An Analysis of Material Use in Living Shorelines

by

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Executive Summary

Coastal areas are increasingly facing compounding challenges, including sea level rise, storms, geomorphic change, and population increases and development. Historically, coastal flooding and erosion have been managed through the addition of "hard structures" to the shorelines, such as seawalls, bulkheads, and dikes. Unfortunately, hard structures result in several adverse impacts, such as increased wave energy, erosion to adjacent properties, and high construction and maintenance costs. Nature-based solutions, such as living shorelines, are increasingly utilized as an alternative to hard structures due to their associated environmental benefits, including coastal protective services, improving water quality, decreasing runoff, and increasing habitat and biodiversity. A variety of materials are used to construct living shorelines, such as oyster shell and rock, although there are knowledge gaps surrounding the most effective design of artificial structures.

Drawing on evidence from intertidal rocky shorelines, habitat complexity, including surface heterogeneity, is positively associated with increased biodiversity. Considering the positive association of surface complexity on increasing species abundance, the addition of surface heterogeneity on living shoreline structures should be further researched. This paper aims to explore the materials used to construct living shorelines, and how changes in the surface heterogeneity of these structures influence eastern oyster abundance. This paper seeks to understand the following questions: 1) how does manipulating the surface heterogeneity of artificial reefs affect eastern oyster abundance, and 2) what is the distribution of different living shoreline materials over time in the United States?

To understand how altering the surface heterogeneity of artificial reefs affects eastern oyster abundance, we developed a field experiment in collaboration with Natrx, a Raleigh-based coastal resilience solutions company. For the experiment, we added four treatments (one treatment with scratches, one treatment with holes, one treatment with a combination of both scratches and holes overlaid, and one control treatment with no modifications) onto each of the four sides of six small-scale 3D-printed naturalistic reef structures, known as ExoForms™. These ExoForms™ were placed in an intertidal marsh off Pivers Island, North Carolina, and regularly monitored for five months. We found that the ExoForm™ treatments with modifications that increased the surface heterogeneity (the treatments with holes, scratches, and combination) led to a considerable rise in oyster abundance during the sample dates. These results indicate that increasing the surface heterogeneity of artificial structures significantly increases oyster abundance. Other species were observed utilizing the structures, including some predators of eastern oysters. We recommend future studies to explore the predator-prey interactions to better understand their overall impact on oyster abundance.

To understand variation in material use in living shorelines over time, I conducted a scoping review of living shorelines along the entire United States coastline. This review identified peer-reviewed, primary literature found in Web of Science that involved a physical living shoreline in the United States. 66 full-text papers were identified in this search, and from these papers, 182 independent living shorelines were identified. The materials used in the living shorelines were divided into seven categories: concrete, rock, wood, mussel, oyster, vegetation only, and alternative novel substrates. Based on this analysis, we found that Florida, North Carolina, Virginia, and Alabama are leading living shoreline project installation, while Florida, Alabama, and New Jersey have the highest usage of alternative novel substrates. Oysters and rock are overall the most commonly used materials. Alternative novel substrates are still used

much less frequently than oyster, rock, wood. However, this may reflect limitations in the design of this review because information about the use of alternative novel substrates may not yet be widespread in peer-reviewed, primary literature. To address this gap, future studies should include additional databases and sources of living shoreline project information.

Altogether, my results show that increasing the surface heterogeneity of artificial structures increased eastern oyster abundance, and that while alternative novel substrates are increasing in use, they are still utilized much less frequently than wood, rock, and oysters. The benefits of living shorelines—particularly when compared to traditional hard structures, make them a useful tool when mitigating hazards like flooding and storm surges. Considering the increasing impact of these hazards on coastal areas, it is likely that living shorelines will continue to be implemented as a coastal resilience strategy. It is crucial to understand the most appropriate and efficient designs and materials to further living shoreline implementation.

Introduction

Coastal areas are increasingly impacted by flooding resulting from several intersecting factors, including sea level rise, storm surges, population increases and development, and geomorphic change (Zhang et al. 2004, Costanza et al. 2008, Neumann et al. 2015). An interest in coastal resilience and nature-based solutions has grown in recent decades to mitigate these challenges in coastal areas. However, the growing popularity of the term "coastal resilience" has led to confusion surrounding the phrase as a concept, term, and restoration goal. Here, we define coastal resilience as "the capacity of the socioeconomic and natural systems in the coastal environment to cope with disturbances, induced by factors such as sea level rise, extreme events and human impacts, by adapting whilst maintaining their essential functions" (Masselink et al. 2019).

Historically, coastal flooding and erosion have been managed through the use of "hard structures," such as bulkheads, breakwaters, dikes, and seawalls. Hard structures are currently the most utilized coastal management option–approximately 14% (12,500 miles) of shorelines in the United States are hardened using these practices (Gittman et al. 2015). However, there are many adverse environmental impacts associated with hard structures (Arkema et al. 2015, Scyphers et al. 2015, Gittman et al. 2016). Because hard structures deflect and magnify waves, they cause stronger waves and increased erosion at adjacent properties (Bilkovic and Roggero 2008). Hard structures are often associated with high construction and maintenance costs as they can require frequent reconstruction (Gracia et al. 2021, Angnuureng et al. 2023). Hard structures do not fare well during storms; Hurricane Irene in 2011 damaged 76% of bulkheads in the Outer Banks, while none of the studied living shorelines sustained damage (Gittman et al. 2014). Thus, nature-based infrastructure such as living shorelines are increasingly utilized to manage coastal flooding and erosion. The most common nature-based infrastructure utilized are living shorelines (Sutton-Grier et al. 2015).

The definition of a "living shoreline" varies greatly across the literature (Smith 2020). Here, we define living shorelines as "a type of coastal protection method that utilizes habitat restoration, sometimes combined with a built structure, to support coastal protective services" (National Oceanic and Atmospheric Administration 2015). A variety of materials have been used in the construction of living shorelines, ranging from rock, concrete, wood, marsh plants, and oyster shell. Compared to hard structures, living shorelines are more resilient to sea level rise because plant and oyster growth can keep pace with rising waters (Currin et al. 2008, Rodriguez et al. 2014) and allow for the marsh to migrate naturally over time (Bilkovic et al. 2016, Peterson 2019). In addition to their protective services, living shorelines further ecosystem services, including improving water quality, decreasing runoff and storm surges, and increasing critical habitat for ecologically and economically important species, such as the blue crab (*Callinectes sapidus*) and eastern oyster (*Crassostrea virginica*) (Scyphers et al. 2011, Gedan et al. 2011, La Peyre et al. 2014). Oysters are often utilized when constructing living shorelines due to their widely documented benefits. Oysters improve water quality through filtration, decreasing nutrients, and sequestering carbon (Coen et al. 2007, Grabowski et al. 2012). Oysters also provide habitat for invertebrates and increase fish production, as well as increase the biodiversity and diversification of the ecosystem (Stunz et al. 2010). Oysters are particularly important for coastal areas impacted by erosion and flooding, as oyster reefs stabilize adjacent habitats and habitats (Scyphers et al. 2011). Oysters have long had economic importance and cultural significance in coastal communities (Kirby 2004).

Oyster populations and natural oyster reefs have been degraded due to several human impacts, including overharvesting and disease (Kirby 2004, MacKenzie 2007, Grabowski et al. 2022). The degradation of natural oyster reefs and their associated ecosystem benefits have furthered interest and funding in oyster reef restoration projects (Grabowski et al. 2022). Living shorelines that seek to promote oyster restoration, in addition to coastal protection, require hard substrates for juvenile oysters to settle (Bayne 2017). In some areas along the East Coast of the United States, such as southeastern North Carolina, oyster recovery is substrate-limited; while there may be sufficient larval supply, the recruitment of oysters is limited by a low amount of substrate available for the oysters to settle (Geraldi et al. 2013). Historically, oyster shells have been the most common and optimal substrate used to promote oyster settlement because shell is biologically appropriate for the recruitment and settlement of oysters (Tamburri et al. 1992, 2008, Mann and Powell 2007, Waldbusser et al. 2011, Levine et al. 2017). Although oyster shell is preferable for oyster restoration projects, research has shown that the limited availability of oyster shell will be unable to meet restoration project demand (Gillies et al. 2015). To address this challenge, alternative novel substrates are now utilized in living shorelines to provide both coastal protective services and encourage oyster settlement. Here, we define "alternative novel substrates" as man-made structures created with the dual purpose of increasing biodiversity and providing coastal protection services, including wave attenuation, erosion control, and storm surge mitigation. Examples of alternative novel substrates include Oyster Reef Ball, ReefBLK™, Oyster Castle®, and BESE-products®.

Recent literature has highlighted the knowledge gaps surrounding alternative novel substrates as a coastal resilience measure. It has been noted that the design of these structures does not often precisely mimic natural oyster reefs; thus, future research should further explore how and when artificial oyster reefs are effective (Morris et al. 2019). Oyster growth and survival rates benefit from the biological and physical refuge created by reef heterogeneity (Bartol et al. 1999), so there has been a call for alternative novel substrate design to incorporate the concepts of heterogeneity and habitat complexity to further oyster restoration.

The positive association between habitat complexity, including reef heterogeneity, and biodiversity has been widely observed (Huston 1979, Underwood and Anderson 1994, Hauser et al. 2006). Intertidal rocky habitats serve as prime examples of the benefits of structural complexity. These shorelines are composed of holes, crevices, and ridges that allow for protection from predation and physical stressors, resulting in greater species abundance and biodiversity (Menge and Lubchenco 1981, Aguilera et al. 2019). Hard structures, particularly seawalls, lack surface complexity, resulting in lower biodiversity than natural shorelines (Chapman and Bulleri 2003, Seitz et al. 2006, Gittman et al. 2016). Compared to natural shorelines, the smooth vertical sides of seawalls do not offer the same protection from physical stressors (Möller et al. 2014), habitat (Chapman and Bulleri 2003, Bilkovic and Roggero 2008), or refuge from predators (Peterson and Turner 1994) that a more structurally complex natural shoreline does.

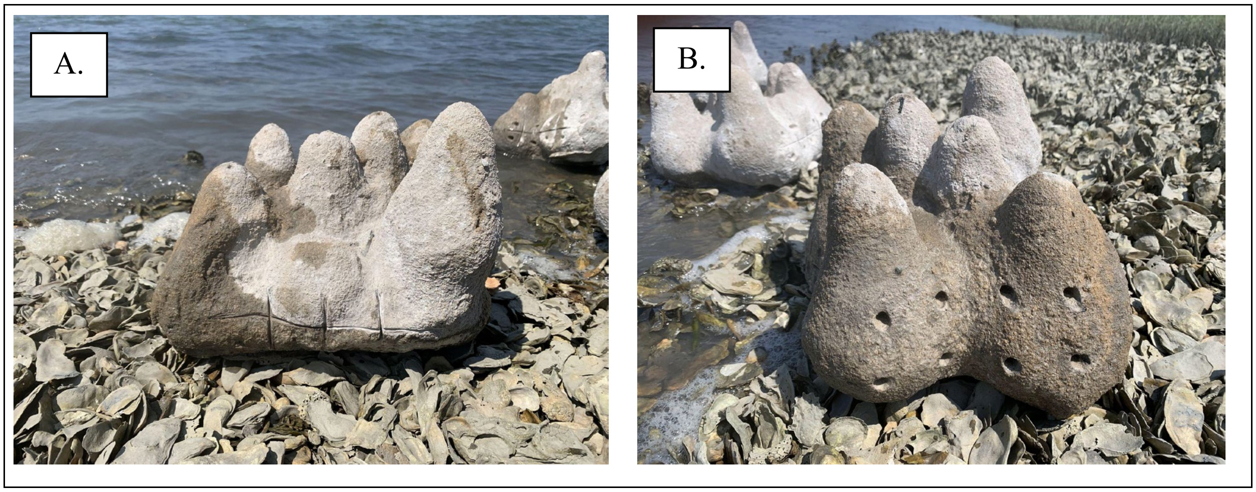
Considering the significance of surface complexity on increasing species abundance, the addition of surface heterogeneity to structures used in living shorelines construction should be explored to increase biodiversity while providing coastal protective services. The materials used in living shorelines are also an important design consideration and should be studied further to understand when and where certain materials are most beneficial. Understanding the most appropriate and efficient materials and designs used in living shorelines is valuable for furthering the implementation of living shorelines. This paper aims to explore the materials used to construct living shorelines, and how changes in the surface heterogeneity of these structures influence eastern oyster abundance. This paper seeks to answer the following questions: 1) how does manipulating the surface heterogeneity of artificial reefs affect eastern oyster abundance, and 2) what is the distribution of different living shoreline materials over time in the United States?

Methods

Field Experiment to Analyze the Impact of Surface Heterogeneity on Species Diversity: Exoforms™ Design, Deployment, and Monitoring

To develop a field experiment that explored the surface heterogeneity of artificial reefs, we collaborated with a Raleigh-based coastal resilience solutions company, Natrx. One of the company's solutions is 3D-printed naturalistic reef structures, known as ExoForms™. ExoForms™ can be deployed as a component of living shorelines and serve as an alternative to hard structures. To study how the surface heterogeneity of structures in living shorelines impacts species abundance, Natrx donated six small-scale ExoForms™ to be modified with a variety of treatments, deployed, and monitored. These sample ExoForms™ were approximately 28 cm in size. Due to the 3D printing process, these structures are not uniform in shape, with slight variations in the size and height of the six spheres.

To test the effects of surface heterogeneity on species abundance, three of the sides of each Exoform were manipulated, with one side left as a control treatment (Image 1-4). One side was scratched with one 18 cm horizontal line and three 6 cm vertical lines spaced 4 cm apart, another side was drilled with eight 10 mm holes spaced 4 cm apart, and the third side overlaid these treatments to understand their combined effect, if any. Thus, each ExoForms™ included all three modified treatments and the control treatment.



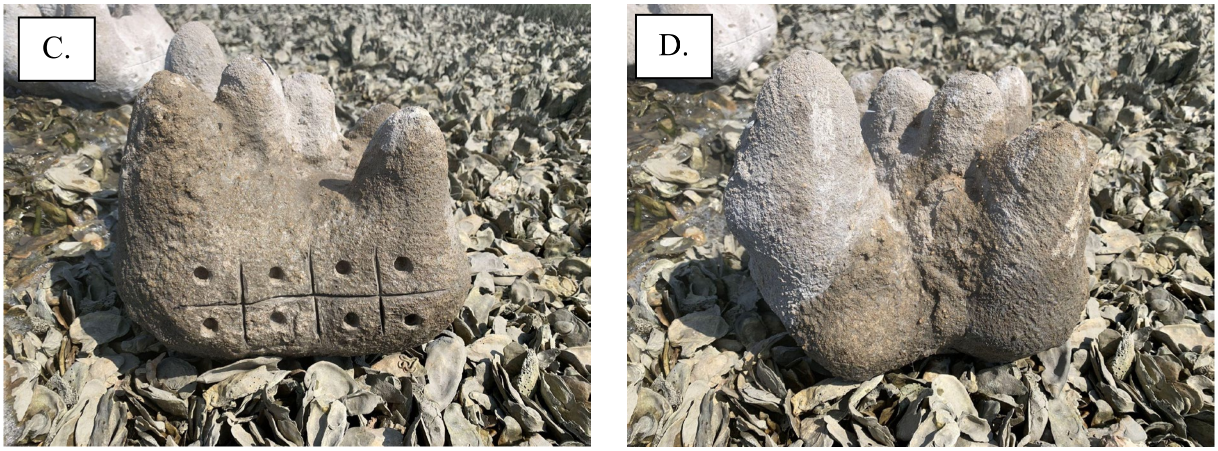


Image 1-4. These images show the four ExoForms™ treatments on their deployment date, June 11, 2023. Photo A shows the treatment with scratches; Photo B shows the treatment with holes; Photo C shows the treatment with both scratches and holes; and Photo D shows the control.

We placed the six ExoForms™ one meter apart in the intertidal zone on Piver's Island near the Duke University Marine Lab (34.720380, -76.674933) on June 11, 2023 (Image 5-6). To test for the effect of seaward-landward orientation, each ExoForm™ was placed at a 90-degree rotation from the previous, so that each manipulation faced the water at least once, with the scratched treatment and the holes treatment facing the water twice. We conducted regular monitoring of the structures for five months (until November 11, 2023) to record changes in species abundance.

Image 5. Photo A shows the site location, in the intertidal zone on Piver's Island near the Duke University Marine Lab.

Image 6. Photo B shows the ExoForms™ in the water on their deployment date, on June 11, 2023.

The data collected on each sample date included percent cover of algae, and counts of barnacles, oysters, and mussels. Additional species present were also recorded in a "catch-all" category. Photographs of each side and top of each ExoForms™ were taken on each sampling date.

We compared average species abundance over the sampling period both by ExoForm™ treatment and ExoForms™ orientation to shore. To analyze the data, we used R Studio to run a generalized linear mixed effects model on oyster counts with treatment and date as fixed effects and Exoform ID as a random effect. Using AIC, we tested four different distributions to determine the best fit for our data. The AIC showed that the negative-binomial distribution provided the best fit to the data. Standardized parameters were obtained by fitting the model on a standardized version of the dataset. A Wald z-distribution approximation was used to compute 95% Confidence Intervals and p-values. Additionally, we ran another GLMM to test whether orientation had a significant effect on oyster abundance. The model included orientation and date as fixed effects and Exoform ID as a random effect and used a negative binomial distribution.

Literature Review of the Materials Used in Living Shorelines

To understand material use in living shorelines under various circumstances, I conducted a scoping review of the literature covering living shorelines constructed along the entire United States coastline. I used Web of Science to search for peer-reviewed literature about living shorelines, using a filter for English language articles only. I used the search term "living shoreline*" so that only papers that self-identified their projects as living shorelines were included. Based on these criteria from Web of Science, 196 papers were identified for further review.

For a paper to be included in the database, the paper had to be: 1) peer-reviewed, primary literature, 2) located in the United States, and 3) a physical living shoreline (which excluded modeling papers, lab experiments, and projects not meeting our definition of living shoreline). 66 full-length papers met these criteria (Figure 1).

Several categories of information were extracted from the papers in the database: bibliographic details, basic study details, habitats restored, living shoreline descriptors, and synonyms for living shorelines. After reviewing and extracting information from the full-text papers, 329 living shorelines were identified from the full-text review. The location of each living shoreline was determined from the text. Multiple papers discussed the same living shorelines, so we used the location and project details to identify duplicate instances of the same living shoreline, which were then removed so that each living shoreline was only included once. After removing the duplicate projects, 182 living shorelines remained for analysis.

To analyze trends in materials used in living shorelines, the materials identified were grouped into seven categories: concrete, rock, wood, mussel, oyster, vegetation, and alternative novel substrates. Rock refers to projects that used rocks, cobble, and granite. Wood includes projects that use either wood or coir. Oyster refers to both bagged and loose oyster shell, as well as oyster shell mats and cages. Vegetation was used as a category when a living shoreline project only used vegetation and included no other materials.

The living shorelines identified in the database were used to create a searchable, public ArcGIS Dashboard with the purpose of creating a resource to allow any user to understand the spatial distribution of living shorelines in the United States, and to identify trends in the materials used in these projects. This Dashboard included each living shoreline's project details, including the project's name, coordinates, state, project cost, materials used, and project purpose. The living shorelines in the database can be filtered on the Dashboard by state and material used. The Dashboard also includes a live map that zooms to specific living shoreline projects, as well as a pie chart, project table, and project count that changes based on the user's inputs.

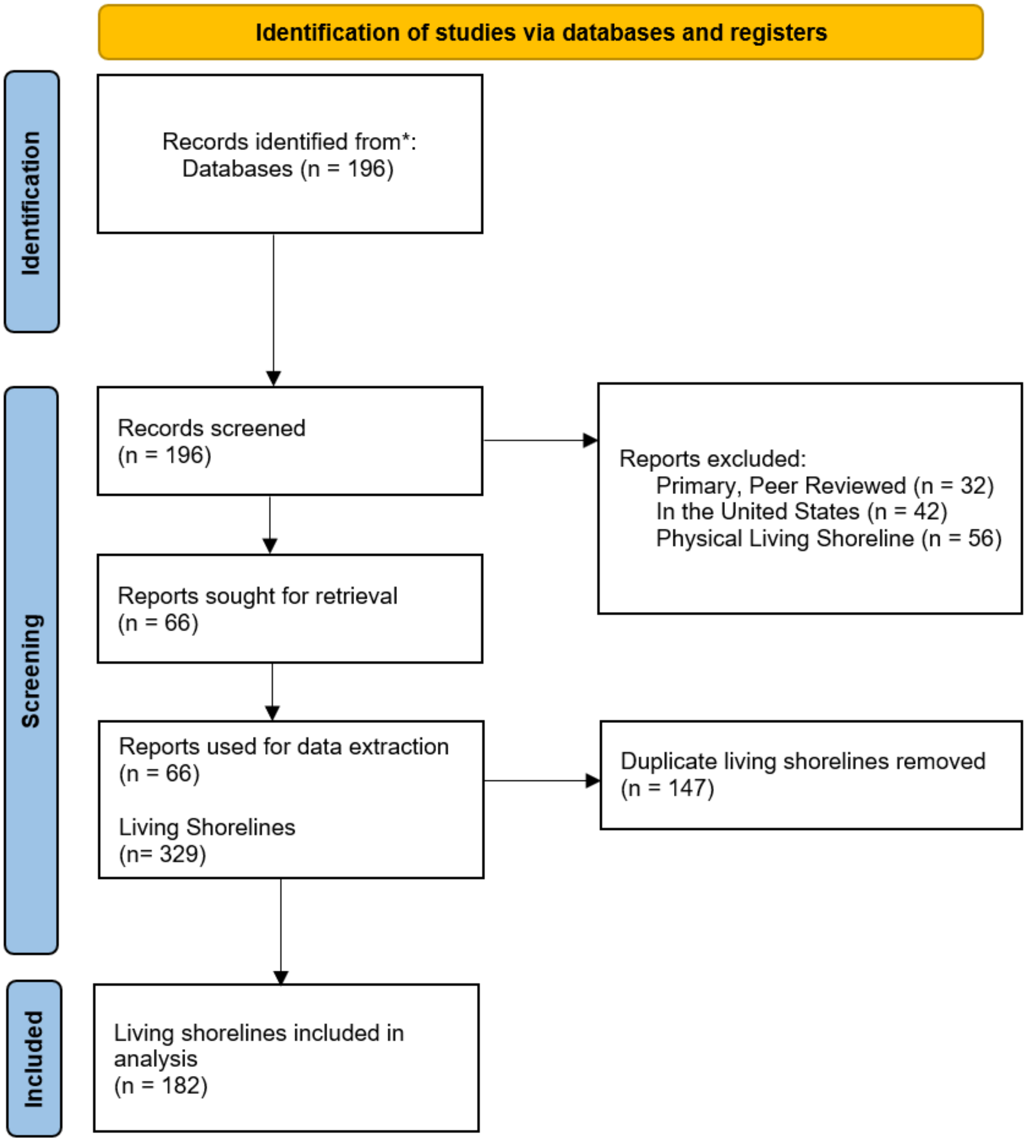
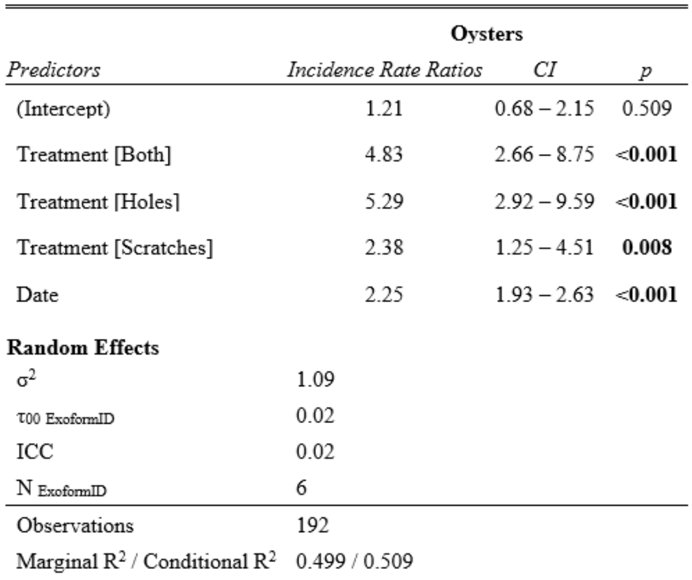


Figure 1. Modified PRISMA Flow Diagram used in the literature review

Results

Field Experiment to Analyze the Impact of Heterogeneity on Species Diversity

The ExoForms™ treatment had a significant effect on oyster abundance (Table 1) with all modified treatments performing better than the control treatment (Figure 2). The treatment with holes performed best, followed closely by the combination treatment. Mussel abundance on the ExoForms™ holes and combination treatments were also notably higher than both the scratches treatment and the control. The effect of the sampling date was also statistically significant and positive with respect to oyster abundance. Across all treatments, oyster abundance increased substantially from mid-July through the end of September, before leveling off and decreasing around the end of October (Figure 3). The ExoForms™ holes treatment experienced the highest oyster abundance across nearly all sample dates, although the combination treatment experienced a similar–although slightly lower–trajectory of oyster abundance. The treatment with scratches and the control treatment both experienced slower initial oyster abundances. However, both treatments had some oyster abundance increases into the end of October, while oyster abundances on the other two treatments had already begun to decline.



	Oysters		
Predictors	*Incidence Rate Ratios*	*CI*	*p*
(Intercept)	1.21	0.68 – 2.15	0.509
Treatment [Both]	4.83	2.66 – 8.75	**<0.001**
Treatment [Holes]	5.29	2.92 – 9.59	**<0.001**
Treatment [Scratches]	2.38	1.25 – 4.51	**0.008**
Date	2.25	1.93 – 2.63	**<0.001**
Random Effects			
σ^2	1.09		
$\tau_{00\ \mathrm{ExoformID}}$	0.02		
ICC	0.02		
$N_{\mathrm{ExoformID}}$	6		
Observations	192		
Marginal R^2 / Conditional R^2	0.499 / 0.509		

Table 1. Results of the generalized linear mixed model for the four ExoForms™ treatments: scratches, holes, combination, and control

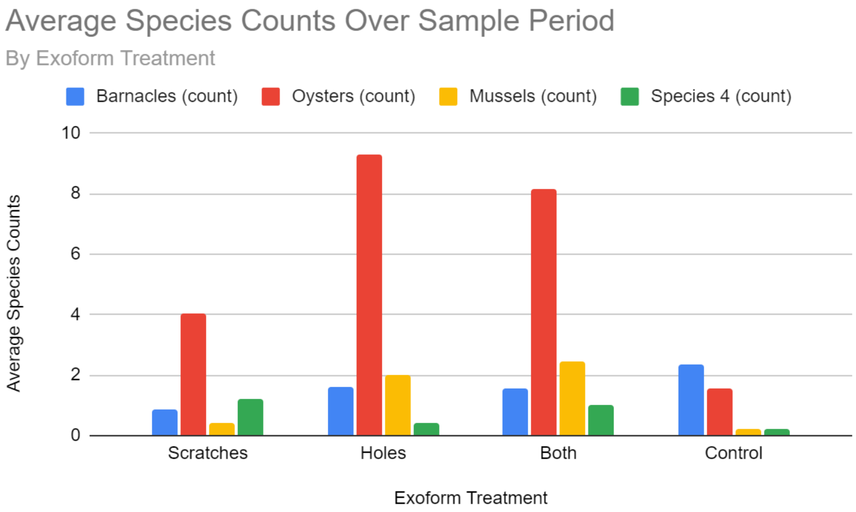


Figure 2. Average species counts by ExoForm™ treatment over the sample dates

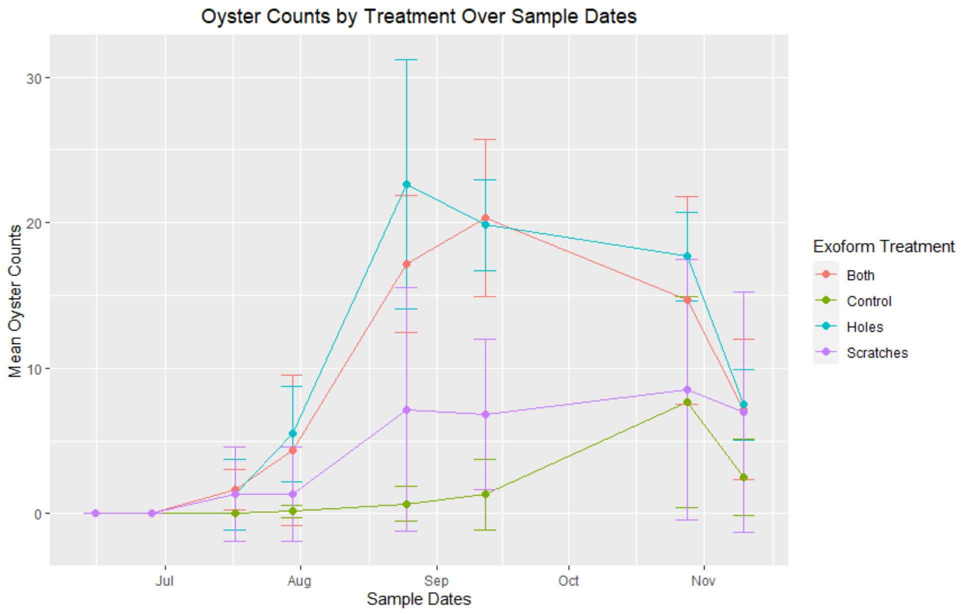


Figure 3. Oyster counts by ExoForm™ treatment over the sample dates

The effect of orientation on oyster abundance was not statistically significant (Table 2). In this study, the only species that appeared to be affected by ExoForm™ orientation were the barnacles, with notably higher species counts on the landward orientation (Figure 4). The effect of the sampling date was still statistically significant and positive with respect to oyster abundance. Across all orientations, oyster abundance increased substantially from mid-July through the end of September, before leveling off and decreasing around the end of October (Figure 5). The results of the analysis show that the orientation was not significant with respect to oyster abundance in this instance.

	Oysters		
Predictors	*Incidence Rate Ratios*	*CI*	*p*
(Intercept)	4.66	3.07 – 7.06	**<0.001**
Orientation [Seaward]	0.87	0.54 – 1.42	0.578
Orientation [Side]	0.79	0.52 – 1.20	0.268
Date	2.29	1.93 – 2.72	**<0.001**
Random Effects			
σ^2	1.28		
τ_{00} ExoformID	0.03		
ICC	0.02		
N ExoformID	6		
Observations	192		
Marginal R^2 / Conditional R^2	0.349 / 0.362		

Table 2. Results of the generalized linear mixed model for the three ExoForm™ orientations: landward, seaward, and side

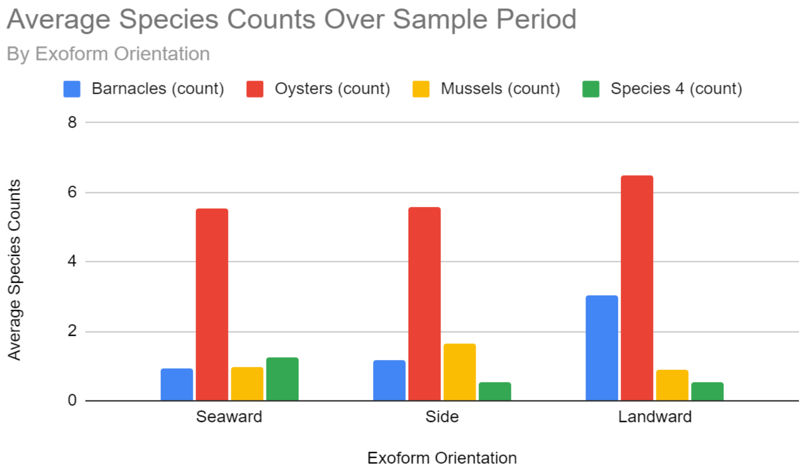


Figure 4. Average species counts by ExoForm™ orientation over the sample dates

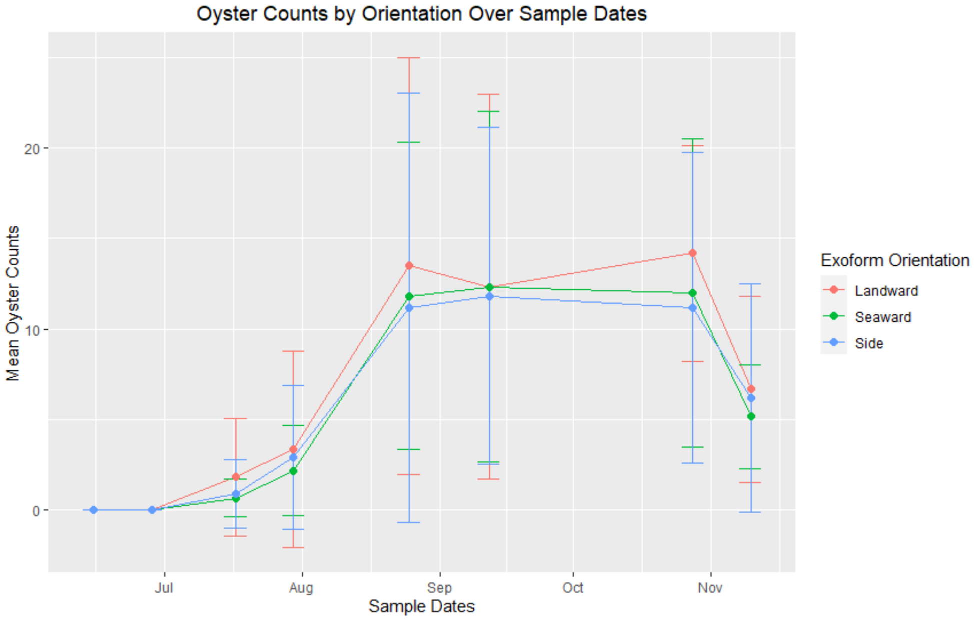


Figure 5. Oyster counts by ExoForm™ orientation over the sample dates

Literature Review of the Materials Used in Living Shorelines

Based on our analysis of living shoreline literature, we found that Florida, North Carolina, Virginia, and Alabama have the highest number of living shorelines. Florida, Alabama, and New Jersey have the highest usage of alternative novel substrates (Figure 6). Many projects utilize multiple materials, typically vegetation being one of these materials. Vegetation is rarely used as the only material in a living shoreline; it is almost always paired with another material, typically rock. Oysters and rock are overall the most commonly used materials by state. When examining material use in each habitat type, we found that oyster is used almost exclusively in habitats classified as oyster reef habitat, while rock is primarily used in saltmarsh and mangrove habitats (Figure 7).

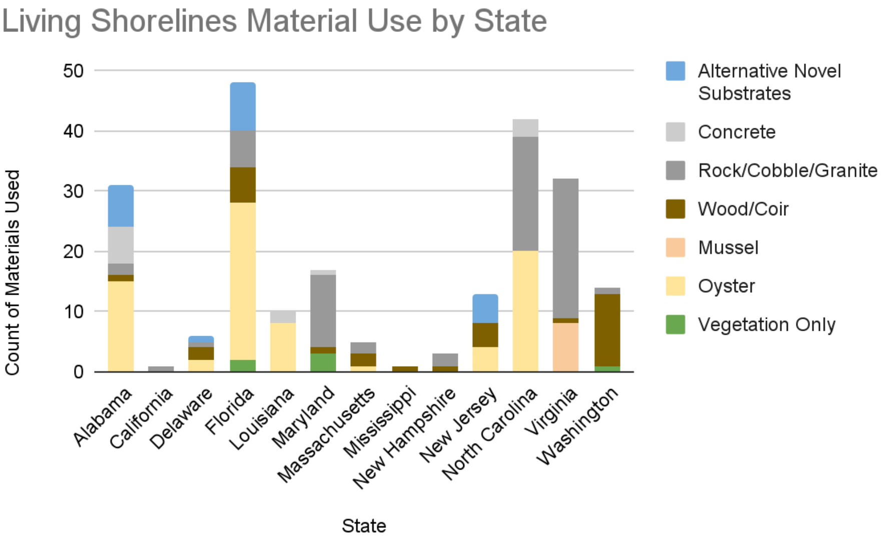


Figure 6. Material use in living shorelines by state

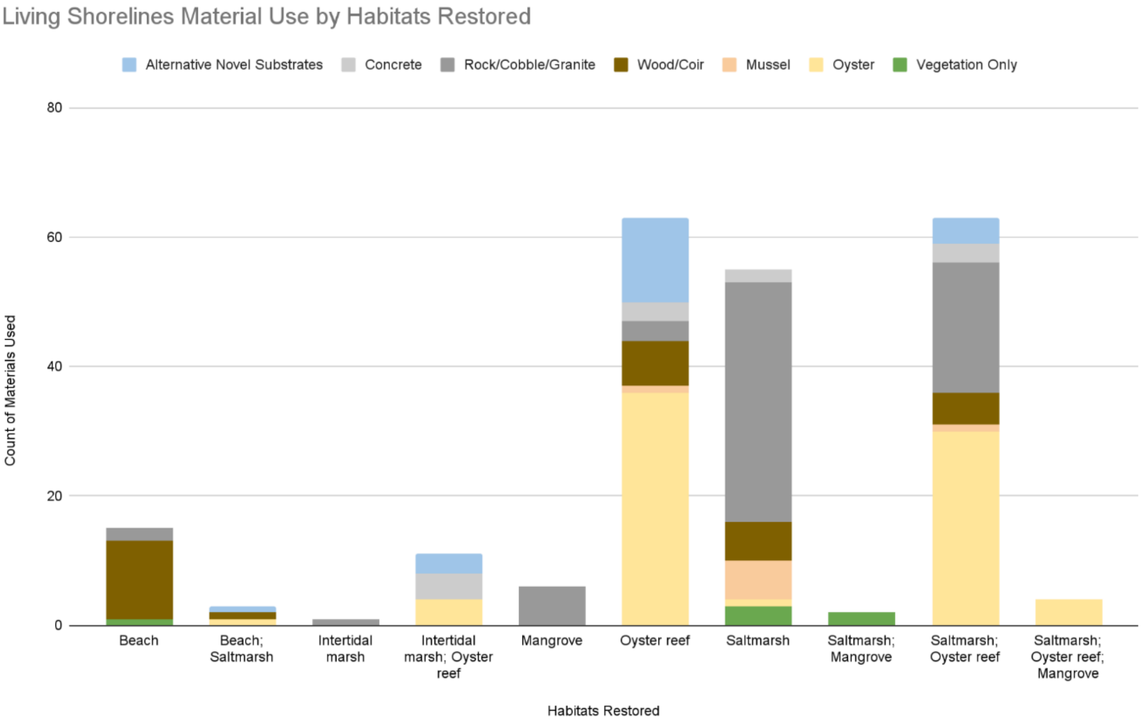


Figure 7. Material use in living shorelines by habitat

Oyster usage in living shorelines appears to have gone through cycles of increasing and plateauing and is never seen to decline in use (Figure 8). Rock use has increased steadily over time. Alternative novel substrates increased primarily during 2015 to 2017, followed by a plateau in use. Alternative novel substrates are still used much less frequently than oyster, rock, and wood.

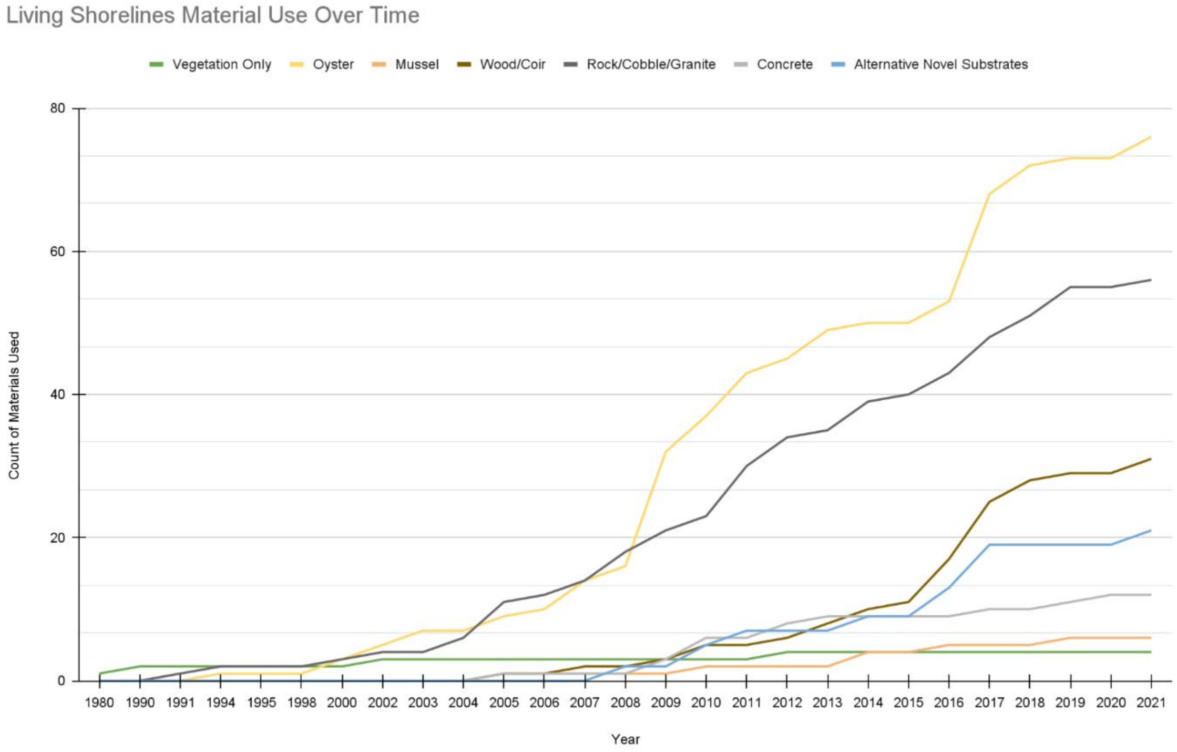


Figure 8. Living shoreline material use over time

Discussion

Our field experiment showed higher abundances of both mussels and oysters on the modified ExoForms™–particularly the holes and combination treatments, suggesting that increasing surface heterogeneity does increase oyster abundance. Creating artificial reef structures–particularly ones that include holes–allow for oyster spat to settle and grow with protection from predators. Studies on the fine-scale alterations to surface heterogeneity have been observed to increase recruitment by providing protection to species such as barnacles and oysters (Coombes et al. 2015). Other species were observed utilizing the artificial structures, including nudibranchs seen eating algae off the structures, and toadfish seen underneath the structures. The benefits of increasing surface heterogeneity to provide habitat for larger species are widely documented (Firth et al. 2014, Moschella et al. 2005).

However, predators of oysters, such as Atlantic oyster drills (*Urosalpinx cinerea*) and Atlantic mud crabs (*Panopeus herbstii*), were also frequently recorded on or near the ExoForms™. Interestingly, pairs of Atlantic mud crabs were seen underneath nearly all the

ExoForm™ from late June to early August. It appeared that the mud crabs were seeking protection while molting and mating occurred, but there lacks supporting literature to confirm this hypothesis. The ExoForms™ may provide protection for juvenile oysters, but the structures also protect their predators, which could negate some of the protective benefits and reduce oyster abundance over time. Future studies should include these predator-prey interactions to understand this dynamic further.

The statistical analysis also showed that the landward-seaward orientation of the structures was not statistically significant with respect to oyster abundance. However, the size of the ExoForms™ likely impacted this observation. Because the ExoForms™ were much smaller than those that would typically be used in restoration, the influence of the landward-seaward orientation on settlement was likely less significant as the oyster larvae had little additional distance to settle on a particular side. Additionally, the tidal and boat-wake impact was likely similar on each of the ExoForms™ sides, because they were smaller and spaced apart from one another. To address this limitation, additional studies should conduct further field experiments using artificial structures that are the same scale as those typically used in living shorelines.

Based on our analysis of living shoreline literature, we found that there are temporal and geographic trends in material use in living shorelines. Oysters and rock remain the most utilized material across a majority of states. Due to the decline in oyster populations, oyster restoration efforts have increased in recent decades (La Peyre et al. 2014). The increased use of oysters in living shorelines reflects the goal of restoring oyster populations while also increasing coastal protective services (Grabowski et al. 2012). However, the cycles of increases and plateaus of oyster use over time likely reflects its limited availability as a material (Gillies et al. 2015). The high usage of rock in living shorelines is likely due to the materials' availability to restoration practitioners. Vegetation is rarely the only material utilized in a living shoreline, and is almost always paired with another material, typically rock. Marsh vegetation, primarily *Spartina alterniflora*, has been discussed as an important characteristic of living shoreline design, particularly for its ability to attenuate waves (Knutson et al. 1982, Roland and Douglass 2005, Gedan et al. 2011, Riffe et al. 2011). It has been documented in the literature that living shoreline designs pair vegetation with rock to increase these coastal protective services (Bilkovic and Mitchell 2013, Smith et al. 2018).

However, there are limitations to this analysis. The information on the proportion of a living shoreline's use of a particular material was rarely available, so the instances of a material being used may not reflect the amount that was used in a particular project. This limitation could alter the overall amount of material being used in living shorelines. Additionally, information about living shoreline projects were only gathered from peer reviewed, primary literature, and meeting our project's inclusion criteria. While this ensured consistency and accuracy in the data collection, it excluded living shoreline projects that were constructed but not written about in scientific literature. To address this limitation, future studies should include additional databases and sources of living shoreline project information.

Conclusion

This project sought to understand material use in living shorelines, and how the surface heterogeneity of artificial structure design can influence species abundance. This study paired a field experiment with a literature review to explore these questions. The field experiment found that increasing the surface heterogeneity of artificial structures significantly increases oyster abundance. The literature review showed there are geographic and temporal trends in the materials used in living shorelines. Here, we found that alternative novel substrates are increasing in use, but at a much lower rate than oyster shell, rock, and wood. However, living shorelines not present in scientific literature were not included in the database due to the review design. This review design could contribute to the exclusion of more recent living shorelines, which are more likely to include the use of novel alternative substrates. Considering the benefits of living shorelines, they are and will continue to be utilized as a management strategy to mitigate flooding and storm impacts. It is crucial to understand the most appropriate and efficient designs and materials to further living shoreline implementation.

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