Nature-Based Solutions for Climate Change Mitigation: How the Eastern Oyster (*Crassostrea virginica*) Can Aid in South Carolina Coastal Resilience

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Abstract

The effects of climate change on coastal communities along the United States Atlantic coast are becoming an increasing threat. The effectiveness and sustainability of traditional built protections that have been used to armor coasts against these threats has come into question as they require costly replacement and maintenance and are a contributor to significant disruptions in the functioning of the coastal ecosystems in which they are used. Nature-based solutions to protecting coastal communities are a cost-effective alternative to traditional coastal protections, and coastal ecosystems have been shown to be resilient to the effects of climate change and to storm hazards. These solutions include using the restoration of natural habitats alone, or in conjunction with built protections to enhance the ecosystem services provided to coastal communities, along with providing dynamic protections to coastal hazards. A tool in the suite of nature-based solutions for coastal resilience on the Atlantic coast is the restoration and creation of oyster reefs for their shoreline protection services. This case study summarizes how nature-based solutions can be an effective alternative to traditional coastal protections, the role of oyster restoration in nature-based solutions and examines how the current oyster restoration efforts in coastal South Carolina can be expanded on to develop nature-based solutions to the effects of climate change.

Introduction

United States (U.S.) Atlantic coastal ecosystems are made up of a diverse array of shoreline habitats, including the critical marine biogenic habitats found in estuaries such as mangrove, oyster reef, salt marsh, and seagrass. These habitats serve as nurseries, breeding and forage grounds, and provide protection to upland habitats while maintaining water quality. However, these habitats have suffered significant declines over the last 100 years and are among the most modified and threatened (Bagget et al. 2015, Gittman et al. 2016). Additionally, the effects of climate change have already begun to alter the function of these coastal habitats. Sea levels have risen about eight inches since the 1880s, with 3.4 of those inches occurring since 1993. This has resulted in coastal flooding occurring 300-900% more frequently than 50 years ago. Sea level rise (SLR) is exacerbated in coastal areas by natural processes such as high tides, wave action, storm surges, and rainfall (EPA 2021a). Combined, these natural processes present a significant threat to the not only coastal ecosystems, but the infrastructure and well being of coastal communities.

Coastlines are home to roughly 42% of the U.S. population (NOAA 2021a). These areas are economically important, generating 58% of the national gross domestic product (GDP) through fishing, transportation, and tourism industries, as well as serving as hubs for trade (EPA 2021b). Climate change impacts are predicted to have an increasingly detrimental effect on coastal communities, with increasing inundation from regular flooding events to threating coastal infrastructure due to the predicted increase in frequency and intensity of storms.

The year 2017 saw the highest costs ever in the U.S. from weather events at $306.2 billion, with Hurricane Harvey alone resulting in $125 billion in costs, second only to 2005's Hurricane Katrina (NOAA 2021b). While not as costly as 2017, 2020 saw a historically active hurricane season. Hurricane Hanna made landfall in Texas on July 25, and by September 18th the 21-name list was exhausted, with the season ending with nine more Greek-alphabet named storms.

Resilience, the ability for coastal communities to recover after events such as storms and flooding, has become a major socioencomic and environmental concern, particularly on the hurricane-prone Atlantic coast (Sutton-Grier et al. 2015, NOAA 2021a). U.S. agencies have made significant investments in flood mitigation, with the Federal Emergency Management Agency alone spending roughly $500 million annually in pre-hazard mitigation (Reguero et al. 2018). However, little of the investment has included incorporating the natural protections of coastal ecosystems. Since the founding of the U.S., more than half of coastal wetlands have been lost, with the most recent loss rate being estimated at 80,000 acres per year (between 2004 and 2009) (NOAA 2021c). By 2100, it is predicted that 33% of U.S. shorelines will be armored with hard structures to protect from coastal hazards (NOAA 2021a). This hard armoring disrupts coastal ecosystems from acting as storage area for flood waters, preventing storm surges from rising and propagating inland, and from responding to climate change impacts (Temmerman et al. 2013). As part of the overall hazard mitigation strategy needed to enhance coastal resilience, there is a need to focus on conserving and restoring coastal ecosystems to harness the natural protections they provide.

This paper will review the use of natural solutions as an alternative to traditional coastal shoreline protections, how oyster restoration is an important tool as a natural solution for climate change mitigation, and examining oyster restoration in South Carolina as a means to create resilience in coastal communities.

Natural Solutions as a Pathway to Resilience

To date, seawalls, riprap, bulkheads, and other hard engineered structures have been the standard approach for protecting coastal infrastructure from wave stress (Fivash et al. 2021, Gittman et al. 2016, Morris et al. 2020, Safak et al. 2020). The viability of these methods of shoreline protection has come into question as these structures can no longer keep pace with the threats that coastal communities face. Hard structures are non-adaptive, requiring maintenance and upgrades that incur significant annual costs and investments (Morris et. al 2019, Morris et al. 2020, Smith et al. 2020). In several reviews of how bulkheads, a widely used engineered structure, held up during storm events, researchers found that between 75-90% of damages during hurricane events could be attributed to a structure containing a bulkhead (Gittman et al. 2014, Sutton-Grier et al. 2015, Smith et al. 2018). Additionally, these structures are a major contributing factor in disrupting the ecological function of coastal habitats (Scyphers et al. 2011). They prevent the natural movement of organisms, alter hydrodynamics and sedimentation, break up estuarine habitats isolating them from upland areas, all resulting in the loss or disruption of intertidal and nearshore subtidal zones. Benthic habitats adjacent to engineered structures are often absent of the complex structure needed to support nurseries, a key role of natural functioning, and in some areas with seawalls the loss of natural vegetative habitat can be complete (Gittman et al. 2016). These implications make the need for an alternative solution to coastal protections given the future climate predictions that will further test the capabilities of hard infrastructure.

Nature-based solutions (NBS) are increasingly being proposed and used as a means mitigate effects of flooding and storm surges as an alternative to built structures (Sutton-Grier et al. 2015, Seddon et al. 2020, Fivash et al. 2021). NBS refer to ecosystem-based approaches to managing and using natural systems to address societal and environmental challenges (IUCN 2021). For the purpose of this paper, NBS will be used to describe the solutions that restore or emulate natural ecosystems to increase resilience (human, ecosystem, and infrastructure) to climate impacts (Luedke 2019, The Nature Conservancy 2021a). Natural coastal habitats have built-in defense systems in the form of salt marshes, coral reefs, mangroves, oyster reefs and dunes (Spaulding et al. 2014). These habitats provide protection through physical barriers and creating an elevational profile that limits inundation (Morris et al. 2019). This occurs through processes such as bed friction, sediment deposition, and vertical biomass accumulation. Restoring these functions through implementing NBS requires habitat be restored or created to provide a duel result that hard infrastructure does not: mitigating climate change effects while harnessing the benefits of ecosystem services provided by natural habitats. NBS tend to cost less than built structures, and although not maintenance free, many natural infrastructure options have the potential to self-repair after damaging events and the costs of creation and upkeep are lower than built structures (Table 1) (Sutton-Grier et al. 2015, McClenchan et al. 2020). This is a key consideration when seeking solutions to both episodic and chronic impacts of climate change.

Table 1: Costs of Shoreline Stabilization Materials

Material	Cost
Breakwaters	$90/ linear foot[1]
Riprap Revetments	$90/Linear foot[1,4]
Bulkheads	$400-1000/ linear foot[1,2]
Granite	$350/ linear foot[1]
Hybrid Marsh and Sill	$250-400[3]
Reef Balls	$40-$400[5]
Oyster Castle (Concrete Block)	$10-18[4]
Oyster Shell	$20-60 sq yard loose, $5-20/Bag[1,2,4]
Marsh Grass Planting	$2-3 per plug[2,3,4]
Mangrove	$10 Gallon pot[2]
Coir Logs	$5-6/ 10 feet[4]

1-Coastal Review (2019), 2-DeVore, 3-Rivers and Coast (2014), 4-Esutuaries.org (2019) 5-Reefball.org (2021)

Natural Infrastructure

The tools to achieve coastal resilience using NBS fall under a spectrum from gray (hard techniques) to green (soft techniques) (Figure 1). On the green side is natural infrastructure, the use of natural landscapes to increase resilience (Sutton-Grier et al. 2015, SCDNR 2019). Natural infrastructure is generally used in low- to-medium energy environments, and methods include the restoration of tidal marsh vegetation, dunes, and oyster reefs to provide coastal protection

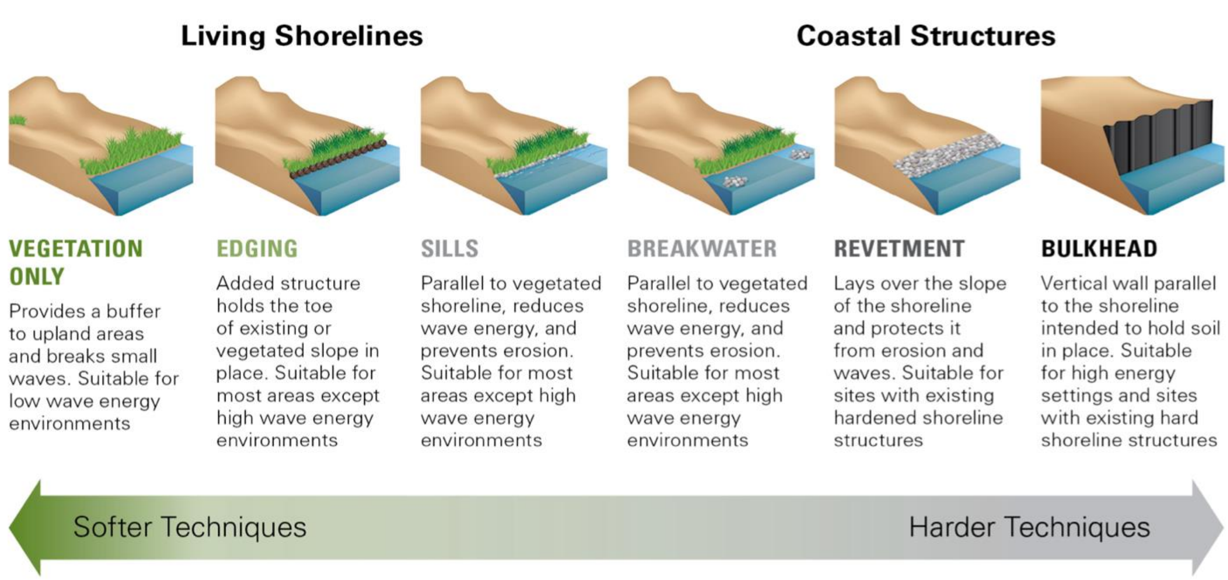

Figure 1. Coastal shoreline stabilization continuum (FEMA 2018)

through the reduction of wave energy and erosion prevention. *Spartina alternaflora* is the dominant marsh grass species of low marsh and estuarine habitats of the Atlantic coast (Ridge et al. 2017). *Spartina* can trap sediment by baffling current and wave energy, significantly reducing wave height before the shorelines, dissipating 50% of wave energy within the first eight feet, with 100% of wave energy being dissipated within 100 feet (Walker et al. 2011). Salt marshes are protective under more frequent and less intense storm events, thus providing substantial flood protection during recurrent events, and as a frontline to larger storm events (Rezaie et al. 2020). Salt marshes, mangroves and oyster reefs are resilient to current rates of SLR because they have the ability to increase their elevation by accumulating belowground biomass and can exhibit greater productivity with increased inundation (Ridge et al. 2017, Fivash et al. 2021, Skalr et al. 2021). Known as living shorelines, these methods for creating natural infrastructure include restoring and enhancing marsh grasses, mangroves, trees, submerged aquatic vegetation, natural fiber logs, and planting oyster shell to encourage oyster colonization.

Hybrid Solutions

Between vegetation enhancement and hard structures are hybrid methods for implementing NBS. These methods harness the strengths and minimize the weaknesses of solely using built or natural infrastructure (Morris et al. 2020). In many urbanized areas, persistent vessel traffic turns naturally low-energy areas into medium and high environments (Safak et al. 2020). These areas are especially challenging because these climates are no longer conducive to solely natural infrastructure methods. Additional interventions to dissipate wake may be required to support living shorelines. Examples of successful hybrid approaches are the use of brush-filled breakwalls, rock sills in front of mangroves, or oyster reefs in front of built structures (Figure 2). While engineered structures are used in these scenarios, the solution still retains the co-benefits of natural solutions (Morris et al. 2018, Smith et al. 2020). Hybrid approaches also extend the range of habitat for NBS (Morris et al. 2019). The use of low-crested rock sills or breakwaters seeded with oyster spat, or oyster structures can aid in encouraging reef growth in areas where colonization on soft substrate would not be possible. Natural solutions can also be effective in protecting built structures (Sutton-Grier et al. 2015).

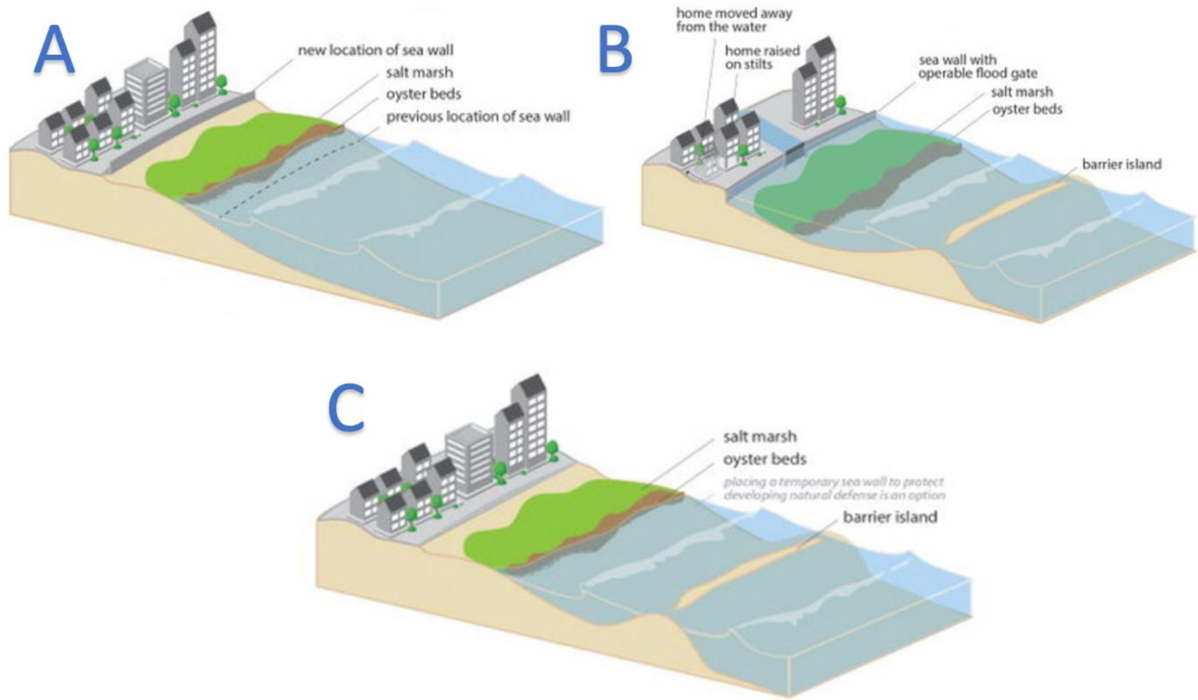

Figure 2. Examples of nature-based coastal protection solutions. A- demonstrates a combination of natural habitats used to provide protection. B- demonstrates managed realignment where natural solutions are used to protect built structures. C- shows hard infrastructure built simultaneously with restored or created natural infrastructure to harness the maximum benefits of coastal protections (adapted from Sutton-Grier et al. 2015)

For example, in the United Kingdom built defenses have been placed further back from the shoreline than in previous projects, while natural infrastructure was established in front with space to develop (van Slobbe 2013). This “managed realignment” of coastal protections has occurred in many places along the North Sea coast and is considered a cost-effective and sustainable solution for communities to deal with sea level rise while maintaining coastal biodiversity (Figure 2) (Sutton-Grier et al. 2015). Additionally, hybrid approaches help engender confidence with communities as it combines the immediate protections and familiarity of built infrastructure while the natural solutions become established. In some scenarios, natural infrastructure would be insufficient to protect coastal communities alone. The Nature Conservancy’s case study of post-Hurricane Sandy Howard Beach, New York, indicated that natural infrastructure alone would not have been sufficient to cope with the slow-moving storm (The Nature Conservancy 2015, Sutton-Grier et al. 2015). Several infrastructure scenarios were examined, and it was determined that for Howard Beach, a combination of a flood gates and sea walls, along with restored marshes and mussel beds would help this community avoid up to $244 million in losses from another storm event like Hurricane Sandy while making the city more livable.

Ecosystem Service Delivery

Using NBS not only aids in the resilience of coastal habitats, but also enhances service delivery to coastal communities (Ridge et al. 2017). Estuarine and vegetated nearshore habitats make up only .7% of global biomass but contribute 23% of the total global ecosystem services (Schyphers et al. 2011, Wang et al. 2019). Coastal wetlands provide the additional benefits of carbon sequestration, water purification, and fishery support. Tidal wetlands contain long-term soil organic carbon which sequesters atmospheric carbon dioxide 10-100 times higher than terrestrial forests and are responsible for 50% of the annual carbon burial of the ocean despite only being 2% of the earth's surface (McLeod et al. 2011, Fodrie et al. 2017, Wang et al. 2019). Because the sediments of wetlands accrete vertically, the rate of sequestration can be maintained as long as sediment accretion is occurring. The physical structure of oyster reefs create habitat for hundreds of other marine species, and single oyster found in a tidal wetland can filter 180 liters of water a day (NOAA 2021d, SCNDR 2021a). In terms of coastal protection, the valuation of services that coastal habitats can be difficult to quantify as there is no standard method for determining values (Sutton-Grier et al. 2015). Table 2 shows examples where valuations have been placed on natural habitats during storm events in the U.S. While it may be difficult to measure and value the benefits and co-benefits of natural and green infrastructure, these services are being continually provided to aid in coastal resilience, while built infrastructure only provides the benefit of protection during a storm event and often does not address flooding issues.

Table 2: Estimates of Ecosystem Service Value for Natural Habitat Hazard Protections

Reference	**Value Assigned to Natural Habitat Coastal Hazard Mitigation**
Costanza et al. 2008	Coastal wetlands in the U.S. were estimated to provide 23.2 billion per year in storm protection services alone based on a model of 34 hurricane events since 1980. Additionally, the study found that the loss of one acre of coastal wetlands equated to an increase in $13,3660 in damages to communities during storm events
Grabowski et al. 2012	In comparing the stabilization of oyster reef habitat versus built structures, it was estimated that one hectare of oyster reef habit provides $85,998 of annual value in ecosystem services over manmade options.
Loerzel et al. 2017	NOAA study of post Hurricane Sandy New Jersey found that $32 million in damages were avoided where marshes were present, valuing an acre of marsh at $557
Barbier et al. 2013	Determined that a .1 increase in the ratio of wetland to open water resulted in avoiding damages of $590,000-$792,000 per storm in Louisiana communities. Marshes reduced property loss due to flooding by 16% annually, 6.1-13.8% from storm surges.
Storlazzi et al. 2019	The U.S. Geological Survey determined that coral reef wave dissipation during storms provide flood damage protection of more than $825 million to more than 5,964 buildings in the U.S, including 33 critical infrastructure facilities.
Rezaie et al. 2020	$8 million in flood damages were avoided in areas with marsh habitat present during Hurricane Sandy
Menendez et al. 2020	Mangroves reduce annual expected flood damages from tropical storm by $60 billion and protect 14 million people in the U.S.
Sun and Carlson 2020	Salt marshes provided $695,000 of value per square mile during tropical storms and hurricanes from 1996-2016 along the Atlantic and Gulf Coasts.

Oyster Restoration for Resilience

One of the tools for nature-based coastal resilience is the restoration of oyster reefs in estuarine systems. Oyster restoration has historically been a fishery effort, but the recognition that oysters provide a multitude of ecosystem services beyond a fishery benefit has shifted the focus along the U.S. Atlantic coast to restoration of the eastern oyster (*Crassostrea virginica*) for ecological benefits rather than fishery enhancement (Hadley et al. 2010, Baggett et al. 2015). In their natural setting, oyster reefs are found seaward of salt marshes and mangroves, ranging from Canada to Argentina (Coen and Luchenbach 2000, Scyphers et al. 2011). Beyond their value as a fishery resource, these reefs attenuate waves, stabilize, and accrete sediments, reduce marsh retreat, and provide nursery habitat.

Oyster reefs have experienced one of the largest global losses of any type of marine habit over the last 100 years due to overharvesting, habitat destruction, disease, shoreline alteration, and sedimentation (Beck et al. 2011, Rodriguez et al. 2014, Morris et al. 2020). Oysters are found in estuaries, sounds, bays, and tidal creeks with salinities ranging from 5 practical salinity units (PSU) to 25 PSU. Reefs vary from intertidal to subtidal and are found as fringing or patch reefs ranging from $10m^2$ to $1000m^2$. Growth rate varies with temperature (6-32 C°), with the optimal growth rate temperature occurring around 25 C°. Growth rates are also heavily determined by salinity and aerial exposure (Ridge et al. 2015). Aerial exposure is the time intertidal oysters are exposed during the tidal cycle, with the highest mean growth (reflecting the optimal growth zone) occurring when reefs are exposed 20-40% of the time (Bost et al. 2021, Morris et al. 2021). Reproduction occurs when water temperatures become greater than 20 C° (SCDNR 2021a). *C. virginica* are broadcast spawners, with the larvae remaining planktonic for approximately 3 weeks before the larvae must attach to a hard substrate (settlement).

The capacity of oyster reefs to grow vertically, spread horizontally, and transgress landward make them an ideal candidate for creating nature-based infrastructure that mitigates erosion and SLR (Bost et al. 2021, Morris et al. 2021). Oyster reefs accrete through skeletal growth, deposition of dead oyster shell, and accumulation of allogenic sediment (from outside of the reef), and the rate at which reefs accrete vertically has been demonstrated to be on pace to maintain elevation with most scenarios of predicted sea level rise (Rodriguez et al. 2014, Ridge et al. 2015, Ridge et al. 2017, Morris et al. 2020). Established oyster reefs have also shown to be resilient to accelerating sea level rise as growth rates on top of the reef increased as oysters exploited the increased inundation time (Walles et al. 2015). Oysters display a natural resilience and adaptive capacity to recover from storm events, and *C. virginica* are robust to fluctuations in salinity (Ridge et al. 2017, Bost et al. 2021). If the environment remains estuarine, they will remain in equilibrium with most future scenarios of sea level rise as evidenced by long term observations of mature reef surface elevation. Additionally, fringing oyster reefs are more resistant to erosion and positioned lower in the tidal frame than marshes, making them an excellent base for marsh grass and mangrove stabilization (Ridge et al. 2017, Fivash et al. 2021).

Successful oyster restoration relies on both understanding and overcoming factors that limit natural establishment and recovery (Howie and Bishop 2021). In terms of using oysters as a natural solution to creating resilient coasts, there is an additional component of building a system in which ecosystem services will be enhanced and persist into the future. The general considerations for restoration projects are that sites must be suitable for oyster settlement, growth, reproduction, and that the proper substrate is used for reef settlement (Bagget et al. 2014). To be successful, approaches either reduce environmental stress to create artificial opportunities for settlement or mimic the positive feedbacks that enable established organisms to persist in non-optimal conditions (Fivash et al. 2021). In restoration for fisheries enhancement, site selection for reefs is generally based on historical distributions of oysters along with biological parameters (Brumbaugh et al. 2006, Howie and Bishop 2021). However, for use in coastal protection NBS, the site locations need to fit the provision of services being sought. While historical baselines can help inform the decision to include oysters in a NBS project, site locations for oyster based NBS need to take into consideration current and future anticipated environmental and land use changes, and the level of hazard risk reduction (FEMA 2021).

Factors Affecting Oyster Reef Establishment

Wave disturbance, predation, and inundation time affect reef development (Scyphers et al. 2011, Fodrie et al. 2014, Theuerkauf and Puckett 2017). The geomorphological, hydrological and water quality parameters of the shoreline being restored are a key consideration in choosing to use oysters in a project. Highly exposed salt marsh shorelines are likely to have a steep, near vertical morphology and would require additional stabilization for reef formation. Benthos adjacent to preexisting structures such as bulkheads can increase wave energy, resulting in bottom scour and increased sedimentation. This can result in buried reefs.

As noted, salinity and aerial exposure control reef growth. The Atlantic Ocean has a salinity of approximately 36 PSU, with salinity decreasing upriver in estuaries (Havens 2018). The optimal range for use in a NBS will depend on the location. For example, in South Carolina, sites with salinity under 15 PSU have not proved successful for oyster settlement, whereas in the Chesapeake Bay, restoration efforts have been successful in locations with salinity as low as 10 PSU (SCDNDR 2019, Chesapeake Bay Program 2021). Larval supply is also an important consideration when using oysters. In restoration efforts from the Chesapeake Bay north, it is common for projects to include population enhancement, with seed planting occurring from either natural or hatchery stocks (Maryland DNR 2020). Because oyster restoration is versatile, projects can be attempted outside where they currently exist if the project design accommodates the relevant environmental and biological site characteristics. As *C. Virginica* are tolerant to a broad range of temperature are salinity, many issues at restoration or living shoreline sites can be mitigated with a good project design that address the other environmental and biological constraints affecting oyster reef settlement and growth (Howie and Bishop 2021).

Settlement on soft substrate by larvae is rare, so providing structures that can support initial reef formation until biological feedbacks step in are the basis for oyster establishment in nature-based infrastructure projects (Keller et al. 2019, Morris et al. 2020). Although oyster shell is the preferred substrate for restoration projects, the lack of availability can present a challenge in its exclusive use. Oyster shells used in restoration projects come from shucking operations, recycling, or dredged deposits (Graham et al. 2017, SDCNR 2021b). However, supplies of dredged shell are finite, and much of the harvested oyster shell that could be used in projects are often disposed in landfills or used in industries such as livestock additives and road construction. This limits the quantity of shell available and makes purchasing shells for ecological restoration projects expensive. Non-oyster shell substrates have been widely studied, and the commonly used choices include plastic mats, limestone, concrete, stone, porcelain, and non-oyster shell (Figure 3) (Morris et al. 2018, Goelz et al. 2020). Monitoring of oyster restoration projects has showed that although some substrates result in higher densities of oysters than others, all the substrates that have been used in projects were successful in attaching oysters and led to reef communities (Theuerkauf et al. 2015, Graham et al. 2017, Goelz et al. 2020). Recently, studies have been undertaken to develop and implement the use of biodegradable substrates that will reduce the introduction of manmade materials and microplastics to the environment during oyster restoration projects (Nitsch et al. 2021).

Image	Substrate	Substrate Advantages
A	Limestone	Readily available and affordable. Calcium carbonate composition has some advantage over other alternatives (Goelz 2017).
B	Non-Oyster Shell	Similar chemical composition to oyster shell (Goelz 2017).
C	Non-Calcium Stone	Despite the lack of calcium carbonate, has been shown to be a successful affordable and readily available alternative to oyster shell (The Nature Conservancy 2019).
D	Oyster Mats	Attached shell attracts larvae for settlement with less shell used than bagged (biodegradable alternatives being developed) (Nitsch et al. 2021).
E	Bagged Oyster Shell	Preferred substrate as bagged shell withstands higher disturbances than loose shell (SCDNR 2019).
F	Oyster Castles	Concrete structure creates habitat for other marine species and additional substrate reinforcement (SCNDR 2019).

Figure 3. Common substrates used in oyster restoration and their advantages.

Case Study: South Carolina Oyster Restoration as a Nature-Based Solution to Building Resilience to the Effects of Climate Change

South Carolina has approximately 2,875 miles of estuarine shoreline and over 500,000 acres of salt marsh, 30% of the tidal salt marsh found the U.S. Atlantic coast (SCDEHC 2019, South Carolina Sea Grant 2014) (Figure 4). 1.3 million people live in the coastal areas of the state, and this area contributes $62.8 billion to the GDP (NOAA 2021e). This shoreline experiences disturbance and erosion due to long term (SLR) and short term (wave energy) causes. As with other estuarine habitats across the world, South Carolina has lost 85% of the historic oyster population and 27% of historic marsh habitat (Purcell et al. 2020). Permits for hardened shoreline were not tracked prior to 2001, but since, the South Carolina Department of Health and Environmental Control's Ocean & Coastal Management division, who overseas coastal permitting, has issued over 1,000 permits for bulkheads, seawalls, and riprap (SCDHEC 2010). Because oyster reefs, and the salt marshes they buffer, can provide natural protections to effects of climate change, there is a great opportunity to build on South Carolina's existing oyster restoration efforts as a nature-based tool to creating resilience in the states coastal communities. This case study will overview the current status of oyster restoration in South Carolina, discuss the challenges to using oyster-based natural solutions to creating resilience in the states coastal communities, and propose how the current restoration efforts can be furthered to accomplish resilience goals.

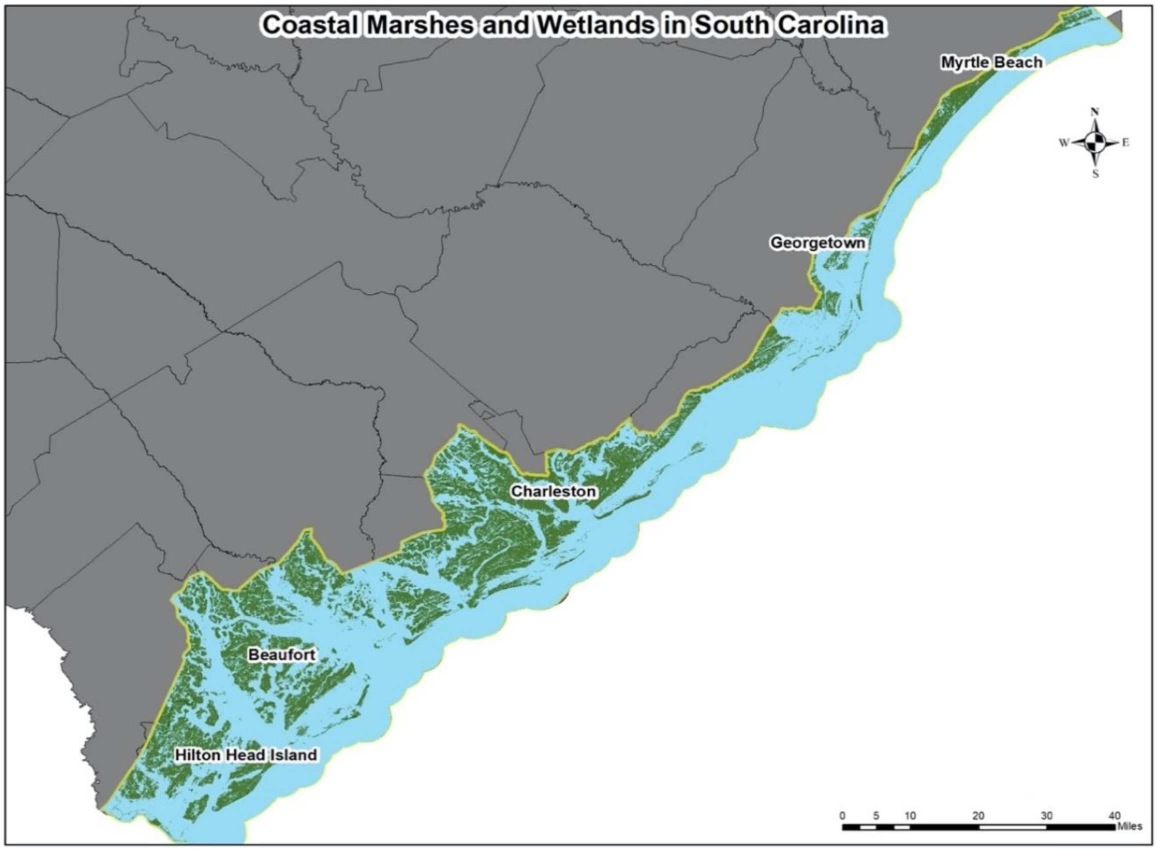

Figure 4. Map of South Carolina coastal wetlands (South Carolina Sea Grant 2014).

Oyster History in South Carolina

South Carolina has deep historical relationship with oysters. Before European settlement, indigenous Americans referred the Charleston harbor as ‘Oyster Bay’, and used oyster shells for food, tools, and trade items (Burell 2003). Archaeologists have marked areas all over the lowcountry where middens of consumed oyster shells have been found, with some being 4,000 years old. From the earliest settlement by Europeans, oysters played an important role in the life of early Americans. Oysters were harvested as a resource for food, as a popular building material known as tabby, and for agricultural purposes. The first evidence of commercial oyster beds appeared in South Carolina’s historical records in 1845, with 400 acres of marshland being granted for an oyster plantation. The industry stayed local to harvesting areas until the development of the ice industry in 1855, when oysters be transported short distances throughout the state. When canning moved to the south in 1890, the industry began an uptick, with 16 canneries operating in South Carolina through the 1930s. From this high point, the industry declined due to lower demand, rising labor costs, pollution, and competition from foreign markets. In 1986, the last cannery closed, with the industry turning to supplying restaurant and oyster roasts demands. While the requirement for replenishment of oyster shells back into the South Carolina's estuaries by shucking houses had been in place since 1906, the closure of canneries and shucking houses stopped the supply of shells to be used in this effort. The reduction of replenished shell, along with overharvesting, habitat loss, and pollution has led to oysters existing in a fraction of their historical range.

Current Status of South Carolina Oyster Restoration

South Carolina Department of Natural Resources

Today, the state's oyster resources are managed by the South Carolina Department of Natural Resources (SCDNR). Recognizing that oysters are key to estuarine ecosystems, the SCDNR undertakes efforts to restore oysters for the ecological services of habitat provisioning, improving water quality, and erosion control (South Carolina Sea Grant 2013, SCDNR 2021a). Compared to other Atlantic coastal habitats, South Carolina's oyster populations are in reasonable abundance, with lack of suitable substrate for larvae to settle on as the main restoration challenge. The SCDNR conducts both large and small-scale community-based restoration to create living shorelines. For the SCDNR, living shorelines refer to techniques intended to stabilize estuarine shorelines at the marsh-water interface to facilitate the growth of marsh vegetation. The SCDNR and community partners have constructed more than 200 oyster-based living shorelines throughout coastal South Carolina. These projects are done using methods on the 'greener' side of the NBS scale: loose oyster shell, bagged oyster shell, concrete oyster castles, cement coated repurposed crab traps.

The SCDNR developed the South Carolina Oyster Recycling and Enhancement program (SCORE), as a community-based habitat restoration, shell recycling, and monitoring program in 2001 (SCORE 2021a). Biologists work in conjunction with citizens to create oyster reefs using bagged recycled oyster shells (and as of 2021, wire reefs) to build reefs in South Carolina's estuaries (Michael Hodges in communication 13 Oct 2021). Because of the preference of oyster larvae to settle on oyster shell, the program uses a combination of recycled and purchased shell to complete project objectives. Shells are collected from recycling locations, participating restaurants, and local events which host oyster roasts (a common occurrence during December-February throughout the state). The remainder of shells needed to accomplish restoration goals must be purchased from shucking houses in other states (South Carolina Sea Grant 2013). Recycled shells are placed at a SCDNR site to quarantine, ensuring that that any pathogens or parasites are not introduced through restoration efforts. Volunteers fill mesh bags with shells, and then the bags are transported to selected construction sites for placement. The SCORE program relies on volunteers to accomplish reef building and habitat restoration goals, hosting events to bag and place shell, along with growing and planting *Spartina* through the *From Seeds to Shoreline Program* with K-12 students. The SCORE programs goals are to:

- Develop a citizen constituency for oysters

- Initiate a grass-roots effort to restore oysters
- Increase public awareness of the value of oysters to the ecosystem
- Influence public policy to provide greater protection for oyster habitats
- Influence lawmakers to provide adequate funding for proper management of oyster resources
- Expand the scope of endeavors by utilizing volunteer labor

Since the program began in 2001, the SCORE program has built over 100 oyster reefs, resulting in the successful stabilization of marsh habitat (Michael Hodges, in communication 13 October 2021). Beyond the efforts of SCORE, several other organizations throughout South Carolina have incorporated oyster restoration into efforts to make coastal habitats resilient.

The Nature Conservancy

The marine program for The Nature Conservancy (TNC) was established in 2008 with the initial goal to pilot oyster reef projects as a habitat restoration method. Since 2008, TNC has headed 14 oyster-related projects in South Carolina, 8 of which are living shoreline reefs. One of these projects, the Goldbug Island Living Shoreline completed in 2016, was built in the vicinity of Charleston to demonstrate a cost-effective method of addressing tidal flooding (The Nature Conservancy 2019). 100 volunteers along with several partners (including the SCDNR) built 240 feet of living shoreline from wood pallets, oyster castle blocks, and oyster shells. Since its construction, the visible shoreline vegetation has increased significantly (Figure 5). TNC and its partner Coastal Carolina University are currently undertaking a one-acre living shoreline project in Georgetown, South Carolina. The Boyd Living Shoreline Project, expected to be completed in

2023, was chosen as an alternative to a seawall to prevent wave erosion. This project is using wood pallets topped with oyster castles and bagged shell to for the benefit of wave attenuation, while also aiming to create the co-benefits of habitat provision and clean water.

Figure 5. Shoreline change since the construction of the Goldbug Island living shoreline by The Nature Conservancy (The Nature Conservancy 2019)

Private Property Owners

Many of the oyster-based living shorelines constructed by the SCDNR and the SCORE program are in highly visible locations (SCDNR 2019). Witnessing the stabilizing effects of the reefs at these restoration sites, coastal property owners in South Carolina have become interested in addressing issues on their private property using living shorelines. Until 2021, South Carolina had no process for permitting living shorelines. To allow for private landowners to implement living shorelines as an alternative to hard structures, the SDCNR along with researchers from the ACE Basin National Estuarine Research Reserve System (NERRS) joined for a NOAA-funded multi-year project to evaluate the effectiveness of green living shoreline technologies to the various environmental conditions found along the South Carolina coast. This effort monitored 62 pre-existing living shorelines, tested the methods already used by the SCDNR in differing locations, and created 16 experimental reefs that tested the effectiveness of coir logs and manufactured wire reefs and differing environmental conditions. This 5-year study provided the scientific information needed by the state regulatory bodies for coastal management to develop effective policy and provide guidance for the construction of living shorelines by private citizens. On May 28, 2021, the regulations became effective. Because this is a novel process in South Carolina, there is no current information on the use of oyster based living shorelines on private property.

National Ocean and Atmospheric Administration (NOAA)

NOAA's role in South Carolina oyster restoration is collaborating with local agencies to provide funding and research under the Coastal Zone Management Act of 1972 (CZMA, 16 §§1451 *et seq.*) The CZMA guides coastal state decisions and actions that manage the natural and built coastal environments to keep the quality of life and economic property of coastal areas in balance (NOAA 2021f). This act also established the National Estuarine Research Reserve (NERR) System which protects estuarine land and waters for the purpose of advancing and applying the knowledge of estuaries to advance management and stewardship. In South Carolina this act established the North Inlet Winyah Bay NERR and the ACE Basin NERR. The North Inlet Winyah Bay NERR partners with the University of South Carolina at the Baruch

Marine Field Laboratory, conducting research on the effects of SLR on South Carolina's salt marshes. As noted, the ACE Basin NERR was the location of several experimental living shorelines that were part of the private shoreline permitting study. In addition to the NERR system, The South Carolina Sea Grant Consortium, part of NOAA's National Sea Grant College Program, supports coastal research and extension through partnerships with the educational institutions (South Carolina Sea Grant Consortium 2021). There are six-member educational institutions part of this consortium in South Carolina. While the oyster related research of the consortium is focused on a sustainable oyster fishery and aquaculture, many of their research initiatives address building coastal resilience in South Carolina, of which NBS are of importance.

Challenges to Building Coastal Resilience with Nature Based Solutions in South Carolina

Knowledge Gaps

There are several challenges to implementing NBS as part of climate change mitigation in South Carolina. The prevailing challenge it that the integration of NBS into climate change and coastal defense strategies is relatively novel. While the concept of communities working with nature to cope with the impacts of climate variability and natural hazards is not new, the classification of such practices as NBS was not in publication until 2008, when used by the World Bank to refer to biodiversity conservation in the face of climate change (Seddon et al. 2021). In the U.S., the U.S Army Corps of Engineers (USACE) began an initiative to "engineer with nature" in 2010, but widespread interest in implementing NBS in coastal protection applications did not occur until the effort to rebuild the region affected by Hurricane Sandy (Kurth et al. 2020, Engineering with

Nature 2021). Although literature on NBS for coastal defense has increased rapidly in recent years, much of this has been focused on areas in the European Union (EU) where NBS has been a research priority of the European Commission (Faivre et al. 2017, Seddon et al. 2021). However, even with the push for research in the EU, wide-scale implementation is still novel and substantial knowledge gaps exist (Turkelboom et al. 2021). In the U.S. where literature and research are less cohesive, the unknowns, lack of quantitative data on the performance of NBS compared to traditional structures, lack of ecosystem services valuation, and lack of cost effectiveness comparisons have hindered widespread implementation (Sutton-Grier et al. 2015, Chausson et al. 2020, NOAA 2021g).

As NBS encompass locally specific biological, ecological, and socioeconomic factors, it can be a challenge to synthesize data between differing communities to inform decision making for using NBS (Chausson et al. 2020). Much of the published information transcends disciplines (physical, natural, and social sciences), and information is often grouped by geographic regions. In a review of the literature on the use of NBS to mitigate climate change impacts, Chausson et al. (2020) found a significant gap in the evidence when considering the social and economic outcomes. The context-specific aspect of NBS can also make it challenging to identify indicators for effective NBS implementation and successful outcomes (Seddon et al. 2021). Broadly, effective implementation of NBS should A) improve the resilience of local communities while enhancing co-benefits to the community and B) restore, maintain, or enhance the capacity of ecosystems to provide services for the communities while withstanding climate change impacts (Seddon et al. 2016). However, climate change will not uniformly affect coastal communities, and fluctuations in ecological and economic conditions can vary greatly from location to location (EPA 2021). It is unlikely that standardized metrics for incorporating NBS into coastal protections will be able to account for the social and ecological dimensions of individual communities (Seddon et al. 2021). Comparing implementation and outcomes across scales, even from state to state, can lead to solutions being dismissed as a possibility if a “one size fits all” approach to NBS is adopted (Sutton-Grier et al. 2018).

In terms using oysters in NBS, while metrics exist for oyster habitat restoration performance and ample technical information on oyster restoration has been published, the scale and method of oyster restoration projects vary significantly along the Atlantic coast due to the specific local challenges that can affect restoration efforts (Bagget et al. 2015, Goelz et al. 2020). This makes it difficult to cohesively compare approaches. Even between restored oyster reefs in South Carolina, Hadley et al. (2010) found differing temporal patterns in density on study reefs. While some reached maximum density after one year, others took up to three, indicating that there may be no typical pattern of development on restored reefs. Hadley et al. (2010) also demonstrated that growth rates at restoration sites within a close distance could differ, further indicating that each site has unique attributes that affect the establishment and growth of reefs. This can pose challenges to developing landscape-level NBS projects. There are also no universal metrics for substrate options in oyster restoration projects, and although developing metrics has been discussed (Goelz et al. 2020, Bagget el al. 2014, Fitzsimmons et al. 2019), there is nothing throughout the literature that would provide standards to the wide range of systems that restoration is occurring in.

Limitations

NBS cannot solve climate change and must be implemented along with policy measures that address climate change impacts (Seddon et al. 2021). In South Carolina, there is no state level plan for climate change adaption (Georgetown Climate Center 2021). This has left South Carolina communities to act on their own when it comes to addressing climate change mitigation, but without the reduction of activities that contribute to climate change, natural solutions may not be able to offset effects (Seddon et al. 2021). While the purpose of implementing NBS into coastal communities is to harness the buffering effects of coastal processes, these systems are dependent on human ones to not increase stress above the threshold of endurance (Kurth et al. 2020). Until these issues are mitigated, the full potential of natural solutions could be limited. The introduction of NBS as a mitigation strategy should not distract from overall climate change mitigation policies.

In using natural solutions for mitigating coastal storm hazards, the problem of "coastal squeeze" can limit where NBS can be implemented. Coastal squeeze is the process in which sea level rise (along with other contributing factors) push coastal habitats landwards toward areas where development or built coastal defenses have created a static margin between land and sea (Pontee 2013). This restricts the ability for shoreline habitats to maintain their position relative to SLR. Although the capacity of oysters (and adjacent salt marshes) to adapt to SLR has been discussed, this will present a challenge in creating new habitat when managed realignment is not possible (Ridge et al. 2015, Sutton-Grier et al. 2015).

Financial and Institutional Challenges

All the discussed challenges present a problem not only in South Carolina, but to all coastal communities in the U.S. where institutional norms can be a barrier to the adoption of NBS. Filling knowledge gaps will provide the science-based evidence for better integration of NBS into planning and policies for coastal communities, but without clear answers that NBS can perform as well as or better than grey infrastructure and values of ecosystem services, managers may find it difficult to sustain public and political support (D'Angelis et al. 2020, Seddon et al. 2021). What is effective is dependent on the perspective and needs of those who are locally involved, and political support and scientific uncertainty can make sustaining support and measuring outcomes difficult.

Although the processes that have led to the degradation of oyster habitat in South Carolina may be clearly identified, this may not be enough to motivate the support of a large-scale use of NBS to restore tidal marsh habitats (D'Angelis et al. 2020). Projects that include NBS require extensive monitoring not only for evaluating efficacy, but also to build the knowledge base to maximize the success of future use (Howie and Bishop 2021). Funds for monitoring typically cover 2-3 years post restoration, and this presents a challenge in justifying these types of projects from a funding and political sense when it can take 5-8 years for the realization of the full effects of a restored oyster reef (Ziegler et al. 2017, D'Angelis et al. 2020, Seddon et al. 2021). The SCDNR Shellfish Research Division and SCORE are limited by personnel, equipment, and funding (Michael Hodges in Communication 13 Oct 2021). This has made it difficult to adequately monitor reefs that have already been constructed. Without sufficient funding and community support, the ability for the programs to expand the construction of new reefs as part of NBS projects will not be possible.

On the federal institutional level, beyond the inadequate general funding for communities to address flooding and SLR, there is a lack of inclusion of NBS within federal plans when it comes to mitigation (Sutton-Grier et al. 2018). While the major agencies that deal with these issues, the Federal Emergency Management Agency (FEMA) and the USACE, provide funding for both pre-hazard mitigation and recovery after storm and flooding events, including NBS into plans has only recently begun to become a regular occurrence. In 2019, the FEMA pre-hazard migration program was replaced with the Building Resilient Infrastructure and Communities Program, which provides funding to incorporate NBS into mitigation activates (FEMA 2021). However, this program only sets aside 6% of estimated disaster expenses after a federally declared disaster, and the funding amount could vary from year to year (Federal Registrar 2020). Although the Engineering with Nature program almost a decade ago, the USACE is currently proposing that an 8-mile concrete seawall be constructed around the Charleston peninsula to address storm surge protection with almost no inclusion of NBS (Figure 6) (USCAE 2021). While this project is still in the proposal phase, it is predicted to cost at least $1.1 billion, with the City of Charleston responsible for 35% of that cost. In its current form, the proposal fails to address problems that stand in the way of Charleston becoming a resilient coastal community. Several low-income neighborhoods would not fall within the protection of the seawall, the seawall would push wave energy onto the surrounding areas, and the project does not address tidal flooding (Coastal Conservation League 2021). While the seawall may provide protection during a storm event, it does not bring ecological or societal benefits to the

Charleston community. Until the use of NBS is normalized in creating resilient coastal communities, it will be a constant challenge for those communities to choose to implement the technique when federal funding and support can be an uphill battle.

Figure 6. U.S. Army Corps of Engineers Seawall Proposal (Current Optimized Plan) (USCAE 2021)

Recommendations to Improve the Use of Oyster Restoration in Building a Resilient Coastal South Carolina

The areas surrounding South Carolina's tidal salt marshes are some of the most highly sought after and densely populated areas of the state (Purcell et al. 2020). Fortunately, nearly a million coastal acres in South Carolina are protected from development. These areas, mostly consisting of the Ashepoo-Combahee-Edisto (ACE) Basin and the Santee River Delta, are managed by various federal, state, and private agencies (South Carolina Sea Grant 2018). Although the status of these habitats plays into the broader ecosystem-based management scheme for South Carolina, it does provide an opportunity to address the societal challenges of climate change to coastal communities through NBS. The Charleston region is the most populous area in South Carolina with roughly a population of 800,000 people and is growing at three times the national average (Charleston Regional Development Alliance 2021). In 2016, Charleston experienced 50 days of high tide coastal flooding, with 89 in 2019 (Voiland 2020). It is predicted that by 2045, this number could reach to 180 days a year (Morris and Renken 2020). This will be compounded by the predicted frequency and intensity of storm hazards (NOAA2021b). These climate change threats are the societal challenges that need to be addressed by NBS projects to safeguard the well being of coastal South Carolinians.

In lieu of a state-wide plan climate plan, organizations and local governments created a collaborative network of public, private, and non-profit organizations to foster a unified regional strategy to increase resilience to episodic and chronic coastal hazards (Charleston Resilience Network 2021). The network leverages the work of member organizations and aids in applying for grants to support projects. The SCDNR, The Nature Conservancy, South Carolina

Sea Grant, NOAA, and the USACE (despite the noted lack of inclusion in the Charleston seawall project), who all participate in designing and implementing NBS, are members of this network. The work of SCORE and The Nature Conservancy with their partners to construct oyster-based living shorelines has shown that reef restoration is an attainable objective and has already demonstrated that collective action of the local community can lead to actions that increase the resilience of tidal marshes. Building on the existing framework of community involvement and the organizations of the Charleston Resilience Network offer a starting point to begin using NBS as part of creating a resilient community.

To inform how oyster restoration can be used in mitigating the effects of SLR on marsh ecosystems, it will require an adaptive management approach. Incorporating scientific uncertainty into restoration for flexible decision making as scientific development brings to light new information (Zellmer and Gunderson 2009, Benson and Garmestani 2011). Continuing to study the conditions that promote the vertical and lateral growth of reefs in estuaries will guide restoration practices to maximize return on the investment of time, money, and sustained shoreline protection (Ridge et al. 2017). As Morris et al. (2021) note, there are many studies on how oyster reefs attenuate waves, but few incorporate the ecological parameters in which oysters thrive. This may indicate that other factors, such as reef width, are as important if this is the primary purpose for reef construction in a NBS project. As most of the existing technical data and information on oyster restoration is heavily focused on the Chesapeake Bay and Gulf of Mexico, future research should include studying parameters of oysters in South Carolina's estuaries as a component of NBS (Spaulding et al. 2014, Myszewski and Alber 2016).

Explore Hybrid Solutions

Charleston, which has faced tidal flooding issues since its settlement in the 1670s, is unlikely to be solely protected by NBS, particularly without rethinking as a society how coastal development and hazards are approached (South Carolina Sea Grant 2014). As evidenced by several hurricanes that have made landfall in the U.S., even modern built technologies are not immune to damage and failure (NOAA 2021b). The efforts of the SCNDR have been primarily an ecology first approach that provides marsh stabilization and habitat provision. The living shoreline study conducted by the SCDNR and its partners found that all the methods of oyster-based restoration were effective in most energy levels found in South Carolina's estuaries (SCDNR 2019, Michael Hodges in communication 13 Oct 2021). However, success was dependent on site conditions. For example, while oyster castles were effective at providing the additional benefit of wave attenuation and habitat provision, they cannot be used on shoreline with a steep intertidal bank or in very soft sediments. Bagged oyster shells also became dislodged at sites with high wave energy due to waves, currents, and boat wake, requiring additional stabilization. To optimize the success of oyster natural infrastructure projects in South Carolina, a similar study to the previous living shoreline study should be conducted with sites chosen to explore both more robust hybrid structures that can be colonized by oysters in the soft sediments found in South Carolina's estuaries and varying slope and energy conditions.

There are currently two opportunities to implement experimental reefs to test oyster-based natural solutions that could provide the benefit of storm protection and flood mitigation services: The mentioned Charleston Seawall Project and the ongoing Charleston Low Battery seawall project (City of Charleston 2021). The low battery project is in phase 2 of replacing the concrete seawall surrounding the tip of the peninsula (Figure 7). This project was necessary because of the erosion and decline of the older wall. The new wall project is being constructed with no NBS. As seen in Figure 7, there is a rock border on the water side of the seawall. While this location does not afford an area of retreat for oyster beds or marsh grass, one of the benefits of using hybrid techniques in developing NBS is that reefs can be formed outside of the confines of naturally occurring conditions (Fivash et al 2021). The technical data exists to allow for experimental hybrid reefs to fortify and develop the natural protections at this site. This would aid in the longevity of this seawall project by reducing wave energy and erosion, promoting the spread of marsh grass, all while increasing the services that oysters provide in a highly visible location.

Figure 7. Left: Charleston Low Battery seawall construction during 2020. Right: Damage to old seawall from erosion (City of Charleston 2021).

As noted, the greater Charleston peninsula seawall project is still in the commenting phase. A small measure of NBS (three living shorelines) was incorporated after initial pushback, however much more shoreline than proposed is conducive to oyster-based living shorelines (Coastal Conservation League 2021, Michael Hodges in Communication 13 Oct 2021). As the project requires significant investment from the Charleston community, there should be continued support for the inclusion of NBS (as being done by the Coastal Conservation League), or the community should outright reject the plan, such as recently done with the USACE proposal for Miami-Dade County in Florida (Coastal Conservation League 2021, Staletovich 2021). The plan similarly only addressed storm protection and lacked inclusion of using the natural protections of mangrove forests and oysters, and the community found that the plan was not in their best interest. With the proposed funding for the Charleston project, there is ample opportunity to include local partners in the development of oyster based NBS to provide natural protections alongside the engineered protections, such as what has been proposed in the collaborative "Imagine the Wall" redesign of the USACE wall by local environmental engineers (Figure 8) (Imagine the Wall 2021).

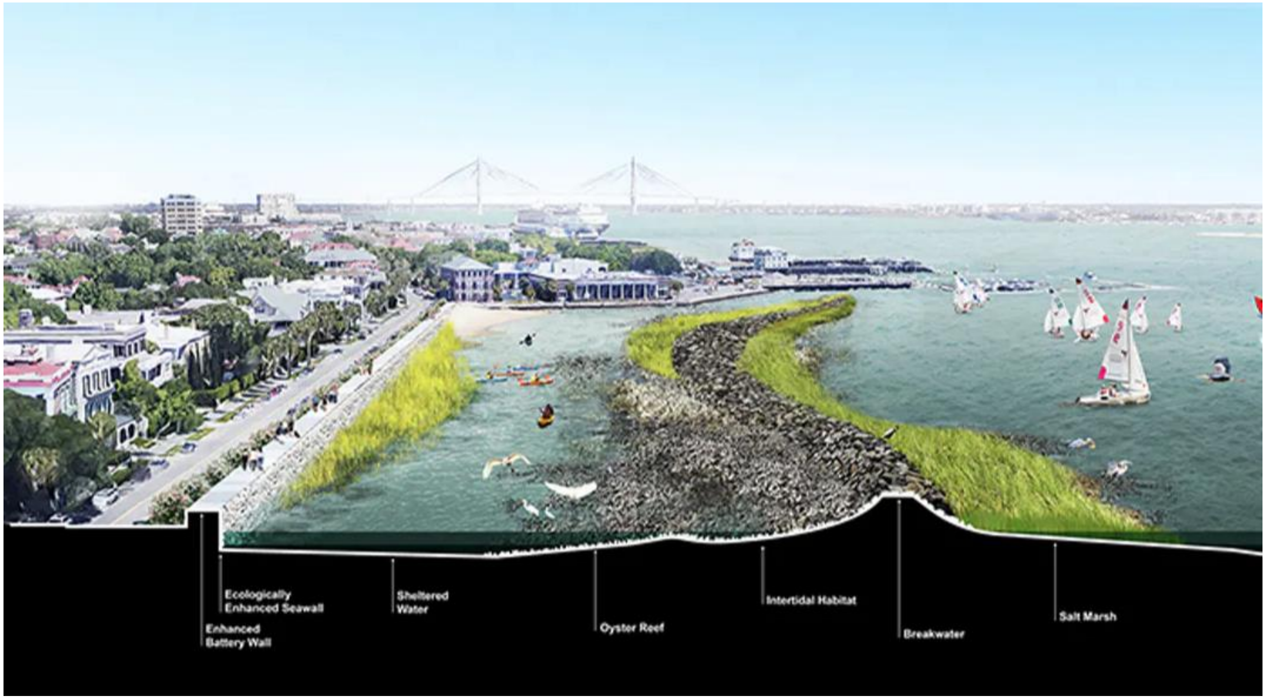

Figure 8. Plan for the inclusion of NBS into future plans for hazard mitigation and protection in Charleston (Imagine the Wall 2021).

Increase Community Involvement

Communities are a keystone to NBS that takes in multiple social, economic, and cultural benefits of local citizens (Seddon et al. 2021). Involving the community in issues that affect them can also help find answers to and solve problems in the local environment (Cuthill 2000). Whether activities fall under citizen science or stewardship, input from non-professional volunteers that collect or analyze data can provide baselines for monitoring data, answer research questions, accomplish restoration goals, while simultaneously performing outreach, education and increasing the scope of projects (Brown and Williams 2018, MacPhail and Colla 2020). Volunteerism supports building social capital while navigating financial constraints, brings scale to strapped programs, enhances community identity, and builds a sense of shared purpose and collective action across neighborhoods and politics (Langenfeld 2009). Although increases in project complexity can require greater investment and training and supervision, South Carolina already has a robust volunteer force involving thousands of volunteers that already participate in SCDNR and TNC events (as well as many other environmentally related efforts throughout the state) (Brown and Williams 2019, The Nature Conservancy 2019, SCDNR 2021a). SCORE is a successful community-based program, and there is a strong foundation on which to build increased volunteer involvement that would allow for the development, research, and monitoring of NBS to be maximized.

The SCORE program does significant outreach to inform citizens about the basics benefits of oysters but does not include the role marsh stabilization in flood mitigation and reducing storm hazards (Michael Hodges in communication 13 Oct 2021). Evidence from other oyster restoration projects has shown that citizen support and contribution is also a means to garner sustained political support (D'Angelis et al. 2019). Incorporating these benefits into an outreach campaign could help relate already ongoing oyster restoration to issues that are present in the everyday lives of coastal South Carolinians. Beyond getting information to the public about NBS and the role oysters can play in coastal resilience, there are several actions that managers and planners can take to increase their use and success throughout the state.

Citizen Science

Citizen science invites non-professionals to participate in both scientific thinking and data collection when provided with learning materials and protocol. This may range from simply data collection to the whole process of asking questions and sharing results of an analysis

(MacPhail and Colla 2020). The involvement of volunteers in research can increase the scale of activities, centralize monitoring efforts, fill knowledge gaps, and in some cases conduct large experiments or activities when budget constraints may be preventative (Dickienson et al. 2010, Hadj-Hammou et al. 2017, Jones et al. 2018). In ecological contexts, citizen science programs that can increase the spatial and temporal scope of projects can be a particular help to scientists in answering questions related to abundance, distribution, changes in habitats and ecosystems that may not be evident when limited monitoring may exclude patterns and trends (McPhail and Colla 2020). Citizen scientists are already used in the SCORE program (mostly through *Seeds to Shoreline*), but there is no formal process for involving these individuals in oyster restoration and monitoring (Michael Hodges in communication 13 Oct 2021). The scale, budget, and logistical limitations of managing South Carolina's estuarine shorelines is a considerable hurdle to maximizing the success of oyster restoration projects. With strong project design, the long-term monitoring and data collection garnered from volunteers could produce reliable data to inform future decisions (Jones et al. 2018). While the immediate outcome of citizen science is the collection of scientific data, programs also benefit from the economic efficiency used by local labor and knowledge, and the benefit of locals to help look after their own area (Cuthill 2000). All the attributes of citizen science provide a means to further apply oyster restoration as a NBS for coastal defense in South Carolina.

Specialist Volunteers and Partnerships

Volunteers may already have knowledge, expertise, or equipment that would allow them to perform some tasks as well as professionals with proper training (Brown and Williams 2019). Specialist volunteers have been used to great effect to bolster the recycling component of

SCORE outside of Charleston (Michael Hodges in Communication 13 Oct 2021). There is only one staff member who runs the shell recycling program, and by using dedicated volunteers to coordinate shell pickups and other volunteers has made this program more effective statewide. A limiting factor to the SCORE program is the infrastructure to perform reef construction. Many sites where reef construction needs to occur are inaccessible by foot, requiring that all the materials for reef construction and volunteers be transported by boat. This limits the scale of reef building, often requiring several events to complete the construction of a single planned reef. Additionally, the soft marsh substrate created by decaying *Spartina* (referred to as pluff mud) creates a logistical issue for monitoring when there are no boats to view sites from the water (SCDNR 2014). There is a small number of dedicated volunteers that provide private vessels, but as shown with the shell recycling specialist volunteers, with a dedicated outreach to local boaters, the scope of reef restoration could be expanded with an increased pool of boat-owning volunteers.

Partnerships with private and educational organizations can bring an elevated level of scientific expertise to oyster restoration projects, as well as overcome the complex technical, legal, and political aspects that can affect the implementation of projects (Leach et al. 2014). The Boyd Living Shoreline project in Georgetown, South Carolina, is an example of how partnerships can bring experience and labor outside of paid professional work. The Nature Conservancy is partnering with Coastal Carolina University to aid with pre- and post-construction monitoring of a living shoreline being constructed to restore habitat and stabilize a shoreline at a Georgetown city park. As noted, the South Carolina Sea Grant Consortium is partnered with six universities that conduct research on sustainable coasts and climate resilience. This program would allow for development and funding for oyster based NBS studies. As one of the challenges in restoration projects is the lack of long-term monitoring data, these institutions also offer an opportunity to provide a means for extensive monitoring and research of pre and post NBS implementation (Ziegler et al. 2021). Additionally, one of the tradeoffs of NBS is that many effective green infrastructure options require some level of regular maintenance (Safek et al. 2020). Having college-level schools participate in the research, monitoring, and maintenance of oyster NBS would allow for landscape-level implementation with a sustained force for monitoring and maintenance.

Conclusion

The effects climate change is already a concern at the forefront of coastal South Carolinians' lives. The predicted increases in SLR, tidal flooding, and storm events will further challenge the economic and social ability of communities to respond to these hazards. NBS offer an opportunity to move from the traditional non-adaptive forms of coastal protection by restoring and enhancing the adaptive natural protections already found in South Carolina's coastal ecosystems. This cost-effective solution can provide long-term protection for coastal communities while harnessing the ecosystem services that traditional built infrastructure does not.

In South Carolina, oyster-based natural solutions are an opportunity to expand on an already existing oyster restoration programs and resources to help build resilient coastal communities. Successful use of oyster NBS projects will depend on the ability of managers to overcome the challenges of implementing NBS and normalizing the use as a climate change mitigation tool.

Due to the work of the SCDNR SCORE program and The Nature Conservancy, the concept of oyster-based living shorelines has been established and has engaged thousands of citizens in the construction of projects. This can be expanded on through a well developed volunteer construction and monitoring program which can overcome funding and infrastructure issues to produce meaningful results. While natural solutions alone will not solve climate change challenges, harnessing the protective ecosystem services that oysters provide alongside engineered structures has the potential to help mitigate coastal hazards in South Carolina's coastal communities. This will provide a great benefit to the communities of coastal South Carolina in the form of community and environmental resilience into the future.

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