Enhancement of Ribbed Mussel Populations in Mid-Atlantic Salt Marshes and Living Shorelines for Water Quality Ecosystem Services

Final Report, April 30, 2019, Region 2 Regional Applied Research Efforts Project #: 83620001-0

Partnership for the DELAWARE ESTUARY

April, 2019 | Report No. 19-04

A publication of the Partnership for the Delaware Estuary—A National Estuary Program

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ORD Research Plan/Project: Safe and Healthy Communities

The Partnership for the Delaware Estuary brings together people, businesses, and governments to restore and protect the Delaware River and Bay. We are the only organization that focuses on the entire environment affecting the river and bay — beginning at Trenton, including the greater Philadelphia metropolitan area, and ending in Cape May, New Jersey and Lewes, Delaware. We focus on science, encourage collaborations, and implement programs that help restore the natural vitality of the river and bay, benefiting the plants, wildlife, people, and businesses that rely on a healthy estuary.

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Acknowledgements

We would especially like to thank Kathleen Drake, Irene Purdy, Marty Chintala, and Suzanna Ayvazian for partnering with us on this research.

We are also grateful for the field and analytic support provided by PDE staff, including: Angela Padeletti, Sarah Bouboulis, Emily Baumbach, Irina Beal, Kurt Cheng, LeeAnn Haaf, Spencer Roberts, Cairra Martin, Sandra Demberger, Kathleen LaForce, and Ryan Flannery.

This project has been funded wholly or in part by the United States Environmental Protection Agency under assistance agreement 83620001 to the Partnership for the Delaware Estuary (PDE). The contents of this document do not necessarily reflect the views and policies of the Environmental Protection Agency, nor does the EPA endorse trade names or recommend the use of commercial products mentioned in this document

Suggested Method for Citing this Report.

Moody, J., M. Gentry, and D. Kreeger, 2019. Enhancement of Ribbed Mussel Populations in Mid-Atlantic Salt Marshes and Living shorelines for Water Quality Ecosystem Services Final Report to EPA Office of Research and Development; **Project #:** 83620001-0. PDE Report No. 19-04. 35 p.

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Executive Summary

Historically, eroding shorelines have been managed through the implementation of hardened infrastructure such as seawalls, bulkheads, and revetments. As these structure are spatially static, they are unable to respond to changing environmental conditions and disrupt connectivity between adjacent habitats. Natural and nature-based approaches, including living shorelines, represent a suite of coastal protection design approaches to stabilize eroding shorelines, while increasing the net ecological uplift within the areas where they are applied. Many of the biotic components of coastal salt marshes provide important ecosystem services and are inextricably tied to the structural integrity and persistence of the marsh (e.g. vegetation and shellfish). These native species represent potential key components of living shorelines to facilitate ecosystem vitality. The ribbed mussel, *Geukensia demissa*, plays such a role.

Ribbed mussels support vegetation production through the deposition of nutrient rich feces and pseudofeces; which, through additional root production, provides additional mussel habitat, creating a positive feedback loop. Additionally, mussels have been found to reduce salt marsh erosion where they exist in great densities through the development of their byssal threads, which bind to plant roots facilitating stabilizing sediments along the marsh edge. Due to their role in important ecological and structural salt marsh processes, ribbed mussels have been suggested as an important biotic component for living shorelines designs. This study was designed to investigate the effects of substrate protection and preference on ribbed mussel recruitment as they relate to materials commonly used in living shoreline installations in the Delaware Estuary. A three-tiered study design was implemented in two representative river systems where living shorelines had been previously installed. First, ribbed mussel densities were quantified on previously deployed living shoreline materials and adjacent natural marsh. Second, to investigate the role of substrate protection on ribbed mussel recruitment and persistence, a field experiment was deployed in both river systems to assess recruitment on exposed vs. protected substrates at three positions relative to the natural marsh edge where living shoreline materials are commonly installed. Third, a field experiment was deployed in Nantuxent Creek to evaluate substrate preference on three commonly used living shoreline materials (coir fiber, oyster shell, and oyster castle material) deployed on recruitment tiles at three protection levels (covered by shell bag mesh, coir mesh mat, or not covered).

Two rivers that are representative of the Delaware Estuary system were selected for this study, Maurice River in Commercial Township, New Jersey, and Nantuxent Creek in Downe Township, New Jersey. Both of these rivers are home to living shorelines constructed by Partnership for the Delaware Estuary (PDE). The two Maurice River living shorelines were installed in 2009 (D15) and 2010 (Matt’s Landing), while the Nantuxent Creek living shoreline was installed in 2014. Both

sites had identical living shoreline designs, with coir log cusps lined with oyster shell bags along their waterward margins. Each living shoreline was planted with native *S. alterniflora* on the year of installation. Adjacent to these living shoreline treatments are paired controls with a natural *S. alterniflora* marsh edge.

Results showed that on materials deployed for ~10 years, mean ribbed mussel density in shell bags was significantly higher ($\bar{x}$=1,771±185 m^{-2}) than on the natural marsh edge ($\bar{x}$=0±0 m^{-2}) and on coir logs ($\bar{x}$=30±18 m^{-2}), which did not significantly differ from each other. Generally, ribbed mussel recruitment was significantly higher on the top surface of shell bags with the surface mesh left intact, than on shell bags where the shell bag mesh was cut to expose the top surface of the oyster shell. However, ribbed mussel surface recruitment was only between 0.5-7.0% of total bag recruitment, and there were no significant differences in total bag recruitment between bags with exposed and unexposed surfaces. Mean ribbed mussel recruitment was significantly greater on recruitment tiles protected by shell bag mesh ($\bar{x}$=1.74±0.36 $tile^{-1}$) than on tiles protected by coir fiber ($\bar{x}$=0.40±0.17 $tile^{-1}$, $p<0.004$) or not protected at all ($\bar{x}$=0.75±0.25 $tile^{-1}$, $p<0.02$), which did not differ significantly from each other ($p>0.70$ $tile^{-1}$). Ribbed mussel recruitment on coir fiber and oyster castle substrates were 163% and 42% of the recruitment that occurred on oyster shell and as such, filtration rate estimates were greatest on oyster castle substrate (503.44 mg h^{-1} ft^{-1}), lowest on coir fiber substrate (129.72 mg h^{-1} ft^{-1}), and median on oyster shell substrate (308.86 mg h^{-1} ft^{-1}).

When living shorelines are newly installed, they are characterized by large expanses of unprotected mudflat surface area. Ribbed mussels have been shown to facilitate growth of vegetation (Bertness 1984), so improving recruitment of these animals to living shorelines can aid in the migration of plants into barren unprotected areas behind shoreline installations. The results from this study identify a relationship between interstitial spaces and ribbed mussel recruitment, as has been shown with oysters. Therefore, maximizing interstitial space within living shoreline materials can help to create the habitat niche needed for population establishment. A key question regarding population development for ribbed mussels is what mechanisms can support populations from younger, more vulnerable, individuals to persist through time. The results from this study indicate that the refuge provided by interstitial space facilitated recruitment, but also that some degree of substrate protection also provided value. Therefore, the incorporation of substrates that are either protected by materials that allow for juvenile mussel passage, such as a ridged mesh that resists sediment collection, or are three-dimensionally robust, with a surface layer providing protection to the interior, will improve the efficacy of ribbed mussel recruitment. Substrate protection material should also have spaces that are large enough to enable the uninhibited passage of ribbed mussel larvae and sediment, to avoid any “clogging” of recruitment paths.

Introduction

Background

Salt marsh ecosystems are distinctive features of the Delaware Estuary along its coastal margins. These marshes provide water filtration services, including removal of nitrogen pollution from the watershed (Nelson and Zavaleta 2012), and aid in mitigating storm hazards by acting as buffer zones (Costanza et al. 2008; Temmerman et al. 2012). Biologically, salt marshes provide habitat for many species, some of which use them as breeding refuges (Weinstein et al. 1984; Weinstein and O'Neil 1986, Weinstein and Kreeger 2000) while others inhabit the ecosystems through all life stages or utilize their resources transiently (Werme 1981; Kneib 1994). These coastal salt marsh systems are particularly threatened by local sea level rise due to the specific tidal ranges in which they exist. Current sea level rise rates at Cape May in New Jersey are greater than 4mm yr^{-1} (PDE TREB 2017), higher than the predicted global rate at 3mm per year (IPCC 2007).

The mechanisms through which salt marshes systems build elevation and persist through rising sea levels are primarily through the capture of suspended sediments and *in situ* production of organic matter (Redfield 1972; Friedrichs and Perry 2001). Lack of sufficient sediment suggests an inability for coastal salt marshes to maintain themselves in relation to current sea level rise estimates (Delaune et al. 1983; Stevenson et al. 1985; Kearney et al. 1988; Hartib et al. 2002; McKee et al. 2004; Turner et al. 2004). But vertical positioning is not enough to allow marshes to persist. External forcing such as wave erosion can account for lateral landward movement in lieu of sea level rise (Mariotti and Fagerazzi 2013; Fagherazzi et al. 2013), and many marshes appear to be vertically stable under current sea level rise conditions but are laterally vulnerable to erosion and sediment transport processes (Kirwan 2016). Estimates of salt marsh loss between 25-75% have been predicted in some Atlantic estuaries by the year 2100 (Kreeger et al. 2010; PDE TREB 2012). Coastal managers need to be able to stem salt marsh losses to retain these ecosystem services and retain their associated economic and ecological benefits.

Tactics to stem the erosion of salt marsh edges are therefore needed. Traditionally, hardened approaches to stabilizing shorelines, such as seawalls, bulkheads, and revetments, are static and unable to respond to changing environmental conditions (Sutton-Grier et al. 2015). Additionally, if constructed without retaining connectivity or if interrupting important ecological processes, these structures can have adverse effects on adjacent habitats (Dugan et al. 2008; Balouskus and Targett 2016; Torre and Targett 2016) and physical processes (Campbell et al. 2005). Natural and nature-based approaches have therefore been favored in recent years, including the application of various types of living shorelines. Living shorelines represent a suite of design approaches aimed at stabilizing erosion or expanding coastal habitats. A common goal is to enhance ecosystem service provisioning of the area within and surrounding the treatments. Since many of the biotic components of coastal salt marshes that provide the aforementioned ecosystem services are inextricably tied to the structural integrity and persistence of the marsh (e.g. vegetation and bivalve shellfish), these native species represent potential key components of living shorelines to facilitate ecosystem vitality. The ribbed mussel, *Geukensia demissa*, plays such a role.

The ribbed mussel is the functional dominant animal of eastern US salt marshes (Kuenzler 1961; Lent 1969; Jordan and Valiela 1982) and provides essential support to the ecosystem. Deposition of pseudofeces and feces by ribbed mussels provides nutrients to the dominant low-marsh species of vegetation, *Spartina alterniflora,* enhancing its productivity (Bertness 1984). With the increased productivity of *S. alterniflora* there is more attachment habitat available for the mussels, creating a positive feedback loop between these two organisms. When considering the large scale retention of nutrients in a marsh, ribbed mussels filter 1.8 times more particulate nitrogen than is removed from the marsh by tidal flushing, about 50% of which is excreted, providing nutrients to plant communities (Jordan and Valiela 1982). The nitrogen that is retained in the marsh due to mussels is prevented from moving off shore, which may limit algal blooms (Valiela et al. 1990), and may also mitigate excessive nitrogen loads produced by anthropogenic activities. Mussels also filter inorganic particulates that are deposited onto the marsh, contributing to increases in marsh elevation. In addition to the direct *in situ* sedimentation from mussels, increased density of *S. alterniflora* facilitates an increase in passive sediment accumulation which raises marsh elevation (Bertness 1984). A previous study observed a landward migration of marsh edge in experimental plots in which ribbed mussels were removed, while control plots had waterward movement of the marsh edge (Bertness 1984).

The Partnership for the Delaware Estuary (PDE) has installed and monitored living shorelines in the Delaware Estuary since 2010. Structural components of PDE's living shorelines have included coconut fiber (i.e. coir) mats and logs, Oyster Castles© (i.e. molded concrete blocks made with a composite of crushed oyster shell and a proprietary cement mixture by Allied Concrete), and mesh bags filled with cured oyster shell. Over time it was observed that along aging living shorelines, ribbed mussel population were expanding within the confines of the oyster shell bags, but that similar population development was not occurring on "exposed" materials such as the surface of coir products or on the flat surfaces of oyster castles. This led to questions regarding substrate preference and the potential benefits of predator refuge as they relate to ribbed mussel population development in living shorelines. It has been shown that oyster recruitment to oyster shell is similar to that on concrete, limestone, porcelain, and river rock (George et al. 2014) and greater than on clam shell and stabilized coal ash (O'Beirn et al. 2000). Additionally, Oyster Castle© material has been shown to be able to retain and enhance biomass to a greater degree than oyster shell (Theuerkauf et al. 2015).

Although substrate preference has been well documented for the eastern oyster (*Cassostrea virginica*), the effect of substrate type on population development of ribbed mussels has not been evaluated. Furthermore, as a motile organism, the ribbed mussel is known to migrate into the void space of cohorts upon settlement, and this might enable mussels to avoid predation and ice (Bertness and Grosholz 1985). If there are substrate preferences and refuge is a primary goal for ribbed mussels post settlement, use of settlement surfaces that provide greater refuge could enhance mussel retention in living shorelines.

This study investigated the effects of substrate protection and preference as they relate to materials commonly used in living shoreline installations in the Delaware Estuary. A three-tiered study design was implemented in two representative river systems where living shorelines had been previously installed. First, ribbed mussel densities were assessed on previously deployed materials and adjacent natural marsh areas to correlate population robustness with material type. Second, the role of substrate protection on ribbed mussel recruitment and persistence was experimentally examined in both river systems by assessing recruitment on exposed vs. protected substrates at three positions relative to the natural marsh edge where living shoreline materials are commonly installed. Third, a field experiment evaluated substrate preference on three commonly used living shoreline materials (coir fiber, oyster shell, and oyster castle material) at three protection levels (covered by shell bag mesh, coir mesh mat, or not covered), which was deployed in one river system.

Research Objectives

The objectives of this project were to:

1. Identify mechanisms that contribute to patchiness and suboptimal ribbed mussel densities in representative salt marshes that are eroding or degraded.
2. Identify new mechanisms tactics to enhance ribbed mussel densities, sizes, and spatial coverage in living shorelines.

Mechanisms that were identified to enhance ribbed mussel populations along marsh shorelines were also interpreted as enhancement of ecosystem services such as water quality benefits. The study also investigated drivers of recruitment and survivorship on natural and augmented shorelines. By investigating a variety of treatment levels including existing population demographics, elevation profiles, and predator exclusion, this study aimed to provide coastal managers with a replicable tool to enhance ribbed mussel populations in salt marshes.

Research Approach

The key goal was to develop new tactics to sustain and maximize key ecosystem services delivered by ribbed mussel populations within eroding and degraded eastern USA salt marshes.

> <u>Hypothesis</u>: *Ribbed mussel populations and associated ecosystem services can be enhanced via periodic amendments of eroding and degraded salt marshes using natural materials and living shoreline approaches.*

The approach for testing the hypothesis was to perform the following tasks:

1) Identify the ecological mechanisms and exposure effects that contribute to patchiness and suboptimal ribbed mussel densities in representative salt marshes that are eroding or degraded.

2) Identify and test new tactics to enhance ribbed mussel densities, sizes, and spatial coverage, such as substrates to enhance recruitment and fiber netting to exclude predators, on both living shoreline project sites and untreated salt marshes.

3) Using prior collected RARE data for their physiological processing rates, estimate and compare key ecosystem services (TSS removal, particulate nutrient removal, levee-building) among ribbed mussel population enhancement tactics and untreated controls.

Task Descriptions and Methods

Task 1a. Mussel Population Density on Previously Deployed Materials

The Partnership for the Delaware Estuary has been installing and maintaining living shorelines in the Delaware Estuary since 2008. After an initial testing phase between 2008-2009, a replicable treatment design was installed in two locations in Maurice River: site D15 in 2009, and site E1 & E2 (Matt's Landing) in 2010. Although these initial treatments have been successful in stemming erosion and promoting stable vegetation growth, natural recruitment of ribbed mussels into the treatment materials was not initially apparent. By 2012, monitoring revealed that mussels had colonized the oyster shell bags on the treatments, but mussel presence along the coir logs appeared to be lower. In order to optimize living shoreline designs and material selection for ribbed mussel recruitment, it was important to quantify the extent of recruitment into the previously deployed living shoreline materials.

Pre-existing living shoreline treatments, and adjacent natural marsh areas, were evaluated to identify potential co-varying factors that influence ribbed mussel densities along the marsh edge. Two living shoreline substrates (coir fiber logs and oyster shell bags) were evaluated for ribbed mussel densities (Fig.1). Sampling occurred at two locations within the Maurice River where living shorelines were installed in 2009 and 2010. Coir log treatments lined with oyster shell bags, approximately ~80' in length, placed so the waterward edge is situated between mean and mean high water were installed at each location at the previously mentioned years. Each treatment was planted with *Spartina alterniflora* the year it was installed, and paired controls consisted of the naturally occurring *S. alterniflora* marsh edge. The two living shoreline installations on the Maurice River, denoted as D15 and Matt's Landing (Fig. 1), were quantitatively surveyed for ribbed mussel population densities on both their shell bag and coir fiber components. All mussels that were visible on the top surfaces of the shell bags and coir logs (D15: n= 12 & 2, respectively; Matt's Landing: n=5 & 4, respectively) were counted. Shell bags and coir logs were measured to calculate an average area per substrate type. Three $1m^2$ plots along the natural, untreated marsh edge at adjacent paired control areas were quantitatively sampled. All samples were normalized per m^2. Data were evaluated to test the effects of location (Matt's Landing and D15) and substrate type (coir logs, shell bags and marsh edge) on

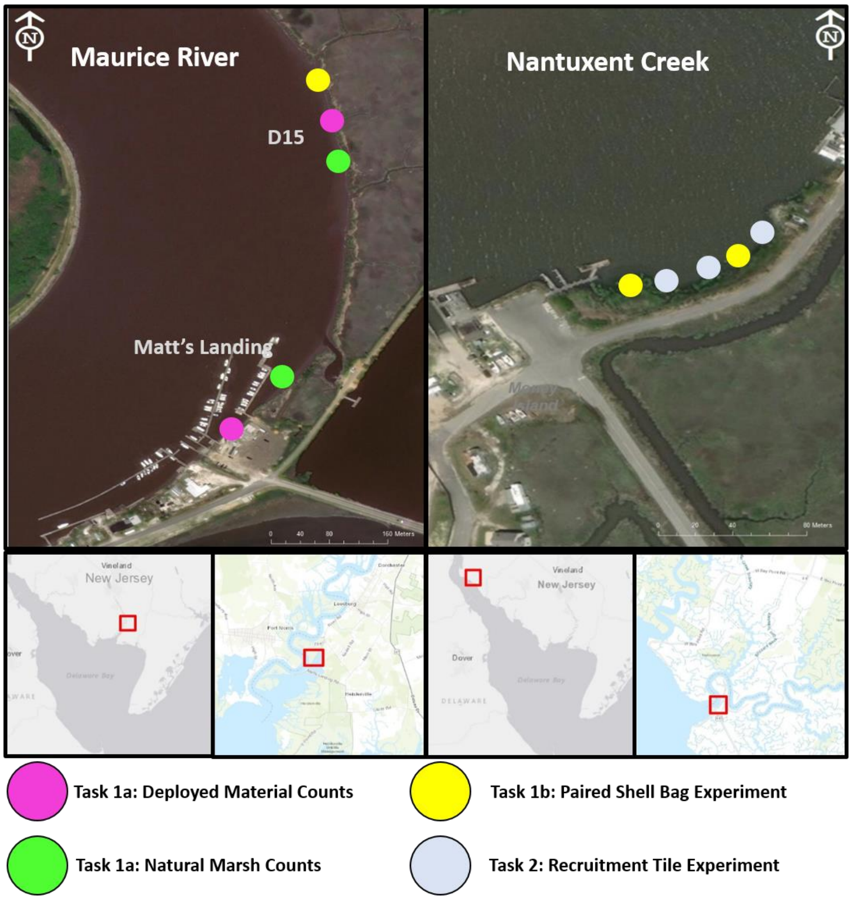

Figure 1 Location of tasks within the Maurice River and Nantuxent Creek study site areas.

mussel density. See Statistical Analysis section for details regarding analytical methods.

Task 1b. Ecological Factors Regulating Mussel Population Density

If greater recruitment of ribbed mussels on oyster shell bags compared to coir fiber logs was observed, it could be attributed to various factors such as material type, material complexity, or tidal elevation placement. It was hypothesized that the oyster shell bags provide a refuge both along the exposed surface and within their interstitial space, unavailable on the coir logs. To understand the effects of the substrate protection, similar materials were deployed with varying levels of surface protection. Additionally, there may be effects regarding relative placement of materials in the intertidal zone. The oyster shell bags were placed waterward of the coir logs, and the height of the shell bags (~6") was nearly 1/3[rd] of the height of the coir logs (16"). If positioning affected recruitment on the materials, materials testing the effects of substrate protection would need to be replicated and deployed at varying positions.

Figure 2 Shell bag with exposed, unprotected surface (a) and placement of shell bag pairs at positions relative to the existing marsh edge (b). Relative shell bag positions were: (i) 1m landward on the marsh platform where ribbed mussels naturally recruit; (ii) along the mudflat/salt marsh interface; (iii) 1m waterward on the mudflat where living shoreline materials are commonly deployed. Bags were fixed in place by affixing them to PVC posts using plastic zip ties.

The effects of substrate protection and shoreline position on recruitment were tested by deploying pairs of substrate protected and substrate unprotected shell bags at three locations relative to marsh edge within two rivers where living shorelines had previously been established: Maurice River and Nantuxent Creek. Shell bags, identical to those used in current living shoreline installations, were used to test the effect of substrate protection on ribbed mussel recruitment. Shell bags were constructed by filling a pre-made 1m PVC tube covered in shell bag mesh with cured oyster shell. After construction, 800mls of Portland cement was added to the center of each bag using a PVC tube. Each bag was subsequently agitated to allow the cement to distribute across the shells in the center of the bag, while minimizing surface coating. Bags in which the oyster shell were considered protected were kept intact. Unprotected shell bags exposed a portion of the oyster shell in the bag by cutting a 365cm^2 oval on the top surface (Fig. 2a). The Portland cement help to secure the shell during deployment and was added to "protected" bags for standardization purposes.

Bags were deployed at three sites on April 20, 2017: site D15 in the Maurice River; and at a previously establish living shoreline treatment and an adjacent, natural marsh area Nantuxent Creek (Fig. 1). At each site, three transects, oriented perpendicular to the marsh edge, were established, and shell bag pairs were deployed at three positions relative to the existing marsh edge: along the mudflat/salt marsh interface; 1m landward on the marsh platform where ribbed mussels natural recruit; 1m waterward on the mudflat where living shoreline materials are commonly deployed. Shell bag pairs were secured to PVC pipes with zip ties (Fig. 2b). Three PVC pipes were used per pair of shell bags, one on either side of the deployed pair, and one in the middle, to minimize bag movement. Shell bags were retrieved on September 13 & 14, 2017. Before removing the bags from the site, mussels on the surface of each bag were counted by laying the template used to cut the bag openings on the surface of both protected and unprotected bags, and counting the mussels visible within its bounds. Bags were then removed from their position and placed into a garbage bag, to prevent mussels that may dislodge from being lost from the sample, and returned to shore. Each bag was taken apart to quantify the total number of ribbed mussels inside. Surface and total bag mussel recruitment were compared to test the effects of site (n=2, living shoreline or natural marsh), position (n=3, mudflat/marsh interface and 1m landward and waterward) and protection level (n=2, sealed and opened oyster shell bags). See Statistical Analysis section for details regarding analytical methods.

Task 2. Ribbed Mussel Population Enhancement in Natural Marshes and Living Shorelines

Living shoreline approaches for erosion control and habitat uplift projects have become more common since Superstorm Sandy in 2012, and certain materials have emerged as being prominent components. Coir fiber logs and mats are commonly used at lower energy sites for direct energy buffering and sediment capture, as well as for building intertidal terraces and compartmentalizing treatment areas. Concrete and shell composites, such as Oyster Castles© (Allied Concrete), are frequently deployed in higher energy areas to attenuate wave energy and provide a quiescent refuge along eroding shorelines where softer tactics can be employed. These materials have also been successful substrates for oyster colonization, and have been utilized as substrate for reef building living shorelines. The relative ease with which these materials can be transported, manipulated, and configured has made them an optimal choice for projects where large equipment is precluded either by space or resource availability. Oyster shell has commonly been used in coastal restoration projects for its ability to absorb, rather than reflect, energy, and as a substrate for reef building. Limitations in shell availability in some areas has resulted in the need for other material types, such as the composite materials.

Although these materials are commonly being used in living shorelines, and similar research has been conducted on substrate preference for oyster recruitment (see Background section), no research regarding substrate preference for ribbed mussel recruitment has been pursued. Three substrate materials commonly used in living shoreline treatments were selected for testing: oyster shell, oyster castle concrete-shell composite, and coir fiber. To test recruitment substrate preference by ribbed mussels, 6in^2 tiles of each substrate type were constructed by pouring Portland cement into 6" x 6" silicon molds. Before the cement hardened, substrate materials were added to the tiles. Cured oyster shell and concrete-shell material were crushed into ~1-3" pieces and placed into the molds to create a near-flat surface (Fig. 3a). Coir fiber mats were cut into 6" x 6" squares and pressed into the cement in two offset layers to create a continuous surface of coir (Fig. 3a). Each substrate was embedded in such a way to ensure that no cement was visible below them. Additionally, profiles of the materials were kept as low as possible, to maintain spatial uniformity between tile types and isolate the materials used. Twenty seven tiles of each type were created, for a total of 81 tiles. Three tiles of each substrate type were randomly assigned placement in square plant drainage trays (n=9 tiles tray^{-1}; Fig. 3b).

Figure 3 Recruitment tiles (a) embedded with three substrate treatment types: coir fiber (top left); oyster shell (top right); and oyster castle (bottom right), and tray of nine randomly assigned recruitment tiles (b) to be deployed in triplicate at three locations in the Nantuxent Creek living shoreline site (n=9 trays total). This tray has a substrate protection level of "no covering".

Since substrate protection was only tested on concrete-shell composite bags in the previous experiment, three protection levels were also tested in this experiment: shell bag mesh; coir fiber mesh; and no protection. The nine trays were randomly assigned into groups of three, and each tray within each group was randomly assigned a substrate protection factor level so that one tray in each group was wrapped in either shell bag mesh

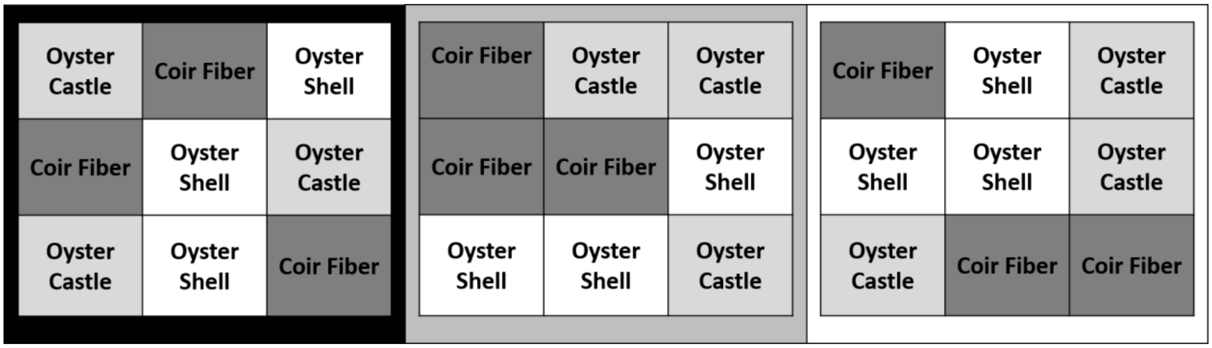

Figure 4 Schematic of a group of three trays with 9 nine substrate tiles at randomly assigned positions and one substrate protection level per tray. Substrate levels are denoted within small squares within each tray. Substrate protection levels indicated by differences in tray borders: black = coir fiber; grey = shell bag mesh; white = no covering. A group of three trays was deployed in three locations in the Nantuxent Creek living shoreline site (n=9 trays total).

or coir fiber, or left uncovered. Each group consisted of three trays (3 tiles of each substrate type $tray^{-1}$, n=9 tiles $tray^{-1}$), each wrapped in one level of protection (Fig. 4). All groups were deployed on the mudflat near mean water at the Nantuxent living shoreline on May 10, 2018. Trays were secured on all sides with wooden stakes driven into the marsh. Trays were retrieved and processed on site September 5, 2018. Mussel recruitment data were evaluated to test the effects of location (n=2, living shoreline or natural marsh), position (n=3, mudflat/marsh interface and 1m landward and waterward) and protection level (n=2, sealed and opened oyster shell bags). See Statistical Analysis section for details regarding analytical methods.

Task 3. Ecosystem Service Uplift Models

As filter feeding bivalves, ribbed mussels contribute to enhanced water quality by removing particulate matter from the water column. Initial capture of particulate matter is indiscriminate, after which sorting occurs. Material that is rejected prior to being ingested is loosely bound in mucus as pseudofeces, whereas, material that passes through the mouth and gut can be rejected as mucus-bound feces. Pseudofeces and feces are subsequently passed to the marsh platform where they can contribute to vertical marsh building processes. Organic materials, such as carbon and nitrogen, are selected by the animal for ingestion. A portion of the ingested material is used for important biological processes such as tissue shell, byssal thread, and gamete production, and a portion is returned to the environment through ammonia secretion and biodeposition. The amount of material that is filtered by mussels is dependent on the animal's water processing rates and the composition of the available seston.

Water quality benefits of ribbed mussel populations on various treatments were estimated by contrasting mussel densities and sizes with established physiological processing models and estimated seston loads. Seasonal physiological rate data from a prior RARE study were determined for ribbed mussels of varying body sizes living in the same systems that were studied in Tasks 1 and 2 using natural seston diets. The rates were applied to recruitment and demographic data from Task 1b, and differences in recruitment among substrates tested in Task 2, to determine differences in filtration services for living shorelines composed of different materials. Average recruitment rates were determined from total shell bag recruitment in Task 1b. Differences in recruitment among substrate types (Task 2) were only conducted in Nantuxent Creek, therefore average recruitment was calculated from the Nantuxent Creek living shoreline and natural marsh sites only. Additionally, since no significant recruitment differences between protected (bag mesh left intact) and unprotected (bag mesh opened on top surface) bags were observed, mean recruitment was calculated from all deployed bags in Nantuxent Creek (n=36). A subset of mussels from each bag (n=25) were measured to determine size demographics from the first year of deployment, which were converted to biomass estimates using size: dry tissue weight relationships assessed during the previous RARE effort. Recruitment differences by substrate were delineated from Task 2 data to determine percent recruitment differences among substrate types (e.g., oyster shell, coir fiber, and oyster castle material). Since shell bags deployed in Task 1b were all composed of oyster shell, the percent differences among substrates deployed in Task 2 (oyster shell, coir fiber, and oyster castle) were applied to the mean recruitment from Task 1b on oyster shell to estimate relative mussel recruitment on coir fiber and oyster castle substrates. Assuming that population demographics would be the same on coir fiber and oyster castle substrates as they were on oyster shell (Task 1b), the estimated recruitment per substrate was multiplied by the relative percentage of mussels per size class on the oyster shell bags (Task 1b) to calculate the number of mussels per size class on the coir and oyster castle substrates. These count estimates were scaled per linear foot as each shell bag was 1' in length. The geometric mean of the measured animals per size class was used to calculate the average dry tissue weight per size class, which was subsequently multiplied by the projected number of animals per class to calculate biomass estimates per size class per substrate.

Water samples from prior RARE projects (2012-2013 in Maurice River, Dennis Creek, and Dividing Creek) and Nantuxent Cove (July 31 and August 16, 2017 at the Nantuxent Creek living shoreline site) were collected in 20 liter carboys from each site. Before filling, the carboy was rinsed with ambient water. The carboy was filled by submerging it 5-10cm below the water surface in the main water channel, being careful not re-suspend soft material from the benthos or collect sediment plumes. Prior to seston, all water was passed through a 100 µm sieve to remove large debris and particle sizes too large for mussels to effectively filter. Replicate samples of seston were collected on pre-combusted glass fiber filters (Whatman GF/F, retention 0.7 µm) using vacuum filtration. All filtration glassware was pre-cleaned and rinsed with distilled water to ensure that it was as particle-free as possible. A few ml of 10% HCl were filtered and allowed to let stand for 2 min, and then rinsed with 10 ml particle-free distilled water. Seston was collected by passing a known volume of mixed water through the filter. To maximize the amount of seston on each filter without clogging the filter, which could introduce error, a test filter was first used per water type to determine the volume needed to clog the test filter; and subsequent filtrations were conducted using 90% of this "clogging volume". Vacuum pressure was set to 20 psi to prevent filter breakdown. After the water had cleared each filter, the filter and its funnel was rinsed with 5 ml of 0.5 M ammonium formate to remove any inorganic salts. Filters were used for determination of total suspended solids (TSS), using the loss-on-ignition method (dry 60ºC for 2 days, weigh). Weights of TSS were divided by the filtered volumes to calculate concentrations. The Delaware Bay values come from the "Lower Side DE" station (Latitude 39°08.16'; Longitude 75°22.80') which was sampled monthly from January to November, during most months from 2009-2011(Kreeger et al. 2016). To estimate differences in filtration capacity per substrate, mussel biomass estimates from each substrate type were integrated with annual weight specific clearance rates from the previous RARE effort and total suspended solid (TSS) measurements from the aforementioned effort, augmented with data collected in Nantuxent Cove in 2017 and Delaware Bay values collected between 2009-2011. Filtration results were scaled per 100' of living shoreline, assuming that the materials deployed would persist.

Task 4. Management Recommendations and Reporting

Outcomes were translated for coastal managers to promote the most successful tactics for conserving and enhancing ribbed mussel-mediated ecosystem services associated with water quality and coastal resilience. Rates of current marsh edge loss are so high that the natural edge community of abundant ribbed mussels and dense vascular plants never has sufficient time to re-establish itself under erosive conditions, since ribbed mussels and plants need a full growing season and sustained recruitment to maintain themselves. Recommendations from this report focused on potential strategies that could be applied to high value salt marshes to maintain and enhance the natural edge community. Results were interpreted to inform the development of living shoreline tactics to boost ribbed mussel colonization and survival, thereby enhancing mussel-mediated ecosystem services. The findings were shared with such stakeholders such as: the State of New Jersey, established workgroups such as the Living Shoreline Workgroup, and at professional meetings and conferences such as the Delaware Estuary Science and Environmental Summit in 2019.

Statistical Analysis

Data were analyzed using a linear model approach using R 3.5.1. A best fit model for each data series was selected based on lowest Akaike Information Criterion (AIC) score using the step function. AIC scores are an estimator to identify the primary factors, or subset of factors, that have the greatest influence on the response variable. Best fit models were evaluated using ANOVA tests and Tukey post-hoc analysis where appropriate (lsmeans package). Type-three sum of squares was selected for any ANOVA analysis where the data set was unbalanced (ANOVA, type=III, car package). Where interactions were identified as significant, data were partitioned by one variable and simple main-effects test was employed to evaluate differences among factor levels at the second variable. Means are presented ± standard error. Table 1 summarizes factor levels for all variables and their associated evaluation.

Table 1 Summary of all factors and their associated levels for each investigation

Factor	Levels	Investigation
Location	**1. D15** **2. Matt's Landing**	**Historical Recruitment into Living Shoreline Materials**
Feature	**1. Coir Log** **2. Natural Marsh Edge** **3. Oyster Shell Bag**	
Site	**1. D15 Natural Marsh** **2. Nantuxent Living Shoreline** **3. Nantuxent Natural Marsh**	**Intertidal Position and Substrate Protection Effects**
Position	**1. Marsh Platform** **2. Mudflat/Marsh Interface** **3. Mudflat**	
Bag Type	**1. Protected (Closed)** **2. Unprotected (Open)**	
Protection	**1. Coir Fiber** **2. None** **3. Shell Bag Mesh**	**Substrate Preference and Protection Type Effects**
Substrate	**1. Coir Fiber** **2. Oyster Shell** **3. Oyster Castle©**	

Results

Task 1a. Mussel Population Density on Previously Deployed Materials

Location and features were selected as independent, additive factors for the best fit model that had significant effects on ribbed mussel population density (Fig. 5). There was greater mean ribbed mussel density at site D15 ($\bar{x}$=1,428±254 m^{-2}) than at Matt's Landing ($\bar{x}$=501±236 m^{-2}), and shell bags had significantly greater mean mussel density ($\bar{x}$=1,771±185 m^{-2}) than both the natural marsh ($\bar{x}$=0±0 m^{-2}) and coir logs ($\bar{x}$=30±18 m^{-2}), which did not significantly differ from each other. Mean shell bag density was greater at D15 ($\bar{x}$=2,009±170 m^{-2}) than at Matt's Landing ($\bar{x}$=1,201±400 m^{-2}).

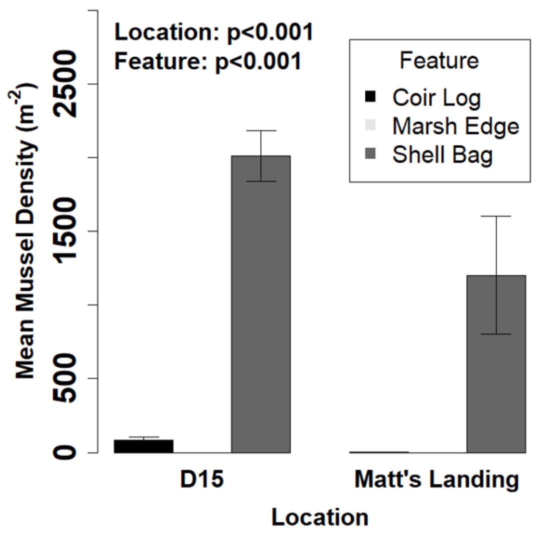

Figure 5 Mean mussel density (m-2) on two previously deployed living shoreline materials (coir logs and oyster shell bags), and along the natural marsh edge adjacent to living shoreline materials, at two locations in the Maurice River (D15 and Matt's Landing). Living shoreline materials were deployed at these sites in 2009 and 2010, respectively. P-values represent the results of a 2-way ANOVA test, with no significant interaction been factors.

Task 1b. Ecological Factors Regulating Mussel Population Density

Site, position, bag type, and the interactions between site and position, as well as between site and bag type were selected as factors influencing surface ribbed mussel recruitment in the best fit model. Site was the most significant factor ($p<8.7E^{-07}$), and best fit models for each site were therefore evaluated with position, bag type, and the interaction between position and bag type as independent variables. At site D15, mean ribbed mussel recruitment was low, and there was no significant difference between the effect of protected ($\bar{x}$=1.55±0.47) and unprotected ($\bar{x}$=0.67±0.44) shell bags on mean surface mussel counts ($p<0.18$, Fig. 6a). There was a significant difference ($p<0.036$) at the Nantuxent living shoreline site on mean surface mussel counts between protected ($\bar{x}$=9.44±2.40) and unprotected ($\bar{x}$=3.00±1.20) shell bags (Fig. 6a). At the Nantuxent natural marsh site, both bag type (p<0.005) and position (p<0.004) had significant effects on surface mussel counts (Fig. 6b). Protected shell bags had significantly greater mean surface mussel counts (x̄=18.33±4.21) than on unprotected shell bags (x̄=7.38±2.57), and surface counts on the marsh platform were significantly lower (x̄=2.40±1.36) than at the marsh/mudflat interface (x̄=18.00±4.79, p<0.006) and on the mudflat (x̄=17.33±4.50, p<0.008), which did not significantly differ from each other (p>0.98, Fig. 6b).

When mussel counts were evaluated for the entire shell bag (Fig. 6c), the best fit model also identified site, position, bag type, the interactions between site and position, and the interaction between site and bag type as factors influencing ribbed mussel counts, just as with the surface mussel counts. The interaction between site and position was significant (p<0.03), and data was portioned by site for main effects testing. There was no significant difference in mean ribbed mussel recruitment by position at D15 (p>0.07), the Nantuxent living shoreline (p>0.71), or at the Nantuxent natural marsh (p>0.09) sites (Fig. 6c). At site D15, mean bag counts were more similar on the marsh (x̄=270±88) and mudflat (x̄=225±28) than at their interface (x̄=82±32), but this pattern was not observed at the Nantuxent living shoreline or natural marsh sites. The lowest mean mussel count at the Nantuxent living shoreline site was at the mudflat position (x̄=148±60), with the marsh (x̄=200±12) and interface (x̄=197±54) positions being more similar. At the Nantuxent natural marsh site, mean mussel counts in shell

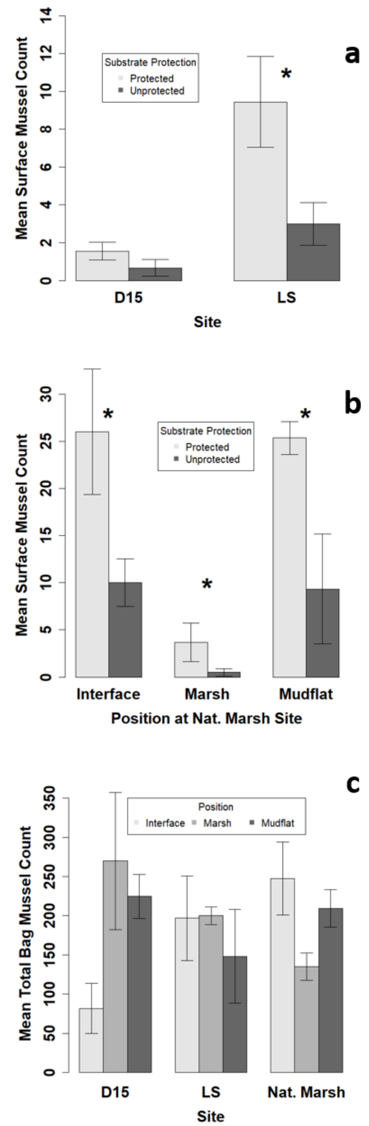

Figure 6 Mean mussel counts on shell bag: (a) surface at D15 and the Nantuxent Living shoreline sites (substrate protection was only significant factor), (b) surface at the Nantuxent Natural Marsh site (substrate protection and position were significant factors), and (c) throughout the entire shell bag (no significant factors). Substrate protection refers to shell bags deployed in tact (protected) or with the top surface of bag mesh removed (unprotected). Position refers to location relative to the marsh/mudflat interface. Asterisks (*) denote significant differences (α=0.05) among factor levels as per results of a Tukey post-hoc analysis.

bags on the natural marsh were lower ($\bar{x}$=135±19) than at the mudflat ($\bar{x}$=209±24) and interface positions ($\bar{x}$=247±46), as was observed with ribbed mussel surface counts. Comparing recruitment in the whole bag to surface recruitment showed that surface recruitment comprised only <1%, 4%, and 7% of all recruited mussels at D15, the Nantuxent living shoreline, and the Nantuxent natural marsh, respectively.

Task 2. Ribbed Mussel Population Enhancement in Natural Marshes and Living Shorelines

Substrate protection and substrate type were identified as independent factors contributing to differences in mean ribbed mussel recruitment. Mean ribbed mussel recruitment was significantly greater on tiles protected by shell bag mesh ($\bar{x}$=1.74±0.36 tile^{-1}) than on tiles protected by coir fiber ($\bar{x}$=0.40±0.17 tile^{-1}, $p<0.004$) or not protected at all ($\bar{x}$=0.75±0.25 tile^{-1}, $p<0.02$), which did not differ significantly from each other ($p>0.70$ tile^{-1}, Fig. 7a). Additionally, mean ribbed mussel recruitment was significantly greater on oyster castle material ($\bar{x}$=1.70±0.34 tile^{-1}) than on coir fiber ($\bar{x}$=0.42±0.16 tile^{-1}, $p<0.006$). However, recruitment on oyster shell tiles ($\bar{x}$=1.00±0.35 tile^{-1}) was not significantly different than on either oyster castle ($p>0.66$) or coir fiber ($p>0.28$, Fig. 7b). As recruitment was significantly greater on tiles protected by shell bag mesh, data were partitioned, and recruitment on these tiles was evaluated independently. Although, not significant ($p>0.24$), there was greater similarity in mean mussel counts between oyster castle ($\bar{x}$=2.11±0.65 tile^{-1}) and oyster shell ($\bar{x}$=2.22±0.76 tile^{-1}) tiles than either to coir fiber tiles ($\bar{x}$=0.88±0.31 tile^{-1}).

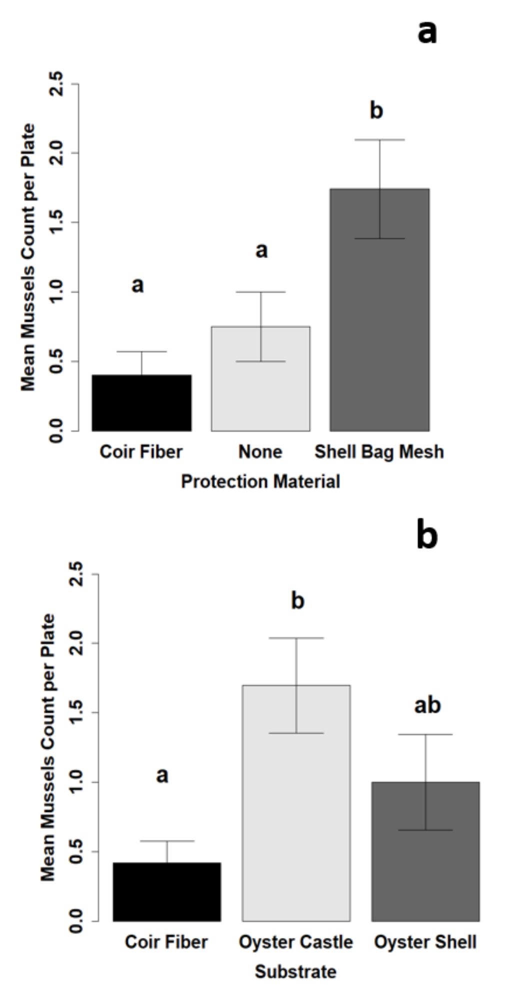

Figure 7 Results from the Tukey post-hoc analysis of mean ribbed mussel counts on (a) tiles under different substrate protection conditions, and (b) tiles made with different substrate materials. Letters denote significant differences (α=0.05) among factor levels as per results of a Tukey post-hoc analysis.

Task 3. Ecosystem Service Uplift Models

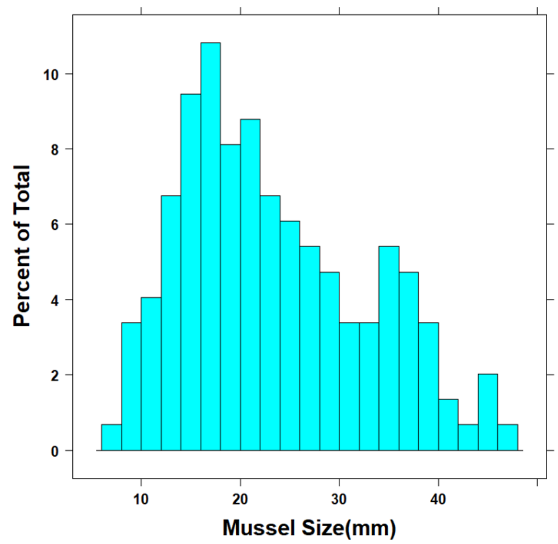

Figure 8 Histogram of ribbed mussel size distributions in deployed shell bags in Task 1b.

Ribbed mussel recruitment on oyster castle and coir fiber substrates were 163% and 42%, respectively, of the recruitment that occurred on oyster shell on the recruitment tiles deployed in Task 2 (Table 2). The average ribbed mussel recruitment in shell bags deployed in Nantuxent Creek in Task 1b was 191 mussels per shell bag, and recruitment per an equivalent deployment of coir fiber and oyster castle material was estimated to be 80.22 and 311.33 animals per bag, respectively (Table 2). Ribbed mussel recruits on oyster shell bags from Task 1b were between 6.92mm and 46.42mm in length with 50% of the animals smaller than 21.5mm and 75% smaller than 30mm (Fig. 8, Table 3). Integration of the recruitment differences and population demographics per substrate type with data from previous RARE efforts regarding shell length:dry tissue weight, annual clearance rates, and seston data allowed for the estimation of filtration rates

Table 2 Mussel recruitment onto different substrates and having different protection types in Task 2. The number of mussels that recruited to each substrate type is reported in columns 3 & 4. Percent by Substrate refers to the percent of total animals recruited during the experiment on each substrate type. Percent relative to shell, reports the percent of animals recruited to each substrate type relative the number that recruited to oyster shell. Mean recruitment was calculated from the total bag recruitment across all deployed shell bags in Nantuxent Creek (n=36). Estimated recruitment is mean recruitment *percent relative to shell.

Substrate	Protection	Mussels	Total	Percent by Substrate	Percent Relative to Shell	Mean Recruitment (Task 1b)	Estimated Recruitment
Coir	Coir	0					
Coir	None	2	10	0.14	0.42		80.22
Coir	Shell Bag	8					
Oyster Castle	Coir	7					
Oyster Castle	None	13	39	0.53	1.63	191.00	311.33
Oyster Castle	Shell Bag	19					
Oyster Shell	Coir	1					
Oyster Shell	None	3	24	0.33	1.00		191.00
Oyster Shell	Shell Bag	20					

(Table 3). Filtration rate estimates were greatest on oyster castle substrate (503.44 mg h^{-1} ft^{-1}), lowest on coir fiber substrate (129.72 mg h^{-1} ft^{-1}), and intermediate on oyster shell substrate (308.86 mg h^{-1} ft^{-1}, Table 3).

Table 3 Calculation of ribbed mussel filtration services by substrate type (column 2). Count refers to the number of animals per size class and Total Recruitment refers to the mean number of animals across deployed shell bags (n=36) in Nantuxent Creek for Task 2, and assuming a similar size distribution of animals across substrates. Substrate:Shell reports the ratio of recruitment per substrate in column 2 compared to recruitment on oyster shell. Projected Counts (ft^{-1}) is the estimated number of animals per size class applying the Count % to the Total Recruitment values per shell bag (~1ft in length). The geometric mean per size class was calculated based on the actual animal measurements and this was used to estimate the per animal dry tissue weight (DTW g) from previously reported shell length to DTW ratios. Dry tissue weight (DTW) per linear foot (gDTW) were obtained from previous studies and were multiplied by DTW*Projected Counts. Annual Weight-Specific Clearance Rates (WSCR) and Total Suspended Solid (TSS) were supplied by previous efforts and multiplied by gDTW per foot to calculate Filtration Rate (ft^{-1}). These results were scaled to a 100 living shoreline (LS).

Size (mm)	Substrate	Count	Count %	Substrate:Shell	Total Recruitment	Projected Counts ft^{-1}	Geometric Mean	DTW g	gDTW ft^{-1}	Annual WSCR $l\ h^{-1}\ gDTW^{-1}$	TSS $mg\ l^{-1}$	Filtration Rate $mg\ h^{-1}\ ft^{-1}$	Filtration Rate $kg\ yr^{-1}\ 100'LS^{-1}$
10	Oyster Shell	6.00	4%	1.00	191.00	7.74	8.95	0.01	0.11	0.26	57.42	1.69	1.48
20	Oyster Shell	57.00	39%	1.00	191.00	73.56	15.25	0.04	3.06	0.26	57.42	45.64	39.98
30	Oyster Shell	48.00	32%	1.00	191.00	61.95	24.11	0.10	6.31	0.26	57.42	94.27	82.58
40	Oyster Shell	30.00	20%	1.00	191.00	38.72	35.04	0.21	8.21	0.26	57.42	122.55	107.35
50	Oyster Shell	7.00	5%	1.00	191.00	9.03	44.02	0.33	2.99	0.26	57.42	44.70	39.16
Total	**Oyster Shell**	**148.00**	**100%**	**1.00**	**191.00**	**191.00**			**20.69**	**0.26**	**57.42**	**308.86**	**270.56**
10	Oyster Castle	9.72	4%	1.62	*311.33*	12.62	8.95	0.01	0.18	0.26	57.42	2.76	2.42
20	Oyster Castle	92.34	39%	1.62	*311.33*	119.90	15.25	0.04	4.98	0.26	57.42	74.40	65.17
30	Oyster Castle	77.76	32%	1.62	*311.33*	100.97	24.11	0.10	10.29	0.26	57.42	153.67	134.61
40	Oyster Castle	48.60	20%	1.62	*311.33*	63.11	35.04	0.21	13.38	0.26	57.42	199.75	174.98
50	Oyster Castle	11.34	5%	1.62	*311.33*	14.73	44.02	0.33	4.88	0.26	57.42	72.87	63.83
Total	**Oyster Castle**	**239.76**	**100%**	**1.62**	***311.33***	**311.33**			**33.72**	**0.26**	**57.42**	**503.44**	**441.01**
10	Coir Fiber	2.52	4%	0.42	*80.22*	3.25	8.95	0.01	0.05	0.26	57.42	0.71	0.62
20	Coir Fiber	23.94	39%	0.42	*80.22*	30.90	15.25	0.04	1.28	0.26	57.42	19.17	16.79
30	Coir Fiber	20.16	32%	0.42	*80.22*	26.02	24.11	0.10	2.65	0.26	57.42	39.59	34.69
40	Coir Fiber	12.60	20%	0.42	*80.22*	16.26	35.04	0.21	3.45	0.26	57.42	51.47	45.09
50	Coir Fiber	2.94	5%	0.42	*80.22*	3.79	44.02	0.33	1.26	0.26	57.42	18.78	16.45
Total	**Coir Fiber**	**62.16**	**100%**	**0.42**	***80.22***	**80.22**			**8.69**	**0.26**	**57.42**	**129.72**	**113.64**

Table 4 Presentations in which portions, or the entirety, of the results of this work were presented. Venue describes either the event or medium in which these data were, or will be presented and Type refers to the manner in which the material was presented.

Date	Venue	Title	Type	Authors
01/23/2017	Delaware Estuary Science and Environmental Summit, Reflecting on Progress, Charting the Future, 1/22-28/2017, Cape May, NJ	Effects of predator availability and substrate position on ribbed mussel recruitment for living shoreline applications	Poster	LaForce, Kathleen, Ryan Flannery, Joshua Moody, & Danielle Kreeger
11/6/2017	Coastal and Estuarine Research Federation 24th Biennial Conference, 11/5-9/2017, Providence, RI	Targeting restoration efforts to maximize ribbed mussel water quality benefits along Delaware estuary salt marshes	Oral	Moody, Joshua, Danielle Kreeger, Kurt Cheng, & Angela Padeletti
03/19/2018	National Shellfisheries Association 110th Annual Meeting, 3/18-22/2018, Seattle, WA	Effects of predation and substrate choice on ribbed mussel recruitment for living shoreline applications	Oral	Moody, Joshua & Danielle Kreeger
7/27/2018	Delaware Center for Inland Bays Science and Technical Advisory Committee Meeting, 7/27/2018, Rehoboth Beach, DE	Ribbed mussel habitat restoration for water quality uplift	Oral	Moody, Joshua
10/12/2018	Atlantic Estuarine Research Society Fall Meeting, 10/11-13/2018, Stockton, NJ	Effects of predation and substrate choice on ribbed mussel recruitment for living shoreline applications	Oral	Bouboulis, Sarah, Joshua Moody, & Danielle Kreeger
10/24/2018	ORD-NEP Webinar	ORD-NEP Collaboration on Strategies for Marsh Restoration	Oral Webinar	Moody, Joshua
01/28/2019	Delaware Estuary Science and Environmental Summit, Estuary 2029: Saving Our System Through Collaboration, 1/27-30/2019, Cape May, NJ	Effects of substrate protection and type on ribbed mussel recruitment for living shoreline applications	Poster	Gentry, Matthew, Joshua Moody, Sarah Bouboulis, & Danielle Kreeger
03/18/2019	US Fish and Wildlife Service Living Shoreline Workshop	Overview of living shoreline efforts across the Delaware Estuary	Oral	Moody, Joshua
10/12/2018	Atlantic Estuarine Research Society Fall Meeting, 10/11-13/2019, Stockton, NJ	Effects of substrate protection and type on ribbed mussel recruitment for living shoreline applications	Poster	Gentry, Matthew, Joshua Moody, Sarah Bouboulis, & Danielle Kreeger
Writing in Progress	Journals being considered: Estuaries and Coasts, Journal of Coastal Research, Journal of Coastal Conservation	Effects of substrate protection and type on ribbed mussel recruitment for living shoreline applications	Journal Article	Moody, Joshua, Sarah Bouboulis, Matt Gentry, & Danielle Kreeger

Task 4. Management Recommendations and Reporting

Management recommendations focusing on strategies and living shoreline tactics to boost ribbed mussel colonization and survival, thereby enhancing mussel-mediated ecosystem services, are discussed in the Synthesis and Conclusions section below. Results of portions of this work were presented at nine venues, and are currently being prepared for submission in a peer-reviewed journal (Table 4). In addition to the formal presentations, these results were discussed with the following committees to provide insight and informally guide portions of the stated work:

1. Delaware Living Shoreline Committee: Developing monitoring plans for living shoreline projects in Delaware: A goal-based framework. A report prepared by the Delaware Living Shorelines Committee Standards of Practice Subcommittee. April, 2018. https://s3.amazonaws.com/delawareestuary/PDE+Reports/2018-DELS+Framework+V.2.0._Final.pdf

2. New Jersey Ecological Projects Committee: Yepsen, M., Moody, J., Schuster, E., editors (2016). A Framework for developing monitoring plans for coastal wetland restoration and living shoreline projects in New Jersey. A report prepared by the New Jersey Measures and Monitoring Workgroup of the NJ Resilient Coastlines Initiative, with support from the NOAA National Oceanic and Atmospheric Administration (NOAA) Coastal Resilience

(CRest) Grant program (NA14NOS4830006), https://www.conservationgateway.org/ConservationPractices/Marine/crr/library/Documents/Framework-Coastal-Wetland-Shoreline-Projects-New-Jersey.pdf

Synthesis and Conclusions

The large discrepancy in mussel density on previously deployed living shoreline materials along the Maurice River (sites D15 and Matt's Landing), which had been available for settlement since 2010, suggested that low recruitment to coir fiber material was not temporal. Shell bags adjacent to the coir fiber logs had significantly higher ribbed mussel densities, compared to coir fiber logs and the natural marsh edge (Fig. 5). Recruitment on the shell bags showed that the lack of recruitment on the other materials were not the result of a lack of available recruits in that area, but this variability may be driven by fundamental structural differences among the substrate types. Coir fiber logs have a dense internal matrix of fibrous material that may be tough for mussels to integrate themselves into. The fact that high densities of mussels were measured in the oyster shell bags (Fig. 5) indicates that the lack of mussels in the natural marsh plots and on the coir fiber logs was not due to low mussel availability, as mussel populations have been observed in nearby intra-marsh creek networks, but likely due to a lack of suitable habitat. Absence of mussels in the natural marsh edge plots could result from high rates of erosion occurring in the Maurice River precluding mussel populations from establishing. This erosive energy may also prevent mussels from becoming established on the surfaces of the coir fiber logs.

A primary difference between the oyster shell bags and the coir fiber logs is the amount of interstitial space, due to the three-dimensional complexity of shell bags. Nestlerode et al. (2007) and O'Beirn et al. (2008) reported that greater interstitial space in substrates resulted in greater recruitment of oysters, similar to results found here. Evaluating the recruitment to the shell bags independently, more than 92% of mussel recruits positioned themselves within the shell matrix of the bags (Figs. 6a-c). These results support conclusions from Bertness and Grosholz (1985) that ribbed mussels tend to orient themselves within void space when available, and highlight the importance of interstitial space for maximizing ribbed mussel recruitment in living shoreline substrates.

In addition to greater interstitial space in shell bags relative to coir logs, the bag material itself may have provided a level of substrate protection unavailable on the coir logs. Although the majority of mussels were found within the shell bag matrix, significantly greater ribbed mussel surface counts were on oyster shell bags that were protected with mesh relative to unprotected bags at the Nantuxent Creek living shoreline (Fig. 6a) and natural marsh (Fig. 6b) sites. Further, recruitment tiles protected by shell bag mesh had significantly greater recruitment than on materials that were not protected (Fig. 7a). It is worth noting that recruitment counts on tiles protected by coir fiber matting were not significantly different than on the unprotected tiles (Fig. 7a), but the coir fiber material frayed readily and the holes became clogged with sediment. This fraying and clogging probably either provided greater predatory access or prevented ribbed mussels from accessing the substrate tiles, respectively, which led to the observed low recruitment on all substrate types that were protected by coir fiber material. These results indicate that substrate protection plays a significant role in the recruitment of ribbed mussels to any materials, but some protection can be provided by the materials themselves if they have interstitial space and three-dimensional complexity.

There was little evidence that position relative to the marsh edge played a role in mussel recruitment. At the Nantuxent natural marsh site, position was found to be a significant factor affecting surface recruitment (Fig 6b), but this result was not observed at D15 or the Nantuxent living shoreline site. Although total bag recruitment was not significantly different by position at the Nantuxent natural marsh site, the mean on the marsh platform was lower than on the mudflat and at the marsh/mudflat interface (Fig. 6c). This difference may be due to site-specific physical factors inhibiting larval transport onto the marsh platform. For example, if the marsh platform is positioned at relatively higher elevation in the tidal prism than the D15 and Nantuxent living shoreline sites, access to the substrate may be temporally limited, resulting in lower access opportunity over the tidal cycle. Future research will focus on placement across the tidal prism to identify tidal elevation effects on recruitment densities.

Substrate type also significantly contributed to recruitment differences among substrate types, with Oyster Castle© material showing significantly greater recruitment than oyster shell and coir fiber (Fig. 7b). Although Oyster Castle© material had significantly greater recruitment than natural oyster shell, the raw data showed that the numbers of recruits to the Oyster Castle© (n=39) and oyster shell (n=24), were closer in value than either was to the number of recruits on coir fiber (n=10). Further, when data were partitioned by protection type oyster, similarities in recruitment between oyster shell and Oyster Castles© were observed. On tiles protected by shell bag mesh, which received the greatest recruitment (Fig. 7a), oyster shell had the highest mean recruitment ($\bar{x}=2.22\pm0.76$), and was more similar to the Oyster Castle© ($\bar{x}=2.11\pm0.65$) than the coir fiber ($\bar{x}=0.88\pm0.31$) substrates. That this similarity did not appear when data from tiles under all substrate protection methods were considered together implies that when there is protection that allows for mussel passage, oyster shell and oyster castle substrate both provide suitable habitat. These data support findings by Theuerkauf et al. (2015) for oysters suggesting that Oyster Castle© are just as effective as oyster shell in attracting recruitment.

Interestingly, recruitment on tiles without substrate protection showed greater mean mussel presence on Oyster Castle© tiles ($\bar{x}$=1.63±0.60) than on oyster shell $\bar{x}$=0.38±0.18) and coir fiber ($\bar{x}$=0.25±0.25). Although efforts were made to normalize the size and shape of the substrate materials being applied to the surfaces of the tiles, the Oyster Castle© substrate had more three dimensional complexity than the shell, and this difference in coarseness between substrates may have allowed for greater refuge on the Oyster Castle© tiles, reflecting the importance of interstitial space found in this study. This advantage of oyster castle seems to be neutralized when an auxiliary substrate protection method is used, such as shell bag mesh. Future studies will need to normalize void space across varying substrates to more closely assess the importance of interstitial space for ribbed mussel recruitment.

Filtration services by ribbed mussels will ultimately reflect the biomass and population size distribution of ribbed mussels present and seston composition. Although filtration capacity tracks with population biomass, it is not enough to have a high level of biomass at a site, the population needs to be stable to sustain these services through time. A high concentration of small animals at a site leaves the population vulnerable to drastic mortality events that young, less hardy individuals are unable to withstand (e.g. predation, icing, and dislodgement). Older, larger individuals are able to withstand physical stressors and biologic interactions with more resilience, and as such, have a higher likelihood of persistence (Franz 2001). Size class distribution appeared hardy in this study, with individuals ranging between ~7-46mm, with 25% of the population greater than 30mm (Fig. 8). Greater filtration services were derived for treatments that had greater recruitment. Therefore, management strategies aimed at achieving water quality benefits should maximize ribbed mussel colonialization and associated filtration services.

When living shorelines are newly installed, they can contain large expanses of unprotected mud flat surface area. Ribbed mussels have been shown to facilitate growth of vegetation (Bertness 1984), and improving recruitment of these animals to living shorelines can therefore also aid in the migration of plants into barren unprotected areas behind shoreline installations. The results from this study identify a relationship between interstitial spaces and ribbed mussel recruitment, as has been shown with oysters. Therefore maximizing interstitial space within living shoreline materials can help to create the habitat niche needed for population establishment which should also be beneficial for colonialization by plants at appropriate tidal elevations. This study did not examine factors that may be important for long term population development of ribbed mussels, such as mechanisms and substrates needed for succession from younger, more vulnerable, individuals to older assemblages. The results from this study indicate that the refuge provided by interstitial space facilitated recruitment, but substrate protection could have more lasting value since predators like blue crabs can consume all mussel sizes. With regard to recruitment, this study found that substrates that are protected by mesh that resists sediment collection, improves recruitment compared to unprotected substrates. Substrate protection material should also have spaces that are large enough to enable the uninhibited passage of ribbed mussel larvae and sediment, to avoid any "clogging" of recruitment paths.

This study provides a foundation to deploy living shoreline materials tailored to maximize ribbed mussel refuge through the use of materials with a high degree of void volume and surface protection. Further studies are needed to better define the types of interstitial space needed for different sizes/ages of ribbed mussels, and benefits of added predator protection at different life stages, to guide long term succession of a healthy and robust ribbed mussel community on a living shoreline.

Project Issues

Task 1a:

- The initial aim was to evaluate plots established under previous RARE funding in addition to the aforementioned locations, but due to large distances between locations, it was deemed that the effort would be comparable, and resources were reallocated to more in-depth surveys at the living shoreline and adjacent areas, such as: deconstructing shell bags for full counts, and evaluating the entire stretch of coir log at the sites. As mussels are naturally patchy, these efforts were warranted to capture the true extent of recruitment since deployment, instead of relying on random sampling that may miss recruitment hotspots.
- Ribbed mussel counts in living shoreline materials and along adjacent areas was initially expected to be conducted in Nantuxent Creek as well as in Maurice River. But the living shoreline in Nantuxent Creek was ~1 year old when this field work occurred and recruitment had been light in its first year. Therefore there was not enough recruitment at Nantuxent Creek to statistically evaluate, and efforts were reallocated to the more in-depth investigation of the older materials in Maurice River as described above.

Task 1b:

- A second set of shell bag pairs was deployed in the Maurice River at Matt's Landing site E1 (Fig. 1). These shell bags were buried during their deployment and therefore no recruitment was able to occur. The sedimentation on top of the sell bags was deep enough that not all bags were able to be recovered. Of those that were, no evidence of recruitment or long-term exposure (e.g. fouling, wrack trapping, vegetation trapping, etc…) was present.

Task 2:

- The first deployment of this task occurred in spring 2017 at Maurice River and Nantuxent

Creek sites. As with Task 1b, the Maurice River treatments deployed at Matt's Landing were either washed away or buried. Additionally, the materials recovered at Nantuxent Creek exhibited little recruitment, precluding robust analysis. Light recruitment at the Nantuxent site was attributed to poor positioning (i.e., in the grass on the marsh platform) and improper size of materials (i.e., 6" disks). Since funds were still available, it was decided to redesign the study to allow for a greater recruitment potential, and more robust analysis. This is described above in Task 2 under Task Descriptions and Methods. It was also decided that since the Maurice River site had proven to be problematic twice, tasks 1b and 2 were only deployed in Nantuxent Creek, but at a greater density.

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