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Living Shorelines: A Review of Literature Relevant to New England Coasts

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ABSTRACT

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Over the last few decades, increasing awareness of the potential adverse impacts of traditional hardened coastal protection structures on coastal processes and nearshore habitats has prompted interest in the development of shoreline stabilization approaches that preserve intertidal habitats or at least minimize the destructive effects of traditional shoreline protection approaches. Although many terms are used to describe shoreline stabilization approaches that protect or enhance the natural shoreline habitat, these approaches are frequently referred to as living shorelines. A review of the literature on living shorelines is provided to determine which insights from locations where living shorelines have proved successful are applicable to the New England shorelines for mitigating shoreline erosion while maintaining coastal ecosystem services. The benefits of living shorelines in comparison with traditional hardened shoreline protection structures are discussed. Nonstructural and hybrid approaches (that is, approaches that include natural or manmade hard structures) to coastal protection are described, and the effectiveness of these approaches in response to waves, storms, and sea-level rise is evaluated.

ADDITIONAL INDEX WORDS: *Coastal protection, soft stabilization, natural and nature-based features.*

INTRODUCTION

Coastal erosion is a natural process, yet for centuries shoreline erosion-control structures such as seawalls, bulkheads, groins, and revetments have been constructed to protect coastal property from waves and storm surges. There are many advantages to these traditional types of shoreline protection; however, their effectiveness diminishes with time, and they are not adaptable to changing coastal conditions (Sutton-Grier, Wowk, and Bamford, 2015). While these structures provide varying degrees of protection to upland property, they have been shown to cause unintended consequences such as increased erosion, flanking of the structure, and loss of available sediment for longshore transport (Campbell, Benedet, and Thomson, 2005; Douglass and Pickel, 1999; Galveston Bay Foundation Staff, 2014; National Research Council, 2007; Swann, 2008; Yozzo, Davis, and Cagney, 2003). In addition to engineering impacts, coastal armoring can cause significant ecological effects. These effects include reduced diversity of aquatic organisms and shore birds, which use the sandy beach for foraging, nesting, and nursery areas (Dugan and Hubbard, 2006; Dugan *et al*., 2008; Ray-Culp, 2007), and loss of the intertidal zone, which is critical to submerged aquatic vegetation (SAV) and shallow water habitats that are vital for specific developmental stages or the entire life cycle of an extensive and diverse range of species, including essential commercial and recreational fish species (Atlantic States Marine Fisheries Commission Staff, 2010; Duhring, 2008a; National Research Council, 2006, 2007; North Carolina Division of Coastal Management, 2006).

As communities begin to adapt to climate change, the initial response is to construct more hardened coastal protection structures (Shepard, Crain, and Beck, 2011). Hardened coastal protection may lead property owners or even entire communities into a false sense of protection from storm surge and wave action. Basing development decisions on the assumption of protection from all disasters can result in devastating consequences in the event of structure failure (Sutton-Grier, Wowk, and Bamford, 2015). A few, spatially separated coastal protection structures should have little effect on coastal habitats; however, shorelines are becoming increasingly hardened, resulting in significant habitat degradation (Currin, Chappell, and Deaton, 2010; National Research Council, 2007). In some areas, over 50% of the shoreline is already protected with manmade structures. In many states, under the common law public trust doctrine, the land between mean high water (MHW) and mean low water (MLW) is held in trust for the public. As such, the public may freely use the intertidal land and water, but vertical structures can cause loss of the intertidal zone, thus restricting or eliminating public access

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to the water (Roberts, 2008; Scyphers *et al*., 2011). Over the last few decades, the increasing awareness of the potential adverse impacts of vertical structures on the coastal environmental has prompted interest in the development of shoreline stabilization approaches that preserve intertidal habitats or at least minimize the destructive effects of traditional shoreline protection approaches (*e.g*., Arkema *et al*., 2013; Augustin, Irish, and Lynett, 2009; Bridges *et al*., 2015; Duarte *et al*., 2013; Feagin *et al*., 2009; Gedan *et al*., 2011; Guannel *et al*., 2015; Pinsky, Guannel, and Arkema, 2013; Scyphers *et al*., 2011; Shepard, Crain, and Beck, 2011; Subramanian *et al*., 2008b). Many states have developed guidelines, incentives, and regulations to encourage or even require property owners to adopt more natural or nature-based methods of shoreline erosion control (Atlantic States Marine Fisheries Commission Staff, 2010; Currin, Chappell, and Deaton, 2010). Nonstructural approaches (such as beach nourishment, restored or enhanced seagrass, vegetated and graded bluffs, and creation or restoration of fringing salt marshes) are frequently referred to as living shorelines. Definitions for living shorelines vary from state to state. The U.S. Army Corps of Engineers (USACE) has adopted the term "natural or nature-based features (NNBF)" (USACE, 2015). The National Oceanic and Atmospheric Administration (NOAA) defines a living shoreline as

> 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*., biologs, oyster reefs, *etc*.) (NOAA Shoreline Website, 2015).

The Maryland Department of Natural Resources (MD DNR) uses the following definition for a living shoreline:

> 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 process. 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 (MD DNR, 2015).

The Virginia legislative definition of a living shoreline is similar to NOAA's but includes water-quality benefits:

> '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 materials (VIMS-CCRM, 2015a).

While recognizing there are many ways to define living shorelines, Restore America's Estuaries (Restore America's Estuaries Staff, 2015, p. 5) uses the following definition in their report:

> Any shoreline management system that is designed to protect or restore natural shoreline ecosystems through the use of natural elements and, if appropriate, manmade elements. Any elements used must not interrupt the natural water/land continuum to the detriment of natural shoreline ecosystems.

In 2012, Connecticut passed legislation to encourage the consideration of "feasible, less environmentally damaging alternatives" of shoreline erosion control. Although Connecticut has not formally adopted a definition for living shorelines, the state is using the following 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 (Barret, 2015).

It is noteworthy that the provided definitions include a structural component. While this can complicate the permitting of these projects, with the exception of the most sheltered sites, living shorelines in New England will need a structural component to provide erosion control.

The lack of a universally accepted definition has led to concern (Pilkey *et al*., 2012; Rella and Miller, 2012; among others) over the potential misuse of the term to include projects with a large hardened component and little emphasis on natural stabilization or habitat restoration. In addition to USACE's "natural or nature-based features," alternatives to the term living shoreline have been suggested, including the terms soft structure, green infrastructure, and ecologically enhanced shore protection alternatives (Rella and Miller, 2012).

Although numerous living shoreline projects have been completed in the Gulf of Mexico and the Chesapeake Bay and its tributaries (Burke, Koch, and Stevenson, 2005; La Peyre, Schwarting, and Miller, 2013; National Wildlife Federation Staff, 2011; Subramanian, 2011; Subramanian *et al*., 2008b), they are uncommon in New England; however, there are several projects in Massachusetts (Massachusetts Executive Office of Energy and Environmental Affairs, 2015a,b). In 2014, the first living shoreline along the Connecticut coast designed to provide coastal protection was constructed. Reef balls were placed offshore in Stratford, Connecticut, to provide protection for the development of a fringe marsh (Sacred Heart University, 2014). On Earth Day, 22 April 2015, Rhode Island installed its first living shoreline (The Nature Conservancy, 2015). While there is much to learn from other areas, the New England shoreline presents unique challenges to the design and construction of living shorelines: larger fetch and consequently larger coastal wave amplitude and period, winter ice, larger tidal range, effects of storm surge, and the highly variable coastal geomorphology necessitate more analysis prior to the design of shoreline stabilization strategies. Even qualitative information is limited on the effectiveness of living shorelines in a variety of environmental conditions, resulting in an inability to predict their coastal protection services in new locations (Pinsky, Guannel, and Arkema, 2013; Shepard, Crain, and Beck, 2011). This review was created to determine which insights from other locations are applicable to the New

England shorelines to encourage successful implementation of living shoreline approaches in the NE.

The following sections discuss the benefits of living shorelines in comparison with traditional hardened shoreline protection structures. Nonstructural and hybrid approaches to coastal protection are described, and the effectiveness of these approaches in response to waves, storms, and sea-level rise (SLR) is evaluated.

Benefits of Living Shorelines

Unlike traditional shore protection approaches, living shorelines provide numerous benefits to the coastal environment. Properly designed living shorelines attenuate wave energy, provide buffers to uplands from storm surge and wave action, reduce the volume and velocity of surface water runoff, and maintain natural coastal processes (Ray-Culp, 2007) thus providing the same protection benefits as traditional coastal protection but with lower initial and maintenance costs (Gittman *et al.*, 2014; Sutton-Grier, Wowk, and Bamford, 2015). In addition to mitigating shoreline erosion, a central goal of living shorelines is to maintain ecosystem services such as critical habitat for economically and ecologically essential fish, shellfish, and marine plants; improving water quality through groundwater filtration; reducing surface water runoff; and decreasing sediment transport (Atlantic States Marine Fisheries Commission Staff, 2010; Augustin, Irish, and Lynett., 2009; Duhring, 2008b; Hardaway, Milligan, and Duhring, 2010; Ray-Culp, 2007). Other benefits are site specific, such as providing shoreline access and nesting and foraging areas to animals such as turtles and horseshoe crabs and resident and migratory shorebirds (Chesapeake Bay Foundation, 2007; Galveston Bay Foundation Staff, 2014). Living shorelines can also provide aesthetic value. By creating a more natural transition from the uplands to the shoreline, recreational opportunities are increased, the appearance of the shoreline is enhanced, and the prospect of viewing wildlife is improved for coastal property owners and the public (Atlantic States Marine Fisheries Commission Staff, 2010; Hardaway, Milligan, and Duhring, 2010; Ray-Culp, 2007).

Types of Living Shorelines

Although many different types of living shorelines exist, they can be categorized into two basic approaches. The first approach is constructed entirely of soft materials with no hard structure. Examples include vegetation (marsh grasses, SAV, beach grass, and upland trees and shrubs) and sand fill for beach nourishment and dune restoration. The second approach uses biodegradable material to provide protection while the vegetation becomes established (coir fiber logs and matting) or hard structures to provide additional protection to the vegetation. Examples include marsh toe revetments, rock sills, breakwaters, and oyster reefs to attenuate the waves before they reach the vegetation. These types are frequently referred to as hybrid living shorelines (Duhring 2008b; Ray-Culp, 2007; Smith, 2008).

Nonstructural Approaches

Shoreline stabilization approaches using only vegetation or fill material are most effective at sheltered sites without critical infrastructure. Fringe marshes with low erosion rates may be enhanced by removal of overhanging trees that provide too much shade for marsh vegetation to flourish. Other sites may require additional effort to restore and maintain natural erosion mitigation.

Marsh Restoration or Creation. The most minimally disruptive approach to living shoreline protection is vegetation management. Removal of overhanging tree branches reduces shade and thereby increases marsh grass growth (VIMS-CCRM, 2006). For narrow or eroding marshes, tidal marsh maintenance and enhancement is appropriate. Plugs of marsh grass can be planted to augment bare or sparse areas of the marsh (Broome, Rogers, and Seneca, 1992). If necessary, fill material is deposited to provide a suitably gradual slope for marsh creation or to enable a marsh to maintain its elevation with respect to the water level (VIMS-CCRM, 2006). The creation or restoration of fringing marshes is the most widely used nonstructural approach to erosion control. Although it is possible to create a marsh on most shorelines, marsh creation is not recommended for sites where they are not a natural feature along comparable natural shorelines (Maryland Department of Environment, 2008). The success of the restored fringe marsh depends on the width of the existing shoreline, the depth and composition of the existing soil, the slope of the shoreline, the shoreline configuration, exposure and orientation, and sun/shade conditions (Maryland Department of Environment, 2008).

Slope or Bank Grading. Another approach to nonstructural living shorelines is to regrade eroding banks to a more stable slope. Figure 1 shows an eroding bluff that has been regraded and planted with stabilizing vegetation. Soft banks and bluffs are susceptible to coastal erosion, particularly if the bank is very steep with little vegetation. Wave action can erode the toe of the bank, causing slumping of the bank material. Soft banks that are mostly covered with vegetation are less susceptible to erosion, while a stable bank will be well-covered with grass, shrubs, or mature trees with a wide base above MHW (Slovinsky, 2011). There are numerous, interconnected factors that influence the stability of a bluff, which include height, sediment type, slope, bluff orientation, topography, vegetation, waves, tides, SLR, ground- and surface water runoff, and upland usage.

Grading of steep, eroding banks can produce a more stable slope; however, if the bank or bluff is currently vegetated, slope planting is a more appropriate response (Maryland Department of Environment, 2008). Regraded banks are frequently stabilized by salt-tolerant plantings. Upland plantings stabilize bluffs and reduce rainwater runoff. Eroding banks can also be protected from erosion by the creation of a salt marsh. Through bank regrading or application of fill material, the intertidal zone can be planted with appropriate, salt-tolerant vegetation, thus creating a fringe tidal marsh (Chesapeake Bay Foundation, 2007; Hardaway *et al.*, 2009; VIMS-CCRM, 2006). Although toe protection can be combined with slope grading, terracing and slope grading are generally not effective shoreline protection for sites exposed to significant wave-induced erosion.

Beach Nourishment. At sites with larger fetches (greater than 0.8 km), creation of a marsh fringe may require sand fill to provide better planting substrate or a sufficiently wide marsh

Figure 1. Erosion of a soft bluff can be mitigated by regrading the bank to a stable slope and then planting it with appropriate vegetation to provide a stabilizing root system. This project used a baffled cell technique and biodegradable matting to provide protection while the native plants became established. Temporary scaffolding was erected to reduce soil compaction and erosion during the construction phase. The mature native plants withstood Hurricanes Irene and Sandy with no major erosion, bank sloughing, or plant loss (New England Environmental, Inc., 2015; photo credit: New England Environmental, Inc.).

fringe (National Research Council, 2007); however, beach and dune restoration without a marsh component may be a more successful solution for some sites (Hardaway, 2013). Natural beaches are in a constant state of flux, responding to changes in wave energy and sea level (Lithgow *et al.*, 2013). Poststorm beaches may have become too narrow and steep for recreational opportunities. Dunes damaged during storms may have steep scarps that could be dangerous for beach goers. With sufficient time and appropriate wave climate, beaches may restore themselves, but few coastal communities can risk the loss of recreational services or erosion control while waiting for natural restoration to occur. Beach nourishment (also referred to as fill or replenishment) "restores" the beach as quickly as possible by importing sand from a land or offshore site. While nourishment may recover some of the ecoystem services that are typically lost on a developed and armored beach, nourishment does not restore a beach. To increase erosion and flooding protection, nourished beaches are frequently built higher and wider than would occur naturally, so waves are unable to form the backshore. Beaches nourished for optimum recreation or scenic views are graded too flat and low to provide storm protection. Nourishment can also bury native vegetation, which can provide an opportunity for invasive species to colonize. Nourished sediment may also adversely affect nesting and foraging of shorebirds and other coastal animals (Nordstrom, Lampe, and Vandemark, 2000).

When evaluating beach nourishment for coastal protection, it is necessary to consider the following details:

(1) added sediment may be transported away from the property owners who are funding the nourishment;
(2) a nourished beach will require maintenance, *i.e.* sediment will need to be added to replace the materials transported away from the beach because of normal wave action and storm damage; and
(3) a high berm will add more protection to the uplands from high waves and surge, but, if it is unnaturally high, a scarp may form that could be dangerous to beach visitors. A lower berm, for example, 0.5 m below the natural level, may be a better option, allowing natural processes to build the final berm (Dean, 2003).

It is not unusual for large volumes of fill material to be transported away from the nourished site within the first winter or after the first storm (Dias *et al.*, 2003). Although frequently identified as a failure by property owners, this is typically the result of the beach transforming into a more natural profile and had been accounted for during the design process (National Research Council, 1995). Therefore, monitoring of nourished beaches is vital to determine whether the fill is performing as expected. Periodic maintenance of nourished beaches should be expected and included in the life-cycle costs of the project.

Dune Creation and Restoration. Dune creation or restoration may be a component of a beach nourishment effort or a standalone project. Although it is more effective to maintain existing dunes, coastal development and storm damage can render intervention necessary. The same process that is found in nature is used to create a dune, but at a faster pace. Dune restoration will be most successful if (1) it is located where the natural dune line should be and, if possible, tied into existing dunes; (2) there is sufficient space for the dune to form and move naturally; (3) manmade damage is mitigated or prevented; and (4) nature is assisted not destroyed (Salmon, Henningsen, and McAlpin, 1982). Figure 2 shows a dune restored after being overwashed during Hurricane Sandy. Planted beach grass and sand fencing help trap windblown sand.

Even in less than ideal conditions, however, beach grass can trap windblown sediment. Figure 3 shows sand trapped that occurred by planting beach grass behind a seawall topped by an asphalt walkway. Although not technically a dune, the trapped

Figure 2. A sand dune is recreated where the nature dune existed before being destroyed during Hurricane Sandy. The dune has been planted with native vegetation. Sand fencing aids natural dune formation while protecting it from damage by foot traffic.

Figure 3. Even on very small sites with less than ideal conditions, beach grass can trap windblown sand, creating a protective barrier to the structure landward. Beach grass was planted on a 6-m-wide property located above a 1-m-high seawall, topped by a paved sidewalk. The trapped sediment is now over 1 m high, and the beach grass is colonizing neighboring properties.

sand has created a protective sand barrier for the resdience located landward.

Although the specifics of dune restoration are complex, three basic approaches are used to create or restore dunes: vegetate, provide additional sediment, or remove manmade structures that hinder dune development (Lithgow *et al*., 2013; Martinez, Hesp, and Gallego-Fernandez, 2013). Sand fences, planted vegetation, fertilization, and water are all used to increase natural dune processes (Salmon, Henningsen, and McAlpin, 1982). Salmon, Henningsen, and McAlpin (1982) created a decision tool for determining the feasibility of dune creation in the Gulf of Mexico and SE Atlantic states. Although dune size and formation vary significantly with location, the recommendations are relevant: If dunes cannot form naturally, manmade dunes will not be successful. Dunes that can not be maintained after wave or storm damage will not be successful, either. Even in locations where dunes can form, dune creation and restoration should be similar to local naturally formed dunes. For instance, in low wave-energy conditions dunes will have lower elevations than dunes in high wave-energy conditions. This is further exacerbated by a lack of naturally available sediment available for transport and dune growth, for example, along the Connecticut Long Island Sound coast.

There must be sufficient quantities of windblown sand for dunes to build naturally. Otherwise, clean sediment of similar composition to that which would occur naturally must be brought to the site to create the dunes. After the dune is formed, fencing and vegetation can be used as barriers to the wind, causing windborne sediment to accumulate around the fence or plantings (O'Connell, 2008). On Cape Cod, Knutson (1980) observed that sand fencing initially traps more sediment than beach grass alone. Once the vegetation is established, Cape American beach grass trapped sand at a rate comparable to multiple rows of sand fencing; however, the planted dunes were lower and wider than the dunes built with fencing. Almost any type of fencing, snow fencing, plastic or fabric fencing, or coniferous (*e.g*., Christmas trees) or other brush can be used to create dunes provided that it does not completely block the wind. Approximately 50% solid material has been shown to work well (Salmon, Henningsen, and McAlpin, 1982; USACE, 1984). The configuration of sand fencing remains a topic of debate. Some researchers found that configuration made little difference to dune formation (Knutson, 1980; Miller, Thetford, and Yager, 2001; O'Connell, 2008). Salmon, Henningsen, and McAlpin (1982) suggest it is a matter of preference rather than scientific confirmation. Others found that the rate of sediment accumulation and the formation of the dune depended on the fencing properties such as porosity, height, size, and shape of the openings as well as the placement of the fencing (for instance, number and spacing of rows as well as location relative to the landward extent of seasonal storm waves) and that fencing of different compositions and in different configurations increases the diversity in the formation and vegetation of the dunes (Nordstrom and Jackson, 2013).

Hybrid Approaches

Not all eroding shorelines are suitable for nonstructural approaches. While shoreline stabilization using only plants may be a viable solution on protected sites, along more exposed shorelines, site conditions, such as wave climate, coastal geomorphology, nearshore bathymetry and land use, will likely require temporary or permanent supplemental structures to ensure planting establishment. In these environments, manmade toe protection, sills, or breakwaters constructed of natural materials such as rock, coir logs and matting, oyster reefs, or other materials are more effective at attenuating wave energy to allow the establishment and maintenance of marshes and beaches. Alternatively, manmade components such as synthetic matting, geotubes, and concrete wave attenuators can be combined with marsh plantings to reduce shoreline erosion while maintaining ecosystem services (Swann, 2008). This combination of vegetation and/or sediment with hard material is referred to as a hybrid living shoreline (Chesapeake Bay Foundation, 2007; VIMS-CCRM, 2015b). Hybrid approaches were found to be more effective than vegetation-only approaches even in locations where marsh plantings mitigated

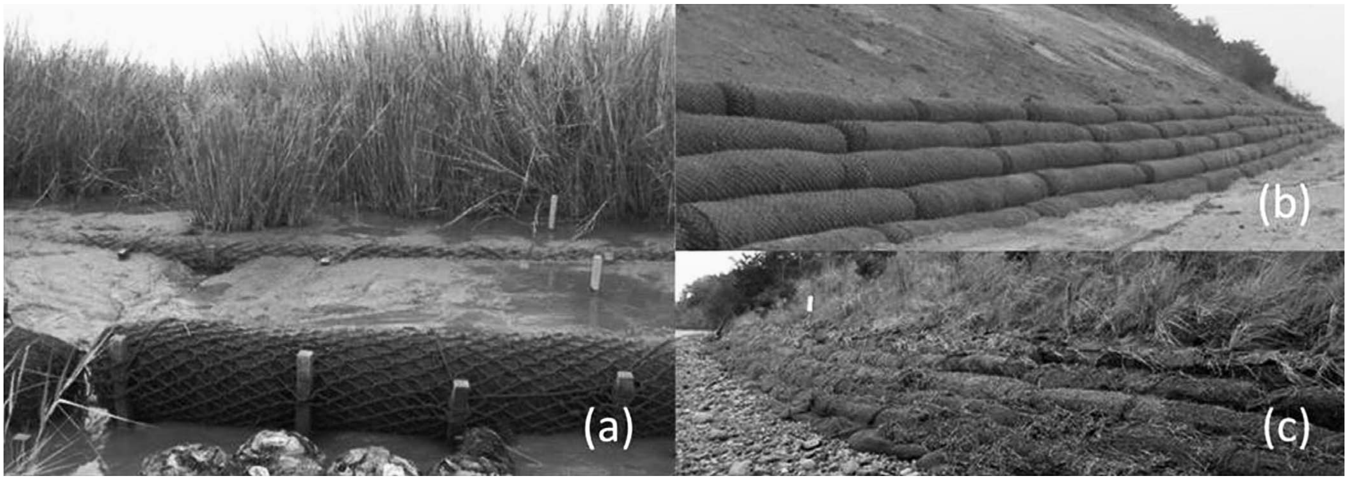

Figure 4. Coir fiber logs are a versatile component of living shorelines. They can provide protection to planted fringe marshes, marsh toe protection, or the foundation for a created dune system. Stacked coir logs provide toe protection to eroding bluffs. (b) and (c) show stacked coir logs during construction and after Hurricane Sandy (photo credit: (a) Delaware Estuary Living Shoreline Initiative, Rutgers University and Partnership for the Delaware Estuary; (b) and (c) Wilkinson Ecological Design).

shoreline erosion and provided habitat protection (Duhring, 2008a). Unlike traditional coastal structures, hybrid living shorelines are designed to perform similarly to the natural ecosystem rather than protect against it (Smith, 2008).

Intensely developed areas may lack the space to create nature-based protection; however, even traditional coastal protection structures such as seawalls, revetments, bulkheads, and breakwaters can be designed by using nature-based components such as tide pools, roughened surfaces for marine flora and fauna, and eco-friendly materials (National Research Council, 2014).

Fiber Logs. Coir logs are used to temporarily protect banks and marsh toe from erosion, while planted vegetation develops strong root systems. Coir fiber logs can also be used as the foundation of a dune system. Coir logs come in a range of sizes and grades and may be placed in single or multiple rows. As shown in Figure 4, coir logs must be securely anchored to prevent wave and tidal current-induced movement. Coir fiber is biodegradable and typically deteriorates in three to five years in low-energy environments, sufficient time for the vegetation to become established (Chesapeake Bay Foundation, 2007; Hardaway *et al*., 2009; Hardaway, Milligan, and Duhring, 2010; VIMS-CCRM, 2006); they are not recommended for high-energy saltwater conditions (Duhring, 2008b; Skrabel, 2013).

Marsh Toe Revetment. Marsh toe revetment is a specialized riprap revetment designed to protect eroding marsh edges or banks from wave-induced erosion. Unlike traditional revetment protection, marsh toe revetment is low profile, only slightly higher than the existing marsh surface, which is usually at or approximately 0.3 m (1 ft) above MHW. The low profile protects the marsh edge from wave action but allows tidal inundation over and through the structure, thus maintaining the marsh ecosystem. Tidal gaps in long revetments provide the same function by allowing tidal exchange (Barnard, 1999; Duhring, 2008a; Hardaway, Milligan, and Duhring, 2010).

Marsh Sills. Marsh sills are very small, low profile stone breakwaters that are used to protect the seaward edge of a planted marsh (Broome, Rogers, and Seneca,1992). Constructed near MLW, they are backfilled with sand to elevate and regrade the slope and then planted with marsh vegetation to create a protective marsh fringe (Duhring, 2008b; Hardaway, Milligan, and Duhring, 2010). Marsh sills are appropriate for eroding shorelines where site conditions are suitable for marshes, although no marsh currently is present (Duhring, 2008b).

Low marsh sills have been used extensively in the Chesapeake Bay and its tributaries; the design has remained fairly consistent (Hardaway, Milligan, and Duhring, 2010). A wider and higher sill would provide more protection from coastal erosion; a too high sill will reduce or eliminate tidal exchange, and the marsh behind it will become stagnant and die. Thus, poorly designed sills can do more harm than good to marine animals (Subramanian *et al*., 2008a). Slopes of 10 horizontal:1 vertical and sill elevations near MHW have been recommended for the Chesapeake Bay (Duhring, 2008b; Hardaway, Milligan, and Duhring, 2010). Hardaway and Byrne (1999) provide recommendations for marsh widths and sill construction; however, Chesapeake Bay has a relatively small mean tidal range of 0.5–1 m (Xiong and Berger, 2010). Therefore, these design parameters may need to be modified for locations with greater tidal ranges.

Figure 5 shows openings or gaps in marsh sills that are recommended to allow tidal exchange and to provide marsh access for marine animals. However, the openings will expose the marsh to waves, which could result in increased erosion. Deposition of sediment in the gaps can also occur, which could reduce or eliminate tidal exchange (Hardaway *et al*., 2007; Smith, 2008). Recommendations for mitigating these concerns

Figure 5. Marsh sills function as low profile stone breakwaters that are used to protect the created or enhanced fringe marshes from wave energy. Some designs have openings or gaps in the sill to allow for the exchange of tidal flow and to provide marsh access for marine animals. Marsh sills are typically constructed at MLW and then backfilled to create a suitable grade for marsh vegetation. The top of the sill is usually near MHW to provide the maximum protection while still enabling exchange of tidal water (Duhring, 2008b).

include creating dogleg or offset openings and varying the opening size and orientation of the sills to allow tidal flow exchange and access to the marsh habitat (Bosch *et al*.; 2006; Hardaway *et al*., 2007). In addition to sill gaps, access to the marsh takes place through interstitial spaces in the sill and by overtopping. The porosity of the sill may be as important if not more important to tidal exchange and species access than the size or number of gaps in the sill length (Hardaway *et al*., 2007). Although no scientific study of the effectiveness or design of sill gaps has been performed to date, empirical evidence suggests gaps approximately every 30 m; however, the final design will depend on local marine species and wave and tidal conditions (Hardaway, Milligan, and Duhring, 2010; Smith, 2008).

Oyster Reefs. Marsh sills are also formed with oyster reefs constructed of bagged or loose oyster shell to provide the same erosion control as rock sills but with additional ecosystem benefits (Atlantic States Marine Fisheries Commission Staff, 2010; Duhring, 2008b; Scyphers *et al*., 2011; Skrabel, 2013; Swann, 2008). Oyster reefs provide a substrate for oyster recruitment and thus are self-maintaining, building the reef dimensions and, therefore, protection and restoration benefits with time (Atlantic States Marine Fisheries Commission Staff, 2010; Gedan *et al*., 2011; Scyphers *et al*., 2011), so oyster reefs are sometimes referred to as living breakwaters (NOAA National Marine Fisheries Service, 2015). Like rock sills, oyster reefs provide habitat and foraging areas for aquatic species; however, as oysters are filter feeders, they also improve water quality and clarity by removing sediment and algae, which improves light transmission and enhances the environment for SAV (Atlantic States Marine Fisheries Commission Staff, 2010).

At present, the literature is limited in describing and evaluating the use of oyster reefs for planted marshes (Atlantic States Marine Fisheries Commission Staff, 2010; National Research Council, 2014), and it is not clear whether uncontained oyster shell is sufficiently resistant to wave action and tidal currents to provide adequate protection; however, even with limited shoreline protection benefits, creation and evaluation of oyster reefs to enhance restoration of oyster beds is warranted at some sites (Duhring, 2008b). Figure 6 shows an oyster reef being evaluated in the Bronx in New York City. Scyphers *et al*. (2011) observed reduced rates of erosion in salt marshes behind restored oyster reefs in Mobile Bay when compared to marshes unprotected by sills or breakwaters, but the rates were still high compared with traditional coastal protection. They suggest that their “ecology-first” breakwaters may be provide sufficient protection during normal wave conditions but are not effective when overtopped by waves and storm surge.

The effectiveness for shore protection of low-profile marsh sills commonly found in the Chesapeake Bay and Gulf of Mexico would be limited by the larger tidal ranges experienced

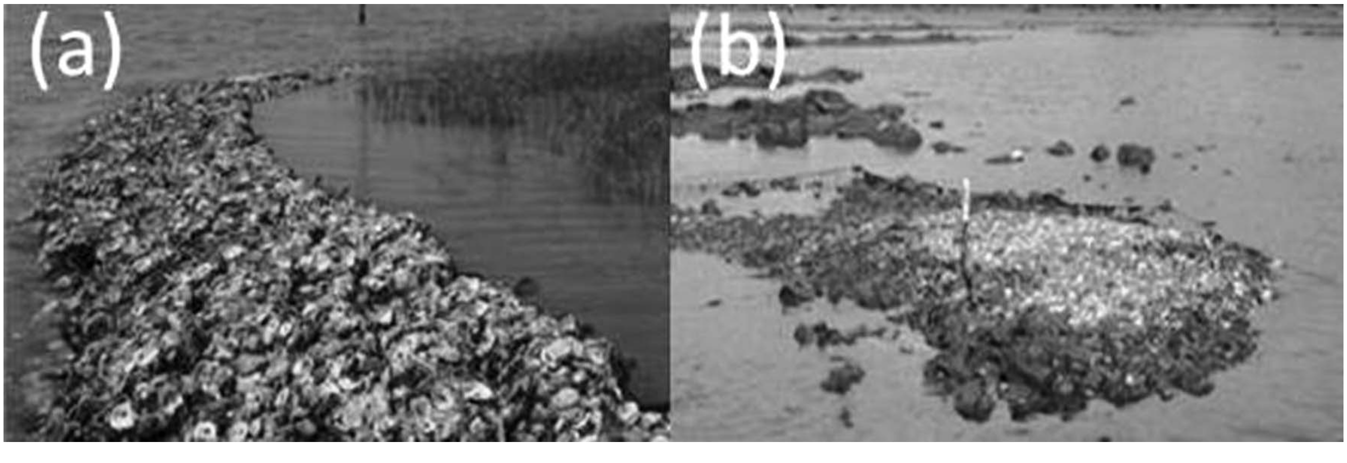

Figure 6. Manmade oyster reefs, constructed of loose or bagged oyster shells, are designed to provide protection to fringe marshes from wave energy as well as providing habitat and forging areas for aquatic species. In addition, oysters are filter feeders, so they improve water quality, enhancing the conditions for submerged aquatic vegetation. As oysters continue to colonize the reef, the protective and restoration benefits provided will increase. (a) A typical oyster reef design (photo credit: North Carolina Coastal Federation Staff, 2008). It is uncertain whether oysters will recolonize created oyster shell reefs in New England. (b) A demonstration site created to evaluate the potential of oyster reefs for habitat restoration and shoreline protection in New York. This site was successful at self-sustainment, so the reef will be increased in size (photo credit: B. Branco, Brooklyn College, *personal communication*).

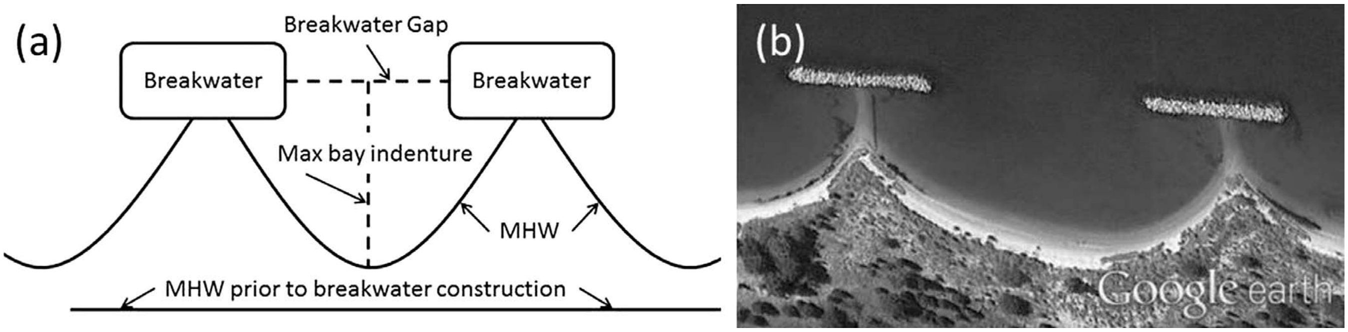

Figure 7. Offshore-gapped-headland breakwaters are becoming an increasingly popular option for shoreline protection in the Chesapeake Bay and its tributaries. The MD DNR uses a ratio of 1:1.65 for the gap between the breakwaters to the distance to the design MHW (maximum breakwater indenture) (Subramania, 2015) based on analysis by Hardaway, Thomas, and Li (1991) on several sites in the Chesapeake Bay. Research by Berenguer and Fernandez (1988) suggest this ratio may be site-specific (image after Hardaway, Thomas, and Li [1991]).

in New England, so large scale oyster reefs have been proposed to protect Staten Island. The Living Breakwaters are similar to traditional breakwaters but are seeded with oysters to reduce risk to coastal storms while providing ecosystem services enhancement (Rebuild by Design, 2015). Oyster populations in Long Island Sound were decimated in the late 1990s due to multinucleated sphere unknown (MSX) and Dermo disease; however, based on the amount of harvested oysters, it appears that the populations have been increasing considerably since the early 2000s (Connecticut Department of Agriculture, 2015; Getchis, *personal communication*). Although the current natural extent of oyster beds is unknown, the historic record shows that natural populations in eastern Long Island Sound were not as substantial as in the western sound. The persistence and growth on oyster beds depend on wind, waves, tidal currents, and ice. Currently, the natural beds are only a few oysters deep, and since most of the subtidal areas are designated harvest areas, the pyramid shape commonly found in the Chesapeake Bay does not exist in Long Island Sound (Getchis, 2015). In Long Island Sound, commercial oystering limits the feasibility of oyster reefs. Most of the nearshore sites suitable for oyster reef construction are designated town, state, or privately held commercial harvesting beds. Additionally, the Connecticut Bureau of Aquaculture has a policy of removing oysters when they reach 5–6 years old to reduce the potential occurrence of MSX (Carey, 2015). Thus, the feasibility of oyster reef sills and breakwaters for living shorelines in Long Island Sound is limited.

Breakwaters. Structural approaches to coastal erosion are not typically considered living shoreline approaches. Breakwaters, groins, and revetments are traditional coastal engineering shoreline stabilization structures. However, offshore-gapped-headland breakwaters, as a component of a living shoreline, have been constructed in the Chesapeake Bay (Hardaway, Thomas, and Li, 1991; Subramania, *personal communication*). Gapped-headland breakwaters are used to create a pocket or crenulate beach, which is the most stable shoreline configuration (Hsu *et al*., 2010). Hardaway *et al*. (1991) examined the effectiveness of the gapped-headland configuration for erosion control for several sites along Chesapeake Bay tributaries and identified design parameters that are currently used by the MD DNR, such as the relationship between the maximum bay indentation (breakwater centerline to MHW) and the breakwater gap. The MD DNR uses a relationship of 1:1.65 (Subramania, 2015) shown in Figure 7; however, Berenguer and Fernandez (1988), in their review of Spanish pocket beaches on the Mediterranean Sea, found an average ratio of 1:0.75, suggesting the breakwater design parameters are site specific.

In comparison to sills, breakwaters are larger with a higher elevation, designed to protect the shoreline from storm-wave conditions. Although breakwaters have been suggested as protection from storm surge, they do not protect against coastal inundation. Breakwaters reduce storm-induced damage by attenuating wave heights, and they provide a protected area landward of the structures so that sediment deposition can increase and the beach can be widened.

Wave Attenuation Devices. Reef Balls, WADs, Coastal Havens, BeachSavers, and Prefabricated Erosion Prevention (P.E.P.) reefs are marine-suitable concrete structures designed to attenuate waves and to provide benthic habitat. These wave attentuation devices may be used where appropriate instead of rock sills (Boyd and Pace, 2012; Duhring, 2008b; Gedan *et al*., 2011; Meyer, Townsend, and Thayer, 1997; Swann; 2008). Of these, Reef Balls (shown in Figure 8) are perhaps the best known with over 4000 projects worldwide, albeit not all of the installations were for erosion protection; many were used to reestablish coral reefs (Fabian, Beck, and Potts, 2013). Wave attenuation devices are deployed as offshore breakwaters to provide the hard coastal protection of a traditional breakwater with the ecological benefits of habitat creation and marsh restoration (Gedan *et al*., 2011). As the wave attenuation devices become colonized with marine species, they provide recreational benefits such as fishing and snorkeling (USACE, 2005).

Despite the number of projects using wave attenuation shapes as breakwaters, there is a scarcity of peer-reviewed literature on their effectiveness for shoreline protection (Fabian, Beck, and Potts, 2013). Design guidleines suggest that the necessary number of rows of attenuation structures is

Figure 8. Wave attenuation devices, such as reef balls, are designed to attenuate waves while providing benthic habitat. Reef balls are available in several sizes. The size selected is dependent on design water depth of the reef. Typically, the height and width of the reef is similar to the design parameters of a traditional breakwater. These reef balls are deployed off Stratford Point, Connecticut, to provide protection to a created fringe marsh (photo credit: (a) A. Dolan, Graduate Student, Sacred Heart University *via* J. Mattei, *personal communication*; (b) J. Mattei, Department of Biology, Sacred Heart University).

determined by the water depth, wave climate, tidal range, and the design attenuation criteria and is similar to the crest width of a traditional submerged breakwater (Reef Beach Company, 2010). Studies have shown problems with settlement of the devices and the need for extensive restoration after storms, which could result in high maintenance costs (Fabian, Beck, and Potts, 2013).

Other Types of Living Shorelines. Although there are other examples of living shoreline approaches such as live fascines, branch packing, and brush mattresses (*e.g.*, Rella and Miller, 2012), most are unsuited to the wave, surge, and ice conditions experienced by New England coasts. Scientists, engineers, and even private property owners are continually developing new technologies for responding to coastal erosion, storm surge, and SLR. Although property owners remain optimistic, no silver bullet has been produced that solves all these problems.

Effectiveness of Living Shorelines

The performance of different types of living shorelines for shoreline stabilization is of critical importance to engineers and property owners. To use living shorelines for coastal protection, the effectiveness of these approaches to attenuate wave energy, and their response to storm surge and SLR must be understood.

Marsh Vegetation

Tidal salt marshes, whether natural or nature-based, can provide critical protection to coastal communities by substantially attenuating wave heights and therefore wave energy, reducing storm surge levels and durations and also mitigating coastal erosion (Anderson, Smith, and McKay, 2011; Bridges *et al.*, 2015; Campbell *et al.*, 2009; Gedan *et al.*, 2011; Guannel *et al.*, 2015; Renaud, Sudmeier-Rieux, and Estrella., 2013; Shepard, Crain, and Beck, 2011; Shepard *et al.,* 2012; SmarterSafer Staff, 2015; Sutton-Grier, Wowk, and Bamford, 2015). Although there is increasing understanding of the performance of the ecosystems services and coastal protection provided by natural and nature-based nonstructural and hybrid features, the number of factors affecting their performance (including geomorphology, ecology and hydrodynamics) as well as the variation within each factor, has hindered our ability to predict the success of a living shoreline for a particular location based on its performance at a different locations (Bridges *et al.*, 2015; Pinsky, Guannel, and Arkema, 2013). Additionally, the effect of vegetation on surge elevations and wave height has only been studied in low-energy conditions, thus the feasibility of relying on tidal marshes to provide coastal protection during storm conditions is not well understood (Anderson, Smith, and McKay, 2011; National Research Council, 2014). Improved understanding of the interdependency of these factors in diverse site conditions may enable coastal managers to reduce the construction of traditional erosion control structures and to encourage the use of ecosystem-based approaches to mitigate coastal vulnerability (Spalding *et al.*, 2014).

Wave Attenuation. Tidal marsh restoration and creation have been shown to mitigate coastal erosion in low wave-energy conditions. Marsh vegetation extensive root systems help to maintain the existing soil, thus reducing sediment transport while plant stems attenuate wave energy (VIMS-CCRM, 2010). The ability of marsh vegetation to attenuate small and medium wave heights (less than 0.5 m) has been well documented in field and laboratory studies using real and artificial vegetation (*e.g.*, Knutson *et al.,* 1982; Kobayashi, Raichle, and Asano, 1993; National Research Council, 2014; Nepf, 1999; Tschirky, Hall, and Turcke, 2000).

Most wave attenuation has been shown to occur in the first few meters of the seaward edge of a marsh (Möller and Spencer, 2002; Shepard, Crain, and Beck, 2011). Knutson *et al.* (1982) observed in their study of wave dampening in *Spartina alterniflora* that, on average, more than 50% of small-amplitude wave energy (wave heights of 0.15–0.18 m) was dissipated in the first 2.5 m of marsh, and 100% was dissipated in 30 m. It is therefore misleading to calculate the average rate of attenuation across the marsh width (Gedan *et al.*, 2011), and even a narrow fringe marsh may be effective in attenuating wave energy (Gedan *et al.*, 2011; Möller and Spencer, 2002). At high wave-energy sites, an abrupt edge reduces the wave heights but leads to near-continuous erosion of the marsh face, an unsustainable condition that will cause narrowing of the marsh width over time (Möller and Spencer, 2002).

The ability of vegetation to attenuate wave energy is affected by vegetation characteristics (*e.g.,* stem height, stiffness, buoyancy and density, marsh width [Bouma *et al*., 2005; Möller, 2006; Sheng, Lapetina, and Ma, 2012; Shepard, Crain, and Beck, 2011]), and wave conditions (*e.g*., incident wave height, period, and direction), as well as water depth and tidal amplitude (Augustin, Irish, and Lynett, 2009). In addition, many vegetation characteristics are modified with wave action (*e.g*., stem stability, relative stem height, and plant orientation [Anderson, Smith, and McKay, 2011]) and through seasonal and spatial variations in vegetation height, foliage, and coverage (Möller and Spencer, 2002). Although understanding of the effectiveness of marsh plants to attenuate wave heights is critical in evaluating their ability to provide coastal protection, the variety of tidal marsh plants and the complexity in quantifying vegetative characteristics in the field makes it difficult to determine the effect of marsh vegetation on wave attenuation (Bradley and Houser, 2009; Cooper, 2005; Knutson *et al.,* 1982; Mendez and Losada, 2004; Möller, 2006; Möller and Spencer, 2002; Möller *et al.,* 1999; Tschirky, Hall, and Turcke, 2000; Wayne, 1976). Gedan *et al*. (2011) observed that wave attenuation is minimal when the water depth is large or small relative to plant height. Wave attenuation is largest when the ratio of water depth to plant height is on the order of 1–2 (Gedan *et al*., 2011). Wave attenuation increases with marsh width and stem density (Anderson, Smith, and McKay, 2011; Tschirky, Hall, and Turcke, 2000); however, no clear correlation of wave attenuation with wave height has been determined nor is the relationship between wave attenuation and wave period well understood (Bradley and Houser, 2009; Möller *et al*., 1999; Tschirky, Hall, and Turcke, 2000). The seasonal variation in vegetation characteristics, such as the presence of foliage and vegetation height, can also result in a temporal variation in the coastal protection provided (Shepard, Crain, and Beck, 2011).

The composition of salt marsh vegetation varies widely because of spatial and temporal changes as well as competition between individual plants of the same and different species. Salt marshes may primarily comprise one species (*e.g.,* invasive phragmites) or a more diverse community of vegetation. Given the complexities of evaluating wave attenuation through one species of marsh vegetation, it is unsurprising few studies exist that evaluate diverse marsh communities. Nor are numerical models similar to those for evaluating the performance of hard structures for coastal defense available for predicting the performance of marsh vegetation (Arkema *et al*., 2013; National Research Council, 2014). Yet evaluation of the effect of marsh vegetation at reducing wave height is critical for predicting the performance of vegetation for shoreline protection (Anderson, Smith, and McKay, 2011).

Shoreline Stabilization. Numerous studies have discussed the ability of marsh vegetation to stabilize shorelines by reducing sediment transport, increasing marsh elevation, and producing biomass (National Research Council, 2014). As with attenuation in marshes, the capability of marsh vegetation to trap sediment is dependent on a number of factors: sediment supply, tidal range (which governs the duration of inundation), marsh elevation, and vegetation characteristics such as density, height, and biomass production (Shepard, Crain, and Beck, 2011). The elevation of the seaward edge of the marsh is vitally important to the health and stability of the marsh. Unless a minimum elevation is maintained, marsh plants will be constantly flooded, resulting in loss of vegetation and edge instability. Processes that help maintain or increase marsh surface elevation such as sediment deposition and root production affect marsh surface elevation and contribute to shoreline stability (Shepard, Crain, and Beck, 2011). Gedan *et al*. (2011) in their review of biophysical models, field tests, and laboratory experiments concluded that coastal vegetation protects shorelines from erosion and wave damage by reducing flow velocities and increasing sediment deposition and soil cohesion.

Storms: Surge and Waves. The effectiveness of living shorelines of providing coastal protection during storms is of particular importance, yet their performance capabilities during storm conditions are poorly understood (Gittman *et al*., 2014; Pinsky, Guannel, and Arkema, 2013). It has long been accepted that salt marshes have the potential to slow and absorb flooding from storm surges by reducing flood peaks and durations through storage and drainage of flood waters; however, their effectiveness is difficult to determine (Augustin, Irish, and Lynett, 2009; Shepard, Crain, and Beck, 2011; Wamsley *et al*., 2010). Studying the effect of Hurricane Irene on shore erosion in North Carolina, Gittman *et al*. (2014) concluded marshes, with and without sills, are more durable and provide better protection from storm-induced erosion in Category 1 hurricane conditions as compared to bulkheads. Möller *et al*. (2014) found that 60% of the wave attenuation during storm events is attributable to vegetation and that even when waves were sufficiently large to damage plant stems, the vegetation prevented soil erosion (Sutton-Grier, Wowk, and Bamford, 2015).

Most of our knowledge about the ability of marshes to attenuated flood waters is from freshwater wetlands. Predictions of the capability of marshes to attenuate waves and store storm water are usually based on rules of thumb. For instance, for freshwater wetlands the U.S. Environmental Protection Agency (2006, p. 1) uses the rule, "A one-acre wetland can typically store about three-acre feet (37,000 m^3) of water, or one million gallons (3.8 million litres)," which is based on a 1963 USACE report that evaluated the attenuation of storm surge for seven Louisiana storms (Shepard, Crain, and Beck, 2011; USACE, 1963a). Wave attenuation and flooding mitigation, however, are too complex for such a simple approximation (Resio and Westerink, 2008). Marsh characteristics, variations in coastal geology, bathymetry and exposure, and storm-specific parameters such as duration, intensity, size, and track all affect the attenuation of waves and flooding (Gedan *et al*., 2011; Resio and Westerink, 2008; Sheng, Lapetina, and Ma, 2012). Additionally, as noted previously, the rate of attenuation varies as the waves traverse the marsh. After 50 years of study, we still do not understand storm surge and wave attenuation in marshes well enough to develop models suitable for coastal planning of marsh protective services (Shepard, Crain, and Beck, 2011). Numerical models of the capability of marshes to reduce flooding have been developed, but they are typically tuned to a particular marsh configuration and storm characteristics. Using field observations from Hurricane Isaac in Breton Sound, Louisiana, Hu, Chen, and Wang (2015) numerically modeled the effect of storm parameters and marsh vegetation characteristics on storm surge. They found in hurricane conditions that the ability of the marsh to affect storm surge was more sensitive to relative stem height than stem density. They also determined that the ability of marshes to attenuate storm surge decreases with increasing wind speed and storm duration; however, to be of value to coastal planners in predicting flooding, numerical models must accurately describe storm conditions, attenuation parameters, and coastal geometry (Resio and Westerink, 2008). So, models to predict the wave attenuation and floodwater storage capability of marshes should be used with caution.

The ability of vegetation to attenuate short-period waves has been studied through field and laboratory experiments (*e.g.*, Knutson *et al.*, 1982; Kobayashi, Raichle, and Asano, 1993; Möller *et al.*, 1999; National Research Council, 2014; Nepf, 1999; Tschirky, Hall, and Turcke, 2000); however, the effects of longer period storm waves may not scale linearly, so the observations from short-period waves are not necessarily applicable (Feagin *et al.*, 2010). Longer period storm waves increase the water level over a longer period of time and with greater force on the vegetation than short waves. Thus, the plants are more likely to bend with the flow, reducing the drag coefficient and wave attenuation (Bradley and Houser; 2009; Pinsky, Guannel, and Arkema, 2013). The decrease in drag coefficient in turbulent flows is critical because storm conditions are highly turbulent. Failure to account for this can overestimate wave attenuation in storms by approximately 20–1600%; thus, to protect coastal communities, marshes may need to be larger than previously thought (Pinsky, Guannel, and Arkema, 2013).

Despite the complexity of storm effects on storm surge and wave attenuation, field and modeling observations show that salt marshes can provide shoreline protection during storms (Möller *et al.*, 2014; Shepard, Crain, and Beck, 2011). During and immediately following a storm, marshes may experience a decrease in plant density and marsh elevation, but as the marsh recovers from the storm, deposition of suspended sediments can increase marsh elevation (Shepard, Crain, and Beck, 2011). Improved understanding of the relationships among vegetation characteristics (*e.g.*, plant height, density, and marsh width) and storm conditions (surge elevation, duration, and wave heights) is needed to estimate the erosion protection provided by nonstructural and hybrid living shorelines (Sheng, Lapetina, and Ma, 2012).

Sea-Level Rise. Considerable speculation exists in the popular press and academic literature on the ability of salt marshes to migrate landward as sea level rises because of coastal landforms and infrastructure. Given limitations of marsh migration, researchers have investigated the ability of salt marshes to maintain their surface elevation relative to SLR (Morris *et al.*, 2002; Shepard, Crain, and Beck, 2011). The long-term stability of a marsh is dependent upon the sea level, primary plant production, and sediment accumulation that regulate the marsh elevation relative to mean sea level (Morris *et al.*, 2002). Natural marshes exposed to large variations in tidal range and marshes with high sediment concentrations will be best able to adapt to large increases in SLR (Kirwan *et al.*, 2010; Morris *et al.*, 2002). Morris *et al.* (2002) developed a model that suggests a marsh ecosystem will be stable against SLR when the marsh elevation exceeds the optimal level for primary production and unstable when the marsh elevation is less than optimal. The optimal range varies regionally, dependent upon tidal range, vegetation, salinity, nutrient loading, and climate (McKee and Patrick, 1988; Morris *et al.*, 2002). Researchers have concluded that salt marshes are better able to maintain their position against gradual SLR than mitigate erosion from storm waves (Feagin *et al.*, 2009; Gedan *et al.*, 2011), so living shorelines would likely provide better coastal protection against gradual, long-term changes than short-term, extreme events such as storms.

Beach and Dune Nourishment

Major beach nourishment and dune recreation projects are not always considered living shorelines; however, they can provide coastal protection with, if not a natural environment, a nature-based environment, conserving the unique biodiversity of a beach/dune ecosystem. Although coastal management still relies almost exclusively on hardened structures (Schlacher *et al.*, 2008), beach nourishment has been shown to be more cost effective over the lifetime of the project (Basco, 1998; Dias *et al.*, 2003; Koster and Hillen, 1995), with much less adverse environmental impact (Dias *et al.*, 2003). When criteria such as environment impacts, recreational opportunities, difficulty in obtaining permits, and public perceptions are considered, beach nourishment and dune creation are even more attractive alternatives to traditional hardened approaches (Basco, 1998).

Beach nourishment, however, has its limitations. Studies have shown that nourishment negatively affects the benthic ecology of sandy shorelines (*e.g.,* Convertino *et al.*, 2011; Jones *et al.*, 2008; Peterson *et al.*, 2006), although Jones *et al.* (2008) observed recovery within a year of beach nourishment. The physical changes caused by nourishment, such as sand compaction by heavy machinery and changes in sediment composition and beach profile, can destroy the habitat of protected species, bury existing vegetation, and temporarily reduce water quality (Berry, Fahey, and Meyers, 2013; Mason, 2009). Despite decades of monitoring, little is known about the temporary and long-term impacts of beach nourishment on the dredge site or beach ecosystem (Peterson and Bishop, 2005). Additionally, significant volumes of placed sediment can be transported alongshore or offshore into sand bars as the nourished beach transforms from a construction profile to an equilibrium profile. This frequently causes the public to perceive that the nourishment project failed (Dias *et al.*, 2003). When a nourished beach is affected by storm-induced erosion, this perception is increased further. Another issue with nourished beaches is that the public develops an unrealistic impression of what a natural sandy shoreline looks like, and future coastal management decisions are then based on the appearance of an artificial coast (Nordstrom, Lampe, and Vandemark, 2000).

The best way to maintain a beach, and thereby reduce coastal erosion and flooding hazards, is to allow natural coastal processes to determine its location and profile, thus enhancing the natural capacity of the beach to provide erosion protection. This is unacceptable in developed areas, as erosion and SLR would move the shoreline landward, which is politically implausible because of the considerable social, economic, and environmental costs (Dias *et al.*, 2003). Many property owners and municipalities are reluctant to create dunes or to increase the height and width of existing dunes because recreational use of the beach and scenic views take precedence over the coastal protection that dunes can provide (Nordstrom, Lampe, and Vandemark, 2000; Parry, 2015). This has resulted in low and narrow restored dunes that provide minimal erosion and surge protection. The practice of grading and raking beaches eliminates plant growth and debris, which are sand traps and a source of nutrients. Dunes devoid of natural vegetation have reduced species diversity and aeolian sand deposition. As a result, beach nourishment does not necessarily restore naturally functioning beach ecosystems and landforms (Nordstrom and Mauriello, 2001; Nordstrom, Lampe, and Vandemark, 2000).

Storms. Beaches and dunes provide protection against wave action and storm surge. As waves approach a sloping beach face, they steepen as the water becomes shallower until the waves become unstable and break, thus reducing the wave energy reaching the beach. Dunes protect against coastal inundation by acting as a barrier to storm surge. Large dunes function as wind breaks, reducing wind effects on coastal property (Mason, 2009). The dynamic nature of beaches and dunes enables them to respond to short-term changes in environmental conditions, such as storm waves, and long-term changes caused by erosion and SLR. By accumulating sand during normal conditions, beaches and dunes can provide sacrificial sand that can be transported offshore into protective sand bars or alongshore to eroding beaches (O'Connell, 2008). The stockpiled sand helps beaches resist wave energy and provides material for natural beach restoration after the storm (Salmon, Henningsen, and McAlpin, 1982). Natural dune restoration can take several years, however, so if protection is needed, restoration may be necessary (O'Connell, 2008). Creation or restoration of beaches and dunes will not protect against all major storms and hurricanes; however, it is widely accepted that beaches and dunes can reduce the level of damage (Salmon, Henningsen, and McAlpin, 1982).The protection provided by beaches and dunes is not uniform. Taylor *et al.* (2015) observed on Texas beaches that for the highest level of protection (from 100- and 200-year storms), beaches must have high dunes (>4 m in elevation along Texas coasts), have building setbacks of 150–200 m of the vegetation line, and have a wide beach and foredune complex. Many sites along the New England coast do not have sufficient sediment supply to naturally create the high, wide dunes necessary to provide protection from storms. In addition, some sites, for example, along the Connecticut coast of Long Island Sound, do not have large, restorative waves to create large dunes.

Dunes can provide significant protection from storm surge. This was demonstrated along the New Jersey shore during the March 1962 storm and again during Hurricane Sandy. Communities that were fronted by protective dunes suffered much less damage than those without. In the aftermath of the 1962 storm, as part of a cost-saving compromise, the beaches and dunes were restored to a level of protection for a 10-year storm (USACE, 1963b). This had the unfortunate result of setting the standard for future dune restorations to an inadequate level for long-term protection (Nordstrom and Mauriello, 2001). Although artificial beach and dune nourishment has many drawbacks, it is the most cost-effective method of maintaining the coastal protection and recreational services of beach-dune ecosystems (Schwartz, 2005).

Sea-Level Rise. As beach-dune systems are sufficiently flexible to adapt to short-term changes in water level caused by storm surge, it is clear that with sufficient sediment and available land to retreat, beach-dune systems are capable of adapting to SLR (Martinez, Psuty, and Lubke, 2004). The ability to retreat, however, is crucial to the adaptive capability of beach-dune ecosystems (Berry, Fahey, and Meyers, 2013; Feagin, Sherman, and Grant, 2005). In areas where the ability to retreat is restricted, for example, by coastal development, the beach-dune ecosystem can become too narrow to maintain a vegetated system (Feagin, Sherman, and Grant, 2005). The loss of vegetation adversely affects the system's ability to adapt its shape and position relative to changes in sea level. Thus, beach and dune ecosystems need to be restored or maintained to enhance their physical and ecological adaptability to SLR.

DISCUSSION

Design of coastal protection is challenging because of the complex and dynamic social, economic, and environmental systems that must be considered (Dias *et al.*, 2003). The design of living shoreline projects is particularly hindered by the lack of peer-reviewed literature on quantitative monitoring and evaluation of implemented living shorelines (Currin, Chappell, and Deaton, 2010). Despite wide-spread agreement that coastal vegetation has a role in providing erosion and surge control, there is a lack of data and design guidelines, as well as best management practices, to ensure successful implementation of living shorelines (Tschirky, Hall, and Turcke, 2000). This lack of knowledge and data poses significant difficulties in developing guidance and policies for implementation and evaluation, as well as needed information on the necessary design parameters to meet erosion control and surge mitigation requirements (Bridges *et al.*, 2015).

Compared with the vast amount of literature on traditional coastal protection structures, very limited rigorous scientific analysis of design and performance specifications for living shorelines exists and even less so for projects in which the primary goal was shoreline stabilization. Therefore, as living shoreline approaches are adopted in new geographical locations or constructed in conditions that had been considered unsuitable, it will be necessary to determine which techniques will work most effectively to reduce erosion, to improve coastal habitat, and potentially to modify the approaches to suit the natural conditions of the shoreline (Smith, 2008).

Some areas, for example, highly developed areas or areas in front of critical infrastructure, may not be suitable for nonstructural or hybrid approaches, but even these shorelines will benefit from components of living shorelines (Miller, 2013; Skrabel, 2013). Incorporating living shoreline principles, such as considering the impact of the structure on the coastal habitat, building sloping or terraced walls, roughening the surfaces, adding crevices and tidal pools, and integrating oyster shell and native plantings, will create protective structures that provide more ecosystem services than traditional designs (Miller, 2013). Every design must be site-specific, which is critical to the long-term performance of natural and nature-based projects (Galveston Bay Foundation Staff, 2014; Hardaway, 2013).

Comparison of structural and living shoreline approaches needs to take into consideration the ecological and social costs and benefits. Traditionally, benefits have focused on protection from storm wave and surge damage, while costs considered only design, construction, and maintenance. Taking into account the full range of costs and benefits will provide a more accurate assessment of the options; still, many unknowns remain.

CONCLUSIONS

Traditional coastal protection has long been used to protect shoreline property from wave damage and coastal flooding, but scientists and engineers now understand the environmental costs in hardening the shoreline. Natural and nature-based approaches offer protection against erosion and creation or restoration of coastal habitats. While there may be a desire to return the shoreline to its natural, pristine condition, this is unlikely to be achieved because coastal management must balance environmental and social priorities. The inability to return to natural conditions, however, should not preclude efforts to restore natural ecosystems function. Use of natural and nature-based features offer decision makers the opportunity to consider physical, environmental, and social objectives along with the trade-offs and compromises entailed (Nordstrom, 2008).

Marsh vegetation has been shown through lab and field experiments to effectively attenuate wave heights; however, living shorelines are not an appropriate solution for all locations or conditions. Yet, even narrow marshes can provide substantial shoreline protection. Combining nonstructural and structural approaches increases the suitability of sites and the protection provided but may diminish ecosystem services. Planning for these nonstructural and hybrid approaches is more challenging than for hardened shoreline protection because the protection provided depends on numerous variable ecological and physical parameters.

Further research into these issues will provide much needed information to develop decision-support tools and design criteria applicable to the environmental conditions along New England coasts. The tidal range, ice conditions, storm surge, and vegetation characteristics must be considered when adapting techniques for New England that have proved successful further south.

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