Enhancing the Water Quality Benefits of Shellfish-Based Living Shorelines in Delaware

Final report for

DNREC Delaware Clean Water Council Community Water Quality Improvement Grant

CWQIG 16-03

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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 collaboration, 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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Introduction

In 2014, the Partnership for the Delaware Estuary was awarded a grant from the Delaware Clean Water Advisory Council to install Delaware's first "hybrid" living shoreline along 300' of eroding salt marsh adjacent to the DuPont Nature Center at Mispillion Harbor Reserve (Fig. 1). Historically, living shorelines have typically been installed along eroding landscapes to stem erosion as a more natural alternative to more structural techniques (e.g., bulkheads, sills, etc). As such, the primary goal of most living shorelines has been erosion control. However since living shorelines can contain a variety of natural components (e.g., plants, sediments, shell, etc), they can also be designed to address a variety of other goals including habitat and water quality enhancement (Mitsch 2012).

The foreshore in front of the DuPont Nature Center is home to an intertidal oyster reef which, coupled with the ribbed mussels that live in the adjacent salt marsh, makes this site a hotspot for important species of bivalve shellfish. The eastern oyster (*Crassostrea virginica*) and ribbed mussel (*Geukensia demissa*) are the two most populous bivalves in the saltwater portion of th Delaware Estuary (Partnership for the Delaware Estuary 2017), and they filter vast quantities of water to satisfy their nutritional demands (Bayne et al. 1988, Kreeger et al. 2018). By removing large quantities of nutrient-rich suspended particles, these bivalve molluscs can help to alleviate the negative ecological effects that are associated with high turbidity and nutrient-fueled eutrophication (Kreeger et al. 2018). When they are abundant and healthy, beds of oysters and ribbed mussels help to control algal blooms,

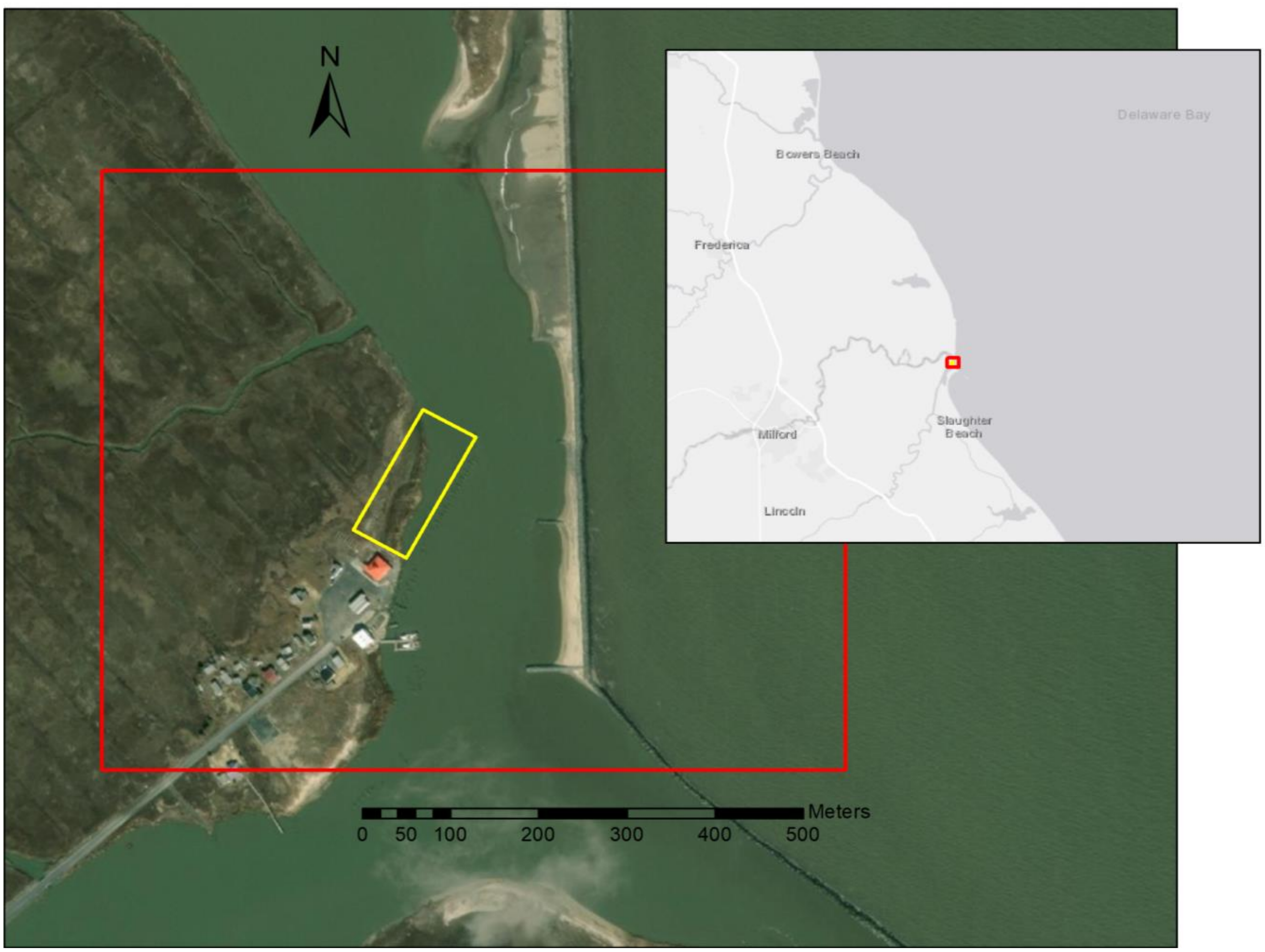

Figure 1. Site overview. Yellow box indicates focal area of living shoreline installation.

promote light penetration for bottom plants, and can help trap sediments that would otherwise contribute to navigation channel filling). The restoration of oyster and mussel populations may therefore be viewed as a promising tool to help achieve water quality targets related to nutrients and light availability (e.g., for submerged aquatic vegetation), as well as aiding in erosion control and sediment management via the sediment trapping and stabilizing properties of robust shellfish beds. In addition, ribbed mussels may promote other water quality metrics, such as those related to pathogens, because this species has the capacity to remove micron-sized bacteria (and possibly human pathogens) (Kreeger and Newell 2000), and ribbed mussels are not prone to the diseases that affect oysters (Dermo, MSX).

For these reasons, PDE believes that the greatest benefits to water quality can be attained via a diversified approach that targets both ribbed mussel and oyster conservation/enhancement. The presence of both oysters and ribbed mussels at this site made it a prime candidate for a multi-shellfish-based living shoreline approach. As the adjacent salt marsh had been observed to be eroding, shoreline stabilization was a stated goal of this effort, but the diverse shellfish community also allowed for an additional goal of water quality uplift via enhanced bivalve filtration,

Figure 2. Summary and timeline of living shoreline construction

Figure 3. Change in vegetated cover between June 30, 2014 (a) and June 5, 2018 (b) at one of the living shoreline treatments at the DuPont Nature Center at Mispillion Harbor, Milford, DE

To attain this water quality goal, materials appropriate for bivale recruitment and colonization were used to construct the living shoreline. Treatment materials were deployed between 2014 and 2015 to create a low intertidal oyster reef breakwater constructed using Oyster Castles® and oyster shell bags, paired with mid-intertidal bio-based components along the eroding salt marsh fringe comprised of coir fiber logs and oyster shell bags (Fig. 2). The mid-intertidal treatments were paired with untreated controls to measure the effects of the installations relative to no action. Results showed that despite severe ice and scour during the winter of 2014-2015, and several powerful coastal storms during fall 2015 to spring 2016, more than 90 percent of installed shellfish recruitment structures (oyster castles, shell bags) persisted (Moody et al. 2016). Many of the coir logs deployed in 2014 were rapidly washed away, unable to withstand the energy. The lost logs were replaced with oyster shell bags, configured in a similar fashion (Figs. 3a & b). The shell bag treatments along the salt marsh fringe trapped sediment and built elevation, resulting in an increase in vegetation robustness, reversing the erosion for a mean net waterward shoreline movement of 3.02m, building 85.3m^2 of salt marsh across the three treated areas (Fig. 3a &b). Conversely, the paired control sites showed a landward movement of 0.67m, for a net marsh loss of 33.3m^2. Additionally, sediments were captured among and landward of the low intertidal oyster breakwater resulting in an increase in the overall elevation across the intertidal mudflat. All results for the previous effort are summarized in Moody et al. 2016. Observations since then have indicated that the landward erosion of the control plots has continued, whereas the treated plots were stable, demonstrating that the net benefits of the living shoreline to marsh acreage continue to mount over time via loss aversion.

These previously reported results demonstrated that the Mispillion Living Shoreline achieved its stated erosion control goal, but to document water quality uplift a suite of additional biological metrics were collected. Bivalve mollusks, such as oysters and the ribbed mussels, are considered to be functionally dominant species in ecosystems where they are abundant (Dame 1996). Oysters and mussels meet their metabolic demands through filter-feeding, a behavior that accounts for their major ecological importance. These animals pump large volumes of ambient water over multiple sets of gills and sort particles to ingest. Through the process of filter-feeding, these animals remove particulate matter and reduce turbidity in their environment (Dame 1996, Kreeger et al. 2018). These types of physiological processes are influenced by multiple factors such as animal mass, water temperature, and food quality and quantity (Bayne and Newell 1983; Winter 1978). Water processing rates scale allometrically with the dry tissue weight of the individual bivalve (Christian et al. 2001; Winter 1978). Water processing rates by whole populations additionally scale with the density and size class structure of the actual population, which can vary widely among mussel and oyster bed locations.

To calculate the change in shellfish filtration capacity that resulted from the living shoreline treatment, oyster and ribbed musel populations were therefore monitored on all structures for density and size demographics, and these demographic data were then converted into shellfish biomass per unit area based on established species-specific relationships between shell length and dry tissue weight. These "biomass density" data were then integrated with species-specific water processing measurements from other studies, as well as Delaware Bay annual average total suspended solid (TSS) and particulate nitrogen (PN) data, to estimate changes in filtration capacity over time. Shell bags and oyster castles attracted moderate numbers of oysters and mussels in summer 2014 and comparatively higher numbers in 2015 and 2016. PDE estimated that the 2016 shellfish living shoreline population were capable of filtering 1,044 pounds of TSS and 28 pounds of PN (Moody et al. 2016). Although these results were promising, a variety of conditions and circumstances can affect the population dynamics of intertidal shellfish. We estimated that it could therefore take 5-10 years before the populations and their ecological functions would fully mature to provide maximum water quality benefits.

Due to the success of the existing living shoreline treatments in stemming erosion and promoting shellfish filtration services, in 2016 PDE proposed to agument the existing living shoreline to hasten the ecological development and coverage of shellfish at the study site. To do this, we proposed to abandon the paired control plots that were situated amongst the earlier 2014 treatments, by treating them living shoreline materials that had been shown to promote the greatest shellfish biomass density. Since shellfish recruitment, survival, and population coverage can likely be further enhanced with materials positioned in different configurations to encourage higher recruitment and predation refuge, this effort provided an opportunity to not only continue test new methods but to also strengthen our previous assessments of the water quality outcomes that resulted from the new tactics. Therefore, PDE directly measured the water quality benefits of the two functional dominant bivalve species that coexsist in different niches at this site, the eastern oyster and the ribbed mussel, by empirically asssessing their seasonal physiological rates at the Mispillion study site (rather than relying on data from other studies). These physioligical data could then be compared to regional estimates of water processing for the two species, helping us understand whether and how filtration services and absorption efficiencies at the Mispillion living shoreline may differ from other sites due a myriad of potential differences.

Finally, PDE partnered with staff at the DuPont Nature Center at Mispillion Harbor Reserve to convey key messages to the public regarding the water quality outcomes from LS investments. Outcomes from this new project were intended to lay the foundation for additional living shoreline projects elsewhere in the Mispillion River system and at other Delaware locations where shellfish-based living shorelines may be viable.

To meet the above goals of this effort, the following tasks were completed:

1. Water Quality Service Assessments of Mussels and Oysters
2. Construction Enhancements to Boost Shellfish Populations
3. Shellfish Recruitment Monitoring and Filtration Service Tracking
4. Comparisons of Water Quality Benefits Attained by Various Living Shoreline Tactics
5. Recommendations for Future Living Shorelines to Enhance Water Quality via Bivalve Shellfish
6. Living Shoreline Outreach

These methods and outcomes for each task are described below in detail.

Task 1: Water Quality Service Assessment of Mussels and Oysters

Methods

There is a strong desire to accurately quantify shellfish-based water processing and filtration activity in many marine, estuarine, and freshwater species, but there have been disagreements with how to properly investigate this behavior (Bayne 2001, Riisgård 2001) and standard methods have not been agreed upon by researchers (Cranford et al 2011). Therefore, methods are typically tailored to address specific questions related to clearance rates (e.g. optimizing for growth in a laboratory). The goal of this study was to measure the clearance rates of bivalves to estimate their contribution to water quality improvements via filter-feeding in natural settings that include living shoreline project sites in Delaware. The composition of natural seston can vary greatly and influence a bivalve's physiological response (Gardner 2002; Hawkins and Bayne 1984; Kreeger and Newell 2001) which supports using natural diets as an appropriate way to measure ecologically relevant physiological functions (Hawkins et al. 1998; Kreeger et al., 1988; Kreeger and Langdon 1994). This study followed the established methods of Kreeger & Newell (1996, 2001) which assesses the *in vitro* filtration rates of bivalves that are freshly collected from the study site and fed on natural diets from the study site, using simulated ambient conditions (temperature, tidal immersion period) to best approximate *in situ* conditions.

To investigate the physiological rates associated with bivalve feeding, digestion and egestion, three seasonal feeding trials were conducted in spring, summer, and fall. Details of the experimental approach, which uses static chamber containing individual bivalves, can be found in several earlier papers (Kreeger 1993, Kreeger and Newell 1996, Kreeger 2011). By conducting the physiological trials throughout the year, this approach captured season variation in both the fitness and reproductive status of the animals as well as natural variation in food composition (seston quality and quantity) and temperature (Table 1). For each trial, ribbed mussels and oysters were hand-collected at the DuPont Nature Center at Mispillion Harbor (Delaware Scientific Collecting Permits # 2018-FSC-007, 2019-FSC-007) with 60 L of ambient river water during an incoming tide approximately one hour post-low tide. Water temperature and salinity were measured with a handheld thermometer and refractometer, respectively. Animals were held in a water-filled cooler with aeration and ambient water was contained in carboys during transport to a non-climate controlled field station to avoid artificial cooling or warming during the experiment. Animals were gently cleaned to remove debris and other fouling organisms, and subsequently allowed to acclimate in a cooler for up to one hour in unfiltered river water. Trials were timed to coincide with natural incoming tides at the field site to simulate re-immersion. Ambient water was filtered through a sieve (53 µm opening) prior to use in feeding trials and seston processing, since neither ribbed mussels or oysters can effectively filter particles larger than 53 µm.

An array of feeding chambers (1000 mL) was set with ten ribbed mussel treatments, twenty eastern oyster treatments, and six controls. All chambers received 800 mL of sieved ambient water. Treatment chambers each received

Table 1. Summary of dates and water temperature and salinity of each seasonal feeding trial for oysters and ribbed mussels collected at the DuPont Nature Center at Mispillion Harbor, Milford, DE.

Season	Date	Water Temperature (°C)	Salinity (ppt)
Spring	2019-04-25	18.4	17
Summer	2018-08-03	27.5	25
Fall	2019-11-05	17.9	24

one pre-cleaned animal while controls did not receive an animal. Water in each chamber was sampled prior to adding the animal and then was sequentially sampled during the feeding trial after the animal was added. Prior to each sampling, water in each chamber was gently mixed using a clean tool (avoiding contact with animals and avoiding resuspension of any biodeposits if present). Visual observation of feces production and shell opening confirmed the initiation of feeding activity, at which point a 10ml water sample was collected every 30 minutes for two hours, resulting in five total samples per chamber. Each sample was transferred to a 20 mL vial containing ~400 µl of Acid Lugol's (for preservation).

In the laboratory, each 10 ml water sample was diluted with 10 mL of filtered isotonic solution (Isotone Diluent II) and processed using a Coulter Multisizer II, following Kreeger et al. (1997). Particle concentrations were assessed for all particles in each water sample that had nominal diameters between 2 and 63 µm, A clearance rate was determined for each beaker from the logarithmic depletion of particle concentration for the 2 hr. trial, as determined from the assessed particle concentrations in the five water samples collected per chamber (i.e. through the duration of the trial). Per chamber, the regression equation predicting the particle concentration over time was used to calculate the initial and final concentration for the 2 hour trial. The trial duration (2 hours), chamber volume (0.8 L), and initial and final particle concentrations were then used to calculate each chamber's clearance rate (L/hr) using the equation of Coughlan (1969). The clearance rates for chambers containing live mussels or oysters were then corrected for non-feeding factors (e.g. particle settlement, cell division) by subtracting the mean clearance rates assessed for control chambers having no live animals. Individual clearance rates per animal (L/hr/animal) were then converted to clearance rates per unit biomass (L/hr/g dry tissue weight) via allometry.

Concurrent with feeding trials, ambient water was analyzed for seston quantity and quality. Measured volumes of sieved (53 µm) ambient water were vacuum filtered, collecting seston onto pre-ashed and pre-weighed glass fiber filters. Samples of filtered seston were then frozen until processed per Kreeger et al. (1997). Seston filters were dried for two days at 60 °C and gravimetrically analyzed for Particulate Matter (PM) by subtracting the initial dry filter weight. Dried seston filters were subsequently combusted for two days at 450 °C to volatilize organic matter, and the remaining non-organic particulate matter was assessed gravimetrically, by subtracting the initial dry filter weight. The Particulate Organic Matter (POM) was then calculated using standard Loss-on-Ignition calculations. The ambient concentration of PM and POM (mg/L) was then determined by dividing the assessed weights per filter (mg) by the associated volume of ambient water that was filtered (L). The organic content of seston was calculated as the fraction of POM to PM (% of PM). Although not funded by this study, additional metrics regarding fecal/ammonia production and absorption efficiency were also collected and will be essential for a future assessment of nitrogen processing when funding can be secured. Statistics were run in R 4.0.2. Proportional data were arcsine square root transformed for analysis.

Results

Seston characteristics in the Mispillion River were assessed during summer 2018 (water temperature 27.5°C), spring

2019 (18.4°C), and fall 2019 (17.9°C). Mean allometric clearance rates for oysters and ribbed mussels ranged from 0.63 to 2.60 l hr^{-1} $gDTW^{-1}$ over three seasons (Table 2). Oyster clearance rates varied significantly among season ($p<0.001$; 1-way ANOVA Type II). A post-hoc Tukey test determined that clearance rates were greatest in fall when compared to spring and summer ($p<0.001$, both comparisons) while spring and summer rates were similar ($p=0.22$). Mussel clearance rates also varied significantly among season ($p<0.001$; 1-way ANOVA Type II). A post-hoc Tukey test determined that the pattern in seasonal clearance rates for mussels matched that of oysters, with greatest rates in fall when compared to spring and summer ($p<0.001$, both comparison) while spring and summer rates were similar ($p=0.90$).

Table 2. Summary of mean allometric clearance rates (l h-1 gDTW-1) for oysters and mussels from the Mispillion. SEM = standard error of the mean; N = sample size, gDTW = gram dry tissue weight.

	Spring			Summer			Fall		
	Mean	SEM	N	Mean	SEM	N	Mean	SEM	N
Eastern Oyster	0.99	0.12	13	1.13	0.11	14	2.60	0.30	17
Ribbed Mussel	0.63	0.09	8	1.16	0.21	7	2.46	0.25	10

Mean PM concentrations ranged from 36.4 to 112 0 mg/l. Mean POM concentrations ranged from 7.15 to 18.5 mg/l. The mean organic content was found to be between 16.6 and 19.6 % (Table 3). Seasonal PM concentrations varied significantly ($p<0.001$; 1-way ANOVA) with highest PM observed in spring compared to summer and fall ($p<0.001$, each comparison via post-hoc Tukey test). POM concentrations also varied significantly ($p<0.001$; 1-way ANOVA) with highest POM observed in spring compared to summer and fall ($p<0.001$, each comparison via post-hoc Tukey test). The mean organic content was observed to be significantly different among seasons ($p<0.01$). A post-hoc Tukey test determined organic content was greatest in summer than in spring ($p<0.01$) and fall ($p<0.05$) seasons, while similar between spring and fall ($p=0.81$).

Table 3. Summary of mean seston quantity and quality for oysters and ribbed mussels from the Mispillion River used to conduct seasonal physiological rate trials. SEM = standard error of the mean; N = sample size.

	Spring			Summer			Fall		
	Mean	SEM	N	Mean	SEM	N	Mean	SEM	N
Particulate Matter (PM; mg/L)	112	5.7	6	36.4	0.66	6	81.0	1.7	6
Particulate Organic Matter (POM; mg/L)	18.5	1.1	6	7.15	0.41	6	13.9	0.59	6
Organic Content (% of PM)	16.6	0.50	6	19.6	0.81	6	17.1	0.55	6

Interpretation

Mean clearance rates for both oysters and mussels increased from spring to summer and fall, with summer and fall clearance rates greater than 1 l hr^{-1} $gDTW^{-1}$ for both species. These results are well within the range of the reported spectrum for these species' clearance rates (Kreeger et al. 2018), and the large variability in literature data likely reflects the diversity of water temperatures, diet types and culture conditions where feeding trials have been conducted. In this study, the summer feeding trial was conducted at a temperature (27.5°C) on par with typical summer temperatures, whereas the spring and fall trials were conducted at times having anomalously higher temperatures (18.4°C and 17.9°C respectively) than what would be considered representative of those seasons (e.g., 12 to 15°C). Unfortunately, spring temperatures rose quickly and fall temperatures fell slowly, and therefore we were unable to assess these rate functions at the targeted "typical" seasonal temperatures. The warm spring water resulted in the shellfish rapid increasing their water processing, and maintaining high rates into the fall, surpassing the summer rate. Despite these anomalous seasonal patterns, both species demonstrated the ability to process water at a wide range of temperatures and salinities in concurrence with typical ranges reported in the scientific literature.

Two other important factors that can influence a bivalve's feeding rate is its nutritional status and the seston composition. The nutritional demands of adult bivalves vary widely throughout the year with cycles of reproduction, growth and quiescence. The quantity and quality of the seston that forms their natural diet also is known to vary widely across daily, lunar and seasonal cycles. The interplay between nutritional demands and food composition are rarely in balance. Thus, very low or very high levels of particulates, high seston inorganic contents, and insufficient essential nutrients (protein, fatty acids) can exert bottom-up limitation pressure on bivalve productivity. Bivalves have considerable plasticity in their feeding and digestive machinery, however. When they are nutritionally limited, bivalves can alter their feeding rates and physiological processing of seston in an effort to optimize net absorption rates for essential nutritional constituents. Although we did not assess the nutritional status of the bivalves studied here, we did assess metrics that describe the general quality and quantity of the seston that formed their diet; i.e., the bulk concentration food (PM concentration), its nutritionally available fraction (POM concentration), and bulk quality (% organic content). Generally, the seston followed typical seasonal patterns with greater PM in spring, likely due to greater spring flow, and lowest PM in summer. Mean PM concentration was more than double in the fall than in the summer. The concentrations of PM were high compared to typical concentrations in Delaware Bay, suggesting that food quantity was not a limiting factor for bivalves at the Mispillion study site. Accordingly, the organic content of seston at the site was observed to be relatively consistent despite the drastic shifts in PM and POM suggesting that food quality remains consistent over the growing season. As turbidity can influence filter-feeding bivalves through gill clogging, it is reasonable to consider that oysters and mussels may have reduced their water clearance rates in the spring in response to very high PM concentrations, whereas they may have filtered more normally during summer and fall when PM concentrations were more acceptable and typical of normal conditions.

Overall, the low salinity in spring coupled with high water temperatures in the spring and fall suggest that our physiological rate results for those times should be interpreted with caution because they might not be representative of more typical seasonal conditions. Specifically, the high fall temperatures potentially spurred greater-than-usual fall rates for water processing by the bivalves. In contrast, our measured clearance rates in spring might underestimate typical spring rates because our (lower) spring rates may have resulted from anomalous low salinity. To estimate the annual rate functions for the Mispillion oysters, we deemed that the lower-than-expected spring rates would generally balance against the higher than expected fall rates. Much of the "growing season" is dominated by summer, and our summer-measured rates appear to be reflective of typical conditions. Although the seasonal pattern for oyster and ribbed mussel clearance rates measured here may be somewhat anomalous, these data are still deemed to be useful in constructing a shellfish physiological database spanning a wide range of conditions for this specific site, and will provide useful data for existing regional databases. Future studies should expand on these physiological studies to bolster our understanding of the environmental and nutritional factors that govern oyster and ribbed mussel filtration rates in Delaware.

Task 2: Construction Enhancements to Boost Shellfish Populations

The goal of the new installation effort was to stem erosion of the marsh edge and facilitate sediment capture for waterward marsh migration in the previously designated control areas, while also providing increased habitat for the further colonization of shellfish for water quality uplift. Oyster shell bags proved to be the most stable material deployed in the original effort, and were selected as the primary material for the 2019 augmentation effort. Coir fiber logs installed in 2014 rapidly degraded along two of the three original marsh-edge cusps and were replaced by oyster shell bags in 2015 (Figs. 2 and 3a & b). Similarly, Oyster Castles ®, although stable for four to five years, began to degrade within three years if not fully colonized by oysters. Conversely, oyster shell bags retained their structural integrity and appeared to provide enhance habitat complexity through the provisioning of interstitial space between the shells. Additionally, it was observed that sedimentation occurred most rapidly along materials installed in a curved or bent configurations (Fig. 2, Oyster Castles ® Added 2015) but, it did not appear that contiguous connection to pre-existing marsh edge or other materials was necessary to retain sediment around structures. So although no faunal trapping occurred in or around the previously deployed structures, additional space for movement around the structures could be provided.

As such, the final treatment design consisted of a series of 10'x 1.5' oyster shell bag cups, perforated with 5' gaps

Figure 4. Oyster shell bags installed on March 15, 2019 in cusp (a-c) and wedge (d) formation to treat former control areas of the initial 2014 living shoreline effort on the living shoreline at DuPont Nature Center at Mispillion Harbor, Milford, DE.

between structures for fauna movement, to be placed along all three of the previous control areas (Figs. 2 & 4a-c). Additionally, a 20' stretch of highly eroding shoreline, just upriver from the previous installation, was treated with a shell bag wedge to provide stable connection between the mudflat and eroding marsh edge (Figs. 2 & 4d). On March 15, 2019, 700 bags of oyster shell were deployed by PDE and a group of five volunteers to install the structures. All structures began trapping sediment within one month (Fig. 5a & b), which has continued through the most recent monitoring activity in November, 2019 (Figs. 5c & d). Few shellfish were observed to have recruited to the newly installed materials as of November, 2019, which was not unexpected as the materials were only deployed for a single recruitment season. Additionally, as these structures were deployed in the high-intertidal, oyster recruitment will likely continue to be low, but ribbed mussel recruitment will likely increase (see Task 3). The observation of low initial ribbed mussel recruitment may be conservative, as mussels tend to colonize interstitial spaces before they become evident on the more visible edge and surface areas (Moody et al. 2020). As the shell bags have a large degree of interstitial space, it is likely that there were mussels present that were not be visible without bag dissection. These structures will continue to be monitored into the future, pending funding, to assess sediment trapping and shellfish recruitment capabilities.

Figure 5. Oyster shell bag cusps trapping sediment approximately one (a & b, April 25, 2019) and eight (c & d, November 22, 2019) months post installation.

Task 3: Shellfish Recruitment Monitoring and Filtration Service Tracking

Methods

To differentiate between populations of shellfish, and their associated filtration activity occurring at different locations across the living shoreline area, the site was delineated into three shellfish sampling areas (Fig. 6):

- Low Intertidal: The area that contained the oyster castle and shell bag breakwaters with a total surface area of 134.7m^2. Sampling occurred on the surfaces of all structures.
- Mid Intertidal: The open mudflat area between the low and high intertidal areas with a total surface area of 1,045.9m^2. Random sampling occurred in three sub-areas, each associated with one of the high intertidal living shoreline treatments along the marsh edge.
- High Intertidal: The surfaces of the oyster shell bags used to construct the three living shoreline treatments along the marsh edge in 2014. Sampling occurred on the top and waterward faces of the shell bags with a total area of 54.5m^2.

Since 2014, oyster and ribbed mussel population densities and demographics have been tracked on the surfaces in all sampling areas. Between 2014 and 2016 oyster and ribbed mussels were counted in their entirety on all materials in each area, and shell lengths were collected for a subset of oysters (but not mussels) and extrapolated to the entire population. No data collection occurred in 2017 due a lack of funding. In 2018 and 2019, it became more difficult to count both populations in their entirety due to a continuing increase in population size. As such, a random subsampling technique was employed using a 0.25m^2 quadrat in which all animals were counted and a subset of 10 oysters and ribbed mussels were measured. Random placement of the quadrat within each sampling area occurred as follows:

- Low Intertidal: Three locations on each level of each breakwater.
- Mid Intertidal: Twelve locations in each sub-area.
- High Intertidal: Three locations on the top and three locations on the waterward face of each living shoreline treatment.

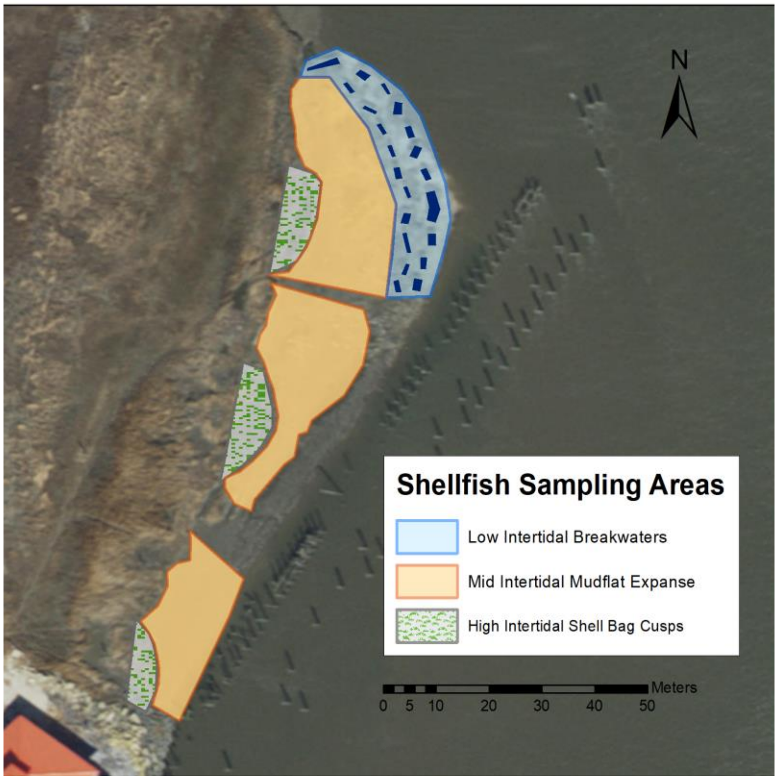

Figure 6. Overview of living shoreline sampling areas for shellfish monitoring.

Shellfish counts per sampling area were averaged and extrapolated to the total surface area available in each, as noted above, to calculate shellfish density each year, which were subsequently compared to assess changes over time. Size measurements for oysters and ribbed mussels were enumerated into 10mm size class bins, and histograms of size frequencies were generated using the histogram() function contained in the lattice package with bin size set to 10 mm using R version 3.0.3 (2014-03-06) -- "Warm Puppy". The bin distribution was subsequently applied to the total number of animals counted to calculate the estimated population size per size class per sampling area. The size class distribution of the total population was converted to estimates of biomass using previously determined relationships between shell height and dry tissue weight for oysters (Kreeger & Thomas 2004) and ribbed mussels (Moody & Kreeger 2020[a]). This allometric equation was used to predict the dry tissue weight for the geometric mean size of a shellfish in each 10mm size class, which was subsequently multiplied by the total number of animals in that size class per year in each subsection. Biomass estimates were then summed across size classes per subsection per year, for both oysters and ribbed mussels.

Total suspended solid (TSS) data were collected at the actual project site, but as these data only represent three time points (one per physiological rate trial in Task 1), a composite TSS dataset of over 1,500 samples collected in Delaware Bay by Kreeger et al. (2015) and from the "Lower Side DE" station (Latitude: 39.133333; Longitude: -75.366667), sampled monthly from January to November, during most months of 2009-2011, was employed. Since clearance rate data were seasonal, monthly TSS concentrations for TSS and pN were averaged per season (Table 4): spring (March-May), summer (June-August), fall (September-November), winter (December-February).

Table 4. Seasonal clearance rates (oyster; ribbed mussel) used to calculate filtration capacity of oysters and ribbed mussels at the DuPont Nature Center at Mispillion Harbor, Milford, DE living shoreline. Temperature and TSS describes the temperature range and average total suspended solid concentrations per season, respectively.

Season	Clearance Rate (l h^{-1} $gDTW^{-1}$)	Temperature (°C)	TSS (mg l^{-1})
Spring	0.31; 0.42	12-17	40.95
Summer	0.45; 0.61	20-25	29.21
Fall	0.31; 0.42	12-17	37.89
Winter	0.03; 0.05	00-09	33.73

Clearance rate refers to the volume of water processed by bivalves for particles removed per unit time (e.g., l h^{-1}). Since the clearance rates derived from physiological trials as a part of this work were deemed not representative of average annual conditions (see Task 1), data from previous physiological rate function studies (Kreeger 1986; Moody & Kreeger 2020[a, b]) were consulted to derive weight-specific seasonal clearance rates for ribbed mussels and oysters feeding at ambient temperatures on natural seston diets (Table 4). These weight-specific clearance rates were lower than what we measured in Task 1 and may be conservative since they are also lower than most literature accounts, but they have the full seasonal compliment of rates. They were therefore used to calculate the volume of water cleared per hour for each size class of animals per shellfish sampling area, per year using, the following equation:

$$Seasonal\ Clearance\ Rate\ per\ Size\ Class\ (l\ h^{-1}) = Seasonal\ Clearance\ Rate\ (l\ h^{-1} gDTW^{-1}) * Biomass\ per\ Size\ Class\ (gDTW)$$

Seasonal filtration rates were calculated using the following equation:

$$Seasonal\ Filtration\ Rate\ (mg\ h^{-1}) = Clearance\ Rate\ (l\ h^{-1}) * TSS\ (mg\ l^{-1})$$

Another factor that is important to consider is the limited feeding time per day at the different elevations of structure along the zonation gradient, since oysters and mussels can only filter seston when inundated. Therefore each sampling area was assigned a feeding time based on the average elevation of each sampling area relative to the local tidal datum. The low, mid, and high intertidal subsection were assigned the average inundation time of 20, 19, and 18 hours per day respectively. An adjusted seasonal filtration rate was calculated using the following equation:

$$Adjusted\ Seasonal\ Filtration\ Rate\ (kg) = Seasonal\ Filtration\ Rate\ (mg\ h^{-1}) * Inundation\ Time\ (h\ d^{-1}) * \left(\frac{365d}{4\ seasons}\right) * \left(\frac{1kg}{1{,}000{,}000mg}\right)$$

Adjusted seasonal filtration rates were subsequently summed to calculate the annual filtration capacity of oysters and ribbed mussels per sampling area. Annual filtration capacities were tracked between 2014 and 2019.

Results

The oyster population was largely comprised of smaller individuals until 2016, when a bimodal size distribution was observed (Fig. 7). Between 2018 and 2019, the population began to exhibit a normal distribution, with the majority of individuals in intermediate size classes, with some older, larger individuals and some smaller individuals entering the population. The numbers of individuals increased each year until 2019, when a decline (24%) was observed. Similar to oysters, the ribbed mussel population displayed a normal size distribution by 2018, with some additional larger, longer-lived animals observed in 2019. The number of ribbed mussels increased between 2018 and 2019 (Fig. 7).

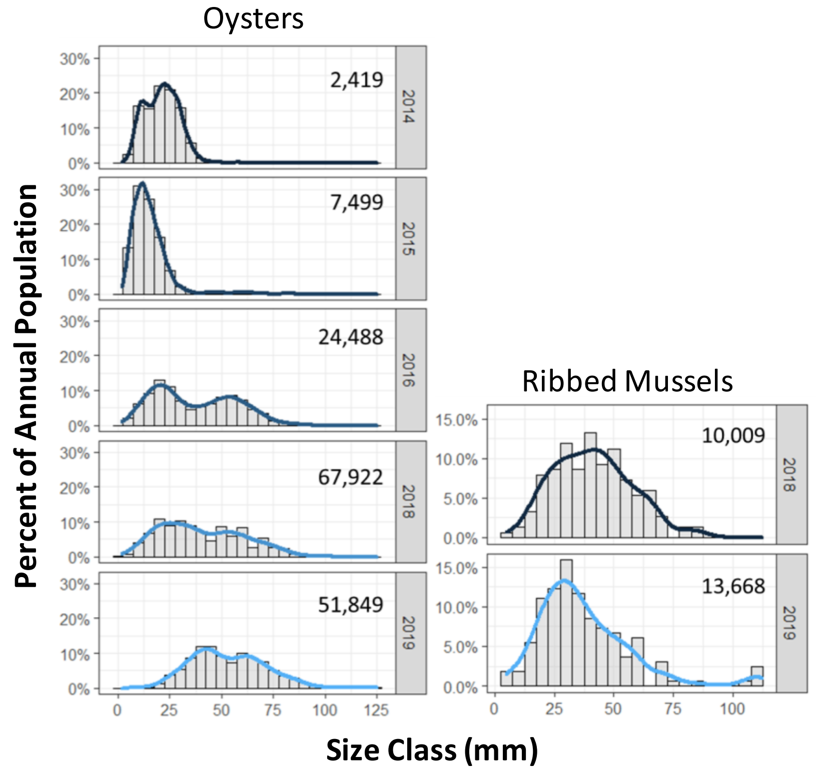

Figure 7. Size class distributions as a percent of the total population of oysters and ribbed mussels over time at the DuPont Nature Center at Mispillion Harbor living shoreline. Numbers in each histogram indicate the total number of individuals on the living shoreline. Numbers in each histogram indicate the total number of individuals on the living shoreline per year. Blue line denotes the density curve distribution for each year.

Total oyster density across the living shoreline increased between 2014 and 2018, but experienced a numerical decline in 2019 (Fig. 8a). In the low intertidal area, a decline was observed since 2016, but increases in oyster density in the mid and high intertidal between 2016 and 2018 compensated for the loss. In 2019, a decline was observed in low intertidal locations, with the high and mid intertidal areas generally maintaining their density. This resulted in an overall decline in oyster density in 2019, but biomass continued to increase between 2018 and 2019 (Fig. 8c). Ribbed mussels experienced an increase in density between 2016 and 2019 across all habitats (Fig. 8b) with the greatest increase in the high intertidal, but no change in biomass was observed (Fig. 8d). Ribbed mussels were not measured in 2016; as such, no biomass data were available.

The overall filtration capacity of the shellfish population on the living shoreline increased from 13.63kg in 2014 to 2,025.60kg in 2019 (Fig. 9). Oyster filtration capacity was low in 2014 (13.63kg) and 2015 (26.77kg), but began to rise two years after construction with further increases in 2016 (462.20kg), 2018 (1,064.67kg), and 2019 (1,743.19kg). Ribbed mussel contributions to filtration capacity were not measured until 2016 (11.67kg), but rose in 2018 (294.62kg) and declined slightly in 2019 (282.41kg).

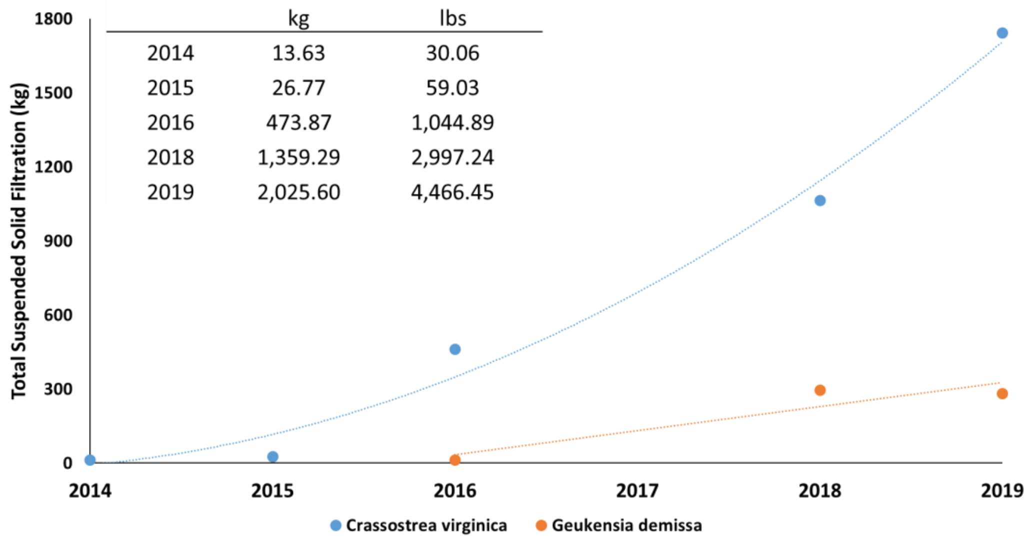

Figure 8. Total suspended solids (TSS) filtration by oysters (Crassostrea virginica, blue) and ribbed mussels (Geukensia demissa, orange) between 2014 and 2019 on the DuPont Nature Center at Mispillion Harbor living shoreline.

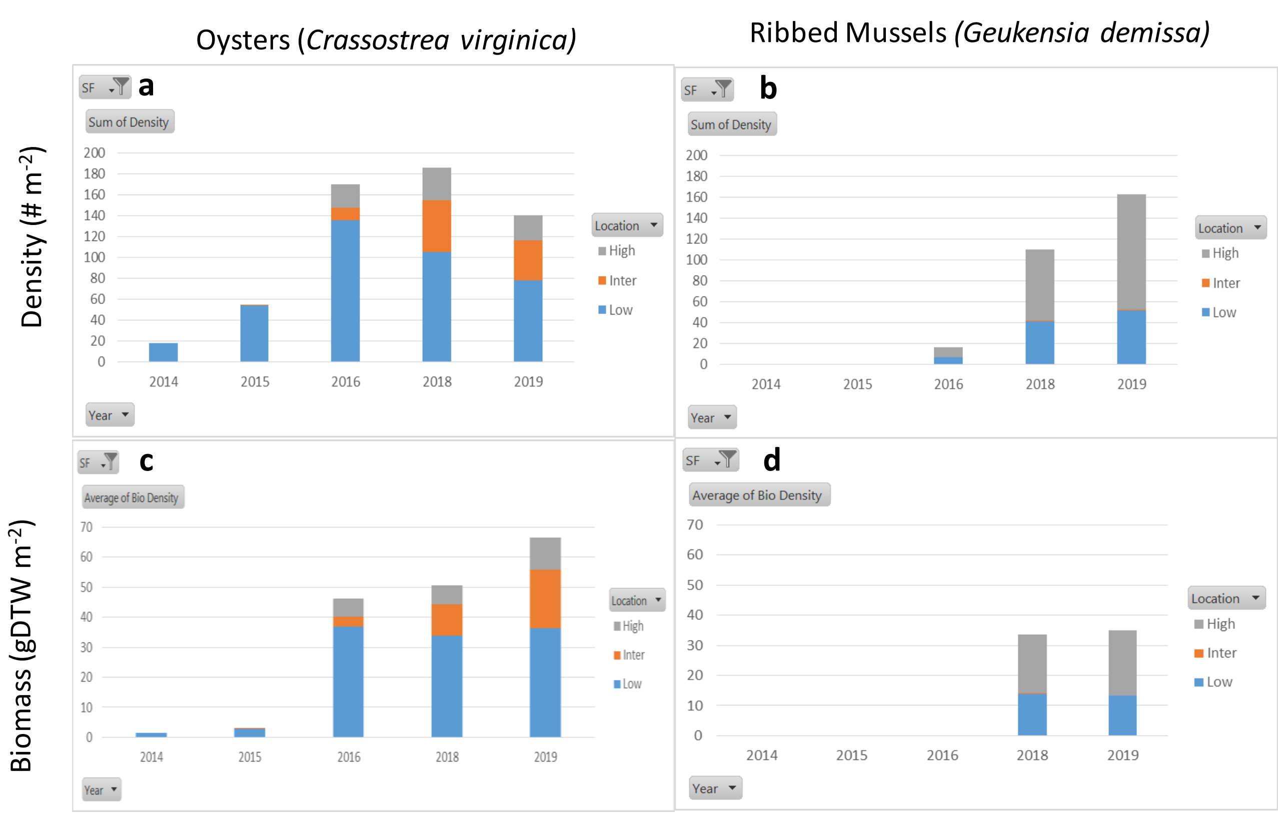

Figure 9. Shellfish population metrics by year for each monitoring area (High, Medium, Low). Metrics include shellfish density (a,b) as the individuals per square meter and biomass(c,d) as the grams dry tissue weight per square meter, for oysters and ribbed mussels, respectively.

Interpretation

For shellfish populations to persist and enhance water quality through the expansion of their population-level filtration capacity, it is not just important to have a large number of individuals present, but also to have individuals of a variety of ages (i.e., sizes). During recruitment events, a large number of individuals may settle, but they will have a very low impact on filtration capacity due to their small size and low summed biomass. Population-level filtration begins to materially increase when some of those individuals survive and grow in body size (to 30-75mm). As mortality tends of affect the youngest and oldest portions of the populations, it is important to have some years of good recruitment but also to have years of good recruit survivorship that allows more individuals to persist (e.g. over winter) and grow into the intermediate size class. Since filtration scales with biomass, it is these larger-sized animals that persist that become the filtration "workhorses," dominating the overall seston filtration rates. As some individuals are able to move into the largest size classes (75-100+mm), greater filtration benefits are observed, but in stable populations, this cohort doesn't represent the bulk of individuals. For shellfish-based living shorelines, a normally-distributed population has a large number of individuals in the intermediate size class to do the work, with support from a smaller percentage of older, larger individuals, and a number of younger, smaller individuals to grow and replenish the larger size classes over time.

The inter-annual trend in oyster distribution data (Fig. 7) highlights that it takes time for a stable (i.e., normal) population to develop. Substrate was deployed in 2014 and although recruitment began that year, it took an additional two years for the population to develop a normal size distribution, while it also expanded spatially. Severe icing and cold temperatures in the winter of 2014-2015 likely resulted in high mortality that prevented many initial 2014 recruits from surviving and growing into 2015. In contrast, the mild winter of 2015-2016 allowed a more sizeable portion of the 2015 population to persist, which is reflected in the greater proportion of larger individuals measured in 2016 relative to 2015. The decrease in the numerical abundance of oysters between 2018 and 2019 was not unexpected, as oyster populations in the Delaware Bay experienced high mortality due to cold temperatures and excessive icing (Dave Bushek and Jenny Paterno, Rutgers Haskin Shellfish Laboratory, personal communication). During that event, it was estimated that many Delaware Bay oyster populations experienced mortality in excess of 50%, whereas the 24% mortality observed on the Mispillion living shoreline was not considered severe.

Although the number of oysters and their density declined between 2018 and 2019, oyster biomass continued to increase (Figs. 8a & c). This indicates that despite the mortality, older and larger individuals were able to survive and continue to grow, while also serving as broodstock to supply fresh recruits to the system. As filtration services are driven by biomass, the functional population-level filtration capacity was able to compensate for the loss in numbers with the expansion in biomass due to this survivorship and per-animal biomass growth. This is evidenced by the increased filtration capacity also observed between 2018 and 2019 (Fig. 9), and highlights the need for a robust, diverse sized population. For maximal filtration services, there is a need to maximize biomass, but a continuous supply of natural recruitment is also required to allow older animals to be replaced as they eventually die. Continued recruitment may also allow for further horizontal and vertical expansion of the oyster reef complex.

On this living shoreline, habitat materials were deployed across three separate areas of the intertidal zone (Fig. 6). As oyster density declined in the low intertidal, possibly due to increased interactions with ice or debris, there were other areas of the intertidal able to compensate for those losses by maintaining densities and growing (Fig. 8a & c). Conversely, the stability of ribbed mussel biomass with increasing density (Figs. 8b & d), coupled with the left shift in mussel size class distribution between 2018 and 2019 (Fig. 7), likely indicates a die-off of larger, older individuals during the winter of 2018 coupled with a large recruitment event in 2019.

Filtration capacity for both oysters and ribbed mussels has continued to increase on the living shoreline since installation in 2014 (Fig. 9). Oyster filtration has been growing at an increasing rate since 2016, while ribbed mussel filtration has shown a more linear growth profile (Fig. 9). The “slower” growth rate of ribbed mussel filtration may be conservative due to differences in oyster and mussel positioning tendencies. Many of the structures were composed of oyster shell bags, and whereas oysters tend to settle to the surface of materials where they cement themselves, ribbed mussels settle and, due to their ability to continually reposition themselves, move into protected spaces. Moody et al. 2020 found that on average, 93-95% of a total shell bag population of ribbed mussels are positioned internally in the interstitial space between the shells. Shellfish monitoring on this living shoreline was non-destructive, and as such, shell bags were not dissected to quantify an absolute mussel density. Therefore, the population-level measurements of ribbed mussel filtration likely underestimates actual rates because our assessment captured only those individuals that were visible without investigating the internal space of the materials. Assuming that that these surface counts truly only comprised ~10% of the total bag population, there may be 10x the ribbed mussel biomass reported here, and thus filtration capacity, contained within the bags

Task 4: Comparisons of Water Quality Benefits Attained by Various Living Shoreline Tactics

In this region, oysters are predominantly subtidal, settling on available surfaces and building reefs. But due to warming temperatures and more mild winters, oysters are becoming increasingly common in low intertidal areas and this expansion of the intertidal zone is likely to continue with climate change. Although the availability of subtidal habitats for oysters may decrease with climate change (due to the geospatial and disease factors), oysters will likely experience a niche expansion along intertidal shorelines in the Delaware Estuary. This presents significant opportunities for working with nature’s change trajectory to increasingly incorporate oysters into shoreline projects in Delaware.

Ribbed mussels, although able to persist subtidally, are physiologically optimized to be positioned higher in the intertidal zone where the internal heat generated from the sun during emersion enhances digestive enzymatic activity and allows for a longer digestive period of a more typically refractory food resource (e.g. detritus and associated bacteria). The lower bounds of ribbed mussel distribution is also governed by predation pressure from blue crabs, which is why the presence of interstitial spaces is important because it provides predation refugia. Additionally, ribbed mussels have a facultative mutualism with the salt marsh cordgrass *Spartina alterniflora*, where the roots of the grass provide an attachment surface and stability for the mussels to burrow in the marsh surface, whereas the mussel benefits the plants by aiding in fertilization via their biodeposition of nutrients in feces and pseudofeces as well as helping with oxygenation via bioturbation.

The three sampling areas of the intertidal zone where shellfish were tracked each contained different living shoreline materials with different goals, and also represent three different ecological niches for the two species of shellfish. These areas were:

- Low Intertidal: Shell bags and oyster castles were deployed to act as independent breakwaters to attenuate energy moving towards the shoreline; primarily considered better oyster habitat due to longer immersion times
- Mid Intertidal: No treatments were directly deployed into the area, but shell had begun to collect over time across this expanse, likely due to the reduced energy from the waterward low intertidal treatments; this area represents a non-treated adjacent area that may possibly gain benefits of the proximate living shoreline materials; not considered primary habitat for either oysters or ribbed mussels-the presence of expanding

shell substrate would provide settlement surface for either shellfish, but the instability of the area may preclude persistence

- High Intertidal: Shell bags deployed to create cusps connected to the marsh edge (Fig. 3) intended to trap sediment and facilitate the expansion of the existing *S. alterniflora* community into the treatment area; primarily considered ribbed mussel habitat due to longer emersion times and the proximity to, and potential presence of, salt marsh cord grass

The low intertidal habitat was primarily colonized by oysters (Fig.8). In 2016, 80% of the oyster biomass was located in the low intertidal, with 7% and 13% in the mid and high intertidal, respectively. By 2018, the mid intertidal oyster biomass had grown to 20% at the expense of the low intertidal (67%), and continued to grow in 2019 to 29% (low and high intertidal 55% and 16%, respectively). These data suggest that as the intertidal expanse continued to collect shell across the pre-existing mudflat, its habitat value for oysters increased, and as such settlement and persistence occurred. This is an example of the expansive nature of oyster reefs, and highlights the scalability of constructed reefs to provide benefits outside of their construction footprint if they are able to create the conditions necessary for expansion.

Ribbed mussel biomass was primarily concentrated in the high intertidal (Fig. 8). Between 2018 and 2019, biomass expanded in the high intertidal (58% and 62%, respectively) while decreasing in the low intertidal (41% and 38%, respectively). Biomass in the mid intertidal was negligible. These data indicate that on this living shoreline ribbed mussels are primarily found in their primary ecological niche, but that they can also be found outside this area (i.e., low intertidal), if substrate is available. That ribbed mussels were not present in the mid region may be a result of the instability of the substrate (e.g., collected shell that can be moved easily by either water action or scavengers), and/or lack of predation refugia. As only two years of ribbed mussel biomass data have been collected, future monitoring is needed to investigate if ribbed mussel biomass in the high intertidal will continue to expand at the expense of the low intertidal, to provide a clearer picture of habitat preference.

These results show that a living shoreline installation can be designed to target specific shellfish life histories and ecological needs to maximize oyster and ribbed mussel filtration capacity across the whole project site. Substrate positioned in the low intertidal was successful in promoting primarily oyster biomass, whereas materials placed in the high intertidal was successful in promoting ribbed mussel biomass (Fig. 8). As a result, filtration capacity has continued to grow each year on the living shoreline. It remains unknown whether the intervening "mid-intertidal" space will eventually become colonized by one or another shellfish species, but in natural settings the vertical ranges of ribbed mussels and oysters often overlap, with oyster recruits sometimes attaching to ribbed mussels, and oyster reef structures often providing refugia for ribbed mussel colonization. When designing shellfish-based living shorelines, it is therefore possible to make use of the variety of niches available to target different communities, and to utilize knowledge about the ecologies of different shellfish in material selection.

As oysters settle and cement to their substrate, materials that are clean of biofouling and which provide a large degree of surface area appear to be optimal. This allows oysters to settle in formations similar to natural reef building processes, whereas materials with a high degree of interstitial space many result in internal oyster settlement, which may ultimately smother many of the animals if they are unable to access food due to positioning away from direct water column access or sedimentation. Conversely, the ability of ribbed mussels to continually reposition themselves make materials with a high degree of interstitial space desirable for that species. Small recruits at low density are able to take advantage of the refuge provided by the space, which are then able to reposition themselves as density grows and sedimentation occurs. On flat surface areas, ribbed mussels are more vulnerable to predation as the attachment strength of their byssal threads is lower than that of oyster cement, but when they can form “mussel clumps” there is safety in numbers and the clumps are impenetrable by predators.

Task 5: Recommendations for Future Living Shorelines to Enhance Water Quality via Bivalve Shellfish

The data collected on the Mispillion living shoreline provides evidence that this restoration effort is *functioning* as a living shoreline and achieving the stated goals of ecological enhancement, erosion control, and promotion of water quality. The emphasis on the project’s functional traits is because there has been a quantifiable beneficial ecological response, with enhanced ecosystem service rate functions, to the installation of the living shoreline materials. The goal of erosion control has been met through the increased elevation and vegetation robustness along the edge of the salt marsh, resulting in a net waterward movement of the shoreline and a substantial gain in salt marsh habitat area (see introduction). Importantly, this outcome of the project can be interpreted as a continued net gain in wetland acreage every year because of loss aversion because the untreated marsh areas have continued to erode. The goal of water quality uplift has been met as evidenced by the increase in shellfish biomass across all three areas of the living shoreline, resulting in a continuing expansion in water filtration capacity each year (Fig. 9).

Although the efforts to design, implement and adaptively manage the Mispillion Living Shoreline have met the project’s goals, it will be important to continue monitoring the site for two reasons. First, as previously stated, ecological function can be compromised by a variety of natural and anthropogenic factors, and living shorelines can be regarded similar to “gardens that need to be tended.” Second, the ecological development of the site has still not reached a successional climax, and the ultimate outcomes will take more time to be understood; hence, it will be important to continue to track its trajectory. Tracking of shoreline stability and shellfish populations will provide us with the necessary information to identify potential deficiencies before they have an opportunity to grow and potentially compromise the living shoreline’s progress.

The concept of a living shoreline as a garden that needs to be tended and periodically augmented does not necessarily mean that it is less effective or more costly than traditional shoreline stabilization tactics (e.g., bulkheads, rip rap). Historically, it was believed that a benefit of hardened, unnatural infrastructure, was that it needed little attention. That line of thinking has been disproven as many of the structures built to provide protection were compromised during Superstorm Sandy as well as subsequent Nor’easters. With climate change and sea level rise, most shorelines will continue to erode landward without some form of sustained intervention and investment, and decisions about whether to intervene and how should be based on goals of local resource managers and landowners, and of course economics (similar to decisions about beach replenishment projects). All shoreline structures can benefit from monitoring to ensure their sustained structural integrity, and living shorelines that seek to enhance ecological conditions should also be assessed for their ecological integrity to ensure that they are providing the intended ecological benefits.

Living shorelines are a new technology, and it is also important to provide the practitioner community (e.g., private, public, and academic partners interested in understanding the benefits and limits of living shorelines) with information regarding tactic outcomes and trajectories. There are few long-term living shorelines available in Delaware, and the Mispillion living shoreline is crucial in providing a case study to transfer technology and to promote an enhanced understanding of the tactic’s benefits. Continued monitoring of the living shoreline will help inform future efforts in terms of tactic selection, outcomes, and ecological succession trajectories.

To build on these data sets and continue to provide this valuable information, the following activities are suggested for continued investment at the Mispillion Living Shoreline project site:

1. Continued monitoring of:

    a. Lateral Migration and Elevation of the Vegetated Salt Marsh Edge: Lateral shoreline movement rates and their variability will provide valuable information regarding appropriate expectations regarding rates and elevation requirements for salt marsh expansion. Additionally, assessments in directly treated and untreated areas will inform expectations regarding positive effects in areas outside the treated footprint of the living shoreline.

    b. Vegetation Development Within and Landward of the Longshore Vegetated Treatments: As the position of the vegetated shoreline changes, vegetation communities may develop at different rates depending on a variety of biogeochemical conditions. Since vegetation density and sedimentation are positively correlated, and as sedimentation can increase elevation leading lower inundation and greater temporal resiliency in the face of sea level rise, understanding the relationships between these factors, within and landward of the treatments, will inform developmental resiliency trajectories at this site and beyond

    c. Geospatial Shellfish Population Densities, Demographics, and Associated Filtration Rates: As stated, shellfish populations can be affected by a variety of natural and unnatural circumstances. Continued monitoring of shellfish population development across multiple areas of the living shoreline will provide valuable data to better understand the development trajectories of shellfish communities and their associated services across multiple niches. These data will inform living shoreline design efforts as well expectations regarding nutrient removal and sequestration. Additionally, the vast mid-intertidal area was not treated with recruitment materials, but has begun to develop a residential shellfish population as a result of the, likely, physical effects on flow dynamics and natural substrate collection of the near-by installed materials. Tracking the development of this spatial population can inform expectation regarding positive outcomes of shellfish-based living shorelines outside of their construction footprint.

    d. Shellfish Recruitment within Shell Bags: As discussed in Tasks 3 & 4, non-destructive monitoring has likely led to an underestimation of shellfish biomass and filtration services on the living shoreline, especially with regard to ribbed mussel populations. A subsampling effort of a shell bags of a variety of ages will provide valuable information regarding population development within protected shell bags and a better estimation of annual filtration capacity.

2. Additional Physiological Trials to Quantify Seasonal Clearance Rates across a Temperature and Salinity Gradients: The three trials conducted under this funding stream have been highly informative regarding water processing rates at this site under high temperature conditions. To better understand the seasonality of shellfish filtration and to construct a more accurate average of annual services, trials aimed at (more typical) lower temperatures in the spring and fall are required. Further, experiments conducted at similar temperatures but varying with regarding salinity will provide the information required to estimate service provisioning under a variety of future conditions including warming water and lowering of salinities from increased precipitation.

3. Process Samples Collected in Previous and Future Physiological Trials: During physiological trials, samples are collected that can provide information regarding filtered nitrogen partitioning by the animals, including background nitrogen concentrations and shellfish feces, excreted ammonia, and shell and body

tissue nitrogen concentrations. Having these samples processed for nitrogen concentration will allow for a mass balance calculation of the fates of the filtered nitrogen including how much is returned to the system (ammonia), how much is deposited in to substrate to enter the microbial food web (feces), and how much is incorporated in to shell and somatic tissues. The goal of these data will be to understand the absorption efficiencies of the shellfish to quantify the net impact on nitrogen removal (short and longer term).

In addition to these recommendations for the Mispillion site, we recommend that additional hybrid living shoreline sites be identified and similar projects implemented. Every shoreline site has unique physical, chemical and biological conditions, and the methods that were developed and adapted will likely need to be modified for different conditions (e.g. slope, fetch, goals). Having more living shoreline project sites around the State of Delaware would also enhance outreach, research and contractor training opportunities. PDE can provide examples of other potentially suitable sites upon request.

Task 6: Living Shoreline Outreach

The main goal of the outreach portion of the project was to work with DuPont Nature Center staff to research, design, create, and install an interactive display about living shorelines and the benefits that they provide to communities and for improved water quality. Early in the project timeline, extensive time was dedicated to researching fabrication options and companies who were able to build an exhibit on living shorelines.

After some research, a connection was made with Scott Shaw, who serves as the chair of the Game Design and Development Program at Wilmington University. Scott has extensive expertise in “gamifying” educational displays to make them intriguing and interactive. By partnering with the University, we were able to engage students to help design and build the display which provided them with an opportunity to work on a real world project. Overall, this partnership was a huge success and something we will continue to explore in the future.

After a few preliminary phone calls, an in-person meeting took place with DNREC, PDE, and Wilmington University in December 2018 to discuss design options for the display, as well as installation logistics related to the available space for the exhibit. Because the main audience that visits the nature center are families with young children, retirees, and preschoolers, we needed to create a product that would be intriguing across all age groups. Ultimately, the group decided that the display would consist of a 5-foot long 3D living shoreline landscape with arcade style buttons for “living shoreline elements” (Figure 10). When a button is pressed, an image of the corresponding element appears on the TV screen. Information about how that element is important to a living shoreline is delivered in both subtitle format and by voiceover audio to accommodate all audiences.

Figure 10. The finished living shoreline display at the DuPont Nature Center at Mispillion Harbor Reserve in Milford, DE.

Eight living shoreline elements are featured in the display including objects that are used to construct living shorelines as well as plants and animals that live in these habitats. The eight elements include coir log, oyster castle, *Spartina alterniflora*, fiddler crab, American oystercatcher, oyster, ribbed mussel, and mud snail (e.g. Figure 11). Topics including erosion, water quality, and land water connection are incorporated into the description of each of these elements and communicates the importance of living shorelines for providing habitat and clean water for plants, animals, and people. Lastly, the 3D living shoreline landscape includes representations of the shoreline before, during, and after the installation of the living shoreline to demonstrate how these projects connect land and water environments and serve as a visualization for how they can help protect shorelines from erosion (Figure 12).

Figure 11. Photo of fiddler crab that is displayed as part of the exhibit. This is a 3D model of a fiddler crab and the user can rotate the image on the screen using the joystick.

Figure 12. Up-close view of a section of the 5-foot long 3D living shoreline landscape featuring representation of a shoreline that has recently had a living shoreline installed including coir logs and oyster castles. Other areas of the landscape show a shoreline with no living shoreline and a shoreline with a mature living shoreline that is inhabited by Spartina alterniflora.

PDE and DNREC wrote narratives with information about each of the eight elements. A voiceover audio recording was created by a student at Wilmington University to accompany the text on screen. In addition, students created 3D pictures of the elements and other University staff helped build the 3D living shoreline landscape. The landscape includes labels and with a key for each of the elements to help visitors identify where the items are located along a living shoreline.

The exhibit was installed in August 2019 and tested over the following few weeks. A reception was scheduled for September 2019 to unveil the living shoreline display to the public and local leaders. Throughout the summer, the DuPont Nature Center hosts “lunch and learn lectures” on various topics with invited guest speakers. The unveiling event was planned to coincide with a lunch and learn lecture with a PDE scientist presenting on the living shoreline and other ecosystems of the Delaware Estuary. After the presentation, DNREC and PDE would introduce the new display and PDE staff and scientists would answer questions while attendees interacted with the exhibit. Unfortunately, the day of the event overlapped with a spring tide, and the local road leading to the nature center was inundated with water and vehicle passage was not possible. Because the nature center is only open to the public from April to September, the event was postponed to spring/early summer 2020 and PDE and DNREC rescheduled the reception for June 3, 2020.

Unfortunately, due to the COVID-19 pandemic, the unveiling reception was cancelled. The State of Delaware was operating under a state of emergency and anticipated a rolling reopening of the economy starting June 1, 2020, however, gatherings of groups more than 10 indoors was discouraged. Both PDE and DNREC agreed it was inappropriate to promote and host an in-person event during this time. While this is disappointing, PDE remains committed to working with the Nature Center when possible in the future and promoting the living shoreline display on social media once it is appropriate for the public to visit the nature center.

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