Living Shorelines and the Efficacy of Oyster Reefs in Mitigating Wave Action and Erosive Processes

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Spring 2020

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Abstract

Global climate change poses a significant threat to coastal communities worldwide, with sea level rise, flooding, intense and frequent storms, accelerated erosion, and storm surge, resulting in billions of dollars of damage. A critical part in addressing these threats lies in coastal adaptation strategies, which will grow in importance as climate change and sea level rise continue. Living shorelines are a nature-based approach to coastal adaptation that utilize native species to increase resilience against erosion and flooding while providing a broad range of benefits known as "ecosystem services." Ecosystems within living shorelines can include marsh grasses, eelgrass, mangrove, coral, and oysters, each of which provides its own benefits to a coastal resilience strategy. Oyster reefs provide a utility similar to that of a breakwater by weakening wave action and decreasing erosion, while providing ecological enhancements such as water filtration, improved biodiversity, and increased benthic-pelagic coupling. In addition, oyster reefs are a more cost-effective option than built infrastructure. They can serve as the backbone of more effective adaptation approaches, whether as a living shoreline or a hybrid approach, not only offering protection against erosion, but also extending the lifetime of built infrastructure.

Oyster reefs require specific environmental factors to recruit properly and to reach full potential. The required conditions can be found in a number of locations, and include variables such as salinity, temperature, dissolved nutrients, and lack of competitors or predators. Oysters are resilient; they have the capability to grow as fast as sea level rise, and can even adapt to unfit conditions in some settings. Choosing the right substrate for recruitment purposes can also help enhance oyster growth, with a variety of options available to tailor the approach to a specific location. Oyster reefs offer great potential as a coastal adaptation measure, offering greater benefits and durability at lower cost than built infrastructure. Reef construction and restoration provide extensive economic and ecological benefits as a resilience strategy against sea level rise and erosion.

Introduction—The Significance of Coastal Adaptation

Global Climate Change is an active and growing threat to coastal communities worldwide, not only threatening populations with sea level rise, flooding, more frequent and intense storms, increased erosion, and storm surge, but also altering climatic conditions such as upwelling and circulation patterns (He & Sillman 2019). At present, approximately 30% of the world population lives on the coast, a number expected to rise to 50% by 2030, while about 10% lives less than 10 meters above sea level (Bilkovic et al. 2017, Martinez et al. 2017). In order to survive changing coastal conditions, communities must either migrate away from coastal areas or take steps to mitigate these impacts. The advancement of sea level rise, ongoing erosion, and increased flooding events are expected to cause $1 trillion of damage annually by 2050. The need to modify shorelines will only continue to grow in an effort to "protect people, property, and critical infrastructure from coastal hazards" (Reguero et al. 2018, Gittman et al. 2016, p. 763). Additionally, increased levels of interaction between human communities and coastal ecosystems have led to ecological degradation and even ecosystem collapse due to inputs such as "excessive nutrients, heavy metals, and other forms of land-derived pollutants" (He & Sillman 2019). The adaptation of coasts to achieve high levels of socio-ecological resilience, or "a systems capacity to respond to the consequences of perturbation… [and] retain the essential structures, processes, and feedbacks" will become increasingly important as climate change worsens and more unpredictable events occur on coastlines (Martinez et al. 2017, pp. 1-2). Coastal adaptation strategies are designed to attenuate wave action, mitigate the strength of tidal forces, and reduce sand erosion, which strategies in turn help to maintain sedimentation and accretion. Overall, the development of a resilient coastline aims to allow for the protection of human infrastructure from events such as flooding and erosion while maintaining the health of the ecosystem and the biotic community.

A variety of coastal adaptation strategies exist: human-built infrastructure, or coastline armoring; natural modification, or living shorelines; and hybrid approaches combining aspects of both built infrastructure and living shorelines. Though built shorelines are a viable option that provide adequate protection to residents and infrastructure, they impose negative consequences on the geomorphological and ecological processes of coastal ecosystems. Hardened shoreline can cause up to a 56% loss of biodiversity, altered sediment transport patterns, changes in salinity, and higher levels of non-native species (Hill 2015, Gittman et al. 2016). The resulting degradation has ramifications for the access to ecosystem services such as heightened fishery productivity and water quality, in addition to deviations in "morphology, hydrodynamics, and sediment and nutrient budgets" (Bilkovic et al. 2017, Cheong et al. 2013, p. 788). The shifts in sediment transport and wave energy can have negative impacts on wetlands especially within estuarine ecosystems, where any change in salinity and water quality can have drastic effects on the health of the biotic community (Hill 2015). In addition, engineered structures require significant maintenance to retain sufficient shoreline protection, a venture that can be extremely costly yet often will not continue to perform at the same level. In the definition by Martinez et al. (2017), armored coastlines are not a truly resilient approach to coastal adaptation, for they do not allow the ecosystem to maintain the same "structures, processes, and feedbacks" as an undisturbed shore.

Unlike built infrastructure, living shorelines demonstrably protect coastal communities, mitigating wave action to reduce erosion, minimizing flooding and storm surge, while providing ecosystem services (Arkema et al. 2017). The implementation of living shorelines can be a vital tool in developing sustainable coastal adaptation practices, providing protection equal to that of built infrastructure along with a number of ancillary benefits that help to revive coastal ecosystems. When incorporated into living shorelines, oyster reefs have the capacity to enhance protective capabilities while adding benefits such as water filtration, increased biodiversity, and increased economic activity. In this paper, I explore the efficacy of integrating oyster reefs into living shorelines, and assess the subsequent levels of success in mitigating erosive processes, decreasing destructive flooding events, and increasing the overall resilience of coastal communities.

Living Shorelines

In general, living shorelines are defined as "the use of natural elements, commonly marsh vegetation, sometimes in combination with a stabilizing structure, to control erosion, restore or conserve habitat, and maintain coastal processes" (Bilkovic et al. 2017, pp. 295-296). Living shorelines provide a synergistic alternative to built infrastructure by establishing native plant and animal populations, occasionally supplemented by engineered structures to facilitate organism growth. By using natural features, living shorelines offer protection to coastal communities while restoring the benefits and ecosystem services that diverse marine habitats can provide (Arkema et al. 2017). This definition largely differs from the goals of hardened shorelines, as this approach strives for a combination of physical protection and the restoration of ecological function. The most important functions of the living shoreline include attenuation of wave energy and reduction of shoreline erosion, while minimizing the ecological consequences that accompany built structures, balancing simple ecological restoration and engineered infrastructure.

Living shorelines can be composed of a variety of ecosystems, commonly including marshes, mangroves, oyster reefs, dunes, or coral reefs, each of which provides the necessary mitigation of wave action and protection from sea level rise while contributing ecosystem services. Salt marshes decrease shoreline erosion due to their expansive root system, mitigating wave action while facilitating sediment transport that allows them to maintain growth adequate to keep up with sea level rise. Mangrove forests drive productive sedimentation almost equal to the rate of sea level rise and dampen coastal stress caused by wave action, providing protection against flooding from storm surge and extreme events. Oyster Reefs are used to enhance living shorelines facing greater exposure to turbulent water, attenuating incoming wave action and helping reduce erosion in marshes and beaches (Bilkovic et al. 2017; Mitchell & Bilkovic 2019). Each component of the living shoreline offers a different service in coastal protection, working collectively to address multiple threats, and can be tailored to each location based on specific issues and functionality of a species within the climate zone. Scientists incorporate an assortment of species to create “synergies… in which at least one species benefits from the presence of another species, without harm to either” (Cheong et al. 2013, p. 788). Focusing on the development of synergistic relationships between ecosystems allows for a more stable, resilient shoreline, which provides more benefits to the human community nearby.

Living shorelines provide a variety of other ecosystem services, or benefits gained from nature, where hardened shorelines fall short. These ecosystem services can include increased biodiversity, enhanced carbon sequestration, increased fishery production, decreased terrestrial runoff, natural resources, maritime jobs, potential for recreation and tourism, and improved water quality (Cheong et al. 2013; Bilkovic et al. 2017). When one takes into account the benefits gained from ecosystem services as well as the ecological harm armoring can cause, in many cases living shorelines may be more cost effective than hardened shorelines. Habitats such as salt marsh, seagrass, and oyster reefs that are integrated into living shorelines support many species of crabs, shrimp, and finfishes, all of which have high fishery value. Living shorelines can help bolster water quality, filtering excess nutrients and balancing out sedimentary processes (Bilkovic et al. 2017). In addition, the restoration of vegetated shoreline helps increase carbon sequestration, which is enhanced by oyster reefs; salt marsh and seagrass accumulate carbon through in situ productivity as well as sedimentation of nutrients, with older ecosystems showing higher levels of sequestration (Cheong et al. 2013).

Through adaptation, coastal communities strive for security in the face of erosion and storm surge, and the development of living shorelines is the most cost-effective, stabilizing form of protection in the long term (Lee Smee 2019). These strategies are built on three principles: “protection, attenuation… of wave energy offshore, and cohabitation,” which allows for a robust connection between ecological health and environmental justice (Moosavi 2017, p. 932). Using living shorelines to achieve resilience also helps with adaptation to sea level rise due to the self-repairing nature of marshes and oyster reefs, leading to significantly lower costs associated with maintenance and construction. Nature-based approaches to coastal adaptation are generally more resilient, responsive to rising sea levels, and self-sustaining with minimal need for maintenance over time if properly engineered and placed in an appropriate location (Moosavi 2017; Mitchell & Bilkovic 2019). Siting, therefore, is critical in determining the level of sustainability for a living shoreline and its ecosystem. Ideally, the chosen site has minimal wave action, which can be established by introducing an oyster reef offshore, to maximize the potential for upland marsh retreat and sediment sully used for marsh accretion (Mitchell & Bilkovic 2019). Oyster reefs primarily weaken wave activity, allowing for the establishment and prosperity of more fragile ecosystems in sites that may have been too turbulent for marsh growth.

The Role of Oyster Reefs

Oyster Reefs, sometimes referred to as “living breakwaters” are massive, dense agglomerations of both living and dead bivalves that form a complex, three-dimensional structure in intertidal and subtidal zones. Composed of shells and biodeposits, the growth of these structures is controlled chiefly by salinity and air exposure during tidal cycles (Ridge et al. 2017b). Global oyster populations are estimated to be 85% functionally extinct, diminished over the last century by harvesting activities, the building of coastal protection infrastructure, excess nutrients and disease. This decline has led to a significant decrease in the protection that naturally occurring reefs once provided (Morris et al. 2019, O’Donnell et al. 2017, Beck et al. 2011). Oysters begin as free-floating larvae, requiring a hard surface in the appropriate habitat for juvenile recruitment, including substrates like rocks, piers, or other oyster shells. Once the oyster attaches to a suitable substrate they are known as spat, and continue to grow and reproduce. Since other oyster shells provide a suitable substrate, oysters tend to grow in reef formations, forming a self-sustaining ecosystem which continues to expand with time and reproduction (Morris et al. 2017). Scientists have developed a number of artificial reef structures designed to facilitate growth if existing reef structures are not available for juvenile recruitment, constructed in a variety of sizes, shapes, and materials, including discarded oyster shells, steel, limestone, and concrete.

Within the living shoreline, the primary function of oyster reefs is attenuation of wave energy that causes erosion to shorelines and marshes, offering the same utility as engineered structures like breakwaters while also providing vital ecosystem services. The vegetation used in the development of living shorelines requires relatively low-energy sites for robust establishment (Mitchell & Bilkovic 2019). Oysters are more resistant to erosion than vegetation and stand lower in the framework of a shoreline, positioning them to produce a “shadow effect,” absorbing and dampening the stress of wave action on marsh ecosystems (Scyphers et al. 2011). Oyster Reefs reduce wave height by around 83% when water level is 1cm below the crest of the reef and about 42% when the water level is 5cm above the crest of the reef; wave height is reduced 11% in the absence of reefs (Morris et al. 2019, p. 1707). Grabowski et al. (2012) estimated erosion prevention services to be valued at $85,998 per hectare of oyster reef, adjusted for the percentage of reef habitat that provides this service. As reefs mature, they have been seen to “not only slow marsh retreat, but also preserve buried marsh carbon during transgression” (Ridge et al. 2017a, p. 1024). Reef structures can increase sedimentation and help facilitate the colonization and retention of plant propagules, promoting the formation of a suitable habitat for marsh formation (Scyphers et al. 2011). In addition, oysters as filter feeders remove floating solids from the water column, increasing water clarity and facilitating seagrass growth through additional light availability (Beck et al. 2011). This increase in seagrass enhances the living shoreline, providing protection from erosion and flooding.

In addition to mitigating erosive processes, oyster reefs adapt to changes in their environment, "recover[ing] quickly from major storm events, and accret[ing] at a rate equal to or greater than sea-level rise or local subsidence" (Morris et al. 2019, p. 1704). The study of intertidal oyster reefs by Ridge et al. (2017b) showed that decade-old reefs grew up to 2cm/year, keeping up with sea level rise. Younger reef growth was even faster, up to 8-11 cm/year, and new reefs took only 4-6 years to reach mean sea level. Hundred-year-old reefs also showed significant resilience, with growth up to 4cm/year in years with higher water levels, showing the ability to maintain growth as sea-level rises. This equilibrium of intertidal reef surface elevation with sea level displays their resilience to sea level rise caused by climate change, showing the "utility and longevity for stabilizing shorelines" (Ridge et al. 2017b, p. 10418). This ability to match sea level rise is a significant advantage provided by the use of oyster reefs. Where breakwaters need to be continually maintained and augmented to provide sufficient protection, oyster reefs are self-sustaining and will continue to aggregate if not disturbed by anthropogenic forces.

Ancillary Benefits & Ecosystem Services

Biodiversity & Fish Stocks

Oyster Reefs provide utility beyond protection from wave action and erosive processes that benefit both people and coastal ecosystems. As a foundation species, or ecosystem engineer, oysters promote biodiversity, providing a habitat for a number of species including "mollusks other than oysters… polychaetes, crustaceans, and other resident invertebrates" (Grabowski et al. 2012, pp. 900-901). These species promote a diverse and balanced food web in the coastal ecosystem, with smaller invertebrates acting as a food source for young fish and crustaceans, while the reef itself provides a nursery for "recreationally and commercially valuable organisms" (Grabowski et al. 2012; Cheong et al. 2013, p. 789). Though claims have been made about lower biodiversity in constructed oyster reefs, Peterson et al. (2017, p. 384) found that "food web structure after 22 months was equivalent." The population of forage species, mainly composed of smaller fish, supports stocks of commercially valuable fish species, indirectly enabling fisheries to increase harvests and providing economic support to the local community. In a study by Scyphers et al. (2011), populations of blue crabs, penaeid and caridean shrimp, and juvenile silver perch increased near oyster reefs. Biodiversity and ecosystem health improved, with an increase in abundance, biomass, and species richness in spotted sea trout, drum, and flounder. In addition, Grabowski et al. (2012) reported that restored oyster reefs with a base area of 10 m^2 yielded an average of

2.6 additional kilograms of “fish and large mobile crustacean production annually, because oyster reef habitat either enhances the recruitment rate of early life stages or enhances growth and survival.” The authors estimated from this data that in 2012, there was an additional commercial fish value of $4,123 per hectare of oyster reef, subject to adjustment for variations in ecological and economic factors. (Grabowski et al. 2012)

Water Filtration & Benthic-Pelagic Coupling

Oysters provide high levels of water filtration, “controlling turbidity, water quality, and primary production by removing algae, bacteria, and suspended organic matter” (Cheong et al. 2013, p.789). These capabilities improve water quality in the coastal ecosystem, as oysters filter pollution and help control levels of nutrients such as nitrogen, preventing adverse events such as algae blooms. As filter feeders, oysters remove suspended solids from the water, providing clearer water and enhancing the photosynthetic potential for seagrasses, thereby facilitating growth. Filter feeding helps reduce anthropogenic coastal nutrient loading and associated harmful algal blooms, which in turn diminish the net primary productivity of these ecosystems and prevent recreational activities. Nutrient filtering leads to a higher level of benthic-pelagic coupling, enabling the transfer of energy through higher trophic levels, and enhancing productivity higher up the food chain. These filtering processes ensure nutrient fixing within the ecosystem, increase food availability for a number of species, and promote a healthy and diverse estuarine ecosystem (Cheong et al. 2013). Grabowski et al. (2012) estimated the value of nitrogen removal services provided by a hectare of oyster reefs to be between $1,385 and $6,716 annually, with phytoplankton consumption resulting in higher water clarity valued at $2,584 due to promotion of vegetation growth.

Carbon Sequestration

Fringing oyster reefs, or reefs that exist next to marshland, enhance the carbon sequestration properties of a salt marsh. Seagrasses and salt marshes are “characterized by high primary productivity and slow remineralization, and, therefore, tend to sequester carbon at much greater rates than terrestrial ecosystems” (Davis et al. 2015). Salt marshes and mangrove forests throughout the globe sequester significant amounts of carbon, and the global destruction of these ecosystems can release up to 1.02 Pg of carbon annually (Bilkovic et al. 2017). Sequestration can range between 58 and 283 g C/m^2 per year, with older, more established systems sequestering more efficiently (Davis et al. 2015). This high rate of sequestration can lead to an annual average of .75 metric tons of carbon benefits per hectare of marsh, equivalent to 2.56 metric tons of atmospheric CO_2 (Davis et al. 2015). Erosive processes along marsh edges leads to the release of previously buried carbon, illustrating the benefit of oyster reef implementation. According to Ridge et al. (2017a), by preventing erosion, the introduction of a fringing oyster reef "can preserve a quarter to half the carbon stored within an eroding marsh shoreline." By including an oyster reef in a living shoreline's structure, carbon retention rates of the marsh or mangrove ecosystem will be safeguarded, and therefore substantially higher than in a traditional, naturally dynamic and highly erosive ecosystem.

Oyster Harvesting

Sustainable oyster harvesting can be carried out in more established reefs, providing the local community with additional maritime jobs, while stimulating local economic activity through shellfish sales. However, traditional harvesting practices such as mechanical dredging and tonging can be extremely damaging to oyster reefs and lead to severe degradation over time (Grabowski et al. 2012). According to the National Oceanic and Atmospheric Administration (2020), the United States oyster industry is valued at $186 million, with 36 million pounds of oysters produced and sold. The industry is extremely lucrative and has the potential to enhance the economic capacity of a variety of coastal communities.

Other Services

Oyster reefs provide a slew of ecosystem services in addition to their protective capacities within a living shoreline. Grabowski et al. (2012) estimate that restored oyster reefs would be valued at between $10,325 and $99,421 per hectare annually due to the aforementioned services. The value realized depends on location, success of implementation, and the specific ecosystem services provided to the community, yet does not take into account some services that are difficult to quantify, such as "recreational fishing, carbon burial, and augmented biodiversity" (Grabowski et al. 2012, p. 906). The Nature Conservancy found that "in addition to significant reductions in height and energy among the highest 10% of waves, 5.6km of oyster reef translated to more than 6,900 pounds of additional catch per year and removal of up to 1,888 kilograms of nitrogen per year from surrounding nearshore waters" (Sutton-Grier et al. 2015, p. 140).

Constraints on Implementation

Successfully constructing these intricate reef structures can be complicated. Oysters require specific conditions to thrive and realize their maximum potential, playing different roles depending on the environment they inhabit. Thus, reef siting and developing an implementation strategy is key to ensuring the success of an oyster reef. In addition, certain factors - disease, substrate destruction, ocean acidification, anoxia, stress and infection induced by non-native species, and unsustainable harvesting practices - can lead to high mortality rates and reef ecosystem collapse (Beck et al. 2011). Even with these challenges, implementing oyster reefs rather than building infrastructure can produce benefits that outweigh the cost of reef establishment in 2 to 14 years (Grabowski et al. 2012).

Siting for Reef Construction

When restoring an oyster reef, siting to maximize growth potential and erosion reduction can be the difference between a successful reef and future collapse. Habitat suitability is contingent on a variety of environmental factors that can determine the success of organism colonization and growth (La Peyre et al. 2015). A suitable site for oyster reef development requires “reliable freshwater inflow, supply of larvae, and adequate circulation to maintain favorable salinity regimes between 5 and 25 ppt” (Cheong et al. 2013). The selection of a site suitable to oyster recruitment is imperative for enabling “spatial heterogeneity in larval recruitment;” just the addition of proper substrate is often not sufficient for successful reef establishment (Kim et al. 2012). Larval transport and retention are influenced by tidal amplitude, river discharge, flooding events, wind conditions, and salinity, making site choice critical for larval survival and spat retention rates (La Peyre et al. 2015). Salinity levels in a site, altered by freshwater inflow rates, can affect “many aspects of [an oysters] life including growth, mortality, reproduction, predation, and disease infection levels” (Kim et al. 2012, La Peyre et al. 2015). In addition to average salinity level, variability in salinity range and timing, especially during spawning season, can also cause dramatic changes. During the period of May to September, optimal salinity rests around 20 ppt, higher than the optimal level for adults, which averages between 10 and 15 ppt. Oysters require a minimum salinity level, ideally between 8 and 10 ppt, mainly impacted by freshwater diversions or alterations in hydrology dynamics (Soniat et al. 2013). Ideal turbidity lies around 60 nephelometric turbidity units, and water temperature requirements depend on oyster species (Beseres Pollack et al. 2012). Finally, competition from species such as hooked mussels and interactions with shell pests must also be taken into account (La Peyre et al. 2017). Taking into account these variables, siting properly is critical to the establishment of an oyster reef that successfully provides shoreline protection and ecosystem services.

Shoreline Exposure

Assessing shoreline exposure determines the most appropriate locations to counteract shoreline retreat. Oysters have the potential to “indirectly affect the propagation of waves by building three-dimensional reefs, and altering coastal bathymetry, a primary control of wave energy” (La Peyre et al. 2015, p. 2). A primary factor in determining suitability for oyster reef construction is the orientation of the shoreline to wave action and dominant winds. The highest potential for erosion control occurs in high exposure coastlines, though there may still be relatively high levels of success in intermediate and low exposure sites. Reef success can be altered by wave height and the distance from marsh edge, both of which alter hydrodynamics and can increase erosion if resulting turbidity is incorrectly estimated in shoreline design. In addition, reef crests more than 25cm below the surface of the water only facilitated 20% wave attenuation, an important factor to consider in the years during reef establishment (Kitsikoudis et al. 2020). Kitsikoudis et al. (2020) found that if hydrodynamics is considered during reef siting, "flow reduction mechanisms may promote sedimentation and habitat creation at shorelines that are sheltered by oyster reefs."

Reef Substrate

The formation of a suitable clutch, or substrate, is critical for reef establishment, and a potent strategy for efficient recruitment. Engineers have developed a variety of potential substrata for oyster reef construction, ranging from the restoration of historically degraded natural reefs to the creation of artificial reef structures on which oysters can recruit and become established (La Peyre et al. 2014). Created oyster substrate can be broadly broken into two categories: "rock" consisting of various types of concrete, crushed limestone, or limestone boulders, and "shell" normally consisting of oyster shells, but occasionally containing shells from other bivalves such as clams, either loose or bound in some way. Research surrounding the use of different substrates is inadequate to determine efficacy and relative rates of success, but correlations in data indicate higher recruitment with the use of some materials. Loose shell reefs seem to be more vulnerable to scattering and burial in early stages if there is no immediate spat recruitment and ensuing growth, especially if used in a site with excessive hydrodynamic energy (La Peyre et al. 2014). Thus, in locations with higher exposure, reefs tend to be more successful with more durable, rocky clutch such as limestone or concrete. When bioengineered substrate is used for reef construction, salinity plays a much greater role in oyster recruitment and population establishment (Bilkovic et al. 2017). At present, restoration projects favor the use of engineered concrete structures, which tend to cost significantly more than the alternatives of shell or limestone. Risinger (2012) found that the use of engineered concrete substrate can act as a scaffolding for oyster recruitment, helping to prevent sedimentation atop reef structure, while providing additional wave attenuation in reef development years. When developing a plan for oyster reef construction, it is important to take into account all the environmental factors present at the location in order to choose the proper substrate and attain a successful and resilient reef.

Construction & Life Cycle Costs

One of the benefits of living shorelines is a significantly lower life cycle cost than that of built infrastructure, as oyster reefs maintain dependability with less long-term maintenance than traditional hardened shorelines. The primary mechanism used in built infrastructure for offshore wave attenuation is a breakwater, which largely offers the same protective services as an oyster reef, but they cause significant ecological damage. Oyster reefs cost about $1.5 million per mile constructed, with the price varying based on the type of substrate, location, and implementation strategies used. Reef structures provide an average of 60% hazard reduction from wind and waves, and about 5% hazard reduction from storm surge when used alone (Reguero et al. 2018). Meanwhile, breakwaters are estimated to cost approximately $17.5 million to $87.8 million per mile (Mangor et al. 2017). In the vast majority of cases breakwaters do not exceed a quarter of a mile in length. Nevertheless, the costs for both structures can vary drastically, and depend on location and materials used, among other variables. In their 2018 study, Reguero et al. found that "marsh and oyster reef restoration are among the most cost-effective measures and together contribute the most to overall damage reduction." In addition, 4 to 6 years after construction, oyster reef structures should be self-maintaining and adapt to sea level rise, especially if sited properly. Conversely, built infrastructure is unable to adapt to sea level rise and would require upgrading and additional maintenance to manage wear and weathering.

Substrate Engineering

In developing the plans for oyster reef implementation, both engineering and ecological principles must be utilized to achieve the maximum level of structural integrity and ecological benefit. The balance between structural and ecological benefits mainly stems from the design of the substrate used. Developing a larger, three-dimensional structure similar to a traditional breakwater can provide a higher level of protection earlier in the lifetime of the project, but does not facilitate long-term oyster recruitment and accumulation, and therefore will fall short in ecological benefits. Conversely, the creation of a large, flat clutch helps to facilitate oyster accumulation over time in the correct environmental conditions, but wave attenuation in the years before reef maturity will be significantly lower, leaving the coastline or marsh at a higher risk for erosion. When designing a substrate, the primary factor to focus on is oyster persistence, encompassing "recruitment, growth, and survival, which are normally surveyed, along with environmental factors such as sedimentation, salinity, and elevation" (Morris et al. 2019, p. 1707). A number of studies have found that an engineered reef substrate helps facilitate early growth in reef construction and promotes the formation of a dense three-dimensional reef long-term (Risinger 2012). These engineered concrete structures can take a variety of forms, including vertical rectangles, hollow cylinders, and hollow spherical shapes with multiple openings. Often these engineered structures can build upon one another, as they are designed to stack in a structurally sound manner to resist collapse from wave action. Engineers must focus on the characteristics of the reef including the length, height, width, density, and crest of the oyster reef, as these can alter hydrodynamics and sedimentation rates. For example, a recent study in the Pacific found that longer and narrower reefs with a high oyster density can lead to increased sediment trapping (Morris et al. 2019).

The Role of Oyster Reefs in Hybrid Approaches

Factors such as "coastal squeeze," or insufficient space on the shoreline, prevent the implementation of solely natural infrastructure. In such cases, a hybrid approach may be used, in which nature-based approaches are combined with built infrastructure. This approach is especially important in urbanized coastal areas, as they often have very little space for introducing natural infrastructure yet suffer from flooding events that can cause extensive damage (Moosavi 2017). These hybrid approaches do not provide the range of ecosystem services gained from living shorelines, yet the incorporation of some aspects of natural infrastructure still contributes co-benefits and ecological enhancement. Both approaches, built infrastructure and living shorelines, have inherent weaknesses, but "using a combination of these approaches can capitalize on the strengths of both while aiming to minimize the weaknesses of each" (Sutton-Grier et al. 2015, p. 143). In using a hybrid approach, a community can avoid the vulnerabilities of natural infrastructure in the years following construction, with built infrastructure providing adequate protection to both coastal communities and ecosystems during recruitment and growth stages. Alternatively, coastal communities can develop natural infrastructure seaward of built infrastructure to extend infrastructure lifetime while gaining ecosystem services and co-benefits (Cheong et al. 2013). Oyster reefs have strong potential as a key element in hybrid approaches; acting effectively as a breakwater, reefs attenuate wave action, reducing erosive processes on the shore. By including reefs in hybrid design structures, built infrastructure located further inland can be protected from wave action and therefore have an extended lifetime, lowering life-cycle maintenance costs while providing ecosystem services to a likely degraded ecosystem. This has especially high potential for urban coastlines, as oysters can help mitigate historically high levels of pollution and nutrient runoff which have degraded an ecosystem for decades. Morris et al. (2019) found that oyster reefs can be used instead of traditional breakwaters with the same level of dependability, if the reef is properly sited and implemented and successful oyster colonization occurs.

Case Studies in Oyster Reef Efficacy

Oyster reefs have been used in living shorelines to varying degrees of success, indicating which factors can lead to a lucrative project, and which factors can be detrimental to project success. The following case studies allow us to determine which approaches can enhance the protection capabilities of an oyster reef while ensuring the ecological functionality of the constructed ecosystem.

San Francisco Bay

In San Francisco Bay, the Near-shore Linkages project was implemented in 2012 in order to increase flooding resilience and decrease erosion while restoring eroded wetlands. Boyer et al. (2017) examined "the individual and interactive effects of restoration techniques on habitat values, and test[ed] alternatives to hard/structural stabilization in a multi-objective pilot climate adaptation and restoration project." This project was centered around the cultivation of a living shoreline composed of eelgrass (*Zostera marina)* and Olympia oysters (*Ostrea lurida)*, both of which are native to the area and are known to produce synergies that can augment the growth and colonization of the other species, as well as promoting overall biodiversity in the bay. This project was sited at the San Rafael shoreline and the Eden Landing Ecological Reserve in Hayward. Construction and planting occurred in July and August of 2012. Within these two sites there were multiple plots, some containing only eelgrass, others only oyster reef, and others with both in order to compare project results.

In both San Rafael and Hayward, engineers tested the success rates of five different types of oyster clutch. The substrates consisted of shell bag mounds and concrete structures including reef balls, oyster ball stacks, oyster blocks, and layer cake designs, each of which was constructed of a mixture containing 20% marine grade cement and 80% material derived from the bay (Boyer et al. 2017). Oyster recruitment was extremely successful, with a total estimated population of over 2 million in the first year, with oysters showing higher attachment levels on vertical surfaces. The different concrete substrate configurations did not show substantial differences in size or oyster density excluding the layer cake formation, which supported fewer than 500 oysters per element due to the higher percentage of horizontal surface on which fewer oysters colonized. The oyster ball stacks, supporting up to 1,000 oysters per element, showed a tendency towards collapse due to wave action, causing reef destruction. Larger reef balls and oyster blocks proved to be the most successful of the cement structures, both of which supported approximately 1,000 oysters per element. Shell bag mounds indicated a higher success rate than any cement structure, with up to 5,500 oysters per element (Boyer et al. 2017). At the Hayward site, scientists found severe predation by the Atlantic oyster drill, which caused significantly higher stressor levels and increased mortality. In the plots with oyster reef construction, biodiversity increased significantly more than in eelgrass-only plots, especially regarding epibenthic invertebrate species.

In determining the placement of a reef, tidal height, surface orientation, and wave direction have a dramatic effect on initial oyster density and sedimentation patterns. Studies showed localized sedimentation next to oyster reefs, with a pattern of erosion on the bay side of the reef and accretion on the shore side. Additionally, fewer waves were recorded in the lee of oyster reefs, showing about 30% wave attenuation in the first three years of construction, with the potential to increase as the reef continues to accumulate (Boyer et al. 2017). This data indicates high potential for both erosion control and wave attenuation in the future with the further colonization of reef sites.

This study concluded that restoring oysters and eelgrass together resulted in the highest level of benefits, yielding greater increases in epibenthic invertebrates, fish stocks, and avian populations. The presence of oyster reefs, however, can limit eelgrass spread, which should be taken into account when planning reef placement relative to eelgrass, and most likely can be avoided if a different configuration is applied. In addition, Hayward seemed to be a significantly less suitable site than San Rafael, most likely due to predation. This study has important implications for the success levels of substrates, showing oyster shell bags to be the most successful, most likely because this technique "offers more surface area than any of the [cement] elements and greater protection from heat or desiccation stress attributed to more shading and water retention" (Boyer et al. 2017, p. 357). Though the project was successful at the San Rafael site, local environmental factors also contribute to the success of a particular substrate. Further, this study displays the importance of meticulous siting for reef construction, displayed by the lower success rate at the Hayward site.

Coastal Louisiana

Since 1932, coastal Louisiana has lost an area of land approximately the size of Delaware, about 4877km^2, due to processes such as "subsidence, sea level rise, tropical cyclonic activity, and direct human activities" (La Peyre et al. 2017, p. 364). Following the extreme destruction caused by Hurricane Katrina in 2005, policymakers in Louisiana implemented more than $50 billion of restoration and adaptation projects, including river reengineering, sediment diversion, marsh and barrier island restoration, and shoreline stabilization and protection, including the creation of oyster reefs using the Eastern oyster (*Crassostrea virginica).* La Peyre et al. (2017) analyzed seven projects across coastal Louisiana, constructed between 2007 and 2011, "ranging from experimental oyster reefs using loose shell clutch, to more bioengineered reefs using a variety of techniques in demonstration projects, to large-scale on-the-ground shoreline protection bioengineered projects" (La Peyre et al. 2017, 366). Each of these projects used a different form of substrate: A-Jacks, Gabion Mats, ReefBlk, loose oyster shell, or OysterBreak rings. A-Jacks consist of 2-foot-tall concrete structures tied together with steel cables, placed atop a crushed stone foundation. Gabion Mats are mattress-shaped mesh frames filled with crushed stone, partially submerged on the edge of a marsh. ReefBlk is formed using triangular rebar frames with mesh bags filled with oyster shells, placed on top of a foundation of crushed stone and anchored in place. OysterBreak structures are bioengineered concrete rings, from 50 to 61cm high, placed next to each other in either subtidal or intertidal formations (La Peyre et al. 2017). Each site had comparable environmental conditions, with mean salinity in the range of 9-21 ppt, similar temperatures, and the same range of dissolved oxygen, turbidity, and chlorophyll a.

Measurements were taken at each site to determine oyster population and density, in addition to densities of competing and predatory organisms, with different sampling approaches based on the type of substrate used. Terrebonne Bay and Sister Lake, with both sites in the mid-salinity range, showed substantially higher oyster density with well over 500 oysters per square meter at two years after construction, and "slowly increasing mean sizes and increasing ranges of oyster class sizes over time" (La Peyre et al. 2017, p. 373). Lake Eloi, Lake Fortuna, and Lake Athanasio all displayed oyster recruitment at significantly lower densities following the first year of construction, falling below 120 oysters per square meter. Conversely, Vermillion and Grand Isle, respectively low-salinity and high-salinity sites, showed very low or no oyster density. In the Terrebonne and Sister Lake projects, hooked mussels, originally considered a competitor, were three times as abundant than the eastern oyster. However, the presence of hooked mussels enhanced the filtration services of the reef, instead showing a complementary relationship with the reef as they are more effective at filtering smaller particles not utilized by oysters. Terrebonne Bay experienced reef failure four years following construction, showing greater than 50% shell loss within the bags of the ReefBlk structure, leading the authors to conclude that the ReefBlk was not a structurally sound substrate and was unable to support the long term development of oyster reefs (La Peyre et al. 2017). In addition, the use of loose shells at the Sister Lake site proved to not be resilient to strong tides and winds, yet did reduce storm surge during extreme storm systems, most likely due to the dissipation of wave energy (Piazza et al. 2005).

The authors used a standardized method to measure shoreline stabilization at each site, utilizing permanent base stakes placed offshore to measure distance from the shore and changes in position. Each site continued to show marsh retreat after construction, though at most sites marsh retreat was significantly lower than at control sites, despite significant storm activity. This reduction in shoreline erosion with very young reef structures gives further proof of the stabilization properties provided by oyster reefs. However, there were indications that "other factors, such as shoreline exposure, adjacent marsh characteristics, or local subsidence may be critical to identifying the most likely sites for successful shoreline protection" (La Peyre et al. 2017, p. 378).

Lessons taken from this study include the importance of salinity regimes, reef exposure, biotic interactions, biofouling, and substrate suitability. The outcomes of the Terrebonne and Sister Lake projects indicate that moderate mean salinities support fast population development and higher productivity rates, two extremely important factors in the advancement of a successful, resilient reef. The project in Terrebonne Bay also showed that the presence of hooked mussels does not necessarily stimulate a competitive relationship. However, due to the lack of reef building properties, hooked mussels can compromise the resilience and stability of a reef in the long term. In addition, there was a high level of biofouling from shell pests, most likely due to salinity and insufficient reef exposure. High levels of competition and predation highlight the importance in determining habitat suitability for competitors and predators in addition to oysters when siting a reef. Finally, the use of a stable substrate is extremely important, as demonstrated by the failure of the ReefBlk structure. The study by Piazza et al. (2005) established the efficacy of using shell as a substrate, given that stability can be augmented in the early stages of reef development to avoid degradation.

New York Harbor

In New York Harbor, the Oyster Restoration Research Project (ORRP) was implemented in 2010 to determine the efficacy of using oyster reefs to augment shoreline protection and provide water filtration services. Eastern Oyster Reefs were constructed in the fall of 2010 at five different sites, off the coast of Bay Ridge Flats, Governors Island, Hastings, Soundview, and Staten Island. Each site used a rock base substrate approximately 50m^2, with a thin mollusk shell veneer and seeded with oyster spat-on-shell, or juvenile oysters. Due to increased erosion and spat loss at specific sites, spat-on-shell were redistributed in June of 2011 at Governors Island, Hastings, and Soundview. Scientists periodically monitored reef development at each site, assessing reef performance chiefly focused on water filtration and habitat provision as ecosystem services (Grizzle et al. 2012).

Oyster populations were relatively successful, but the winter of 2010-2011 showed evidence of spat loss, likely due to high turbidity and strong current. Environmental conditions remained in the correct range for Eastern Oysters, with an exception at the Hastings site, where salinity dropped significantly below the optimal range for several weeks during the summer of 2011. The Soundview project showed the best development after a year, exhibiting high potential for long-term reef sustainability. Though spat-on-shell retention was not high at the Soundview site, recruitment from wild oysters was significant. In addition, the Governors Island reef showed high potential for future restoration and resilience despite initial spat transportation issues; spat retention and growth was strong and consistent, as well as wild oyster recruitment on the substrate. The reef at Hastings initially showed high spat mortality rates, likely due to exposure to extremely low salinity levels in 2011, however it also showed the highest colonization rates for wild oysters, suggesting that natural recruitment may be sufficient for long-term sustainability (Grizzle et al. 2012). The reefs developed at Bay Ridge Flats and Staten Island, sampled in 2012, had no live oysters, indicating the unsuitability of the sites chosen. Both of these reefs were found covered with sand and with significant loss of shell material, implying the presence of extremely high energy waves and currents which hindered growth and colonization (Grizzle et al. 2012).

The authors collected wild oysters at Soundview and Hastings to test for disease, historically a factor in oyster mortality in New York Harbor. Wild oysters at Hastings were infected by both MSX and Dermo, two major oyster diseases. Infection was highest in larger oysters, yet very few oysters showed advanced infection. At Soundview, the oysters were only infected with MSX, with no indication of advanced-stage disease. Though disease was not initially considered as a factor for oyster mortality, it may be a factor in reef sustainability at these locations in the future. Mortality due to MSX can limit the lifespan of an individual oyster to about 5 years, though this has become a relatively typical lifetime length in the mid-Atlantic and northeastern United States (Grizzle et al. 2012).

In monitoring water filtration properties, Grizzle et al. (2012) found that during the first year, chlorophyll-a uptake occurred at a low level at Hastings and Soundview, but these data sets were variable most likely due to wave action and boat wakes stirring up sediment. Overall, the reefs did not make a significant impact on chlorophyll-a concentration during the first year, and even showed a net negative removal rate over the monitoring period. During the second year, removal levels were significantly higher due to the increase in oyster size and density, showing approximately a 20% removal rate during an ebbing tide, and 21.8% removal during a flood tide at Soundview.

Biodiversity tended to increase at the reef sites over time, with sampling focused around the more successful reefs at Soundview and Hastings. In the first year, the Staten Island reef showed the highest taxonomic diversity, with 23 taxa, in addition to the highest densities, with 5,000 individuals per tray, compared to other reefs, with only about 1,000 individuals per tray. During the second year, biodiversity followed a similar trend of general taxonomic richness and density increase, especially during the summer months (Grizzle et al. 2012).

From these experimental reefs, the authors developed a number of recommendations for future oyster reef projects. First, the implementation of larger reef substrate can allow for greater reef development and therefore, higher performance. Grizzle et al. (2012) hypothesize that a larger footprint will allow for greater spat-on-shell retention in high energy environments in addition to increasing the likelihood of wild oyster recruitment, which can help to decrease the lifetime cost of the project. Next, the authors discussed the development of retention techniques for oyster spat-on-shell plantings during implementation. Oysters have a natural tendency to clump during recruitment, therefore the formation of spat-on-shell “blocks” during the nursery phase could increase resilience to high energy from wave, wind, and boat wakes. Alternatively, a biodegradable mesh could be placed atop spat-on-shell to protect them from erosion during development, enabling them to adhere properly to the substrate. Finally, the development of disease resistance and adaptation to a wider range of salinities in oysters will be extremely important in this area of the country in order to prevent mortality. These characteristics can potentially be developed through intentional siting at high or low salinity sites. For example, at the

Hastings site, oysters were exposed to extremely low salinity levels, and surviving oysters were less vulnerable to salinity fluxes in the following years (Grizzle et al. 2012). Governors Island has shown strong potential for oyster reef growth beyond this study, which has made it the location for the *Billion Oyster Project,* which strives to improve water quality, attenuate wave action, and facilitate higher levels of biodiversity (O'Neil et al. 2016).

Conclusion

This paper proves the efficacy of oyster reefs as a cost-effective, resilient, and successful method for wave attenuation and erosion control within either a living shoreline or a hybrid approach to coastal adaptation. Due to the many ecosystem services provided and to lower costs for implementation and maintenance, oyster reefs should be considered as a primary alternative to artificial, built infrastructure. When developing a living shoreline strategy, it is imperative to site the project properly, taking into consideration salinity regimes, water temperature, freshwater inflow, and biotic interactions with competitors and predators to realize the full potential of the project, as displayed in the case studies by Boyer et al. (2017), La Peyre et al. (2017) and Grizzle et al. (2012). In addition, the substrate chosen for oyster clutch makes a significant difference in retention and recruitment rates for an oyster reef. The study by Boyer et al. (2017) showed that bagged oyster shells were significantly more successful than bioengineered concrete structures, but that with the use of concrete substrate oysters accumulated more on vertical surfaces than horizontal surfaces. This case study in San Francisco Bay demonstrates the importance of substrate design and material. La Peyre et al. (2017) documented the importance of a stable substrate in long-term oyster reef survival, as seen in the failure of ReefBlk in the Terrebonne reef. Oyster reefs have high potential to augment both protection capacity and ecosystem services within living shorelines, and therefore should be a primary consideration for use in coastal resilience projects throughout the globe. Reef failure did occur in some projects, though mainly due to improper siting, therefore potential for collapse can be avoided in future projects with sufficient research and due diligence before reef implementation. Oyster reefs are thus extremely useful in increasing coastal resilience, proving to be more cost-effective than built infrastructure, to decrease erosive processes, and to attenuate wave action, in turn enhancing the capabilities of living shorelines or hybrid approaches to coastal resilience.

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