment and Control over time
Lewes	Marsh	1	Vegetation Robustness	n.s.	No difference between Treatment and Control over time
Lewes	Marsh	2	Vegetation Robustness	Treatment:Year (p<0.001)	Change in vegetation robustness differed between treatment and control over time
Lewes	Marsh	3	Vegetation Robustness	Treatment:Year (p<0.02)	Change in vegetation robustness differed between treatment and control over time
Lewes	Marsh	4	Vegetation Robustness	n.s.	No difference between Treatment and Control over time
Lewes	Marsh	5	Vegetation Robustness	Treatment:Year (p<0.01)	Change in vegetation robustness differed between treatment and control over time

Appendix B. Metric Data Tables

Table B1. Means and SEMs of elevations relative to Mean Low Water at each site within the Lewes and Inland Bays project locations, monitored during 2014 (baseline), 2015, and 2016.

AOI	Site	Plot	2014	2015	2016
Lewes	Marsh Treatment	1	0.01+/-0.00	0.02+/-0.00	0.05+/-0.02
Lewes	Marsh Control	1	0.01+/-0.02	(-0.03)+/-0.01	0.06+/-0.02
Lewes	Marsh Treatment	2	0.18+/-0.02	0.45+/-0.03	0.64+/-0.02
Lewes	Marsh Control	2	0.13+/-0.01	0.07+/-0.01	0.17+/-0.01
Lewes	Marsh Treatment	3	0.48+/-0.20	0.63+/-0.12	0.84+/-0.16
Lewes	Marsh Control	3	0.28+/-0.01	0.20+/-0.02	0.26+/-0.01
Lewes	Marsh Treatment	4	1.14+/-0.08	1.07+/-0.08	1.14+/-0.07
Lewes	Marsh Control	4	1.16+/-0.08	1.09+/-0.08	1.12+/-0.06
Lewes	Marsh Treatment	5	1.36+/-0.00	1.42+/-0.00	1.39+/-0.22
Lewes	Marsh Control	5	1.39+/-0.04	1.43+/-0.03	1.45+/-0.04
Inland Bays	Rip Rap Treatment	1	0.25+/-0.03	0.26+/-0.03	0.24+/-0.05
Inland Bays	Rip Rap Control	1	0.01+/-0.01	(-0.01)+/-0.02	(-0.06)+/-0.02
Inland Bays	Rip Rap Treatment	2	0.49+/-0.03	0.69+/-0.02	0.62+/-0.03
Inland Bays	Rip Rap Control	2	0.14+/-0.02	0.11+/-0.02	0.10+/-0.03
Inland Bays	Rip Rap Treatment	3	0.71+/-0.02	0.80+/-0.01	0.81+/-0.04
Inland Bays	Rip Rap Control	3	0.26+/-0.03	0.20+/-0.01	0.22+/-0.02
Inland Bays	Rip Rap Treatment	4	1.07+/-0.18	0.98+/-0.05	0.92+/-0.01
Inland Bays	Rip Rap Control	4	0.81+/-0.01	0.78+/-0.01	0.79+/-0.01
Inland Bays	Rip Rap Treatment	5	0.48+/-0.03	1.48+/-0.15	1.36+/-0.19
Inland Bays	Rip Rap Control	5	0.91+/-0.01	0.89+/-0.001	0.80+/-0.10
Inland Bays	Marsh Treatment	1	0.28+/-0.05	0.26+/-0.04	0.23+/-0.03
Inland Bays	Marsh Control	1	0.28+/-0.02	0.30+/-0.02	0.23+/-0.02
Inland Bays	Marsh Treatment	2	0.48+/-0.02	0.66+/-0.02	0.62+/-0.01
Inland Bays	Marsh Control	2	0.37+/-0.02	0.42+/-0.00	0.36+/-0.03
Inland Bays	Marsh Treatment	3	0.51+/-0.01	0.72+/-0.02	0.69+/-0.02
Inland Bays	Marsh Control	3	0.43+/-0.01	0.48+/-0.01	0.45+/-0.02
Inland Bays	Marsh Treatment	4	0.77+/-0.01	0.82+/-0.02	0.79+/-0.02
Inland Bays	Marsh Control	4	0.80+/-0.03	0.82+/-0.02	0.81+/-0.02
Inland Bays	Marsh Treatment	5	0.96+/-0.01	1.01+/-0.00	0.96+/-0.01
Inland Bays	Marsh Control	5	0.92+/-0.01	0.98+/-0.01	0.94+/-0.01

Table B2. Means and SEMs of vegetation robustness at each site within the Lewes and Inland Bays project locations, monitored during 2014 (baseline), 2015, and 2016.

AOI	Site	Plot	2014	2015	2016
Lewes	Marsh Treatment	1	0.00+/-0.00	0.00+/-0.00	0.00+/-0.00
Lewes	Marsh Control	1	0.00+/-0.00	0.00+/-0.00	0.00+/-0.00
Lewes	Marsh Treatment	2	0.00+/-0.00	0.01+/-0.01	0.57+/-0.03
Lewes	Marsh Control	2	0.00+/-0.00	0.00+/-0.00	0.00+/-0.00
Lewes	Marsh Treatment	3	0.00+/-0.00	0.19+/-0.09	0.65+/-0.20
Lewes	Marsh Control	3	0.00+/-0.00	0.00+/-0.00	0.00+/-0.00
Lewes	Marsh Treatment	4	0.27+/-0.09	0.35+/-0.06	0.60+/-0.04
Lewes	Marsh Control	4	0.42+/-0.26	0.24+/-0.13	0.57+/-0.03
Lewes	Marsh Treatment	5	0.19+/-0.07	0.37+/-0.05	0.52+/-0.04
Lewes	Marsh Control	5	0.44+/-0.05	0.42+/-0.02	0.41+/-0.06
Inland Bays	Rip Rap Treatment	1	0.00+/-0.00	0.00+/-0.00	0.00+/-0.00
Inland Bays	Rip Rap Control	1	0.00+/-0.00	0.00+/-0.00	0.00+/-0.00
Inland Bays	Rip Rap Treatment	2	0.00+/-0.00	0.30+/-0.16	0.71+/-0.03
Inland Bays	Rip Rap Control	2	0.00+/-0.00	0.00+/-0.00	0.00+/-0.00
Inland Bays	Rip Rap Treatment	3	0.00+/-0.00	0.00+/-0.00	0.51+/-0.05
Inland Bays	Rip Rap Control	3	0.00+/-0.00	0.00+/-0.00	0.00+/-0.00
Inland Bays	Rip Rap Treatment	4	0.01+/-0.01	0.18+/-0.13	0.43+/-0.00
Inland Bays	Rip Rap Control	4	0.93+/-0.04	0.87+/-0.04	0.63+/-0.01
Inland Bays	Rip Rap Treatment	5	0.00+/-0.00	0.51+/-0.26	0.42+/-0.07
Inland Bays	Rip Rap Control	5	0.77+/-0.02	0.80+/-0.01	0.43+/-0.03
Inland Bays	Marsh Treatment	1	0.00+/-0.00	0.00+/-0.00	0.00+/-0.00
Inland Bays	Marsh Control	1	0.00+/-0.00	0.00+/-0.00	0.00+/-0.00
Inland Bays	Marsh Treatment	2	0.00+/-0.00	0.31+/-0.04	0.41+/-0.02
Inland Bays	Marsh Control	2	0.00+/-0.00	0.00+/-0.00	0.00+/-0.00
Inland Bays	Marsh Treatment	3	0.00+/-0.00	0.22+/-0.09	0.51+/-0.07
Inland Bays	Marsh Control	3	0.00+/-0.00	0.00+/-0.00	0.00+/-0.00
Inland Bays	Marsh Treatment	4	0.41+/-0.02	0.41+/-0.07	0.40+/-0.01
Inland Bays	Marsh Control	4	0.61+/-0.12	0.57+/-0.09	0.46+/-0.04
Inland Bays	Marsh Treatment	5	0.62+/-0.02	0.71+/-0.01	0.34+/-0.02
Inland Bays	Marsh Control	5	0.94+/-0.02	0.91+/-0.06	0.51+/-0.01

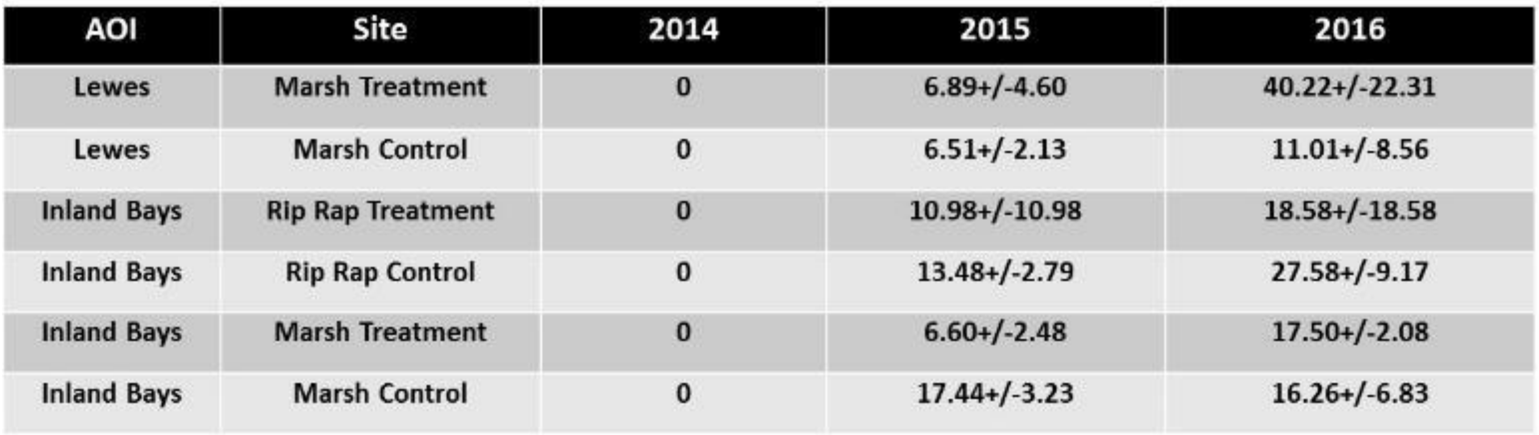
Table B3. Means and SEMs of mussel density at each site within the Lewes and Inland Bays project locations, monitored during 2014 (baseline), 2015, and 2016.

AOI	Site	Plot	2014	2015	2016
Lewes	Marsh Treatment	1	0.00+/-0.00	0.00+/-0.00	0.50+/-0.71
Lewes	Marsh Control	1	0.00+/-0.00	0.00+/-0.00	1.66+/-2.08
Lewes	Marsh Treatment	2	56.67+/-56.56	0.33+/-0.33	1.67+/-1.67
Lewes	Marsh Control	2	5.33+/-2.84	0.00+/-0.00	8.00+/-0.57
Lewes	Marsh Treatment	3	231.67+/-160.77	110.67+/-110.67	166.50+/-155.50
Lewes	Marsh Control	3	2.33+/-1.20	1.33+/-1.33	1.67+/-0.88
Lewes	Marsh Treatment	4	151.67+/-96.80	41.67+/-8.82	46.67+/-12.73
Lewes	Marsh Control	4	115.33+/-79.98	128.00+/-86.26	73.33+/-41.87
Lewes	Marsh Treatment	5	0.00+/-0.00	0.00+/-0.00	0.00+/-0.00
Lewes	Marsh Control	5	0.67+/-0.33	0.33+/-0.33	0.00+/-0.00
Inland Bays	Rip Rap Treatment	1	0.00+/-0.00	0.00+/-0.00	0.00+/-0.00
Inland Bays	Rip Rap Control	1	0.00+/-0.00	0.00+/-0.00	0.00+/-0.00
Inland Bays	Rip Rap Treatment	2	0.00+/-0.00	0.00+/-0.00	223.00+/-140.99
Inland Bays	Rip Rap Control	2	0.00+/-0.00	0.00+/-0.00	0.00+/-0.00
Inland Bays	Rip Rap Treatment	3	0.00+/-0.00	0.00+/-0.00	3.00+/-1.73
Inland Bays	Rip Rap Control	3	0.00+/-0.00	0.00+/-0.00	0.00+/-0.00
Inland Bays	Rip Rap Treatment	4	0.00+/-0.00	0.00+/-0.00	3.67+/-3.18
Inland Bays	Rip Rap Control	4	0.67+/-0.67	0.33+/-0.33	222.67+/-35.78
Inland Bays	Rip Rap Treatment	5	0.00+/-0.00	0.00+/-0.00	0.00+/-0.00
Inland Bays	Rip Rap Control	5	0.00+/-0.00	0.00+/-0.00	7.00+/-2.64
Inland Bays	Marsh Treatment	1	0.00+/-0.00	0.00+/-0.00	0.00+/-0.00
Inland Bays	Marsh Control	1	0.00+/-0.00	0.00+/-0.00	0.00+/-0.00
Inland Bays	Marsh Treatment	2	0.00+/-0.00	0.00+/-0.00	167.33+/-32.75
Inland Bays	Marsh Control	2	0.00+/-0.00	0.00+/-0.00	0.00+/-0.00
Inland Bays	Marsh Treatment	3	0.00+/-0.00	0.00+/-0.00	108.00+/-63.85
Inland Bays	Marsh Control	3	0.00+/-0.00	0.33+/-0.33	0.00+/-0.00
Inland Bays	Marsh Treatment	4	0.67+/-0.67	1.00+/-0.58	439.00+/-68.13
Inland Bays	Marsh Control	4	0.67+/-0.67	0.00+/-0.00	131.33+/-34.59
Inland Bays	Marsh Treatment	5	0.00+/-0.00	0.00+/-0.00	6.33+/-2.97
Inland Bays	Marsh Control	5	0.00+/-0.00	0.00+/-0.00	6.67+/-1.86

Table B4. Means and SEMs of bearing capacity at each site within the Lewes and Inland Bays project locations, monitored during 2014 (baseline), 2015, and 2016.

AOI	Site	Plot	2014	2015	2016
Lewes	Marsh Treatment	1	8.63+/-1.62	6.67+/-0.67	6.33+/-1.80
Lewes	Marsh Control	1	5.71+/-0.45	6.67+/-0.67	4.50+/-0.25
Lewes	Marsh Treatment	2	4.95+/-0.91	10.17+/-1.59	9.00+/-2.74
Lewes	Marsh Control	2	5.67+/-0.35	6.75+/-0.43	6.08+/-0.96
Lewes	Marsh Treatment	3	6.67+/-1.61	11.67+/-1.74	11.17+/-3.63
Lewes	Marsh Control	3	2.75+/-0.35	4.42+/-0.46	4.08+/-1.26
Lewes	Marsh Treatment	4	3.92+/-1.10	2.58+/-0.55	4.42+/-1.66
Lewes	Marsh Control	4	4.67+/-0.51	3.08+/-0.65	2.33+/-1.09
Lewes	Marsh Treatment	5	3.00+/-0.52	2.75+/-0.63	2.08+/-0.46
Lewes	Marsh Control	5	4.79+/-0.62	3.50+/-1.04	3.58+/-0.68
Inland Bays	Rip Rap Treatment	1	1.25+/-0.20	1.75+/-0.25	2.08+/-0.33
Inland Bays	Rip Rap Control	1	1.50+/-0.31	2.13+/-0.13	4.08+/-0.82
Inland Bays	Rip Rap Treatment	2	1.13+/-0.18	1.00+/-0.29	1.25+/-0.00
Inland Bays	Rip Rap Control	2	1.00+/-0.32	3.33+/-0.73	3.08+/-0.46
Inland Bays	Rip Rap Treatment	3	0.88+/-0.85	1.67+/-0.93	0.88+/-0.88
Inland Bays	Rip Rap Control	3	1.75+/-0.69	3.50+/-0.29	2.08+/-0.17
Inland Bays	Rip Rap Treatment	4	0.95+/-0.43	1.25+/-0.75	0.87+/-0.87
Inland Bays	Rip Rap Control	4	7.02+/-0.70	4.00+/-0.58	4.75+/-1.01
Inland Bays	Rip Rap Treatment	5	2.00+/-0.84	2.75+/-0.50	1.25+/-0.00
Inland Bays	Rip Rap Control	5	2.75+/-0.25	3.00+/-0.00	2.33+/-0.44
Inland Bays	Marsh Treatment	1	2.37+/-0.49	4.83+/-1.01	2.25+/-0.75
Inland Bays	Marsh Control	1	2.33+/-0.80	3.67+/-0.73	2.00+/-0.50
Inland Bays	Marsh Treatment	2	2.63+/-0.17	1.00+/-0.14	3.58+/-0.79
Inland Bays	Marsh Control	2	2.17+/-0.60	3.00+/-1.15	0.92+/-0.08
Inland Bays	Marsh Treatment	3	2.67+/-0.60	1.75+/-0.25	2.75+/-0.38
Inland Bays	Marsh Control	3	1.33+/-0.15	3.75+/-0.63	0.92+/-0.22
Inland Bays	Marsh Treatment	4	7.16+/-0.55	7.83+/-1.01	8.50+/-1.32
Inland Bays	Marsh Control	4	6.75+/-0.48	6.83+/-0.67	5.58+/-0.96
Inland Bays	Marsh Treatment	5	1.79+/-0.29	2.17+/-0.46	1.83+/-0.44
Inland Bays	Marsh Control	5	3.92+/-0.29	2.25+/-0.00	3.00+/-0.66

Table B5. Means and SEMs of feldspar measurements at each site within the Lewes and Inland Bays project locations, monitored during 2014 (baseline), 2015, and 2016.



AOI	Site	2014	2015	2016
Lewes	Marsh Treatment	0	6.89+/-4.60	40.22+/-22.31
Lewes	Marsh Control	0	6.51+/-2.13	11.01+/-8.56
Inland Bays	Rip Rap Treatment	0	10.98+/-10.98	18.58+/-18.58
Inland Bays	Rip Rap Control	0	13.48+/-2.79	27.58+/-9.17
Inland Bays	Marsh Treatment	0	6.60+/-2.48	17.50+/-2.08
Inland Bays	Marsh Control	0	17.44+/-3.23	16.26+/-6.83

Appendix C. Transects from Digital Shoreline Analysis System

Figure C1. Transect locations and lengths (between most waterward and landward vegetation lines) generated from DSAS for the Lewes study location.

Figure C2. Transect locations and lengths (between most waterward and landward vegetation lines) generated from DSAS for Inland Bays Rip-Rap study location.

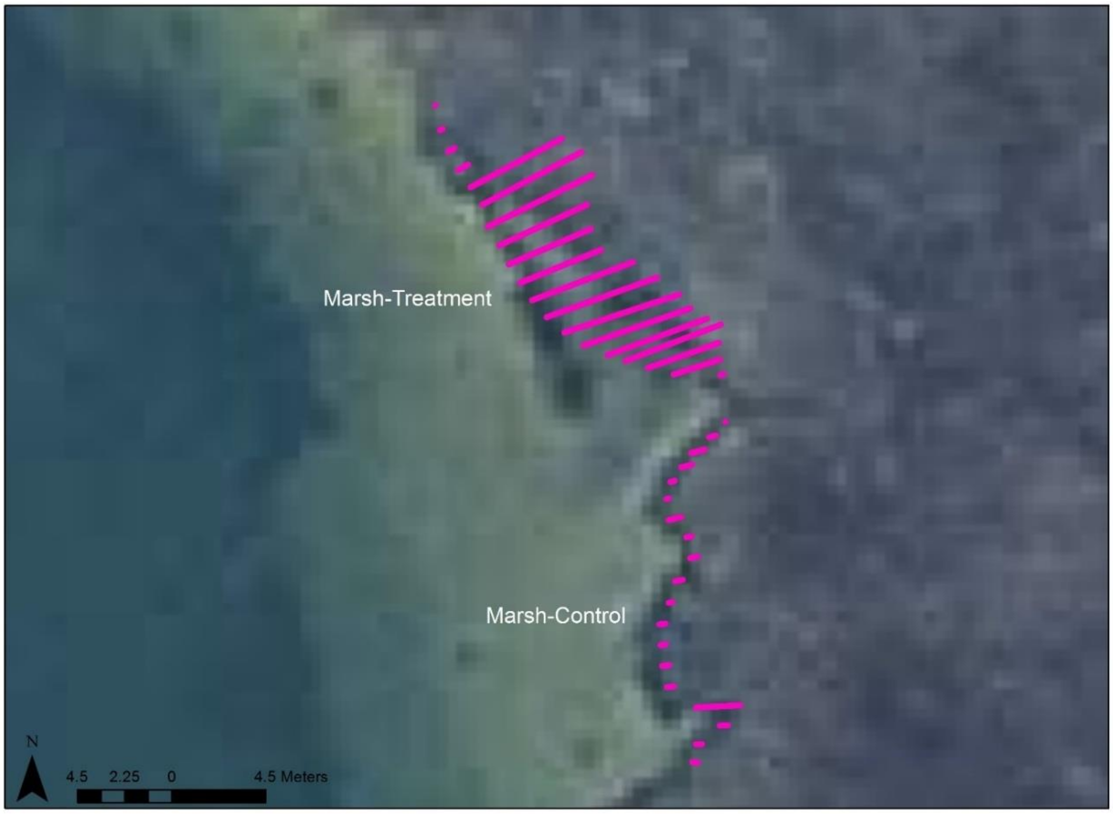


Figure C3. Transect locations and lengths (between most waterward and landward vegetation lines) generated from DSAS for the Inland Bays Marsh study location.

Appendix D. Photographic Time Series of Living Shoreline Treatments

Figure D1. Time series for Lewes Marsh site living shoreline looking southeast: a) pre-installation, April 2014; b) post-installation June 2014; c) June, 2015; d) August, 2016.

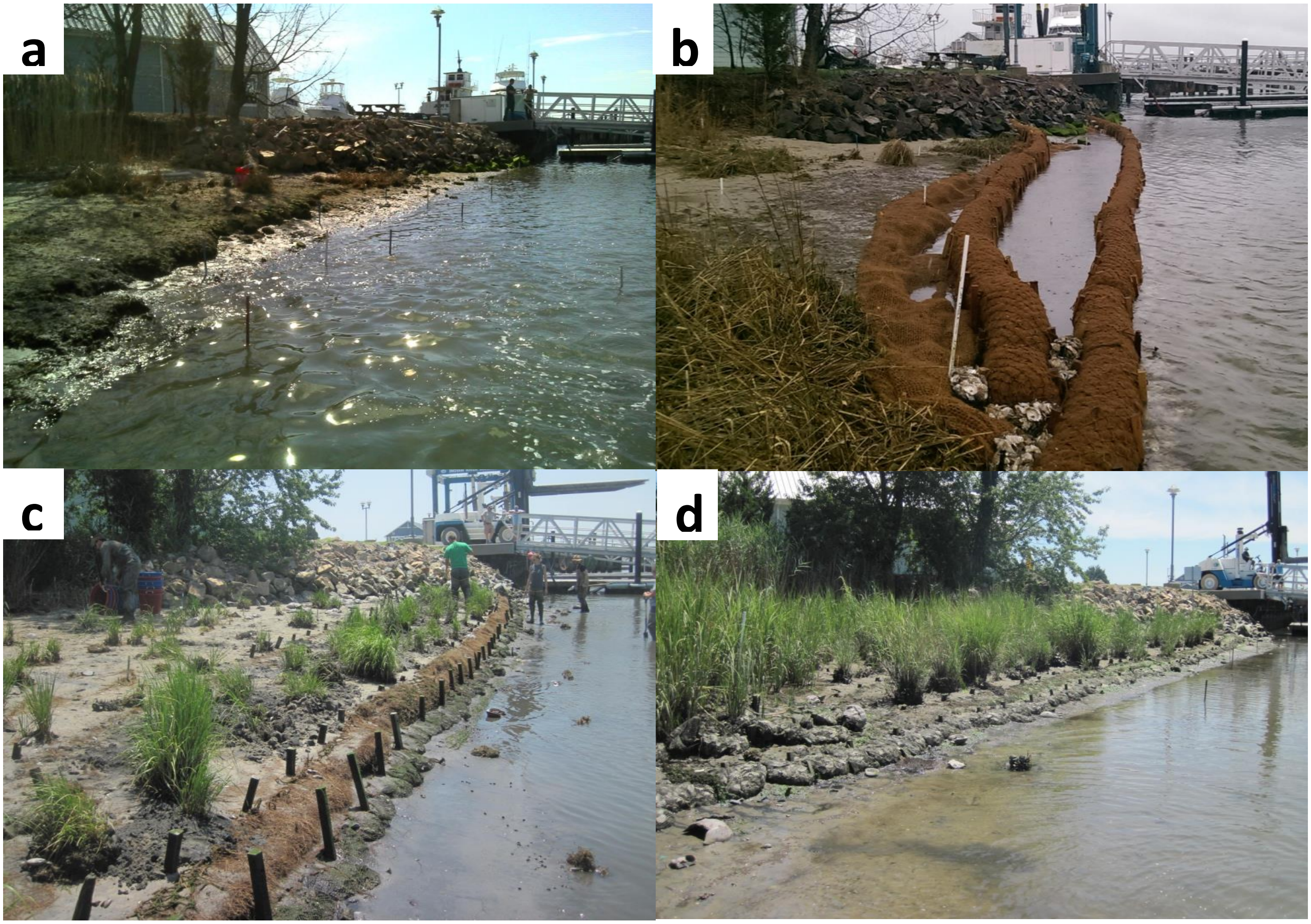


Figure D2. Time series for Inland Bays Rip Rap site living shoreline looking south: a) pre-installation, April 2014; b) post-installation April, 2014; c) June, 2015; d) August, 2016.

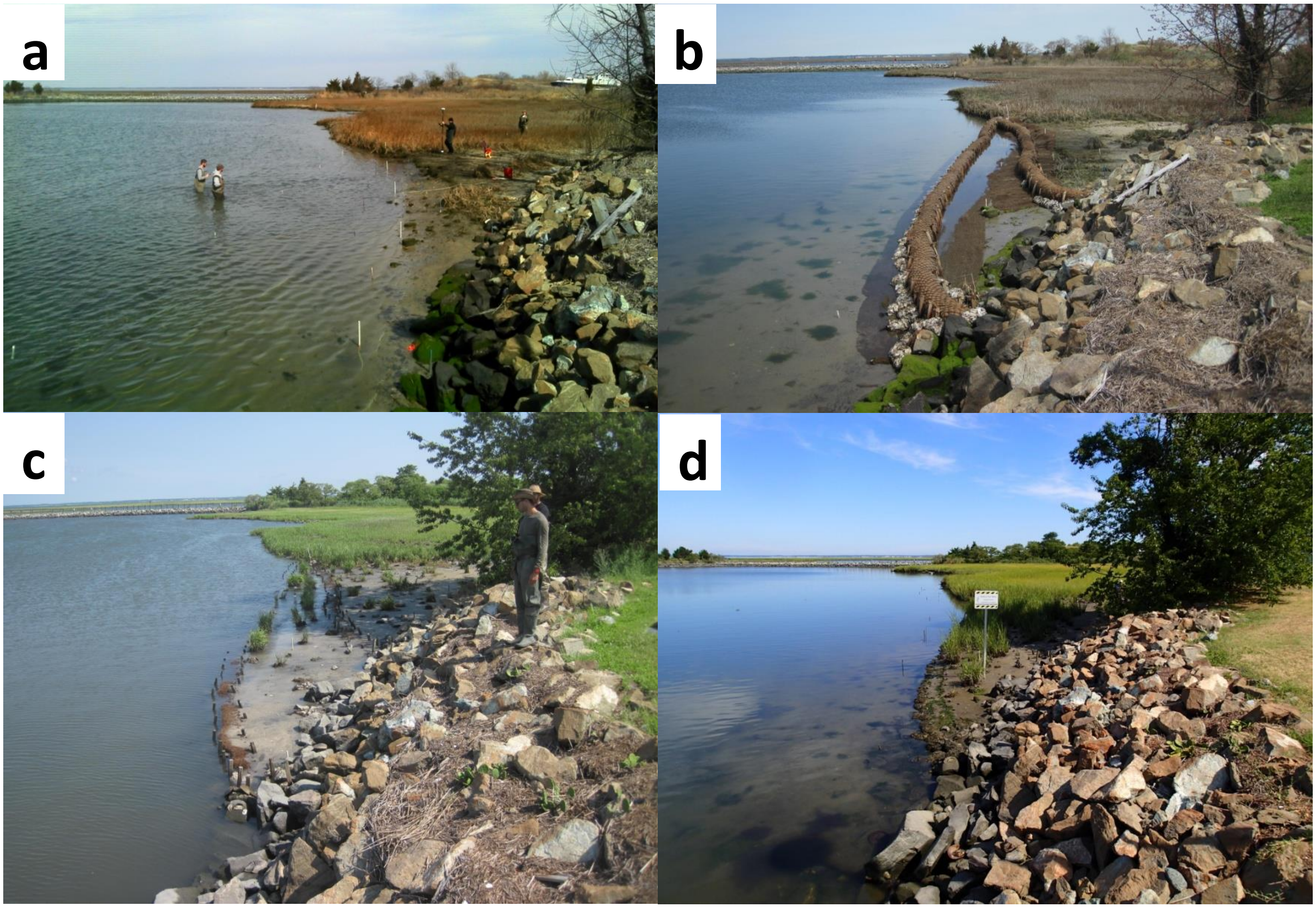


Figure D3. Time series for Inland Bays Rip Rap site living shoreline looking north: a) pre-installation, April 2014; b) post-installation April, 2014; c) June, 2015; d) August, 2016.

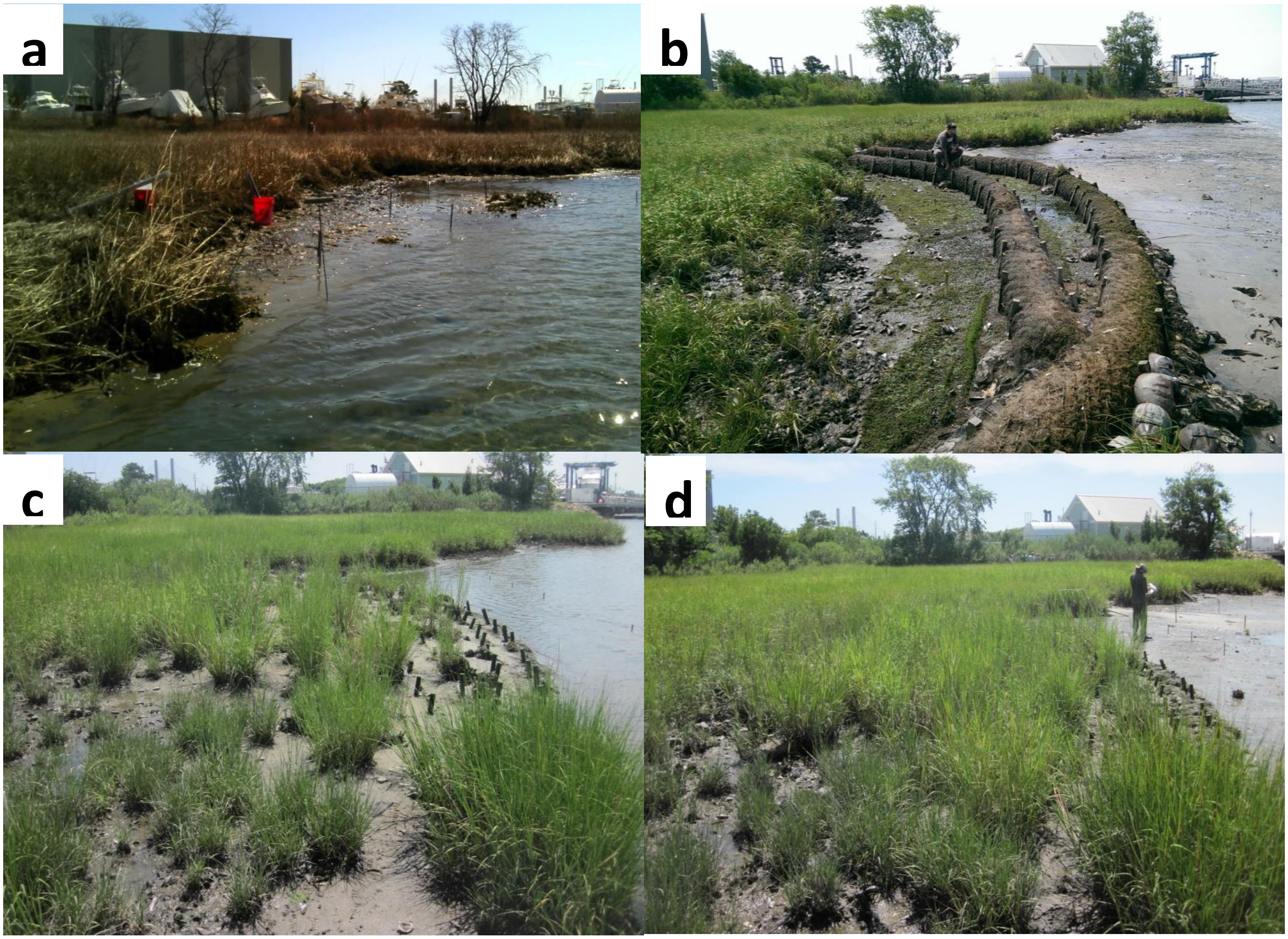


Figure D4. Time series for Inland Bays Rip Rap site living shoreline looking north: a) pre-installation, April 2014; b) post-installation April, 2014; c) June, 2015; d) August, 2016.