A Review of Living Shorelines: Evaluating nature-based solutions to preserve our shorelines and combat sea-level rise

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ABSTRACT

Increased human populations along coastlines, increased storm duration and intensity, and sea-level rise exacerbate coastal erosion, effectively pressuring business and homeowners to implement shoreline stabilization and protection measures. Historically, traditional shoreline protection has been achieved through the installation of shoreline armoring structures, such as bulkheads, seawalls, and riprap revetments. However, a growing body of evidence exemplifying the adverse consequences shoreline armoring structures have on shorelines and the ecosystem has led to concern about the use of these structures. In order to avoid further coastal ecosystem degradation, the "living shoreline" approach was introduced. Living shorelines have the unique ability to restore and preserve coastal ecosystems while also providing protection from sea-level rise to coastal communities. This paper reviews and evaluates current shoreline armoring and living shoreline approaches to determine drawbacks and benefits as sea-level rise persists, and provides an emphasis on site-specific design, long-term monitoring, and landscape-scale analysis as the living shoreline concept continues to develop and evolve.

INTRODUCTION

1.1 BACKGROUND

1.1.1 SEA-LEVEL RISE

Sea-level rise continues to be a growing concern for researchers, regulators, and coastal communities. Since the 1800s, the change in sea-level rise can be mostly attributed to anthropogenic climate warming and can occur in two distinct ways: eustatic sea-level rise, or the melting of land ice, and isostatic sea-level rise, or ocean expansion (Church *et al.*, 2011; Milne *et al.*, 2009; Le Cozannet *et al*, 2019; Le Cozannet *et al.*, 2014). The intensity at which sea-level is rising puts coastal communities at risk. More than 51% of the population in the United States lives in coastal communities ("Preface", 2006). Growing coastal populations continue to increase pressure on coastal ecosystems, such as estuaries, salt marshes, and wetlands, and exacerbate coastal erosion (Bilkovic *et al.*, 2016). These coastal ecosystems are characterized by an abundance of natural resources that can support local communities (Currin *et al*., 2017), and thus, these populations rely on estuaries for shipping, fisheries, transportation, and recreation. This can result in dense infrastructure, increased development, and alteration to inter-tidal and sub-tidal areas (Bilkovic *et al.*, 2016; "Preface", 2006). In addition to urban development and anthropogenic activities, erosion and the subsequent loss of valuable and sensitive coastal ecosystems can stem from severe storm events, tidal cycles, and sea-level rise (Riggs & Ames, 2003; Dahl & Stedman, 2013; Polk & Eulle, 2018); the rate at which each of these factors occurs is intensified by anthropogenic climate warming.

Erosion of the coastal zone puts coastal habitats and communities at risk (Polk & Eulle, 2018). Shoreline retreat, in the form of permanent passive submersion and coastal erosion, is a negative consequence of sea-level rise and has led to action to achieve shoreline protection for coastal communities landward of vulnerable shorelines (Bird, 1996; Stive *et al.*, 2002; Le

Cozannet *et al.*, 2014). Coastal erosion can be caused by a range of different processes affecting the morphology of the coastline, including sediment redistribution (Slott, Murray, & Ashton., 2010), biological processes (Gedan *et al.*, 2011; Storlazzi *et al.*, 2011), and other coastal processes (Regard *et al.*, 2012; Le Cozannet *et al.*, 2014). Although coastal erosion is a threat to coastal communities, it is a natural process and is critical to the ecological health of coastlines (Subramanian *et al.*, 2006; Smith, 2006). Erosion provides sediment to increase the elevation of the marsh, which is imperative to assist shorelines in remaining stable and preserving coastal habitats as sea-level rises (Smith, 2006). Areas that are already sediment starved rely on erosional processes to replenish and restore shorelines and offshore bottoms (Subramanian *et al.*, 2006). However, urban development and anthropogenic activity has resulted in the acceleration of coastal erosion.

1.1.2 SHORELINE STABILIZATION

1.1.2.1 "Hard" Stabilization Methods

Fear of accelerated erosion and the loss of land to waves and tidal energies has resulted in property owners relying on shoreline stabilization methods for protection (Smith, 2006). In addition to preventing erosion, other motivating factors include preserving recreational beaches, improving navigation, improving landscape aesthetics, improving riparian access, and decreasing flooding (Duhring, 2006). The most popular method to prevent erosion and stabilize coastal shorelines is shoreline armoring. There are many shoreline armoring methods, but seawalls, bulkheads, and revetments are among the most popular. These armoring structures have been placed throughout the U.S. in an attempt to reduce erosion and flooding threats to communities (Charlier, Chaineux, & Morcos, 2005; Bilkovic *et al.*, 2016). The prevalence of armored structures along coastlines increased substantially in the second half of the 1900s (Dugan *et al.*, 2011; Bilkovic *et al.*, 2016). Aforementioned, the Chesapeake Bay experiences high rates of erosion; this issue has led to 18% of the tidal shorelines being armored with greater than 50% of urban sub-watersheds being armored (CCRM, 2013; Bilkovic *et al.*, 2016). In 2013, it was reported that 14% of all U.S. shorelines had already been hardened (Gittman *et al.*, 2015; Currin *et al.*, 2017). These structures have been shown to be effective at stopping the landward migration of the shoreline, but they eventually increase erosion and can disrupt the essential connection between upland and inter-tidal habitats (Currin *et al.*, 2017). This can result in a loss of valuable ecosystem services such as fishery habitat and water quality mediation (Currin *et al.*, 2010; Gittman *et al.*, 2016; Currin *et al.*, 2017). This will, in turn, be detrimental to the prosperity of coastal communities. Although armoring structures are installed with the intention to protect upland areas and slow coastal erosion, modification of coastal ecosystems is a primary cause of wetland loss in the United States (Table 1; Dahl & Stedman, 2013; Currin *et al.*, 2017). There has been a 50% reduction of the United States' wetlands (Dahl, 2006; Swann, 2008). Furthermore, although structural shoreline stabilization applications are successful in stopping immediate erosion, they can have a detrimental effect to the ecosystem and the services they provide by eventually exacerbating erosion, as detailed below (Smith, 2006). Ecosystem services potentially lost may include carbon sequestration, erosion protection, nursery habitat, wave attenuation, shoreline stabilization, water filtration, and recreational activities (Rogers & Skrabel, 2001; Bozek & Burdick, 2005; Roland & Douglass, 2005; Craft *et al.*, 2008; Polk & Eulle, 2018). Armoring structures attempt to mimic some of these protective ecosystem services, such as wave attenuation and shoreline stabilization but can have long-term negative consequences that reverse original performance and intention. Long-term consequences include vertical erosion, loss of down-drift sediment, and erosion of nearby natural and nature-based shorelines (Douglass & Pickel, 1999; Campbell, Benedict, & Thomson, 2005; NRC, 2007; Swann, 2008).

1.1.2.2 "Soft" Stabilization Methods

Coastal ecosystems are dynamic systems that are capable of adapting to sea-level rise naturally (Morris, 2007; Mitchell & Bilkovic, 2019). Complex feedback loops that rely on plant production and sediment capture, among many other factors, allow for vertical marsh growth and landward migration when necessary and where possible (Fig. 1.1; Mitchell & Bilkovic, 2019). In undisturbed settings, or settings that are not highly urban, a no-action strategy allows a natural landward migration for shorelines in response to sea-level rise (Hobbs *et al.*, 1981; Hardaway *et al.*, 2002; NRC, 2007; Swann, 2008). Thus, in these low-energy environments, new strategies are being implemented to provide protection to coastal communities and protection and/or restoration to ecosystem services.

During the mid-1980s, "soft" shoreline stabilization was introduced as an alternative to "hard" shoreline stabilization, or shoreline armoring (Jefferson Patterson Park and Museum, 2007; Subramanian *et al.*, 2008). These "soft" shoreline stabilization methods incorporated many elements that are present in today's "living shoreline" technique, which is now favored over shoreline armoring by the environmental community due to the plethora of benefits provided when implemented (Jefferson Patterson Park and Museum, 2007; Subramanian *et al.*, 2008). The living shoreline technique embraces the use of elements natural to coastal ecosystems to stabilize and protect shorelines (Pilkey *et al.*, 2012). These shorelines are designed with the intention of maintaining or minimally disrupting coastal ecosystems and coastal processes (Jefferson Patterson Park and Museum, 2007; Subramanian *et al.*, 2008). The ability for communities to persist and thrive as sea-level rises is dependent on the preservation and restoration of coastal ecosystems. Although wave attenuation, flood prevention, and rising tides can be managed through shoreline armoring, without the valuable assets present in natural coastlines, communities will suffer. However, property owners have historically been more concerned with halting erosion than protecting natural habitats; thus, the goal of the "living shorelines" approach is to reduce the dependence on traditional shoreline erosion control, shoreline armoring, by providing erosion control and flood protection through nature-based projects (Pilkey *et al.*, 2012). Along with erosion control and flood protection, other roles of living shoreline projects include maintaining natural coastal processes and sustaining biodiversity (Swann, 2008).

Due to their ability to stabilize shorelines with minimal impact to the ecology of the ecosystem, living shorelines have the potential to increase coastal community resilience to sea-level rise (Fig. 1.2; Sutton-Grier, Wowk, & Bamford, 2015; Van Slobbe *et al.*, 2013; Mitchell & Bilkovic, 2019). The complex and dynamic nature of shorelines presents a challenge; each site varies tremendously, which makes the design and implementation of living shoreline projects more demanding than that of shoreline armoring. Therefore, a unique design must be applied to each site to ensure the success of the project. The "living shoreline" approach may not stop erosion entirely, but if applied and monitored successfully, projects have the potential to reduce erosion and enhance habitat and may be substantially less expensive than armoring projects (Smith, 2006). To ensure the success of projects, continued research and long-term monitoring is essential as sea-level rise and the associated consequences are persistent and ever changing.

1.2 OBJECTIVE

The purpose of this paper is to review existing shoreline stabilization methods and attempt to thoroughly consider benefits and drawbacks that their implementation will provide to protect both ecosystems and communities from continued erosion and advancing sea-level rise. Three objectives of this study are to:

- Determine the benefits of living shorelines in relation to sea-level rise,

- Highlight the efficacy of site-specific design, long-term monitoring, and landscape-scale analysis for living shoreline implementation,
- Emphasize the importance of living shoreline implementation to combat consequences of climate warming and sea-level rise

1.3 SIGNIFICANCE

Although there have been many efforts to slow the effects of anthropogenic climate warming, impacts will persist and continue to arise. Coastal erosion and sea-level rise remain as tremendous threats to coastal communities and ecosystems. As consequences evolve, it is imperative that methods used to combat these consequences evolve as well. Living shoreline projects have the potential to maintain and preserve natural habitats and communities that lay beyond through these ever-changing consequences. It is necessary to determine, evaluate, and explain the potential benefits that using natural or nature-based shoreline stabilization can provide in order to encourage acceptance and future implementation from property owners across the United States.

Cause	Primary Mechanism
Direct habitat change	Dredging, construction, filling in or over, erosion, prospecting machinery (marsh buggies)
Sea level rise	Increased flooding of plants
Subsidence increases	
Natural	Net loss in vertical accretion without compensation
Oil and gas withdrawal	Accelerated net loss in vertical
Soil drying	Soil shrinkage, net loss in vertical
Hydrologic Changes/Effects	
Saltwater balance	Physiological stress leading to plant community change or death
River levees	Restricted sediment supply
Sediment sources	Less sediment from less overbank flooding in rivers or marsh; delta switching
Canals	Change in sediment source and distribution, salinity and water levels; widening; channel theft
Spoil banks	Change in sediment source and distribution, salinity, and water levels; water movement over and under marsh
Hurricanes	marsh destruction
Boat wakes/waves	Bank erosion
Vegetation changes	
Quantity	Change in physiological responses to salinity, sediment trapping, organic deposition, flooding
Quality	Change in organic deposition, sediment trapping, intraspecific competition
Pollutants (brine, drilling fluids, and other)	Death of plants
Other	
Introduced pests	Death of plants by parasitic insect (primarily on alligator-weed)
Muskrat "eat outs"	Reduced vegetation cover leading to pond formation

Table 1. An example of wetland loss and primary mechanisms from the northern Gulf of Mexico (source: Turner, 1990; Kennish, 2001)

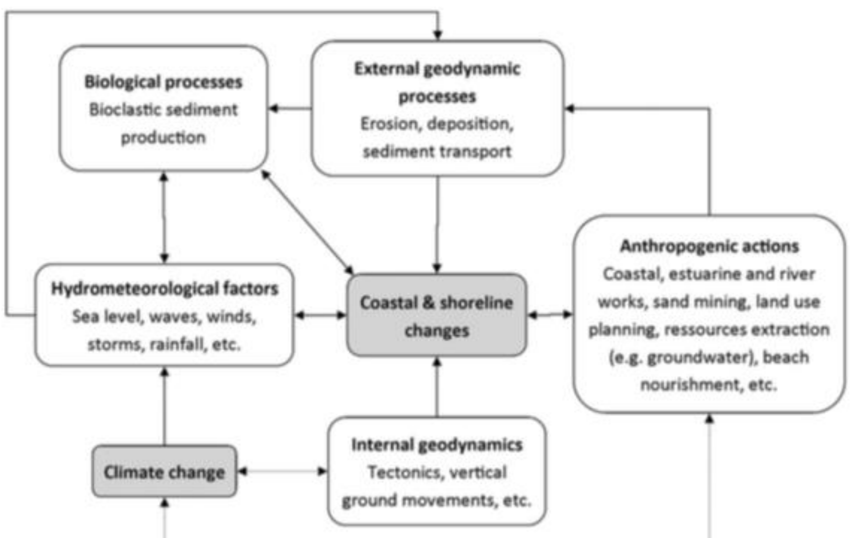

Fig. 1.1. Potential factors and processes involved in shoreline changes. Feedbacks are indicated by arrows. Due to the multitude of factors, shoreline dynamics are complex (source: Le Cozannet *et al.*, 2014).

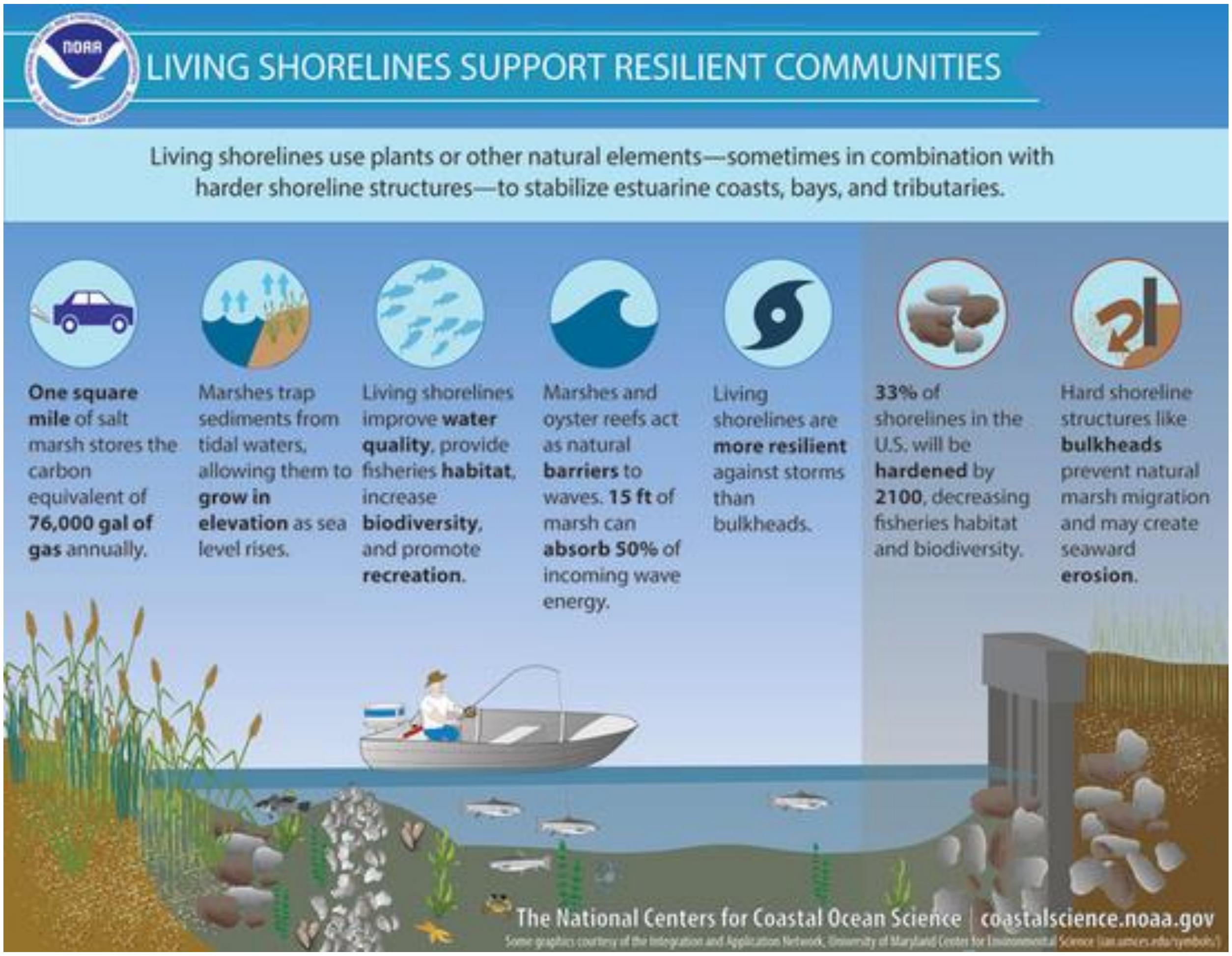

Fig. 1.2 Ways living shorelines contribute to the resilience of coastal communities (source: http://www.fisheries.noaa.gov/insight/understanding-living-shorelines).

AN OVERVIEW OF TRADITIONAL SHORELINE PROTECTION – SHORELINE ARMORING

2.1 BACKGROUND

Shoreline erosion is a natural process that is viewed as undesirable by many property owners, which has led to extensive shoreline armoring of United States coastlines (Pilkey *et al.*, 2012). Shoreline armoring refers to the impact of fixed, engineered structures such as bulkheads or offshore breakwaters (Duhring, 2006). These structures do not allow marshes and beaches to move inland, a process referred to as landward migration, in response to sea-level rise, which will result in the drowning of shoreline ecosystems (Pilkey *et al.*, 2012). There are many studies that suggest that there is already sufficient knowledge to ensure success in limiting erosion through “traditional” shoreline protection (Smith, 2006). These authors claim that integrating elements that are used in living shoreline approaches may lead to less effective erosion control for hardening structures that have already been established (Smith, 2006). However, it is often overlooked that erosion of shorelines is a natural process happening over time, and this illustrates a flaw with structural systems as they do not have the capacity to adapt to erosion and sea-level rise as natural systems do (Subramanian *et al.*, 2006). In many states, the land between mean high water and mean low water is held by the government for the public; therefore, the public may freely use these areas for individual shoreline stabilization projects, which has resulted in an increase of shoreline hardening to prevent property erosion (Roberts, 2008; Scyphers *et al.*, 2011; O’Donnell, 2017). In San Diego Bay, 74% of the shoreline is armored; in Barnegat Bay, NJ, 71% of the shoreline is armored; hundreds of miles of shorelines throughout the Chesapeake Bay have been hardened since the 1970s (Chesapeake Bay Program, Tidal Sediment Task Force of the Sediment Work Group, 2005; Davis, Levin, & Walther, 2002; Virginia Institute of Marine

Science, 2004; Titus, 1998; "Preface", 2006). These are just some examples that represent the extent of shoreline hardening in the United States.

2.1.1 CONSEQUENCES OF SHORELINE ARMORING

Waterfront development has caused a significant loss of shallow water habitats (Seitz & Lawless, 2008), and hard structures along the shoreline can result in additional negative consequences. Hard structures alter sediment transport and sediment deposition and, despite intentions, can result in an increase of erosion through sediment starvation, increased turbidity, and increased scouring (Bozek & Burdick, 2005; Douglass & Pickel, 1999; Pilkey & Wright, 1988; Polk & Eulle, 2018; Rogers & Skrabal, 2001; Yozzo *et al.*, 2003). Shoreline vegetation is further reduced and replaced when armoring is installed, which can reduce water filtration and habitat functions ("Preface", 2006). In a study by Garbisch *et al.* (1973), it was found that marsh vegetation seaward of bulkheads suffered 63% mortality post-construction (Currin *et al.*, 2010). Hardening structures may also steepen shorelines and result in the reduction of nursery and refuge habitat ("Preface", 2006). In North Carolina, similar to many other states, the most frequently applied shoreline stabilization practice is to install a bulkhead (Currin *et al.*, 2010). Scouring at the toe of bulkheads erodes shorelines and deepens adjacent water, which reduces or eliminates shallow sub-tidal habitat (Riggs, 2001; Bozek & Burdick, 2005; Currin *et al.*, 2010). Marsh vegetation mortality, in the study completed by Garbisch *et al.* (1973), was mainly attributed to increased turbidity and scour, providing evidence supporting the potential negative consequences of shoreline armoring structures. The loss of nursery and refuge habitats and the deepening of nearshore waters decrease fish and invertebrate diversity and abundance (Rozas, 1989; Currin *et al.*, 2010). Deepening of nearshore waters also allows for large predatory fish to access nursery areas (Rozas, 1989; Currin *et al.*, 2010). This enhances their feeding efficiency on small and/or juvenile fish, decreasing diversity and abundance further and negatively affecting fisheries by decreasing the amount of fish available for commercial catch (Rozas, 1989; Currin *et al.*, 2010). Numerous additional studies have documented lower abundance and diversity of species adjacent to bulkhead shorelines when compared to their natural counterparts (Currin *et al.*, 2010). The James River in Virginia exhibited lower fish diversity and community integrity along bulkhead shorelines in a study by Bilkovic and Roggero (2008; Currin *et al.*, 2010). Partyka and Peterson (2008) found that epifaunal-nekton and infaunal species abundance and density decreased at hardened shorelines in the Pascagoula River in Mississippi (Currin *et al.*, 2010). Lastly, Bilkovic *et al.* (2006) completed a study in the Chesapeake Bay that showed when the amount of developed shoreline exceeds 10 percent, microbenthic biology integrity was significantly reduced (Currin *et al.*, 2010).

While the short-term reduction in erosion provided by hard structures is beneficial, the long-term consequences outweigh the immediate benefits of shoreline armoring. Small and few "traditional" shoreline stabilization structures may have less extensive consequences on coastal habitats and ecosystems, but as mentioned above, shorelines have been extensively hardened, which has resulted in significant habitat degradation (Currin, Chappell, & Deaton, 2010; NRC, 2007; O'Donnell, 2017). Multiple structures in proximity degrade estuarine and other coastal ecosystem conditions through increased water depth, decreased sediment supply and transport, and tidal wetland loss (Center for Coastal Resources Management, 2005; Duhring, 2006; North Carolina Division of Coastal Management, 2006b; NRC, 2007). The negative effects that occur when shoreline hardening is extensive emphasize the importance of landscape-scale analysis. The consequences extend to adjacent and nearby shorelines even when structures are not present at those sites. Proximity of hard shoreline structures depends mostly on how coastal homeowners choose to protect their shorelines; and they are continuing to choose to harden their shorelines even in medium- to low-energy environments (Subramanian *et al.*, 2008).

2.1.2 A TRANSITION AWAY FROM SHORELINE ARMORING

Bulkheads and other hard, fixed structures do not allow for the migration of the shore as sea-levels rise, resulting in the eventual drowning of shallow marsh ecosystems and the loss of valuable wetland vegetation (Bozek & Burdick, 2005; Currin *et al.*, 2010; National Research Council, 2007; Titus, 1998). Further, development near coasts can potentially result in shoreline recession, causing habitat loss due to coastal squeeze (Bendoni *et al.*, 2016; Riggs & Ames, 2003; Rogers & Skrabal, 2001; Polk & Eulle, 2018). Coastal squeeze, as defined by N. Pontee, is "intertidal habitat loss which arises due to the high-water mark being fixed by a defense and the low water mark migrating landwards in response to sea-level rise." (2013, pg. 206). Thus, the threat of coastal squeeze, along with various other consequences, has led to a push from scientists and policymakers to transition away from recommending hard shoreline stabilization structures to more nature-based approaches, such as living shorelines. However, more often than not, extensive structural components are used in nature-based solutions for shoreline stabilization and erosion control; this practice is most successful when structural components aid natural components. There are potential benefits to using structural components in nature-based approaches. In some cases, they may be necessary to provide vegetation with an adequate, stable growth environment (Subramanian *et al.*, 2006). Structures can also assist vegetation in reducing erosion by attenuating waves. However, even these structures can have adverse impacts when not designed correctly. For example, reduced tidal exchange can occur where structure height is greater than one foot above mean high water, and it is still not well understood how fixed marsh structures affect sediment transport and habitat accessibility (Burke, Koch, & Stevenson, 2005;

Duhring, 2006). Additionally, property owners prioritize effectiveness, durability, and cost instead of environmental considerations (Gittman & Scyphers, 2017; Scyphers *et al.*, 2015b; Smith *et al.*, 2017). Therefore, many property owners immediately implement shoreline armoring as they believe it is the cheaper and more effective option. However, a study completed by Gittman & Scyphers (2017) suggest that nature-based methods are cheaper than armoring methods. The purpose of the study was to document installation costs for shoreline protection structures (Gittman & Scyphers, 2017). Table 2 shows the cost range found in the literature review study. The number of estimates represent the amount of cost estimates found throughout their review (Gittman & Scyphers, 2017). Living shoreline installation cost ranges from $228 USD to $6,205 USD per linear meter (Table 2; Gittman & Scyphers, 2017) which is less expensive that bulkheads, groins, ripraps, and breakwaters. As such, a growing body of scientific evidence exhibiting the ways in which the living shoreline approach may be a better option for shoreline stabilization and protection (Bilkovic *et al.*, 2016).

In the transition to and development of the living shoreline approach, the core values and goals became "lost in translation" in some projects. Due to many living shoreline projects using a hybrid approach, or incorporating hardened structures into the design, there has been and continues to be misuse of the term to facilitate more shoreline armoring projects. One massive misuse of the term was applied to a study advertised as a living shoreline project completed on Dauphin Island, Alabama. In the 1950s, approximately 3 hectares (ha) from Saw Grass Point Salt Marsh, the largest marsh on the east end of Dauphin Island, were destroyed during dredging to create Fort Gaines Harbor and Pass Drury Channel (Swann, 2008). Additional marsh had been lost following the creation of Fort Gaines Harbor due to high boat traffic, tropical storms, and hurricanes (Swann, 2008). In 2004, a grant was obtained and used to "protect and restore" the marsh, using what was referred to as coastal havens (Swann, 2008). These "coastal havens" functioned as detached breakwaters and were meant to reduce the effects of boat wakes and storm surges through wave attenuation (Swann, 2008). In April of 2005, 182 units were placed in two rows along the marsh (Fig. 2.1; Swann, 2008). Marsh vegetation, *Spartina alterniflora*, was planted as an afterthought in order to follow living shoreline principles. In August of that same year, Hurricane Katrina destroyed the vegetation planted in the original effort (Swann, 2008). The decision was made not to replant *S. alterniflora* based on the assumption that the designed system, if properly functioning, would decrease wave and tidal energies enough for vegetation to colonize barren areas; however, after one year, there had been no measurable recolonization or expansion of vegetation in initial or barren areas (Swann, 2008). There was not enough long-term monitoring to determine vegetation change or to monitor any adverse effects these breakwaters may have had on the existing ecosystem (Swann, 2008). Although it was claimed that the breakwaters would allow for oyster substrate, reflect wave velocity, and allow for tidal exchange (Swann, 2008), they are still massive structures along the shoreline that could result in similar negative consequences to bulkheads and revetments. This project should not be classified or advertised as a living shoreline project. In a paper titled "*Rethinking Living Shorelines,*" Orrin Pilkey urges the reconsideration of living shoreline definitions to prevent misuse of the term and future shoreline armoring (pg. 5, 2012). Without the specifications that natural elements should outweigh structured elements in living shorelines, it is likely that the term will continue to be misused and shorelines will continue to be armored.

2.2 SIGNIFICANCE

In summary, the multitude of negative consequences associated with shoreline armoring include: habitat loss and fragmentation (Dugan *et al.*, 2011; Peterson & Lowe, 2009), alterations to sediment (Bozek & Burdick, 2005; NRC, 2007), deepening of nearshore waters (Bilkovic & Roggero, 2008; Toft *et al.*, 2013), increased turbidity (Bozek & Burdick, 2005), decreases in abundance and diversity of species (Bilkovic *et al.*, 2006; Bilkovic & Roggero, 2008; Chapman, 2003; Isdell *et al.*, 2015; King *et al.*, 2005; Moschella *et al.*, 2005; Morley, Toft, & Hanson, 2012; Peterson *et al.*, 2000), and prevention of landward migration (Bilkovic, 2011; Bilkovic *et al.*, 2016; Titus *et al.*, 2009). The alteration in sediment transport and deposition, along with some other negative consequences of shoreline hardening (increased scouring and turbidity and prevention of landward migration), can result in increased erosion of the shoreline (Bozek & Burdick, 2005; Douglass & Pickel, 1999; Pilkey & Wright, 1988; Polk & Eulle, 2018; Rogers & Skrabal, 2001; Yozzo *et al.*, 2003). There are many places in the United States that continue to choose shoreline armoring despite the associated negative consequences. With a potential consequence of armoring being shoreline erosion, there needs to be a transition to nature-based shoreline stabilization as a shoreline protection method. In the future, coastal communities will begin to experience increases in sea-level rise that could result in the disappearance of salt marshes and seagrass beds. Not only will this eliminate an important form of protection from flooding, erosion, and continual rising water levels, but will also diminish or extinguish a main source of income and livelihood. A transition from shoreline armoring to natural or nature-based shoreline protection is imperative in combatting future effects and consequences of enhanced erosion and sea-level rise. If structures are to be used in nature-based solutions, careful and intricate design plans are needed in order to ensure they do not inhibit or impede the natural functions of coastal ecosystems; furthermore, long-term monitoring of these non-structural or hybrid solutions will help researchers and regulators understand the response of these systems to sea-level rise and ensure the success of future projects.

Fig. 2.1. Photograph of Saw Grass Point Salt Marsh after the installation of the 182 coastal havens (source: Swann, 2008).

	# of estimates	Cost range ($ / linear m)
Bulkhead	8	$462-$6,002
Groins or jetties	12	$1,300-$49,639
Living shorelines	4	$228-$6,205
Riprap or revetment	2	$341-$2,716
Breakwaters	2	$368-$49,639

Table 2. A summary of installation values from the study completed by Gittman & Scyphers (2017) in a review of scientific and technical documentation of shoreline infrastructure (source: Gittman & Scyphers, 2017).

AN OVERVIEW OF THE LIVING SHORELINE APPROACH

3.1 BACKGROUND

The "living shoreline" approach is a shoreline stabilization method that incorporates the installation, maintenance, and preservation of native vegetation and natural habitat elements (Davis *et al.*, 2015). Natural habitat elements may include: marsh vegetation, submerged aquatic vegetation, woody debris, oyster reefs and/or shells, *etc.* ("Preface", 2006). Shoreline stabilization projects incorporating these elements are hypothesized to provide better habitat, water quality functions, and shoreline protection than shoreline armoring ("Preface", 2006). The approach provides both shoreline stabilization and restoration of important ecological functions, which are both essential to preserve as sea-level rise intensifies (Mitchell & Bilkovic, 2019).

3.1.1 VARIOUS DEFINITIONS

There are many ways to define living shorelines, and these definitions often vary on a state-to-state basis. There are also some national definitions provided by organizations such as the National Oceanic and Atmospheric Administration (NOAA) (O'Donnell, 2017). The definitions found below are meant to exemplify similarities and differences and highlight the need for a more consistent, universally accepted definition of living shorelines to prevent misuse of the term and facilitate more consistent implementation of the living shoreline approach to shoreline stabilization.

<u>Maryland Department of Natural Resources definition</u>:

> Living shorelines are the result of applying erosion control measures that include a suite of techniques which can be used to minimize coastal erosion and maintain coastal processes. Techniques may include the use of fiber coir logs, sills, groins, breakwaters or other natural components used in combination with sand, other natural materials and/or

marsh plantings. These techniques are used to protect, restore, enhance, or create natural shoreline habitat (Maryland Department of Natural Resources).

Virginia legislative definition:

> "Living shoreline" means a shoreline management practice that provides erosion control and water quality benefits; protects, restores, or enhances natural shoreline habitat; and maintains coastal processes through the strategic placement of plants, stone, sand fill, and other structural and organic material (Virginia Living Shorelines Policy & Legislation).

Connecticut working definition:

> A shoreline erosion control management practice which also restores, enhances, maintains or creates natural coastal or riparian habitat, functions and processes. Coastal and riparian habitats include but are not limited to intertidal flats, tidal marsh, beach/dune systems, and bluffs. Living shorelines may include structural features that are combined with natural components to attenuate wave energy and currents (Barrett, 2015; O'Donnell, 2017).

NOAA definition:

> A shoreline management practice that provides erosion control benefits; protects, restores, or enhances natural shoreline habitat; and maintains coastal processes through the strategic placement of plants, stone, sand fill, and other structural organic materials (*e.g.,* bio-logs, oyster reefs, *etc.*) (NOAA Shoreline Website; O'Donnell, 2017).

Ideally, key terms that should be incorporated into living shoreline definitions are dynamic, function, habitat, and processes (Smith, 2006). Successful projects should be dynamic (variable and changing), properly functioning (have wave-sediment-flora-fauna interactions), have habitat accessibility (water-land interface that permit the use of shoreline and sub-tidal areas by an assortment of plants and animals), and lastly, mimic natural coastal processes (hydrology, chemistry, and biotic activities that are usually found in natural coastal environments) (Smith, 2006). Erosion control and flood protection are seen as the primary benefits while the restoration and preservation of ecosystem services are seen as secondary benefits. Benefits of living shorelines include but are not limited to lowering construction costs, maintaining the connection between aquatic and upland habitats, preserving or restoring nursery habitats, reducing wave energy, reducing storm surge and flood waters, and increased filtration of pollutants (Garbisch & Garbisch, 1994; Subramanian *et al.*, 2008; Scyphers et al., 2011; Bilkovic & Mitchell, 2013; Gedan *et al.*, 2011; Davis, Takacs, & Schnabel, 2006; Swann, 2008; Davis et al., 2015).

It is important to note that each of the above definitions allows the use of structural components and does not specify the extent or method to which they may be used (O'Donnell, 2017). Despite the differences in defining elements, each living shoreline project should have one element in common: the reliance on natural methods to manage shoreline erosion that do not sever the connection between riparian, inter-tidal, estuarine, and aquatic areas that are essential for ecosystem services (Pilkey et al., 2012).

3.2 LIVING SHORELINE METHODS

There are two basic approaches to living shorelines (Table 2; O'Donnell, 2017). The non-structural methods are constructed entirely of soft material (*e.g.* marsh grasses, submerged aquatic vegetation, beach grass, upland trees, shrubs; O'Donnell, 2017). Non-structural methods are most successful and recommended for low-energy environments experiencing mild erosion (Duhring, 2006). These lower-energy shorelines tend to occur where the widest fetch, or where the wind blows in a constant direction, is less than 1 mile (Luscher & Hollingsworth, 2005;

Garbisch &Garbisch, 1994; Hardaway & Byrne, 1999; Duhring, 2006). Shorelines in medium- to high-energy environments may require a hybrid approach to provide adequate erosion control and allow for vegetation growth (Currin, Davis, & Malhotra, 2017; Mitchell & Bilkovic, 2019; Subramanian *et al.*, 2008; Smith, 2006). Hybrid methods use a combination of structural elements (*e.g.* marsh toe revetments, rock sills, breakwaters, or oyster reefs) or biodegradable materials (*e.g.* coir fiber logs, matting) and non-structural elements to ensure vegetation development and provide protection from waves, tidal currents, and storm surges (O'Donnell, 2017). Along these more exposed shorelines, wave climate, coastal geomorphology, and land-use are important factors to consider when designing living shorelines (O'Donnell, 2017). The structural elements are presumably beneficial because they preserve eroding tidal marshes and allow for the creation of marshes where they did not previously or naturally exist (North Carolina Division of Coastal Management, 2006b; Duhring, 2006). Ideally, hybrid living shorelines are designed to mimic natural environments, and if that is not possible, they are meant to assist natural elements rather than protect against them (Smith, 2006; O'Donnell, 2017). The success and proper functionality of hybrid living shoreline solutions is delicate and dependent on determining the fine line between structure placement and desired habitat area (Smith, 2006).

Although there are many different types of coastal ecosystems in which a living shoreline may be implemented, one of the most common methods in the United States usually involves the conservation or restoration of a fairly narrow band, less than or equal to 30 meters, of marsh habitat that is well flushed by tides (Currin *et al.*, 2010; Davis *et al.*, 2015). However, it is important to note that these qualifications are not necessary for living shoreline projects. Chosen methods are dependent on individual project goals, site suitability, and site-specific design. These designs are meant to mimic natural coastal systems, but they are engineered systems that can frequently differ from natural coastal marshes (Mitchell & Bilkovic, 2019). For example, vegetation is originally planted in a grid, so plant density is controlled by design instead of inundation (Mitchell & Bilkovic, 2019). This may alter sediment capture and transport among other processes. Additionally, living shoreline designs often have a gradual slope while natural shorelines in erosive areas often have a scarped edge and complex micro-topography (Mitchell & Bilkovic, 2019). Lastly, many projects use hybrid approaches which usually have hard, fixed structures that can potentially affect sedimentation and faunal sediment patterns (Mitchell & Bilkovic, 2019). Long-term monitoring is essential to ensure successful implementation and/or modification of the engineered system if it is not evolving to mimic natural shoreline processes.

3.2.1 NON-STRUCTURAL METHODS

3.2.1.1 Marsh restoration or creation

Marsh vegetation and wetlands have substantially declined due to development along coastlines. Marsh restoration or creation is a minimally disruptive vegetation management method for living shorelines (O'Donnell, 2017). The main element is restoring or planting marsh vegetation, such as *Spartina alterniflora*, on coastal shorelines. Removal of overhanging tree branches reduces shade over these new or restored plantings and can increase marsh grass growth (VIMS-CCRM, 2006; O'Donnell, 2017). While it is possible to create marshes on low-energy shorelines, it is not recommended to create marshes where they are not a natural feature along adjacent or comparable natural shorelines as it may alter or impede the success of the project (Maryland Department of Environment, 2008; O'Donnell, 2017). The success of marsh creation or restoration depends on aspects such as width of the existing shoreline, exposure and orientation, and the sun/shade conditions (Maryland Department of Environment, 2008; O'Donnell, 2017).

3.2.1.2 Grading

Soft banks along shorelines are extremely susceptible to erosion, and the susceptibility increases if there is no vegetation present (O'Donnell, 2017). Wave and tidal action, even in low-energy environments, can cause slumping of the bank (O'Donnell, 2017). Many factors and elements influence the stability of a bank: height, sediment type, vegetation, waves, sea-level rise, and upland usage (O'Donnell, 2017). The goal of grading is to reduce the steepness of the bank, effectively decreasing erosion caused by wave action at the bank toe. A stable bank will be extensively covered with various types of vegetation (marsh grass, shrubs, mature trees; Slovinsky, 2011; O'Donnell, 2017). Not only does upland vegetation stabilize the bluff, but it also reduces rainwater runoff (O'Donnell, 2017). Grading is generally not an effective shoreline protection method for high-energy environments experiencing increased wave action (O'Donnell, 2017).

3.2.1.3 Beach Nourishment/ Fill

When necessary, sometimes fill material is deposited on the shore to provide a gradual increase in elevation to allow marshes to maintain their elevation and allow retreat of wetlands with sea-level rise (VIMS-CCRM, 2006; O'Donnell, 2017). This method restores the marsh or beach using sediment from other sites or offshore, replenishing sediment supply decreased as a result of coastal erosion and sea-level rise (O'Donnell, 2017). Although this a popular method to apply, especially on beaches in high-energy environments, there are some drawbacks. First, beaches nourished for recreation and unimpeded views are too low to provide substantial protection from storm events and increased tidal and wave action due to sea-level rise (O'Donnell, 2017). Second, the addition of sediment to beaches, dunes, and marshes can cause the unintended burial of native vegetation and disrupt habitat (O'Donnell, 2017). This reduces stabilization of the coastal ecosystem further and provides an opportunity for invasive species to colonize (O’Donnell, 2017). Lastly, because of the differences in original sediment and the additional sediment, fill may also affect the nesting and foraging of shorebirds and other animals (Nordstrom, Lampe, and Vandemark, 2000; O’Donnell, 2017). This method is mostly used for upkeep of beaches for recreational purposes or to raise the elevation of a marsh to allow for an increase in vegetation growth and density.

3.2.1.4 Dune Creation and Restoration

Dune creation and restoration may be part of a beach nourishment project, but these projects can also stand-alone (O’Donnell, 2017). These living shoreline projects are most successful if they are located where the natural dune line exists or in proximity to the natural dune line. Additionally, success is more likely if there is space for the dune to build and migrate naturally (Salmon, Henningsen, & McAlpin, 1982; O’Donnell, 2017). Three basic approaches are used in each design to achieve dune creation or restoration: plant vegetation, transport and provide sediment, and remove structures that hinder dune migration (Lithgow *et al.*, 2013; Martinez, Hesp, & Gallego-Fernandez, 2013; O’Donnell, 2017). In order for dunes to build naturally over time, there must be significant quantities of windblown sand (O’Donnell, 2017). Therefore, dune creation and restoration may be the only way to ensure dune persistence for protection from rising tides and increased storm surges in some areas. Adding fencing and vegetation to dunes can add another barrier to the wind, increasing sediment and sand accumulation around the fences and plantings (O’Donnell, 2017). In many cases, the desires of homeowners and coastal communities to have unimpeded views and an aesthetically pleasing shoreline prevents dunes being high enough to provide adequate protection from the consequences of anthropogenic climate warming including increased duration and frequency of severe storm events and future sea-level rise.

3.2.2 HYBRID METHODS

3.2.2.1 Fiber Logs

Fiber logs can temporarily protect shorelines from wave and tidal forces while vegetation establishes and develops a stronger root system (O'Donnell, 2017). The logs come in many sizes and grades, and they can be placed in either a single or multiple rows depending on the energy level of the environment (O'Donnell, 2017). These structures are biodegradable and typically deteriorate within five years in low-energy environments, which is an acceptable period for vegetation to mature and become established (Chesapeake Bay Foundation, 2007; Hardaway *et al.*, 2009; Hardaway & Duhring, 2010; VIMS-CCRM, 2006; O'Donnell, 2017). These structures are not recommended for high-energy saltwater environments as they may degrade too early for vegetation to become fully established. However, fiber logs are a great alternative to long-term hybrid structures as they will eventually let the shoreline function independently and similar to a natural shoreline.

3.2.2.2 Rock Sills

Rock sills are low profile breakwaters that are installed to protect the edge of a marsh (Fig. 3.1; Broome, Rogers, & Seneca, 1992; O'Donnell, 2017). They are constructed near mean low-water parallel to the shore and are backfilled with sand to regrade the slope (O'Donnell, 2017). After the backfill is completed, the area is planted with marsh vegetation in order to stimulate a more natural marsh edge (Fig. 3.2; Duhring, 2008; Hardaway & Duhring, 2010; O'Donnell, 2017). This process can be applied to restore previously vegetated sites or to create marshes at non-vegetated sites (Duhring, 2006). If the sill is not designed correctly, allowing for tidal exchange and habitat access for both sub-tidal and inter-tidal species, the marsh and its habitat value may not develop, and the shoreline may continue to erode (Smith, 2006). Additionally, if this exchange is not facilitated, the marsh that lies beyond the sill may develop to become a dead-zone for species (Smith, 2006). A poor design may be found in too high sill, effectively eliminating the exchange and connectivity necessary (Subramanian *et al.*, 2008; O'Donnell, 2017). In order to facilitate adequate tidal exchange as well as habitat access, windows or tidal gaps are often used in conjunction with marsh sills (Smith, 2006). Using tidal gaps may be the only way to ensure that connectivity between sub-tidal, inter-tidal, and upland habitats is maximized (Smith, 2006).

3.2.2.3 Toe Revetments

Toe revetment can be very similar to rock sills; however, the main goal is to stabilize the eroding edge of a natural tidal marsh (Fig. 3.3; Duhring, 2006). When a toe revetment is implemented, the space upland is not used for backfill and new vegetation plantings. It is installed to protect natural or previously restored marshes from wave-induced erosion (O'Donnell, 2017). These structures are low profile and allow for protection of the marsh edge while tidal inundation moves over and through the structure (O'Donnell, 2017). However, just as rock sills can be poorly designed, toe revetments can exhibit similar consequences if poorly designed. Therefore, the monitoring of sites with these structures is essential as sea-levels rise to ensure both consistent tidal exchange and proper erosion control protection.

3.2.2.4 Oyster Reefs

Marsh sills and toe revetments can also be formed with oyster reefs or shells (Fig. 3.4). The hybrid solutions provide erosion control with additional ecosystem benefits (Duhring, 2008; Scyphers *et al.*, 2011; Skrabel, 2013; Swann, 2008; O'Donnell, 2017). This provides a more natural and cohesive substrate for oyster spat and recruitment (O'Donnell, 2017). Eventually, these structures become self-maintaining and increase the protection and restoration potential of the project (Atlantic States Marine Fisheries Commission Staff, 2010; Gedan *et al.,* 2011; Scyphers *et al.*, 2011; O'Donnell, 2017). Oyster reefs provide areas for habitat and foraging, and as oysters are filter feeders, they improve water quality and clarity (Atlantic States Marine Fisheries Commission Staff, 2010; O'Donnell, 2017). This also improves light transmission throughout the water column and enhances environmental conditions for submerged aquatic vegetation (Atlantic States Marine Fisheries Commission Staff, 2010; O'Donnell, 2017). This is extremely important for supporting an abundance of diverse species. Oyster reefs, because they are self-maintaining systems and can move landward as sea-level rises, may be a cheaper hybrid option because they will involve less long-term monitoring than fixed structures. If possible, oyster reefs should be one of the first and preferred hybrid living shoreline options explored as they have the ability to adapt to sea-level rise while also contributing to shoreline erosion control and protection.

3.2.2.5 Breakwaters

Breakwaters are rock structures that are larger and have a higher elevation than sills (O'Donnell, 2017). These structures are designed and implemented to protect the shoreline from higher-energy conditions such as storm-waves (O'Donnell, 2017). They provide protected areas landward of the structure to help increase sediment deposition and widen the shoreline (O'Donnell, 2017). Breakwaters are able to attenuate wave energy and heights but do not protect against coastal inundation (O'Donnell, 2017). Although breakwaters installed with living shoreline projects have the intention to protect, they also classify as large, fixed structures that, if poorly designed, can also have adverse effects such as those outlined in the shoreline armoring section above.

3.3 SIGNIFICANCE

Nature-based approaches to shoreline stabilization have the capacity to protect shorelines while also preserving coastal ecosystems. Ideally, where possible, non-structural living shoreline methods are preferred as they are able to closely mimic natural systems. If hybrid structures are needed, short-term or natural approaches should be considered for installation first. Two hybrid options, fiber logs and oyster reefs, are better suited to adapt to sea-level rise and assist coastlines rather than inhibit or degrade ecosystem services. Oyster reefs are able to keep pace with rising sea-levels, and fiber logs allow for the development of a marsh system before degrading and allowing natural processes to take over. Although hybrid living shorelines are frequently designed and installed, even most of these stabilizing structures are not sustainable in the face of sea-level rise. As previously mentioned, Pilkey *et al.* found that a growing number of projects classified as living shorelines, according to various definitions, are relying more on structural stabilization (2012). The project on Dauphin Island outlined above is one extreme example of projects advertised as "living shorelines" as an excuse for further shoreline armoring. While it is not realistic or possible to use only "soft" shoreline stabilization methods in every living shoreline project, where possible, "hard" stabilizing structures should be kept to a minimum or not used at all. Both the purpose of the project and area conditions will affect the design. While shoreline protection is a primary goal as sea-level rises and storms become more frequent and intense, without the restoration and preservation of natural coastal ecosystem benefits, shorelines will not be able to support communities; therefore, the goal of the methods listed above is to provide protection while preserving important ecosystem services to not only combat sea-level rise but also allow the ecosystem and communities to prosper in its wake.

	Potential functions								
	Dissapates wave energy	Prevents flooding	Reduces erosion	Provides native habitat	Supports native populations	Provides foreign habitats, may promote invasion	Prevents faunal access to shoreline	Living organism subject to disease	Potentially self-sustaining under SLR
Living shorelines									
Marsh	Yes, amount depends on marsh width	No	Depends on setting (Yes in low energy)	Yes	Yes	No (typically)	No	Yes	Yes, with retreat corridor
Marsh with rock sill	Yes	No	Yes	Depends on setting (Yes on rocky coast)	Yes, although possibly reduced	Depends on setting	Reduces access	Partially	Marsh only, with retreat corridor
Marsh with oyster sill	Yes, amount depends on marsh width	No	Yes	Yes	Yes	No (typically)	No	Yes	Both, but marsh requires retreat corridor
Traditional hardening									
Rock Revetment	Yes	No	Yes	Depends on setting (Yes on rocky coast)	Possible	Depends on setting	Replaces shoreline	No	No, and may prevent retreat of other habitats
Timber/concrete Bulkhead	Reflects energy	Depends on design/height	Yes	No	Possible	Yes	Replaces shoreline	No	No, and may prevent retreat of other habitats

Table 3. A comparison of some different nature-based shoreline stabilization methods (source: Mitchell & Bilkovic, 2019).

Fig. 3.1. Photograph of rock sill and marsh transplanting two years post-construction in North Carolina (source: Currin, Chapel, & Deaton, 2010).

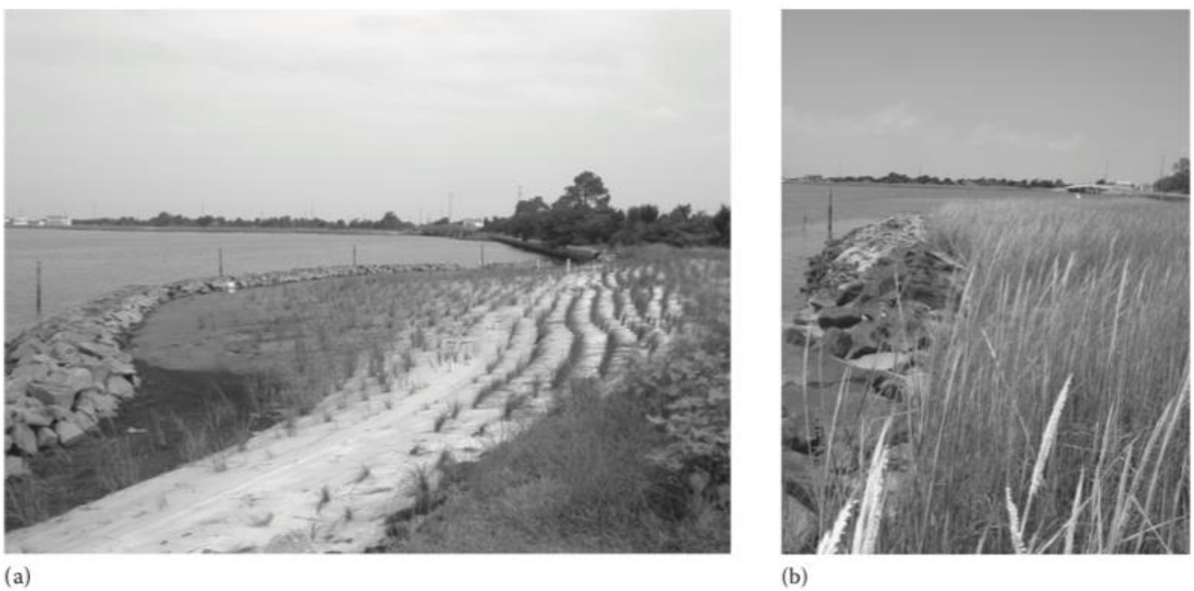

Fig. 3.2. (a) Photograph of rock sill and marsh transplanting in North Carolina (emphasizing the bare substrate) and (b) photograph depicting the vegetation that has filled the bare area behind the sill (source: Currin, Davis, & Malhotra, 2016).

Fig. 3.3. Photograph depicting toe revetment in North Carolina (source: Currin, Chapel, & Deaton, 2010)

Fig. 3.4. Photograph depicting oyster reef restoration in North Carolina (source: Currin, Chapel, & Deaton, 2010)

BENEFITS OF LIVING SHORELINES: ECOSYSTEM SERVICES SUPPORTED BY NATURAL AND NATURE-BASED SOLUTIONS

4.1 BACKGROUND

An examination across the continental United States, completed by Pilkey *et al.* (2012), indicated that there is a need to reassess what the "limited" use of rock means, where some design elements are appropriate, and where they are not (pg. 3). Pilkey *et al.* (2012) claims that traditional shoreline erosion control structures present in living shoreline projects are not restoration projects and should not be considered or advertised as such (pg. 3). The extensive evidence outlining the lack of sustainability and adverse impacts of most stabilization structures should provide motivation to transition away from these traditional methods. In order to protect coastal ecosystems and the communities that lay beyond, it is imperative to reconsider protection methods and the inconsistencies that remain among them. The high usage of armoring structures instead of living shorelines, or excessive structures even living shorelines (despite low-energy environments), is due to multiple issues including public policy impediments, a lack of education, and slow permitting processes (Fear & Currin, 2012; Polk & Eulle, 2018). In order to overcome difficulties in the transition to nature-based approaches, benefits of living shorelines must be identified and evaluated. Landscape-scale analysis, to delineate how benefits from living shorelines exceed those of more traditional methods, and long-term monitoring, to ensure success of living shoreline projects, are imperative in order to spark community-level motivation to implement more small-scale living shoreline projects. A concern shared by many researchers is that living shorelines using massive hard engineered structures will cause long-term environmental degradation and result in an initial false sense of accomplishment, shifting focus away from trying to maintain natural shorelines and the essential processes and benefits that accompany them (Pilkey et al., 2012).

4.2 ECOSYSTEM SERVICES

The sections below will review many of the ecosystem services analyzed in various studies focused on living shoreline projects. The purpose of these sections is to show the impact and importance of continuing to implement and improve living shoreline projects.

4.2.1 Carbon Sequestration

Many researchers and studies have acknowledged the tremendous potential salt marshes and other coastal ecosystems would have to sequester carbon; however, there is a need for research that quantifies the total impact of that sequestration. Estuaries are characterized by high primary productivity and slow remineralization (Davis *et al.*, 2015). The combination of these two elements results in tidal wetlands having being able to sequester carbon at higher rates than terrestrial ecosystems (Mcleod *et al.*, 2011; Davis *et al.*, 2015). Sequestration rates can vary tremendously, and this is presumably because of variability among ecosystems such as plant community, density, climate, salinity (Chmura *et al*., 2003; Ouyang & Lee, 2014; Davis *et al.*, 2015). Even so, vegetation characteristics such as stem density, plant height, and shallow below-ground macro organic matter in restored marshes will typically match that of adjacent natural marshes within two to three growing seasons (Currin, Delano, & Valdes-Weaver, 2008; Craft, Broome, & Campbell, 2002; Davis *et al.*, 2015). It may take longer for the infaunal benthic community of created and restored marshes to reach equivalent levels to that of natural marshes (Craft *et al.*, 1999; Sacco, Seneca, & Wentworth, 1994; Davis *et al.*, 2015). For the purpose of this paper, one study will be reviewed that quantified the total impact of sequestration in a few, small-scale living shoreline projects.

In a study by Davis *et al.* (2015), carbon sequestration rates were measured in living shorelines. One main finding in the study was that apparent carbon sequestration rates decreased with marsh age (Fig. 4.1; Davis *et al.*, 2015). Lower sequestration rates in older created, restored, or natural marshes is potentially the result of an enrichment of labile organic matter in younger marshes (Davis *et al.*, 2015). Generally, in tidal marshes, carbon sequestration occurs when production of below-ground biomass outpaces remineralization (Davis *et al.*, 2015). It was found that carbon sequestration at the younger sites exhibited rates two to three times greater than carbon sequestration at older sites (Fig. 4.2; Davis *et al.*, 2015). As these marshes matured, the original sediment had been altered through inputs from below-ground biomass, particulate matter trapped from incoming wave and tidal waters, and associated benthic and interstitial community production (Davis *et al*., 2015). A coastal ecosystem's ability to alter elevation in response to sea-level rise is one factor that contributes to their carbon sequestration capacity (Connor, Chmura, & Beecher, 2001; Davis *et al.*, 2015). In this study, however, despite the perceived relationship between elevation increase, below-ground biomass, and sequestration, there were no relationships found between elevation and carbon sequestration rates (Davis *et al.*, 2015). This may be because of greater remineralization rates in high versus low marsh elevation sediments (Davis *et al.*, 2015). In restored and created marshes, such as the ones examined in this study, initial carbon sequestration and accumulation rates provide an exaggerated estimate of total carbon sequestration (Davis *et al.*, 2015). This is due to the young, carbon rich sediments and vegetation installed which can provide false initial total core estimates (Davis *et al.*, 2015). In reality, only a small fraction of the initial material will be preserved for long periods of time (Davis *et al.*, 2015). Thus, as the soil ages, contributions of labile and semi-labile components will decrease, and subsequently, the apparent carbon sequestration will also decrease until the equilibrium between remineralization and carbon inputs is reached (Davis *et al.*, 2015).

Not only do living shorelines help sequester carbon from the atmosphere, but they also help prevent the erosional release of carbon that is stored in the deeper zone of coastal ecosystems. The primary goal of the living shoreline approach is erosion control and shoreline protection; however, by providing a barrier between a body of water and eroding shorelines, there is a carbon benefit of decreasing erosion-related carbon losses along inter-tidal habitats (Pendelton *et al.*, 2012; Davis *et al.*, 2015). In this study, five living shoreline sites were investigated. The marshes that were surveyed ranged from 12 to 38 years old (Davis *et al*., 2015). The carbon sequestration rates ranged from 58 to 283 g C m^{-2} yr^{-1} and were found to be decreasing with marsh age (Davis *et al*., 2015). This living shoreline area had an average sequestration rate of 75 g C m^{-2} yr^{-1} which is comparable to a cumulative annual carbon benefit of 18.75 metric tons (Davis *et al.*, 2015). According to the researchers, this is approximately the removal of 64 metric tons of carbon dioxide (Davis *et al.*, 2015). The U.S. Energy Information Administration suggests that a gallon of E10 gasoline burned generates roughly 18.95 lbs. of CO2 (Davis *et al.*, 2015). Therefore, using their results and the gallon estimations, Davis *et al.* estimated that the 6 miles of living shorelines in North Carolina offset the equivalent of 7525 gallons of gasoline per year (2015). Studies such as this, where sequestration values are quantified and compared to everyday applications, can help motivate officials and regulators to implement more living shoreline projects in the future.

Although carbon sequestration rates slow as tidal marshes mature, if current shoreline armoring were replaced with living shoreline projects, the total amount of potential carbon sequestration would be significant. Therefore, implementing small-scale living shoreline projects will contribute to the overall effort to slow climate change and all the subsequent effects. More research is needed to understand carbon sequestration rates for different living shoreline approaches.

4.2.2 Habitat Creation and Enhancement

Living shoreline projects often involve some level of marsh vegetation restoration or plantings. As shown above, the implementation of living shorelines and vegetation into coastlines can result in an increase in carbon sequestration and decrease in erosion-related carbon losses. However, many researchers have also discussed the habitat enhancement benefits vegetation provides. Marsh vegetation provides the main form of primary production in many coastal ecosystems, and therefore, shorelines with vegetation can support an abundance of different species through bottom-up control. Apart from food resources, submerged aquatic vegetation can also provide valuable and important refuge for juvenile fish and crustaceans (Ruiz *et al.*, 1993; Currin *et al.*, 2010). It can provide nursery habitat for many fish, whose larvae are transported into the estuary and then spend juvenile years in the sub-tidal waters (Ross, 2003; Currin *et al.*, 2010). Additionally, vegetation can support non-aquatic species that rely on coastal wetlands and ecosystems. 80% of the United States' breeding bird population relies on coastal wetlands (Kesselheim & Slattery, 1995; Subramanian *et al.*, 2006). Of the 800 species of protected migratory birds, 50% rely on coastal ecosystems (Kesselheim & Slattery, 1995; Subramanian *et al.*, 2006). Lastly, almost amphibian species in North America rely on coastal wetlands for breeding (Hammer, 1996; Subramanian *et al.*, 2006).

One way that researchers are able delineate the benefits vegetation and living shoreline projects provide to ecosystems, such as habitat preservation, is comparing natural and nature-based shorelines to hardened shorelines. Recent studies have shown that sites with shoreline armoring, bulkheads or rock revetments, have a lower abundance of organisms (Wetlands

Watch, 2007; Subramanian *et al.*, 2008). It has also been recorded that hardened shorelines have a lower abundance of crabs and fish when compared to shorelines with vegetation (Wetlands Watch, 2007; Subramanian *et al.*, 2008). The installation of shoreline armoring structures not only immediately decreases vegetation density and abundance but can also continuously decrease habitats over time through increased erosion, scouring, and turbidity. A study completed in the Chesapeake Bay found that species' responses to shoreline restoration can occur almost immediately (Davis *et al.*, 2006). Before restoration, 18 macro-faunal species were collected at marsh sites and 14 species at bulkhead sites (Davis *et al.*, 2006).

Sietz *et al.* (2016) also found that benthic abundance and diversity were higher in habitats adjacent to natural shorelines than habitats adjacent to hardened shorelines (Subramanian *et al.*, 2008). So, not only does shoreline armoring have adverse effects on the shorelines on which they were installed, but consequences can adversely affect shorelines adjacent or nearby. Similarly, natural and nature-based projects may have the ability to positively affect adjacent shorelines by providing nesting, foraging, and refuge habitat to native and migrating species. Sietz *et al.* (2006) also found that predator abundance and diversity were highest adjacent to natural marshes (Subramanian *et al.*, 2008). Crab density was also documented and was found to be higher in natural marshes than in bulkhead habitats (Sietz *et al.*, 2006; Subramanian *et al.*, 2008). These results suggest an essential relationship between marshes, infaunal prey, and predator abundance (Sietz *et al.*, 2006; Subramanian *et al.*, 2008). This is imperative to understand, as many miles throughout the United States have been hardened and continue to be hardened each year, which increases the vulnerability of valuable habitat for species (Subramanian *et al.*, 2008). Even in areas without shoreline armoring, marsh habitats may be put at risk due to higher population density and urban development along United

States’ shorelines. While many individuals do not understand or have concerns about the potential effects of habitat degradation, the benefit to cost ratio for a living shoreline is significant (Subramanian *et al*., 2006). For each dollar spent to install a living shoreline, as much as $1.75 USD is returned to the economy due to improvements to resources (U.S. Army Corps of Engineers, 1990; Subramanian *et al*., 2006). This includes submerged aquatic vegetation, sub-tidal species, and wetland habitats (U.S. Army Corps of Engineers, 1990; Subramanian *et al*., 2006). This is extremely important for the continuation and prosperity of local fishing industries in coastal communities.

4.2.3 Water Quality

Vegetation and habitat preservation are directly related to water quality. Salt marshes have the ability to trap silts and pollutants, including nitrogen and phosphorous, that are transported through storm-water runoff to receiving waters (Knutson *et al.*, 1982; Subramanian *et al*., 2006). Inter-tidal and sub-tidal habitats with vascular plants and benthic algae remove nitrogen through denitrification and direct plant uptake (Currin *et al.*, 2010). However, in highly urban areas, such as the Chesapeake Bay watershed, only approximately 30% of nitrogen is from surface water runoff (Subramanian *et al*., 2006). The majority of pollutants move unimpeded to waters through sub-surface flow and groundwater (Subramanian *et al*., 2006). Tobias *et al.* (2001) demonstrated that fringing marshes also effectively remove groundwater nitrate inputs (Currin *et al.,* 2010). When this groundwater flow reaches a coastal ecosystem, denitrification will likely occur (Subramanian *et al*., 2006). Salt marsh vegetation, and other high productivity plants, move large amounts of biomass belowground to drive a process which converts nitrogen, thereby dampening coastal eutrophication (Subramanian *et al*., 2006). Therefore, natural and nature-based solutions can assist in improving the water quality of estuaries, especially those that are affected by dense coastal population, urban development, or agricultural lands.

Nutrients are not the only elements affecting water quality along coastlines. As discussed previously, many shorelines in the United States are experiencing high erosion rates due to various factors. Erosion of shorelines can cause sediment pollution and affect light transmission to submerged aquatic vegetation. For example, in the Chesapeake Bay, approximately 4.7 million cubic yards of sediment cloud the water column every year (Knutson *et al.*, 1982; Subramanian *et al*., 2006). The majority of that sediment pollution is from tidal erosion occurring both on the shoreline and offshore (Subramanian *et al*., 2006). Oyster reefs used in living shoreline designs can assist with clearing the sediment from the water column, which can improve light transmission, keep submerged aquatic vegetation healthy, and preserve submerged habitats. Through oyster and mussel recruitment, installing vegetation, and shoreline stabilization, sediment reduction and water quality improvement can be achieved along natural and nature-based shorelines.

4.2.4 Wave Attenuation

Vegetated shorelines, in both natural and nature-based settings, can attenuate wave energy and decrease shoreline erosion (Gedan *et al.*, 2011; Currin *et al.*, 2017), and vegetation application is critical in the design and development of living shorelines (Knutson *et al.*, 1982, Roland & Douglass, 2005; Riffe *et al.*, 2011; Gedan *et al.*, 2011; Polk & Eulle, 2018). Plant height and density are correlated to a salt marsh's ability to dissipate wave energy (Gedan *et al.*, 2011). As long as there is sufficient sediment supply, wave attenuation can result in sediment capture and accretion, allowing the marsh to alter elevation with sea-level rise (Mitchell & Bilkovic, 2019). However, there are many factors that affect wave attenuation and sediment capture such as marsh width, vegetation type, stem height, soil composition, water depth, and tidal amplitude (Morris *et al.*, 2002; Bilkovic *et al.*, 2016). Erosion of the marsh edge primarily occurs during periods in which un-vegetated areas of the marsh edge are exposed to wave energy (Marani *et al.*, 2011; Currin *et al.*, 2017). Although sloping shorelines can dissipate wave energy, vegetation aids the shoreline by increasing friction, dampening waves, and decreasing turbulent mixing which results in increased attenuation and sediment accretion (Möller, 2006; Yang *et al.*, 2012; Currin *et al.*, 2017). Several studies emphasize the capability of vegetation to dissipate waves and that wave reduction increases with increased marsh stem density or canopy height (Leonard & Luther, 1995; Möller, 2006; Yang *et al.*, 2012; Currin *et al.*, 2017). Knutson *et al.* (1982) observed, in a study focusing on the wave dampening capacity of *Spartina alterniflora*, that on average, the majority of low-energy waves were dissipated in the first 2.5 meters of the marsh, and 100% were dissipated in 30 meters (O'Donnell, 2017).

High wave energy can negatively impact coastal ecosystems by reducing the vegetation density (Keddy, 1982; Safak *et al.*, 2020) and obstructing larval recruitment and survival of oyster reefs (Wall *et al.*, 2005; Safak *et al.*, 2020). Coastal ecosystems, both natural and nature-based, provide crucial protection to coastal communities by attenuating waves (Anderson, Smith, & McKay, 2011; Bridges *et al.*, 2015; Gedan *et al.*, 2011; Guannel *et al.*, 2015; Shepard, Crain, & Beck, 2011; Shepard *et al.*, 2012; Sutton-Grier, Wowk, & Bamford, 2015; O'Donnell, 2017). Although it has been shown by many researchers that vegetation and other living shoreline methods can be effective at attenuating wave energy, the effect of vegetation on wave dissipation has mainly been examined in low-energy conditions; therefore, the feasibility of relying on salt marshes and similar ecosystems to provide protection from extreme storms events is not well understood (Anderson, Smith, & McKay, 2011; O'Donnell, 2017). There is a maximum wave energy that determines marsh stability and persistence. In a study completed by Schwimmer (2001), it was found that wave power, especially wind-driven waves, was significantly correlated with erosion rate (Currin *et al*., 2017). Other sources of energy such as boat wakes and tidal currents also contribute to increased erosion (Fig. 4.3; Currin *et al*., 2017). Shafer, Roland, & Douglass (2003) estimated the critical wave energy threshold for marsh stability by modeling heights of waves along a given shoreline using average water depth and fetch (Currin *et al*., 2017). For example, an analysis of modelled wave heights, representing a spectrum of energy levels, along the Gulf of Mexico indicated that the critical threshold for marsh existence was predicted to be 80% wave heights below 0.15 and 0.3 m (Shafer, Roland, & Douglass, 2003; Currin *et al*., 2017). Roland & Douglass (2005) applied this approach for *Spartina alterniflora* in coastal Alabama and found the critical wave threshold to be 0.3 to 0.4 m (Currin *et al*., 2017). In areas that experience critical wave heights more frequently, a hybrid approach may be necessary to aid in marsh stability. Additionally, in high-energy environments, an abrupt edge can reduce wave heights but results in near-continuous erosion of the marsh face, which will cause narrowing of marsh width over time and the eventual drowning of the ecosystem (Möller & Spencer, 2002; O'Donnell, 2017).

Although there has been a lack of focus on living shorelines in high-energy environments, many researchers still claim that living shorelines, both non-structural and hybrid, provide more protection from erosion than shoreline armoring structures. Gittman *et al*. (2014) studied the effect of Hurricane Irene on shore erosion in North Carolina (O'Donnell, 2017). They concluded that marshes, both with and without sills, provide better protection and are more durable in Category 1 hurricane conditions when compared to bulkheads (Gittman *et al.*, 2014; O'Donnell, 2017). Observations such as this will be an important consideration when designing and installing living shorelines in areas more likely to experience extreme weather events and hurricanes. Although a living shoreline's ability to dissipate wave energy and protect coastlines from erosion is a delicate process and dependent on many factors, it is generally accepted that living shorelines can provide more protection than shoreline armoring structures and are more beneficial to the overall health and prosperity of the coasts. Möller *et al.* (2014) determined that 60% of wave attenuation occurring during storms is due to marsh vegetation, and even when waves were large enough to damage marsh plants, vegetaion still prevented soil erosion (Sutton-Grier, Wowk, & Bamford, 2015; O'Donnell, 2017).

However, Hu, Chen, and Wang (2015) found that a marsh's ability to attenuate waves and storm surges decreases with increasing storm duration, intensity, and wind speed (O'Donnell, 2017). Longer-period storm waves can increase the water level over time, exerting a greater force on vegetation; thus, during extreme weather events, vegetation is more likely to bend with the flow of the surge, reducing wave dissipation level (Bradley & Houser, 2009; Pinsky, Guannel, & Arkema, 2013; O'Donnell, 2017). As such, there is a need for more research on how living shorelines attenuate waves and prevent erosion in medium- to high-energy environments. Even so, it would be beneficial to transition back to more natural shorelines in place of shoreline armoring to protect coastal communities from storm and sea-level rise induced erosion as they have been shown to more effectively attenuate waves without extensive consequences. One study, by Safak *et al.*, 2020, observed wave transmission through break-walls composed of tree branches. The results of the study indicated that well-engineered semi-porous living shoreline structures act as buffers against boat traffic and waves (Safak *et al.*, 2020). There have been many additional studies analyzing and emphasizing the effectiveness of hybrid living shorelines on wave attenuation and shoreline erosion control; living shorelines are considered a viable method to dissipate wave energy and protect shores.

4.2.5 Shoreline Stabilization

A main goal of any shoreline modification is stabilization. The dissipation of wave energy in low- to high-energy environments is extremely important in providing erosion control and shoreline stabilization. The term erosion is often used to describe either the volume of sediment removed from nearshore zones or the retreat of a shoreline as measured by a range of indicators (Boak & Turner, 2005; Le Cozannet *et al.*, 2014). Implementing living shorelines will not only help stabilize the shoreline through reducing or eliminating erosion but will also help shorelines persist through sea-level rise by increasing their elevation. Vegetation, through wave reduction, can trap sediment which leads to sediment accretion and elevation increases (Fig. 4.4; Fonseca, 1996; Currin *et al.*, 2010; Friedrichs & Perry, 2001; Morris *et al.*, 2002; Mudd *et al.*, 2010; Currin *et al.*, 2017). This helps the marsh retreat with sea-level rise (Currin *et al.*, 2017). The capability of vegetation to trap sediment is dependent on a number of factors (O’Donnell, 2017). These factors include, but are not limited, to sediment supply, tidal range, marsh elevation, and vegetation characteristics (Shepard, Crain, & Beck, 2011; O’Donnell, 2017). Gedan *et al.* (2011), among many other authors, concluded that coastal vegetation protects shorelines from erosion by effectively dissipating waves, increasing sediment deposition, and increasing soil cohesion (O’Donnell, 2017). The extensive root system of marsh vegetation also helps to maintain existing soil in coastal ecosystems thus reducing sediment transport as vegetation dissipates wave energy (VIMS-CCRM, 2010; O’Donnell, 2017). Additionally, vegetation contributes organic matter to the sediment through root production, effectively taking up space in the sediment and raising the surface elevation of the marsh (Baustian *et al.*, 2012;

Mitchell & Bilkovic, 2019). Unless a minimum elevation is maintained and adapts to match the pace of sea-level rise, marsh plants will be continuously flooded, resulting in the loss of vegetation and decreasing edge stability (O'Donnell, 2017).

Vegetation presence and growth are essential factors in ensuring the marsh sustains a minimum elevation as changes ensue. Plant growth is an important moderator of marsh stability, marsh adaptability, sediment accretion, and marsh surface elevation (Mitchell & Bilkovic, 2019); therefore, marsh plantings are integral to the sustainability of living shorelines, especially as coastlines become increasingly threatened by coastal erosion and passive submersion due to sea-level rise (Mitchell & Bilkovic, 2019). Processes such as sediment accretion through vegetation make natural and nature-based living shorelines self-sustaining erosion control devices (Currin *et al.*, 2017). Living shorelines, in many areas across the country, are a better option than shoreline armoring due to their ability to protect communities, preserve the ecosystem, and stabilize shorelines, while allowing for migration of wetlands as sea-level rises.

For higher-energy environments, hybrid living shoreline projects are an alternative to non-structural nature-based solutions to coastal erosion and sea-level rise provided that "hard" elements assist natural elements (Pilkey *et al.*, 2012). Marsh edge stability is frequently achieved through the use of rock or oyster sill structures or coir logs (Mitchell & Bilkovic, 2019). Coir logs can be placed against undercut banks along shorelines acting as a medium for plant propagation and provide temporary structural protection (Pilkey *et al.*, 2012). Sill inclusion in nature-based projects enhances sediment deposition and increases chances of sediment accretion (Currin, Delano, & Valdes-Weaver, 2008), helping increase shoreline resilience (Mitchell & Bilkovic, 2019). Similar to seagrass beds, oyster reefs can help trap sediments and build reefs further stabilizing shorelines (Meyer, Townsend, & Thayer, 1997; Currin *et al.*, 2010).

Encouraging oyster and mussel settlement may further increase marsh stability, and, in some cases, rock sills may help with oyster recruitment by providing the marsh with a hard substrate (Bilkovic & Mitchell, 2017); however, hard structures, such as rock sills, in living shorelines may be one contributing factor to observed low mussel recruitment due to reduction of larval access to the marsh surface (Bilkovic & Mitchell, 2017; Mitchell & Bilkovic, 2019). Hybrid living shorelines, or the continued use of "hard" structures along the shore, may have additional consequences as well.

A review of living shorelines completed by Currin *et al.* (2017), limited their term of "living shoreline" to projects where the footprint of natural vegetation exceeded that of hard stabilization structures. Many of the sites that were reviewed were still accompanied by shoreline structures such as oyster or rock sills. Oyster sills are preferable to rock sills as they provide more benefits to the ecosystem and have the ability to keep pace with local sea-level rise. There is a need for more research on living shorelines without a structural component. However, in conclusion, Currin *et al.* (2017) found, through the comprehensive review, that the use of living shorelines, with or without low oyster or rock sills, is preferable to traditional shoreline armoring practices because they stabilize the shoreline while maintaining ecosystem services.

As previously discussed, living shorelines are a very dynamic and delicate method to erosion control and shoreline stabilization. Living shoreline methods and marsh resilience are strongly connected to physical setting (Currin *et al.*, 2017). Without proper design and long-term monitoring, the success of the living shoreline may be in question. Regulators and officials should recognize a living shoreline's ability to stabilize the coastlines throughout the progression of sea-level rise. These shoreline protection methods benefit both the ecosystem and coastal communities; therefore, in order to stabilize shorelines, further shoreline hardening should be prohibited, and shorelines already hardened should consider the possibility of reverting to nature-based shorelines for shoreline stabilization and sea-level rise protection.

4.3 SIGNIFICANCE

Many shorelines throughout the continental United States are being constantly eroded. While erosion is a natural process, it poses a threat to homes, communities, and businesses in close proximity to the coast. When shoreline armoring is installed along these coasts, erosion control and storm protection are the primary goals, and as a consequence of shoreline hardening, coastal ecosystems are suffering. However, many people do not understand the consequences of destroying natural coastal ecosystems. One example is habitat degradation, which will harm local fishing economies. In contrast, living shoreline methods restore and protect coastal ecosystem services while providing protection to coastal communities. Making benefits of natural and nature-based methods known to regulators, officials, and homeowners is important to motivate implementation of small-scale living shoreline projects as an alternative to shoreline armoring. Not only will living shorelines allow for communities to benefit from habitat restoration and the improvement of water quality, but it will also help protect communities from future sea-level rise.

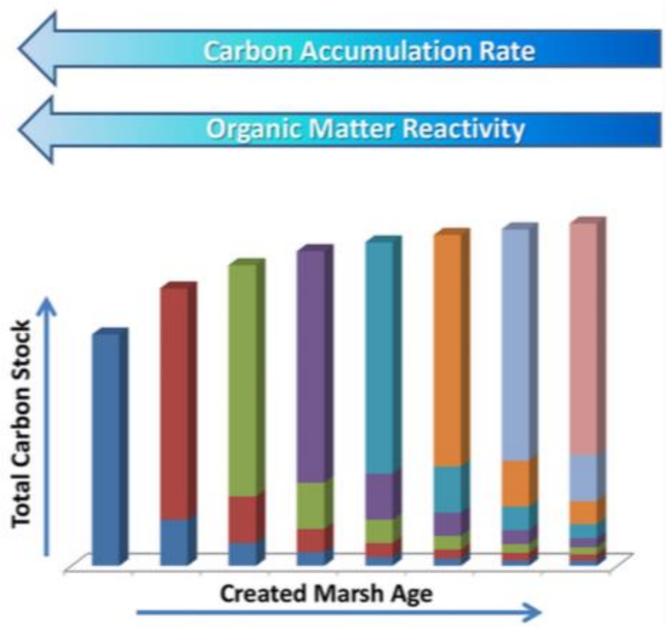

Fig. 4.1. Model of burial and turnover in a created marsh. At each step, new carbon is added to the soil as below-ground biomass (different colors). The decrease in size of these additions over time represents remineralization. (source: Davis *et al.*, 2015)

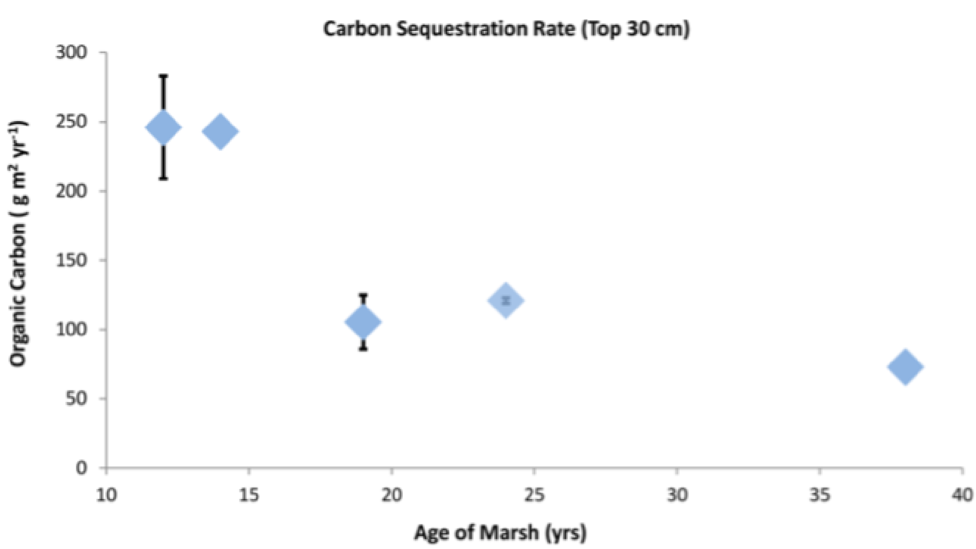

Fig. 4.2. Carbon sequestration rate in a study completed by Davis *et al.*, 2015. Newly created marsh carbon sequestration rates are two to three times greater. Points without error bars represent single cores collected during the study (source: Davis *et al.*, 2015)

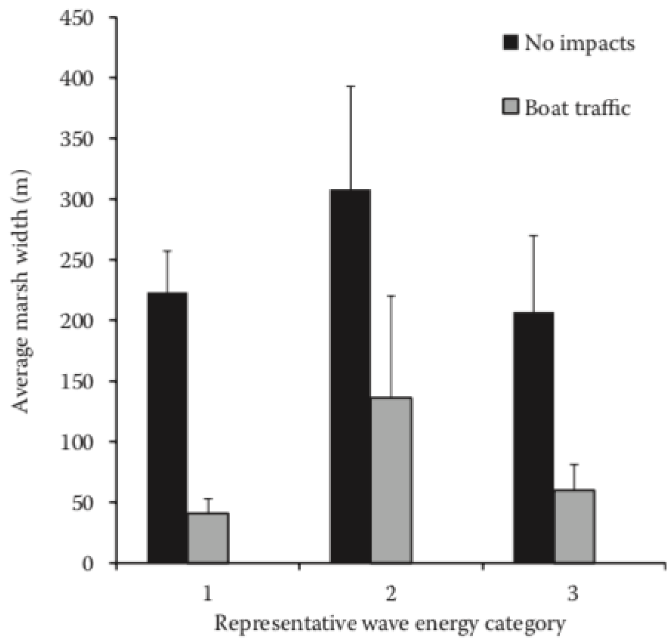

Fig. 4.3. Boat wake impacts on marsh width in low-energy wind conditions (source: Currin, Davis, & Malhotra, 2016)

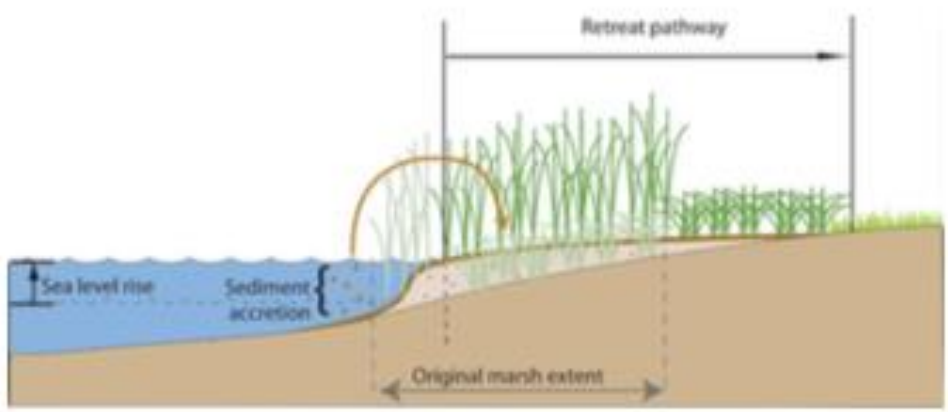

Fig. 4.4. Diagram depicting processes that help shorelines adapt to sea-level rise. Marsh vegetation dissipate wave energy and collect sediment, allowing the marsh elevation to adapt to changing sea-levels (source: Mitchell & Bilkovic, 2019)

IMPORTANCE OF SITE-SPECIFIC DESIGN, LONG-TERM MONITORING, AND LANDSCAPE-SCALE ANALYSIS

5.1 SITE-SPECIFIC DESIGN AND LONG-TERM MONITORING

The varied results and contrasting information on living shorelines and the studies reviewing and analyzing them indicate the importance of site-specific design during applications for nature-based approaches. The "one-size-fits-all" approach that has been applied when implementing shoreline armoring is not a successful approach to the living shorelines concept (Jefferson Patterson Park and Museum, 2007; Subramanian *et al.*, 2008). Even though shoreline armoring applications seem relatively simple to implement, and even when carefully designed, these shoreline protection methods can have unintended consequences for both wildlife and people (Jefferson Patterson Park and Museum, 2007; Subramanian *et al.*, 2008). This demonstrates that living shorelines, which are much more dynamic and delicate systems, require considerable site-specific engineering to ensure that functional ecosystem benefits are achieved (Subramanian *et al.*, 2006). If appropriately placed and designed, living shorelines can enhance ecosystem services capacity by more than 90% (Rodríguez-Calderón, 2014; Bilkovic *et al.*, 2016). Determining a successful design for both "soft" and "hard" methods while maintaining ecosystem services can be very challenging, and hence, is of great importance, especially in medium- to high-energy environments (Subramanian *et al.*, 2006).

First, sites need to be analyzed to determine whether they are suitable to sustain living shorelines. Although there are many studies detailing site conditions and the type of living shoreline installed, the results and success rates in these studies vary. A detailed base site suitability document would be beneficial so projects have a starting point for possible methods and approach to design and implementation. An example of a similar document was created by Currin, Davis, and Malhotra (2016), and it provides a brief list of some site suitability qualifications (Table 3). A lack of information exists on the science behind the effectiveness of living shoreline projects for different types of shorelines and under different energy regimes and storm conditions (NOAA, 2006; Subramanian *et al.*, 2008). Site-specific conditions of tidal currents and amplitude, elevation, underlying geomorphology, and wave energy are only some elements that dictate the design of living shoreline projects (Currin *et al.*, 2010). These parameters and background conditions will continue to evolve as climate change and sea-level rise persist and as natural processes and storm events continue the evolution of coastlines. Local sediment supply is an important siting factor, especially where the potential for marsh retreat is limited (Mitchell & Bilkovic, 2019). Accretion raises the elevation of the marsh over time and can keep it in the proper position in the tidal frame as sea-level rises (Mitchell & Bilkovic, 2019). Consideration should be given to the immediate and adjacent shorelines to determine proper sediment accretion potential (Boon & Mitchell, 2015; Mitchell & Bilkovic, 2019). Additionally, unlike shoreline armoring, one cannot assume factors determining site suitability and design are the same or even similar as conditions close by or on like shorelines. For example, a large fetch is not a concern if the wind rarely blows from that direction, and wind direction and intensity are dependent on a multitude of factors that differ at each specific site (Currin *et al.*, 2017). Often, wave regimes are modelled using average water depth, but this may not adequately capture the importance of nearshore bathymetry to shoreline energy regimes (Currin *et al.*, 2017). Therefore, extensive site-specific engineering is needed for living shoreline projects to be successful. Additionally, adjacent shoreline evaluation should not only be applied to the sediment supply consideration. To determine adequate design and evaluate comprehensive benefits, adjacent shorelines should be monitored long-term as well.

Long-term monitoring after implementation for a multitude of sites with different conditions may make future implementation easier. Funds for long-term monitoring are often limited due to the smaller scale on which living shorelines are completed (McClenachan *et al.*, 2020). However, long-term monitoring is essential in determining how successful projects respond to sea-level changes. Without the funds for researchers to continue monitoring living shoreline projects, it is likely that the success of the shoreline in the context of continued sea-level rise will not be guaranteed. In addition, coastlines are not expected to respond similarly to the same rates of sea-level change, and many areas within the United States alone will experience different levels of sea-level rise (Gornitz, 1991; Fletcher, 1992; Le Cozannet *et al.*, 2014). Although living shorelines do have the capacity to adapt to rising sea-levels (Moosavi, 2017; Sutton-Grier, Wowk, & Bamford, 2015; Toft *et al.*, 2017), their ability relies on proper site design and incorporating processes occurring in natural systems (Mitchell & Bilkovic, 2019). The ability to mimic natural shorelines is what makes living shorelines so valuable in protecting coastlines through sea-level rise, and that ability is dependent on the setting, design, and type of monitoring and maintenance (Mitchell & Bilkovic, 2019). Appropriate and successful designs have the ability to enhance longevity by embracing the dynamic characteristics of natural marshes and shorelines (Bilkovic & Mitchell, 2017; Mitchell & Bilkovic, 2019). The only way to ensure that proper design is used and that natural processes are occurring throughout changes in sea-level is to incorporate long-term monitoring into living shoreline project implementation. One way to motivate long-term funds for smaller-scale living shoreline projects is to research landscape-scale benefits that relate to these projects such as cumulative sediment accretion.

5.2 LANDSCAPE-SCALE ANALYSIS

Small-scale living shoreline projects have the ability to potentially slow or reverse erosion in low-energy coastal environments (McClenachan et al., 2020). These projects are often cheaper than shoreline armoring projects; however, due to their small size, there is often limited funding for long-term monitoring and an underestimation of their impact on altering local ecosystems (McClenachan et al., 2020). There are not many studies available that examine the large-scale impact small-scale living shoreline projects can have on the surrounding environment. To emphasize the importance of landscape-scale analysis, one extensive study will be reviewed. McClenachan et al. (2020) completed a study quantifying cumulative impact of small-scale living shoreline and oyster reef restoration projects on shoreline erosion. It is important to note that individual sites were being monitored, but there had not yet been a combined cumulative impact analysis for shoreline erosion (McClenachan et al., 2020). Differing techniques and goals of separate living shoreline projects make it difficult to compare project efficacy and quantify overall benefits that can be provided to the ecosystem through multiple sites (McClenachan et al., 2020).

The researchers used DSAS (Digital Shoreline Analysis System) to quantify cumulative shoreline change for multiple small-scale restoration projects in one ecosystem. The study site for this particular project was Mosquito Lagoon, FL where 89 oyster reef and 14 small-scale living shoreline restoration projects have occurred over the past 12 years (McClenachan et al., 2020). In Mosquito Lagoon, when the study was completed, a total of 11.3% of shorelines were hardened, and there was already extensive development along the northern shoreline (McClenachan et al., 2020). Many waterways and coastlines in Florida, including the study site, have high human use and increased wave energy from boat traffic and other human activities; this drives the need for shoreline stabilization and erosion control through shoreline restoration

(McClenachan et al., 2020). Oyster reefs were restored with the goal of recreating historical reefs that have either died or been destroyed due to the level of human activity for ecological benefits (McClenachan et al., 2020). Slowing or reversing shoreline erosion was seen as a potential secondary benefit (McClenachan et al., 2020). Additionally, shoreline restoration projects were implemented to help with coastal erosion in urban settings (McClenachan et al., 2020). Both oyster reef and shoreline restoration reversed erosion (McClenachan et al., 2020). Cumulatively, the oyster reef restoration added 290 m^2 of land per year, and cumulatively, the shoreline restoration added 348 m^2 of land per year (McClenachan et al., 2020).

By restoring parts of an area with high human activity, the cumulative effect was significant and not only stopped shorelines from eroding but also resulted in accretion. These oyster reefs and created shorelines will also have an extremely positive effect on the ecosystem and biodiversity within. The oyster reefs will provide more substrate for further oyster recruitment, improve the quality of the immediate and surrounding water, and provide protection to sub-tidal and inter-tidal vegetation. The vegetation installation also improves water quality and improves habitat for aquatic species. The restoration of nursery habitat will, in turn, improve the local fishing industry and help the coastal communities prosper. In contrast, if shoreline hardening had been the chosen method for stabilization, the shorelines would have continued to erode, adjacent shorelines would begin to erode (or exacerbate erosion on adjacent shorelines), habitats would suffer, species diversity and abundance on immediate and adjacent shorelines would decrease, and water quality would decrease. These are only some examples of how both living shorelines and shoreline armoring can either positively or negatively impact, respectively, adjacent and nearby shores.

5.3 SIGNIFICANCE

Individuals install shoreline armoring structures without knowing the long-term effects of these methods. The key to understanding the sustainability of living shorelines through sea-level rise is to implement long-term monitoring. Additionally, to ensure the highest level of success in the living shoreline approach, site-specific design is necessary. Eventually, the presence of hard shoreline stabilization structures will result in further eroding of shorelines, both immediate and adjacent. Additionally, shoreline armoring structures are not sustainable in the face of sea-level rise; therefore, additional funds will be needed to adjust the structures to remain in the correct tidal frame as sea-level continues to rise. Landscape-scale analysis of positive effects of small-scale living shoreline projects can serve as encouragement to install more of these projects. By only monitoring and analyzing specific projects, the underestimation of the scale of the benefits may lead to the perception that large-scale living shoreline projects or shoreline armoring structures will provide substantial protection to coastlines.

Region	LS Type	Fetch Criteria	Additional Comments
North Carolina[a]	Vegetation	<1 mile (1.6 km)	May be longer if sandbars/mudflat present
	Hybrid	1–3 miles (1.6–4.8 km)	
Virginia[b]	Vegetation	<1000 ft (<0.3 km)	Average and maximum fetch. Nearshore depth of <3 ft
	Hybrid	1000 ft to 5 miles (0.3–8.0 km)	
Gulf Coast[c]	Vegetation	<0.5 miles (<0.8 km)	Nearshore depth <1 ft
	Hybrid	1–2 miles (1.6–3.2 km)	Nearshore depth <2 ft
Delaware[d]	Vegetation	<0.5 miles (<0.8 km)	
	Hybrid	0.5–1.0 miles (0.8–1.6 km)	Vegetation with minimal structure like biologs
	Hybrid	>1 mile (<0.8 km)	Limited success without structural reinforcement
New Jersey[e]		None	Erosion history, tidal range, wave height, offshore depth, and other factors instead of fetch
Washington State[f]	Vegetation	1–5 miles (1.6–8.0 km)	With southerly fetch, multiply by 0.5 if north facing. May require log breakwater as well

Table 4. Few recommendation guidelines for living shoreline site suitability as compiled and tabled by Currin, Davis, & Malhotra (2017) (source: (a) North Carolina Division of Coastal Management, 2011; (b) Hardaway *et al.*, 2010; Gulf Alliance Training Program, 2010; Partnership for the Delaware Estuary, 2012; Johannessen *et al.*, 2014)

FUTURE OF LIVING SHORELINES AND SEA-LEVEL RISE

6.1 ADAPTATION

There have been many observations and recommendations made concerning the use of living shorelines to combat consequences of climate change and sea-level rise. Although there has been urging from the environmental community to transition away from traditional shoreline armoring to natural or nature-based shoreline protection, shoreline hardening continues to be used throughout the United States. A large part of the issue is individual homeowners and their desire to immediately stop the erosion and recession of their property. There are three main challenges to expanding the use of living shorelines as outlined by Bilkovic *et al.* (2016): (1) Coordination of regulatory agencies, (2) Enhanced public acceptance, and (3) Securing funds for long-term monitoring and research to support science-based policy.

A science-based panel, the Estuarine Biological and Physical Processes Work Group formed by The Division of Coastal Management in 2002, evaluated erosion control methods, such as plantings, vegetation control, beach fills, sill, breakwaters, revetments, and bulkheads, in order to determine which would be appropriate for various shorelines (North Carolina Division of Coastal Management, 2006a; Currin *et al*., 2010). Ecological functions and values of different shoreline types in North Carolina were considered (Currin *et al.*, 2010). Among the final recommendation made by the panel, the group determined that seawalls and/or bulkheads should be a last resort to stabilize shorelines where natural tidal wetland elements are already present (North Carolina Division of Coastal Management, 2006; Currin *et al.*, 2010). To build on that recommendation, researchers need to emphasize that when site suitability allows it, living shorelines should be the first method recommended for erosion control, shoreline stabilization, and protection. Additionally, sometimes necessary conditions can be created through grading, moving design elements channel-ward, or filling nearshore water (Bilkovic & Mitchell, 2016). This recommendation was made in North Carolina in 2002; however, in 2010, Currin et al. observed that shoreline armoring was still the preferred and most used practice in the state (2010). Developing policy that follows science- recommendations is crucial to the expansion of the living shoreline approach. While some states have policies in place, the time and length it takes to complete permits deter individual businesses and homeowners from installing living shorelines instead of shoreline armoring.

While policy and incentives are imperative to the continued and expanded use of living shorelines, the approach is not generally considered suitable in areas with medium- to high-energy. Additionally, urban areas present a challenge to the success of living shoreline methods as they do not provide the desired conditions to allow for shoreline persistence and migration through sea-level rise. If current "soft" stabilization living shoreline methods are inadequate in areas of high coastal and urban traffic, it would be beneficial to continue to adapt living shoreline designs. Although these populated and developed areas may prevent creation or restoration of the living shoreline practices described above, even with some structural components, the concept is constantly evolving. Researchers should continue to evaluate new ideas that may replace current and further hardening of shorelines as sea-level continues to rise and coastal populations continue to grow. The development of design standards in these higher-energy environments will increase the resiliency potential (Mitchell & Bilkovic, 2019). Toft *et al.* (2013) claimed that in highly urban areas, as seal-levels rise, modifications or additions of natural elements to hard structures may be the only approach to restore some level of ecosystem services (Bilkovic & Mitchell, 2016). The goal of this type of enhancement would be to restore habitats and improve nearshore conditions around previously installed armoring (Toft *et al.*, 2013; Bilkovic &

Mitchell, 2016). This has been an accepted conclusion for high-energy and highly urban environments as the current methods are not sustainable in these types of sites.

However, a study completed in 2017 near Staten Island shows how the living shorelines concept is capable of evolving to meet the needs of both humans and wildlife in "unsuitable" conditions. SCAPE landscape architects, in collaboration with marine ecologists and engineers, developed "The Living Breakwater" project for the U.S. Department of Housing and Urban Development's Rebuild by Design Initiative (Moosavi, 2017). The design created was recommended for Staten Island as it is vulnerable to increased wave action, storm surge, and erosion (Moosavi, 2017). The proposed layered design includes stepped shorelines and dunes, tidal flats, inter-tidal and sub-tidal breakwaters, and living shorelines as well as an increase of foundation heights of buildings located on the coast (Fig. 6.1; Moosavi, 2017). The combination of these elements is to create multiple levels of defense mechanisms that are less likely to fail singularly (Fig. 6.2; Moosavi, 2017). Including multiple design and habitat elements may maximize diversity and expand a living shoreline's functional value (Davis et al., 2006). The design also incorporated oyster restoration as one of the many critical habitats of the breakwaters (Moosavi, 2017). The Living Breakwaters project is also an excellent example of trying to tackle the key challenges of living shoreline implementation and expansion. The projects aims to support social agendas while also trying to achieve environmental outcomes and ensure safety (Moosavi, 2017). The goal is to regenerate social resiliency by creating a network of recreational and educational indoor and outdoor spaces along the shoreline (Moosavi, 2017). While this project is fairly new and will require long-term monitoring to ensure the success of the design, it provides a great example for what innovation can provide for the living shorelines approach.

6.2 FUTURE AVENUES FOR RESEARCH

Significant evidence suggests the effectiveness of nature-based solutions for shoreline stabilization, as detailed in this paper, but uncertainties create potential challenges (Schoonees *et al.*, 2019; Narayan *et al.*, 2016; Hall *et al.*, 2018; Strain *et al.*, 2018). While nature-based shoreline stabilization methods have the ability to retreat as sea-levels rise, there is a limit to what they can endure. If sea-levels rise at a more rapid pace than natural and nature-based shorelines can recede, then they will eventually drown, leaving the coastlines vulnerable. Many individuals believe that the ongoing battle with sea-level rise is already a lost cause. In areas experiencing increasingly rapid rates of sea-level rise, the living shorelines approach may not be the best option. Innovation and implementation adaptation for living shorelines is one avenue for future research; however, it may not be one that should be relied on due to future uncertainties concerning sea-level rise. One drawback of the living shoreline approach is that the vitality of nature-based approaches throughout sea-level rise is currently unknown, and more research needs to be conducted to determine the effectiveness and longevity of nature-based shorelines under different sea-level rise scenarios. Other future avenues for research could focus on methods other than the living shoreline approach in high-energy environments or areas experiencing rapid increases in sea-level rise. Two of these methods include managed retreat and environment-friendly grey infrastructure. While there is not currently a high motivation to retreat from the shorelines, retreat would allow for the preservation of natural and nature-based shorelines. Where there is not a willingness to retreat, environment-friendly grey infrastructure is a better solution to coastal erosion and protection than traditional shoreline armoring (Schoonees *et al.*, 2019). The current desired outcomes of shoreline protection methods throughout the world are "the use of natural processes and resources to achieve solutions that are socially, economically, and environmentally beneficial," (Schoonees *et al.*, 2019, pg. 1712). The best ways to achieve this in different environments needs further research.

6.3 SIGNIFICANCE

As sea-level rise becomes increasingly severe, what is important to those coastal communities will be lost as a cumulative result of the consequences brought about by anthropogenic action. Not only will the local economy be damaged, but the coastal way of life as we know it will be significantly altered. Adapting and creating new approaches is essential to expanding living shorelines. The protection of the ecosystem and the safety of coastal communities will grow more imperative as sea-level rises. The importance does not only lay in economic impact but also in the priceless and unquantifiable value of peace and joy that coastlines are able to conjure. While this paper focuses on the economic and ecological benefits living shorelines provide, the preservation of natural ecosystems may have much more value than what meets the eye. A poem written by Wendell Berry beautifully encapsulates the unseen value of coastal environments. Titled "*The Peace of Wild Things*", it reads:

When despair for the world grows in me
and I wake in the night at the least sound
in fear of what my life and my children's lives
may be,
I go and lie down where the wood drake
rests in his beauty on the water, and the great
heron feeds.
I come into the peace of wild things
who do not tax their lives with forethought

of grief. I come into the presence of still water.
And I feel above me the day-blind stars
waiting with their light. For a time
I rest in the grace of the world, and am free (Berry, 1968).

Living shorelines are as essential to maintaining this peace as they are to protecting coastal communities and their way of life despite continuing consequences of anthropogenic climate change and sea-level rise. The well-being of coastal communities depends on the success of the preservation and maintenance of natural and nature-based shorelines. It is only when the living shoreline approach is not an option that other methods should be explored. The living shoreline can not only provide protection and stabilization during sea-level rise but can also help the ecosystem and coastal communities prosper in its wake.

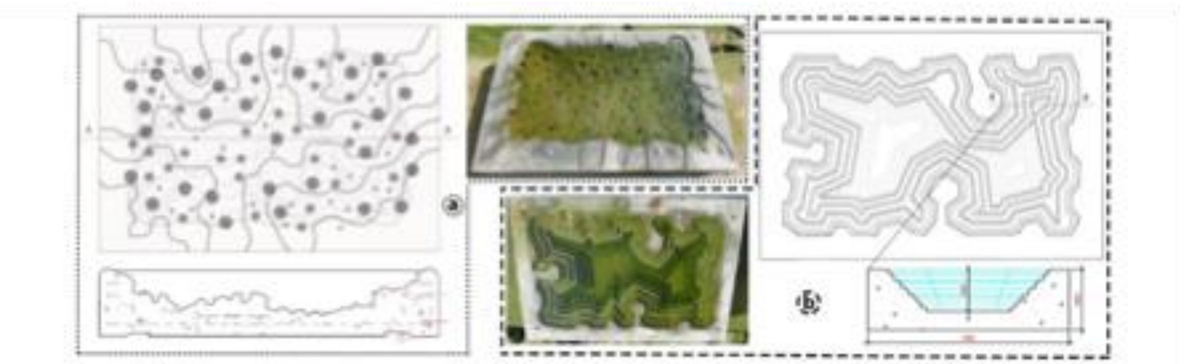

Fig. 6.1. (a) Design 1 picturing pools with pits and grooves, (b) Design 2 picturing a unit with randomized steps. (source: Nguyen *et al.*, 2016; Moosavi, 2017).

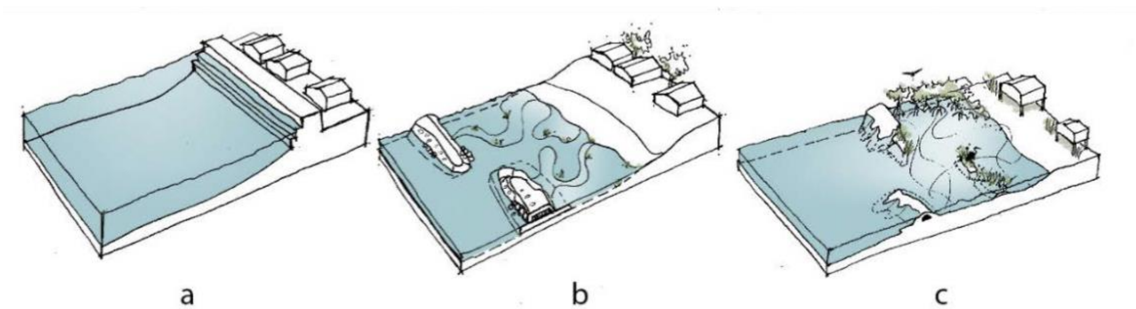

Fig. 6.2. A spectrum of different approaches, multiple defense mechanisms: (a) modified seawall, (b) breakwaters with tidal pools, (c) Hybrid features combining structural, nature-based, and natural features with elevated buildings (source: Moosavi, 2017).

CONCLUSION

The goal of the living shoreline approach is to restore and preserve coastal ecosystems while protecting coastal communities from negative consequences of exacerbated shoreline erosion and sea-level rise. Often, the desire to halt immediate shoreline erosion leads to shoreline armoring, and over time, the subsequent negative consequences from armoring have threatened the prosperity and viability of coastlines. Living shorelines are a nature-based approach to contribute to shoreline stabilization while restoring ecosystem services that have been lost or destroyed. Ecosystem services include, but are not limited to, carbon sequestration, wave attenuation, water quality improvement, habitat creation or enhancement, and shoreline stabilization. Key issues in the expanded use of the nature-based approaches is developing effective and appropriate public policy and motivating property owners to implement living shorelines instead of stabilization structures. Site-specific design, long-term monitoring, and landscape-scale analysis are essential in supporting and encouraging science-based policies. As sea-levels rise, the response and effectiveness of living shoreline projects will be an important consideration for future implementation and adaptation of the living shoreline approach. Continued research in highly urban areas or high-energy environments can contribute to the expansion of the living shorelines approach, making it applicable in a variety of conditions.

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