Living Shorelines in the Southeast: Research and Data Gaps

Prepared for the Governors South Atlantic Alliance

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Photos clockwise from left:

Carteret Community College, N.C.; http://www.coastalreview.org/2015/07/report-cites-benefits-of-living-shorelines

Oak Point, Wadmalaw Island, S.C; The Nature Conservancy; http://projects.tnc.org/coastal/

Canaveral National Seashore, FL; http://patimes.org/sustainable-coastal-restoration-stabilization-living-shoreline-project-floridas-east-coast/

The Little St. Simons Island, GA; http://marex.uga.edu/living-shorelines/?hc_location=ufi

About the Georgia Coastal Research Council:

The Georgia Coastal Research Council (GCRC) was established to provide mechanisms for improved scientific exchange between coastal scientists and decision makers, and to promote the incorporation of best-available scientific information into State and local resource management. The Council is not a policy organization, but rather seeks to provide unbiased, objective information about scientific issues. Baseline support for the program is shared by the Coastal Resources Division of the Georgia Department of Natural Resources (through the Coastal Management Program) and Georgia Sea Grant, with project-specific support from the National Science Foundation and other agencies. For more information, please contact us at gcrc@uga.edu or see our website at: http://www.gcrc.uga.edu.

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Introduction

The edge of the shore is a dynamic area that is constantly gaining and losing land due to the forces of waves, wind, and tides. Natural events (e.g., storms and longshore transport) and human activities (e.g., the presence of coastal structures and boat traffic) influence the rate of coastal erosion, as do the effects of rising sea level. Sea level rise changes the location of the shoreline, moving it landward and exposing new areas to erosion. The coast is also experiencing development pressure from the increasing number of people living on and moving to coastal areas. From 2000 to 2010, most of the coastal counties in the Southeast experienced growth at or above 10 percent, and this is expected to continue (Mackun and Wilson 2011). As populations increase, demands for housing, commercial development, and associated infrastructure also increase.

The traditional approach to protecting coastal infrastructure and shorelines from erosion has been the installation of engineered barrier structures such as bulkheads, seawalls, revetments, groins, and breakwaters, referred to collectively as hard armoring. These hard barriers between the land and water are designed to protect the coastline and associated structures from wave energy. However, hard armoring can have environmental drawbacks such as reducing sediment sources along the shore, starving nearshore beaches, and preventing the landward progression of fringing beaches, marshes, and mudflats. On an eroding shoreline, hard structures tend to increase wave reflection and cause scouring at the edges of the structure creating further erosion, narrowing the width of the nearshore environment, and increasing the water depth. They can also negatively affect water quality in the adjacent subaqueous land, eliminate the connections between upland, intertidal, and subtidal areas, and result in losses of ecosystem productivity (NRC 2007).

Living Shorelines

"Living shoreline" is a broad term that encompasses a range of shoreline stabilization techniques along estuarine coasts, bays, sheltered coastlines, and tributaries. A living shoreline has a footprint that is made up mostly of native material. It incorporates vegetation or other living, natural 'soft' elements alone or in combination with some type of harder shoreline structure (e.g., oyster reefs or rock sills) for added stability. Living shorelines maintain continuity of the natural land-water interface and reduce erosion while providing habitat value and enhancing coastal resilience" (NOAA 2015).

Living Shoreline at the NOAA Lab, Beaufort, NC

(Credit Carolyn Currin)
Source: NOAA 2015

Table 1: Common Construction Materials for Living Shorelines

	Material type	Description	Function
Green Materials	*Marsh grasses*	Native grasses planted within the intertidal or mid-intertidal area or at the mean high tide mark. Plantings may be more successful when performed in Spring in areas of existing marsh where there is < 3 miles of open water, and where the prevailing winds will not destroy the newly established vegetation.	Dissipate wave energy Filter upland runoff Improve habitat for fish and wildlife Base of food web
	Mangroves	Mangroves are woody plant communities that are found in estuarine tropical and subtropical environments including central and southern Florida, and portions of south Louisiana.	Stabilize shoreline Trap sediments and nutrients Dissipate wave energy Provide habitat for fish and wildlife
	Tree and grass roots	Vegetation colonized naturally or planted. Common riparian vegetation used at specific sites differ depending on the species native to that area, but typically includes a combination of native woody trees, shrubs, and grasses.	Stabilize the riparian zone above high tide Minimize bank erosion Filter upland runoff Provide habitat
	Submerged aquatic vegetation	SAV is vegetation rooted in the substrate of a body of water (usually no deeper than 10 feet) that does not characteristically extend above the water surface and usually grows in beds. Creates a natural shoreline buffer when used with other living shoreline components such as marsh grasses, reduces coastal erosion via root growth.	Dissipate wave energy Stabilize sediments, Improve water quality Provide habitat Base of food web
	Natural fiber logs (bio-logs)	Made of biodegradable coconut fiber and netting. Logs are placed at the foot of bank slopes or in the water, molded to fit the bank line, and then anchored in place.	Stabilize slopes and minimize bank erosion Trap and retain sediment Retain moisture
	Filter fabric	A porous layer of geotextile material placed beneath rock sills and breakwaters, or under oyster bags to prevent sand movement into or through the rock, concrete structure, or oyster shell bags.	Trap sediments
	Natural fiber matting	Made of coir fiber, wood, straw, jute, or a combination of organic, biodegradable materials.	Prevent sediment loss Trap sediment Stabilize shoreline
	Oyster reefs (natural)	Oyster reefs can be enhanced or created at living shoreline sites as protective structures. Oyster shell bars use natural shell material (e.g., oyster shell bags, oyster encrusted mats), and appear and function similarly to a natural shoreline oyster reef when mature.	Dissipate wave energy Decrease erosion Provide fish habitat Improve water quality
Gray Materials	*Low-crested segmented rock sills*	Freestanding rock structures placed in the water parallel to shore. Sills are generally segmented and stand no more than 6 to 12 inches above mean high water so that boats- and wind- induced waves can pass over the sill and wildlife has access to the water and the shoreline habitat.	Dissipate wave energy Protect eroding marshes and shorelines
	Breakwaters	Structures constructed from rock, rubble, or recycled concrete that are placed parallel to the shore in medium- to high-energy open-water environments. Can be seeded with oyster spat to create a “living” breakwater where conditions are suitable for oyster growth.	Dissipate wave energy Provide habitat Stabilize shorelines Improve water quality
	Sediment-filled geotextile material tubes	Placed parallel to shore in high-energy environments. The tubes serve as a hard surface on which oysters can construct reefs.	Dissipate wave energy Provide habitat
	Oyster (structures & fabricated)	Oyster castles or reef balls are hollow concrete structures that provide a surface on which oysters colonize and form small living reefs. Gabions filled with limestone rubble or oyster shell and oyster encrusted crab pots can also create suitable oyster habitat.	Dissipate wave energy Decrease erosion Provide fish habitat Improve water quality

Adapted from NOAA (http://www.habitat.noaa.gov/restoration/techniques/lsimplementation.html)

The growing body of scientific evidence demonstrating the negative environmental effects of traditional “gray" approaches to shoreline armoring has led to substantive changes in how shorelines are managed and a search for alternative, "green" solutions that incorporate natural materials such as vegetation, biodegradable fiber logs, and woody debris (Table 1). These “living shorelines” are designed according to specific location conditions, and can use various combinations of green and gray techniques depending on their topography, and hydrology. Considerations for designing a living shoreline include shoreline type, erosion rate, fetch (distance across open water), tidal currents and amplitude, salinity regime, and bank height and slope. The orientation of the shoreline in relation to the directions of prevailing winds and wave energy are also important to consider (Whalen et al. 2011). Wave energy is related to wave height and describes the force a wave is likely to have on a shoreline. Different environments will have lower or higher wave energy depending on environmental factors (e.g., shore orientation). Boat wakes can also generate waves (SAGE 2016). This report concentrates on sheltered areas with limited fetch and wave heights of less than two feet (i.e. tidal creeks, estuaries) and partially sheltered areas (i.e. shallow embayments) with a longer fetch and wave heights ranging from two to five feet (SAGE 2015).

Figure 1 shows a continuum of techniques that can be applied to sheltered intertidal areas, which are the focus of this report. These range from vegetation only, to hybrid approaches such as edging that stabilize the slope or hold the "toe" of a planted area, to the placement of low rising sills or revetments put in place to protect vegetation (Bilkovic et al. 2016). Living shorelines use as many natural habitat elements as are appropriate for site conditions and are designed to achieve multiple ecosystem services, including stabilizing the shoreline and reducing current rates of shoreline erosion and storm damage;

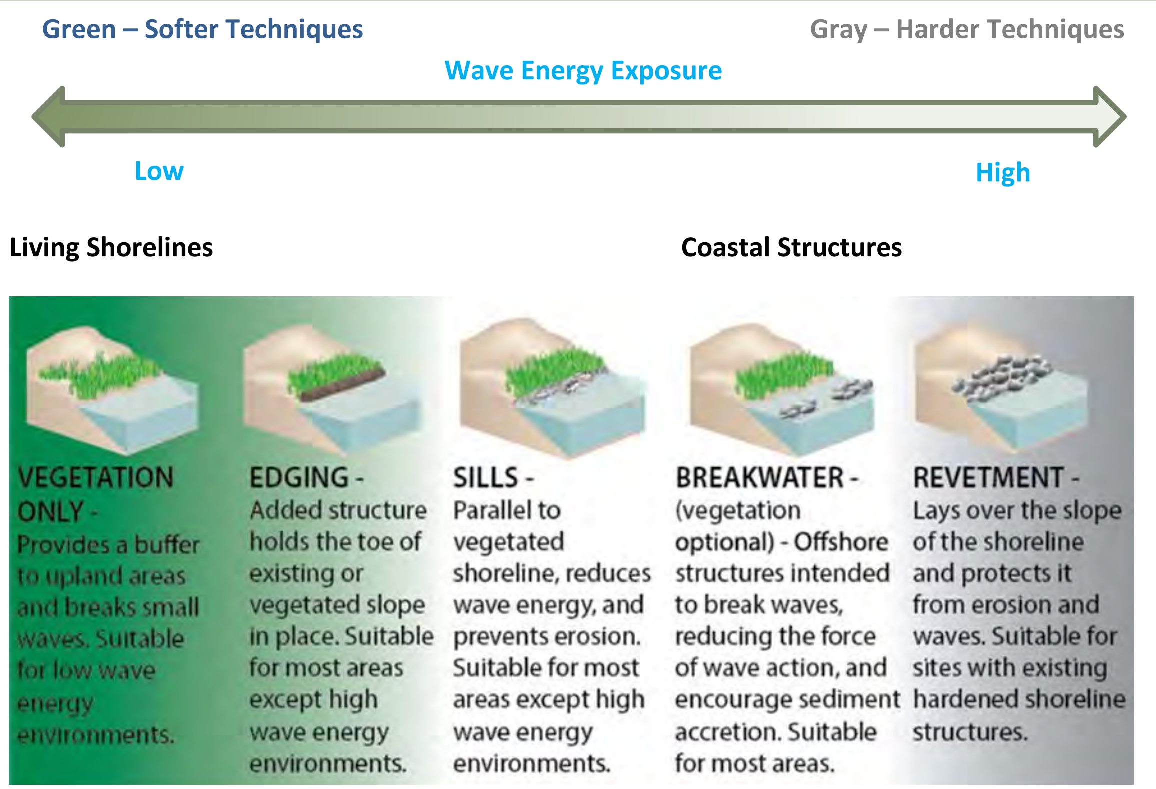


Figure 1. A continuum of green (soft) to gray (hard) shoreline stabilization techniques. Adapted from a more detailed continuum in the brochure, *Natural and Structural Measures for Shoreline Stabilization* (SAGE 2015).

filtering sediment, nutrients, and pollutants; providing habitat for fish and other aquatic species; increasing flood storage capacity; slowing stormwater runoff; and maintaining connections between land and water ecosystems to enhance resilience (NOAA 2015).

The purpose of this report is to synthesize scientific information relevant to living shorelines in the states of North Carolina, South Carolina, Georgia, and Florida. Whenever possible, we focus on research conducted in the Southeast although we also included work from the Gulf States and Chesapeake Bay. Where information on living shoreline was lacking, we drew on relevant material from studies of restored, submerged oyster reefs as well as natural and restored salt marshes and mangroves. Part One of the report provides a brief overview of the types of approaches that have been used in the region. Parts Two, Three and Four describe research on the physical, biological, and chemical characteristics, respectively, of living shorelines in salt marshes, which is the focus of the majority of the published studies. Part Five summarizes what little information is available regarding living shoreline projects in Florida mangroves. Part Six is a summary and a discussion of data gaps.

We also compiled information on 441 living shoreline projects in the southeastern region. The majority of these projects are in Florida (244), with 163 in South Carolina, 28 in North Carolina, and 6 in Georgia (Figure 2). Details about each project are included in Appendix A. Note that this list will likely grow as additional projects are identified.

Appendix B is an annotated bibliography of material relevant to living shoreline research in the southeast region. The bibliography contains 21 case studies of regional living shorelines, 5 databases of restoration/living shoreline projects, and information about 13 federal and state agencies and non-profit groups involved in living shorelines. It also provides summaries of 86 research papers and proceedings and 55 other publications including reports, books, book chapters, theses, and treatises.

Part One –Living Shorelines Approaches in the Southeast

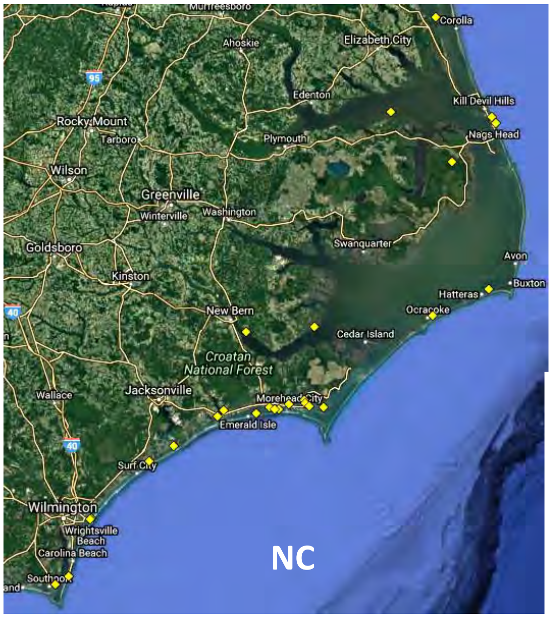
There are various approaches to living shoreline projects, ranging from those that only use vegetation to those that include edging, sills and breakwaters. Below we provide a brief description of each of these approaches, as well as bulkheads, which are sometimes included in studies as a contrast with living shorelines.

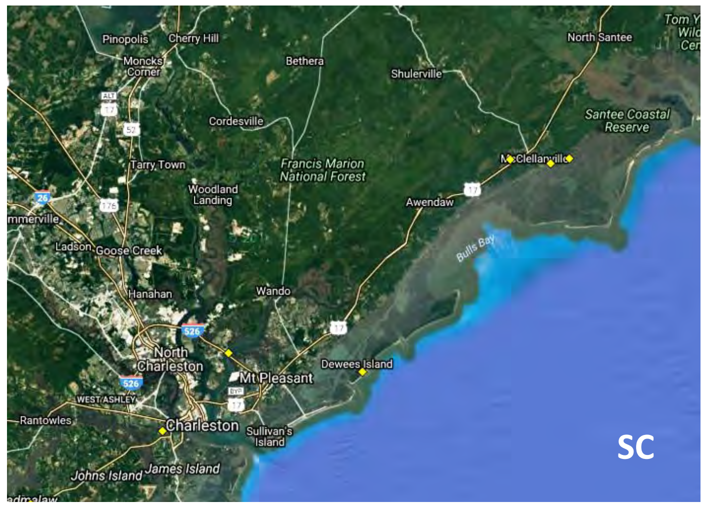
Vegetation only

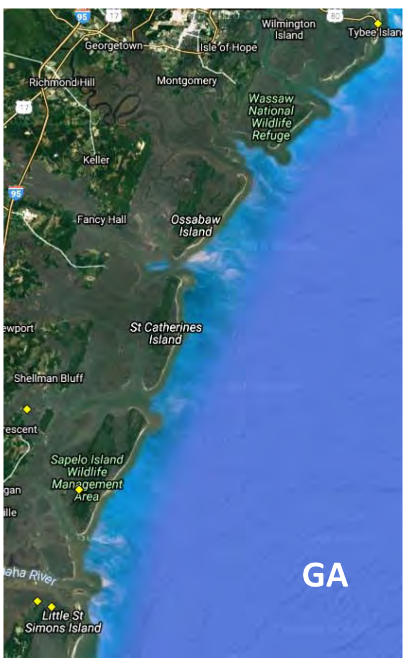
Salt marsh grasses are the dominant intertidal vegetation in North Carolina, South Carolina, Georgia and northern Florida, whereas mangroves are more prevalent in the central and southern portion of Florida. The presence of these plants helps to protect against erosion by dissipating wave energy and trapping sediment. Studies have shown that 50 percent of wave energy is dissipated in the first eight feet of marsh, and 100 percent of wave energy is dissipated in 100 feet of marsh (Walker et al. 2011).

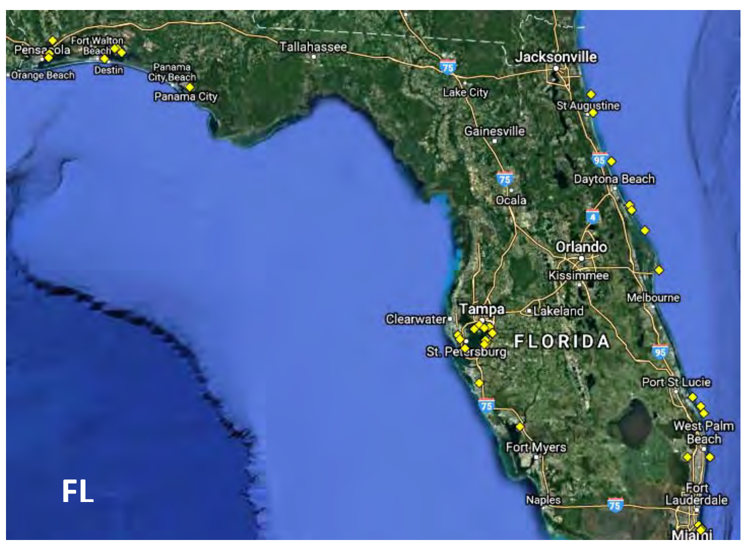
Living shoreline projects along low energy shorelines (fetch < 1 mile) can control minor erosion through vegetation enhancement and bank grading (Whalen et al. 2011). Lower grade slopes allow for the dissipation of wave energy and provide a better base for vegetation growth. Characteristics of suitable areas for grading include: active erosion at the top and toe of the bank; low cleared banks with lawns;

Figure 2. Locations of living shoreline projects in the southeastern region (indicated by yellow dots). For more information, see Appendix A.









unstable high banks with undercut or falling trees; unstable banks adjacent to tidal marshes; and banks with no adjacent bulkheads, revetments or upland improvements (CCRM 2016).

All of the vegetation-only projects included in Appendix A were located in Florida, where we identified 202 projects that used vegetative plantings to stabilize both marsh and mangrove areas. Note that some of these were restoration rather than living shoreline projects.

Edging

Edging is used in situations where added structure is required to hold the slope in place. Many natural substances are used as edging in living shoreline projects, including bagged oyster shell, large branches, matting, and logs. Fiber logs (i.e. bio-logs) are made of biodegradable coconut fiber and netting; fiber matting can be made of coir fiber, wood, straw, jute, or a combination of organic, biodegradable materials (NOAA 2015). Edging materials are placed at the foot of upland and vegetated areas or in the water, molded to fit the bank line, and then anchored in place in order to stabilize slopes and minimize bank erosion, trap and retain sediment, and hold moisture (Miller et al. 2016). Vegetation can then be planted on top of the stabilized slope. Sites suitable for edging include marsh restoration areas and planted marshes on tidal coves; very shallow tidal creeks; tree removal areas; graded or terraced banks under landscape restoration; elevations higher than mid-tide level; and areas with minimal wave and boat wake action (CCRM 2016).

Figure 3. Example of use of marsh toe revetment in a living shoreline

Marsh toe revetment placed directly against the edge of an eroding tidal marsh.

(Source: CCRM, VIMS; http://www.ccrm.vims.edu/livingshorelines/photo_gallery.html)

Edging can be installed at the bottom edge or "toe" of the intertidal area. These are referred to as marsh toe revetments, which are distinct from revetments that are applied along the entire intertidal slope. Marsh toe revetments can be used where existing marshes have eroding edges and scarps, or where the upland bank is experiencing minor erosion in spite of the presence of marsh vegetation (Figure 3). Sites suitable for marsh toe revetments include wide tidal marshes greater than 15 feet; marshes with edge erosion or minor upland bank erosion; and areas with very shallow water near a marsh edge with a hard sand bottom (CCRM 2016).

Edging and marsh toe revetments are used in all four southeastern states covered in this report, with the largest number of projects in South Carolina. Georgia has used this form of living shoreline on two sites on Sapelo Island as well as St. Simons Island and Tybee Island (Figure 4).

Figure 4. Living shoreline using vegetation and edging on Sapelo Island, Georgia

Construction of this living shoreline consisted of grading the eroding embankment and placing a granite toe on the lower intertidal embankment for added support. Mesh bags of recycled oyster shells were then arranged in two layers along the creek bank and secured with non-treated pine stakes. Native marsh plants as well as upland plants were also installed.

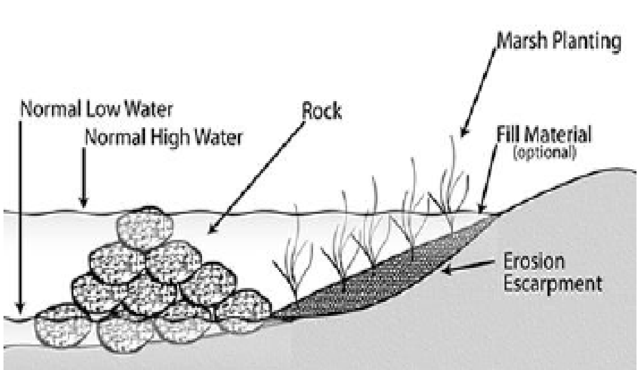
(Source:https://www.estuaries.org/pdf/2010conference/wednesday17/galleon3/session2/mackinnon-j.pdf)

Sills and Breakwaters

Sills are low-elevation (0 to 1 ft above MHW), typically stone structures that are constructed in the water parallel to the existing shoreline (Figure 5). Sills are often used as a way to shield fringe marshes or wetlands that require a higher degree of protection than marsh toe revetments can provide. Sills dissipate wave energy and reduce bank erosion, causing waves to break on the offshore structure, rather than upon the natural, more fragile shore (Miller et al. 2016). The area of water created between the sill and the shoreline allows for the accretion of sand and sediment and can, over time, eventually result in increased elevation of the bottom. This effect further stabilizes the shoreline or marsh behind the sill and replaces lost and eroded land (Miller et al. 2016).

Breakwaters are coastal engineering structures typically constructed parallel to the shoreline that are designed to reduce the amount of wave energy experienced by the area directly behind them. Breakwaters are distinguished from sills in that they are typically constructed in deeper water, further from shore, in more energetic wave climates, and tend to be slightly larger. When used as a part of a living shorelines project, breakwaters are designed to reduce wave energy to acceptable levels to allow the establishment of a vegetated (typically marsh) shoreline in its lee (Miller et al. 2016).

Figure 5: Use of Sills in Living Shorelines
(Source: NC DCM 2014)



In many cases, sills and breakwaters are constructed with natural materials designed to recruit and support living resources. These again function to provide protection and stabilization of shorelines in sheltered areas. Oysters are typically targeted due to their ability to grow rapidly in brackish water, near estuarine river mouths, and in near shore areas (Miller et al. 2016). Areas suitable for oyster reef construction include places with very low energy settings with very minor erosion, evidence of healthy native oyster populations, and oyster living on fixed structures. In addition, a hard sand bottom will result in less settling and siltation over the reef than muddy sediments (Miller et al. 2016).

Marsh sills are used extensively in North Carolina and are usually made of stone or bagged oyster shells. The majority of projects involving breakwaters are found in Florida, although there are also living breakwaters in North Carolina and South Carolina. Restoration of the native oyster populations and oyster shell reefs is gaining in popularity as a way to both protect eroding shorelines and restore the ecosystem benefits that the reefs convey.

Marsh Bulkheads

Hard structures, such as dikes and bulkheads, are vertical barriers that fall into the "gray" category of shoreline armoring. When used in sheltered shorelines, they can be installed anywhere along the gradient between the upper edge of the intertidal zone (i.e. at the marsh/upland border) and the edge of the shoreline (i.e. the marsh/creek border). These are primarily built out of wood or concrete, and, when properly designed and constructed, can reduce or temporarily eliminate shoreline retreat. The area landward of the bulkhead is typically filled, and the marsh behind it is often converted to uplands (NRC 2007).

Bulkheads can have negative environmental effects. They can sequester sediments previously supplied from the upland, leading to sediment starvation below the structure (NRC 2007). In addition, as waves break against the bulkhead, the wave energy is reflected both upward and downward, increasing current velocity around the structure and leading to scour at the base. Generally, the scoured area becomes as deep as the original depth of the water. Existing wetlands and submerged aquatic vegetation beds in front of the bulkhead can also be scoured away leading to a loss of habitat complexity and biodiversity (Thomas-Blate 2010). Despite these problems, bulkheads have long been used in sheltered areas and remain popular throughout the southeast region.

Part Two – Physical Effects of Living Shorelines in Marshes

Habitat distribution

The presence of a living shoreline can affect the distribution of habitats across the intertidal zone. If an eroded shoreline is planted, areas of mud flat or open water may be converted back to intertidal vegetation. The installation of oysters as part of a marsh toe revetment or a living sill or breakwater can provide additional habitat for bottom-dwelling organisms and may also attract fish and other nekton (i.e., organisms that can actively swim against the current). Hard structures, including bulkheads, may also provide habitat for attached organisms such as bivalves.

The addition of new habitat may come at the expense of another. In a Virginia marsh where 6.2 acres of shallow subtidal bottom were converted to intertidal marsh sill habitat, Bilkovic and Mitchell (2013) found a significant reduction of infauna (annelids, arthropods, molluscs, and phoronids), while the addition of a rock structure facilitated recruitment of filter feeding epifauna (mussels, oysters, barnacles). They concluded, "a marsh-sill may be viewed as providing a net positive ecological benefit when (i) the only alternative is traditional hardening (bulkhead, riprap), (ii) the sill is likely to be colonized by filter-feeding epifauna due to placement within the estuary, and/or (iii) the sill footprint can be minimized and shallow subtidal habitat maintained. Alternatively, a marsh-sill should be viewed more negatively in situations where the sill unnecessarily or extensively replaces existing habitat" (Bilkovic and Mitchell 2013). In particular, adverse effects can occur in situations where sufficient offshore shallows are not maintained for nekton refuge habitat (Bilkovic et al. 2016). The introduction of artificial structures can also provide an opportunity for the introduction of non-native species (Bilkovic et al. 2016). Additional studies detailing the effects of living shoreline projects on organisms are reviewed in Part Three.

There is also the potential for negative effects on neighboring habitat when a project is improperly designed or executed. Installing a living shoreline can result in loose oyster shells and other materials damaging a neighboring marsh. Waste, such as empty oyster shell bags, may be transported to adjacent shorelines, and existing marsh or submerged aquatic vegetation (SAV) may be damaged if the effect of the structural component expands following installation (NCDCM 2014). A study of 36 hybrid and non-structural living shorelines in Virginia found "end-effect" erosion in two sites where the untreated marsh edge at the end of the marsh toe revetments had undergone accelerated erosion (Duhring et al. 2006). Another assessment by Fear and Bendell (2011) of 27 living shoreline projects with marsh sills in North Carolina found that the majority of the sills were functioning properly and no upland was being formed behind the marsh vegetation as result of sediment trapping. However, they were unable to determine if the marsh sills were affecting the adjacent properties.

Erosion control

Living shorelines prevent or control erosion through a variety of mechanisms including wave attenuation, sediment trapping, and storm surge protection. These mechanisms work together to protect, create or restore shorelines. For example, the plant stems and leaves of coastal vegetation slow wave velocity and reduce turbulence resulting in increased sediment deposition (Bendell 2006). In addition, plant roots slow erosion rates indirectly by stabilizing the soil (Feagin et al. 2009).

Wave attenuation

Wave attenuation is generally greater across vegetated wetlands than unvegetated mudflats (Gedan et al. 2011). Knutson et al. (1982) reported that marshes in Chesapeake Bay with *Spartina alterniflora* significantly reduced wave energy by 64% within the first 2.5 m of marsh and minimal wave energy persisted beyond 30 m of marsh. In addition, Shepard et al. (2011) found positive correlations between marsh width and wave attenuation in a meta-analysis of global studies. Their results showed that marshes less than 10 m in width can reduce wave heights by 80% for waves <0.5 m in height and by 50% for waves >0.5 m in height. Vegetation density and stiffness, and marsh width were the factors most commonly cited as important determinants of wave attenuation within salt marshes by the studies included in the review.

Wave attenuation results from interaction with the site's bottom and vegetation, and any structure that interferes with the wave's progress such as a sill or breakwater. For example, the physical structure of a fringing oyster reef can serve to protect salt marsh habitat by dissipating erosive wave energy (Gedan et al. 2011). A study of two oyster reef restoration projects in Mobile Bay, Alabama, estimated that the reefs would reduce wave height by 51-90% and wave energy by 76-99% (Kellogg et al. 2011). Manis et al. (2015) used a wave tank to evaluate the wave energy attenuation associated with living shorelines in Mosquito Lagoon, a shallow-water estuary in Florida. Four living shoreline techniques were assessed, including a control (sediment only), oysters alone (*Crassostrea virginica*), cordgrass alone (*Spartina alterniflora*), and a combination of both. Time since placement (newly placed, one year after placement) was also assessed to see how wave energy attenuation changed with natural oyster recruitment and plant growth. Wave energy was generated to represent energy from boat wakes. Although all one-year-old treatments attenuated significantly more energy than newly placed treatments, the combination of one-year-old *S. alterniflora* plus live *C. virginica* was the most successful.

Sediment trapping

The ability of coastal vegetation to prevent erosion through sediment trapping may depend upon marsh characteristics such as the degree of slope. Results from a meta-analysis of 36 global independent comparisons of the effect of vegetation on shoreline stabilization by Shepard et al. (2011) indicate that coastal marshes promote vertical sediment accretion, reduce sediment loss, and maintain or increase the surface elevation of the shoreline. Of the studies included in the analysis, accretion was the most frequently evaluated response (64%), followed by erosion (22%) and elevation change (14%). A positive effect of marsh vegetation was reported in 58% of studies. Factors most frequently identified as being correlated with shoreline stabilization included vegetation characteristics such as species identity, vegetation density and height, and biomass production. In contrast, a study by Feagin et al. (2009) comparing small wave (<10 cm) erosion of salt marsh with and without vegetation in experimental (water flume) and field settings (steeply sloping salt marsh on Galveston Island, Texas) found that wetland vegetation provided no significant direct erosion protection at the marsh fringe. Instead, they found that vegetative roots indirectly reduced erosion by adding organic debris and fine-grained sediment to the soil matrix, causing the soil to become more cohesive. They concluded that, "coastal vegetation is best suited to modify and control [erosion] in response to gradual phenomena like sea-level rise or tidal forces but is less well-suited to resist punctuated disturbances at the seaward margin of salt marshes, specifically breaking waves" (Feagin et al. 2009).

Sills and breakwaters installed as part of a living shoreline project are able to facilitate sediment accretion on their landward side. In a study on the Outer Banks of North Carolina, Currin et al. (2008) assessed three restored marshes located landward of a stone (granite boulders) sill constructed as part of a living shoreline stabilization project and compared them with natural fringing marshes. During the three-year study period, sediment accretion rates in the restored marshes were approximately 1.5- to 2-fold greater than those recorded in the natural marshes.

In a study conducted in the Chesapeake Bay, Burke (2005) worked with a survey team to assess hybrid shore erosion control projects that used sand fill material and marsh plantings contained by a breakwater/sill system, rock sills alone, or stone groins to restore marsh fringe habitat. Two of these projects used low profile sills and were designed primarily for habitat benefits, and six were primarily constructed for erosion control purposes. The "habitat first" projects experienced the greatest shoreline erosion and marsh stress or direct loss of shoreline. The two stone groin erosion control sites underwent a moderate degree of marsh stress or loss. The four "erosion control first" sites with sills and a breakwater had the least erosion and habitat loss, although this was likely due in part to the fact that they were located in areas with healthy marsh communities and little or no shoreline erosion. Marsh loss was influenced by a variety of factors, including bank erosion; higher average fetch; substrate conditions; boat wakes; steepness of marsh gradients; marsh shading; movement of groin structures; and littoral drift patterns.

An evaluation based on field evaluations and observations of 36 living shoreline projects in Virginia was conducted by Duhring et al. (2006). Most of the projects were judged to provide effective erosion control, and 55% (N=20) were also judged to be effective as living shoreline treatments, based on marsh conditions. However, they did find that vegetation-only projects were generally not as effective for reducing upland bank erosion as those with sills, apparently because the vegetation-only projects were narrow and therefore not wide enough to produce wave and erosion reduction. Although they did not quantify sediment accumulation, the authors noted that at eight sites little sediment had accreted behind the sills and at several sites an un-vegetated border persisted between the rock sill and the marsh. However, a subsequent analysis of these same 36 sites using the Digital Shoreline Analysis System to compute shoreline change showed that 14 of the 20 successful sites from the above study by Duhring et al. had reduced erosion rates and eight of these 14 sites had measurable accretion, which was defined as a lateral increase of > 0.003 m/yr. The remaining six sites still had measurable erosion, but erosion was less than the up or down river areas (Berman et al. 2007).

Although not studies of living shorelines per se, research has shown that artificial reefs can also contribute to sediment trapping. Kroeger (2012) investigated restored intertidal oyster reefs located in front of eroding shorelines at two sites in Alabama. At the time of the survey, the two reefs had been in place for 8 and 16 months, respectively. Bathymetric profiles showed that sediment accretion occurred directly landward of the reef breakwaters. Swann (2008) evaluated 182 units of precast marine concrete breakwaters that were installed offshore of Dauphin Island, Alabama in 2005. Nineteen months following installation, sediment accretion measured at five locations at the base of the breakwaters' sheltered side averaged approximately 15 cm.

Storm surge protection

The ability to attenuate wave energy and trap sediments may allow living shorelines to protect against large storm surges. Two studies from North Carolina compared the amount of shoreline protection provided by bulkheads to that provided by natural marshes and marshes with constructed sills during Hurricane Irene (Category 1). A visual survey of approximately 40 km of bulkheads at two sites by Peterson and Bruno (2012) found that about 30% showed some sort of damage at one site and about

5% were damaged at the other site. In contrast, riprap revetments, sills, or hybrid structures did not show any obvious damage. In the second study, Gittman et al. (2014) reported that in the area where the strongest sustained winds blew across the longest fetch, 76% of surveyed bulkheads were damaged, whereas no impairment was detected in marshes with or without sills. Across sites within 25 km of Irene's landfall, the storm had no effect on marsh surface elevations, again regardless of the presence of sills. Although vegetation density was temporarily reduced at these sites, it recovered to pre-hurricane levels within a year. The authors of both studies concluded that marshes with and without sills are more durable and may protect shorelines from erosion better than bulkheads in a Category 1 storm.

More general studies of storm surge projection suggest that the effectiveness of coastal wetlands decreases as the intensity of storm surge increases. Gedan (2011) calculated wave attenuation in five mangrove and ten coastal salt marsh sites using measurements from previous investigations of the spread of small wind waves and larger storm surge waves. He found that the degree of wave attenuation provided by vegetation decreased during actual storm surges when wave heights were highest. Another study by Feagin et al. (2010) indicated that, although the above-ground portions of vegetation are effective at reducing wave energy on the landward side of marshes, storm surges can still penetrate diffuse vegetation because they raise the bottom-water level over a longer period of time and with greater force than individual waves.

Part Three – Biological Effects of Living Shorelines in Marshes

Vegetation

Although salt marsh vegetation characteristics have been extremely well-studied, there is a paucity of literature specific to living shorelines. In their survey of living shoreline projects in Virginia (bank grading and planted marsh vegetation), Duhring et al. (2006) found that the band of planted vegetation in vegetation-only projects sometimes failed, potentially due to high levels of inundation or the presence of overhanging trees shading the planted areas. They also found that vegetation planted in early spring was more successful than that planted in summer. In the Currin et al. (2008) study conducted to evaluate hybrid marsh/sill living shoreline projects on the Outer Banks of North Carolina, described above, they found that after three years the vegetation in restored marshes still generally differed from controls. During the three-year study period, average *S. alterniflora* stem density in natural marshes ranged between 130 and 222 stems/m^2, and mean maximum stem height exceeded 64 cm. In contrast, only one of the three restored marsh sites achieved *S. alterniflora* stem densities equivalent to that of the natural fringing marshes, and at all three sites the percent cover and maximum stem heights were significantly lower in the restored marshes than in the natural marshes.

As with salt marsh vegetation characteristics, there is also a great deal of information on marsh restoration projects as well as trajectories of recovery after disturbance. Craft et al. (2002) evaluated wetland vegetation for 15 years following the creation of a brackish water estuarine marsh on the Pamlico River in North Carolina in 1983. The marsh was created by grading an upland site to intertidal elevations, planting with *Spartina* spp. and *Juncus roemerianus*, and then introducing tidal inundation. Results showed that vegetation development was dependent on elevation and frequency of tidal inundation. *S. alterniflora*, which occupied low elevations along tidal creeks and was inundated frequently, developed to levels similar to the natural marsh (750 to 1,300 g/m^2) within three years after creation. *S. cynosuroides*, which dominated interior areas of the marsh and was flooded less frequently, required 9 years to consistently achieve levels equivalent to the natural marsh (600 to 1,560 g/m^2). *S. patens*, which was planted at the highest elevations along the terrestrial margin and seldom flooded, never consistently developed biomass comparable with the natural marsh. Relevant observations for living shorelines come from studies of tall-form *S. alterniflora*, since it grows at the creek edge which is the location of many projects. In a wrack disturbance study conducted on Sapelo Island, Georgia, we found that tall *S. alterniflora* met our long-term target (vegetation cover and above-ground biomass indistinguishable from that measured in reference plots) after 2 years (Alber, unpubl.).

Broome et al. (1986) reported that after three growing seasons, the community structure of a restored *S. alterniflora* marsh in North Carolina was similar to a nearby natural marsh in terms of aboveground standing crop biomass, stem height, and the number of flowering stems. After three years, the restored marsh had lower stem densities with larger individual stems but, after five growing seasons, they were similar to the natural marsh. Belowground biomass increased during the first three growing seasons and was similar to the natural marsh after four growing seasons. Broome et al. (1982) studied two brackish-water marshes created on graded upland sites in North Carolina. *S .alterniflora, S. patens* and *Juncus roemerianus* in the created marshes had similar stem heights and densities as natural marshes after three growing seasons, whereas S*. cynosuroides* in the created marsh had greater stem densities, with smaller individual stems than in the natural marsh. However, aboveground biomass of all four plants was similar in the natural and the created marshes after three growing seasons.

Organisms

Vegetated salt marshes provide habitat for a wide variety and density of animals, and in cases where the living shoreline replaces a mud flat it is likely to affect the surrounding fauna. McFarlin et al. (2015) evaluated the effects of loss of *S. alterniflora* on benthic invertebrates in salt marshes following a period of sudden dieback after a record drought in Georgia in 2000–2002. They found significantly lower abundances of invertebrates (epifauna, macroinfauna, and meoifana) in bare plots as compared to reference plots, and differences in community assemblage between bare and vegetated sites. Organism abundances were positively related to *S. alterniflora* stem density, although factors such as soil macro-organic matter and moisture content, which are associated with increased stem density and canopy coverage, also contributed to this finding.

A study by Davis et al. (2006) quantified how quickly living shorelines can assume “natural” ecological function. On the upper Western Shore of the Chesapeake Bay, macrofauna at bulkhead sites slated for living shoreline installation were sampled before and after construction. Species with higher densities at control marshes than at bulkhead sites prior to bulkhead removal (e.g., mummichog (*Fundulus heteroclitus*)), grass shrimp (*Palaemonetes pugio*), and spot (*Leiostomus xanthurus*)) were expected to increase after living shoreline installation, and those with higher densities at bulkheads (e.g., white perch (*Morone americana*)) were expected to decrease. Two months after restoration, densities of mummichog, grass shrimp, and pumpkinseed (*Lepomis gibbosus*) had increased at the constructed living shoreline site relative to the control marsh, though densities of some marsh species had not. These results suggest that certain species can respond almost immediately to installation of living shorelines.

The varied components associated with hybrid living shorelines (i.e. sills, breakwaters) are generally thought to increase structural complexity and thereby serve to increase the abundance and diversity of associated organisms. In a study of living shorelines in Chesapeake Bay, Davis et al. (2006) evaluated the species assemblage associated with four structural habitat types (vegetation, oyster shell, riprap, and woody debris). They found that each habitat hosted different collections of species, with vegetation serving the greatest nursery function, oyster reef providing the greatest refuge for species such as blue crabs, and riprap hosting the greatest proportion of adult stages. In a synthesis of six studies of restored oyster reefs conducted in the southeastern U.S. (Texas, North Carolina, South Carolina, Virginia), Peterson et al. (2003) found that oyster reef sills increase the abundance of both highly and less reef-dependent species by enhancing recruitment and providing refuge from predation.

The effect of marsh sills on organisms has been well-studied in North Carolina, where several studies have compared them with unvegetated bulkheads and natural marsh (no sill). Peterson and Bruno (2012) found that the marsh sill sites served as an additional predation refuge for juvenile fish and crustaceans, provided new hard substrate for oysters and other epifauna (mussels, crabs), and may serve a similar function as intertidal oyster reefs. Likewise, Gittman et al. (2016) found that marshes with sills supported higher abundances and species diversity of fishes and filter-feeding bivalves than either unvegetated habitat adjacent to bulkheads or control marshes. These differences were only detected at sites three or more years after construction, indicating that these effects may take time. This may explain the results from Currin et al. (2008), who found no significant difference in fish and crustaceans' use of natural fringing marshes and marshes behind stone sills after one year.

The literature on oyster restoration also suggests that subtidal reefs can provide viable habitat for oysters as well as other fixed and mobile species. In the study by Swann (2008) that examined breakwaters off Dauphin Island, Alabama, he found that oyster density 19 months following installation was 205 oysters/m^2. In addition to controlling erosion, the breakwaters served as "coastal havens", providing habitat for a wide array of organisms including locally important species such as spotted seatrout (*Cynoscion nebulosus)*, blue crabs (*Callinectes sapidus)* and Gulf stone crabs (*Menippe adina)*, eastern oyster (*Crassostrea virginica)*, red drum (*Sciaenops ocellatus)*, southern flounder (*Paralichthys lethostigma)*, and various species of commercially important shrimp. In another study, a band of oyster cultch added to the toe of a marsh restoration site supported numerous oyster reef-associated species at equal or greater densities than adjacent natural reefs after two years (Meyer and Townsend 2000). Finally, Scyphers et al. (2015) found that oyster breakwaters in Mobile Bay, AL supported live ribbed mussels. Breakwaters also had increased species richness of associated juvenile and smaller fishes compared to mudflat controls, although larger fishes did not appear to be affected by the breakwater. Sampling revealed that more than 35 species of fishes, shrimp, and crabs inhabited or used the complex structure provided by the breakwaters. Results similar to these three studies were also obtained in Louisiana (La Peyre et al. 2014) and Alabama (Scyphers et al. 2011).

Part Four – Chemical Effects of Living Shorelines in Marshes

Particle removal

Particulate material is generally removed from the water as it passes over coastal wetlands. For example, Leonard et al. 2002 evaluated the removal of suspended sediments from overmarsh tidal flows by two marshes in Prospect Bay, Maryland: one dominated by *S. alterniflora* and the second by *Phragmites australis.* Suspended sediment concentrations decreased by as much as 15 mg/l over a distance of 1.5 m from the creek edge in both marshes, and were significantly lower than those observed in adjacent, non-vegetated areas. Suspended sediment concentrations were consistently lower during ebb than during flood tides, suggesting that most removal occurs during the rising tide. Maximum deposition occurred closer to open water and decreased with distance into the interior, and sediment trap data indicated that the interiors of both marshes tended to receive slightly more organic than inorganic material (Leonard et al. 2002).

Although there have been few studies of particulate removal in living shorelines, those that incorporate oysters likely benefit from their ability to reduce turbidity by filtering out suspended inorganic material, phytoplankton, and detritus (i.e., seston) (Dame 1996). In a study in South Carolina that evaluated particle removal by intertidal oyster reefs constructed from 2000 to 2003 and natural reefs, Grizzle et al. (2008) measured short-term (up to 1.3 h) removal of seston using in situ fluorometry and lab analysis of chlorophyll *a* (chl-a) concentrations upstream and downstream of the reefs. Although the results were variable among reefs, % removal of chl-a ranged from −9.8% to 27.9%, with a mean of 12.9%. These data indicate that restored oyster reefs may provide water quality improvements as soon as two years after construction.

Nitrogen removal

Coastal wetland sediments are sites of active nutrient cycling, and are particularly active in terms of denitrification and sulfate reduction. Nitrification–denitrification cycling is stimulated in sediment by internal oxygen transport through the soft tissues of salt marsh grasses resulting in oxygenated areas surrounding the roots and rhizomes (Koop-Jakobsen and Giblin 2010).

Baas et al. (2014) studied nitrogen cycling in salt marshes that had experienced dieback in comparison to planted plots and reference areas. Potential denitrification rates increased with greater *S. alterniflora* density, and they suggested that either benthic microalgae or *Spartina* influence the organic carbon pool available for denitrification and/or that photosynthetic production stimulates nitrification and subsequently denitrification.

In addition to microbial processing that occurs in the mud, coastal vegetation and the microalgae on its leaves and/or roots are also effective in removing nutrients from the water column (NRC 2007). Sparks et al. (2015) evaluated nitrogen removal in a restored *J. roemericanus* marsh in the Grand Bay National Estuarine Research Reserve in Mississippi. Through introduction of a $^{15}NO_3$ groundwater solution, they found that ~97% of nitrogen was removed by fully (100% initial planting density) and partially (50% initial planting density) vegetated plots, whereas ~86% was removed in non-vegetated controls. While the restored vegetated treatments only removed an additional 10% of the NO_3, the principal difference was the ability of the vegetation to decrease the total nitrogen pool available for export through the system. The authors concluded their study demonstrates the effectiveness of vegetated areas at removing excess nitrogen from porewater.

The presence of oyster reefs in a living shoreline project is also likely to affect nutrient cycling. A nutrient budget for an intertidal oyster reef In Bly Creek, South Carolina removed an estimated 189 g N /m^2 /year from the water column (Dame et al. 1989). In Mobile Bay, AL, Kellogg et al. (2011) estimated that two oyster reef restoration projects with a total length of 3.6 miles would remove between 280 and 4,160 pounds of nitrogen per year from bay waters. The authors concluded that although this reduction was too small to noticeably affect nitrogen levels in the entire bay, water quality in the vicinity of the reefs would be improved enough to avoid algal blooms or fish kills.

The removal of nitrogen by oyster reefs can be through enhanced denitrification, which would return the nitrogen to the atmosphere, but it can also be through direct assimilation into tissue nitrogen as the oysters grow. At a restored reef site in the Choptank River in Maryland, Kellogg et al. (2013) found that fluxes of O_2, NH_4, and NO_2 +NO_3 at the restored site were enhanced by at least one order of magnitude during all seasons. Seasonal denitrification rates at the restored site ranged from 0.3 to 1.6 mmol N_2-N/meter/hour. Restoration enhanced the average standing stock of assimilated nutrients by 95 g N/meter. Nitrogen in shells of live oysters and mussels at the restored reef accounted for 47% of total nitrogen. The authors concluded that oyster reef restoration can not only significantly increase denitrification rates but also enhance nutrient sequestration via assimilation into oyster shells.

Part Five – Living Shorelines in Mangroves

Mangroves are intertidal trees found along tropical shorelines around the world. In the Southeast, mangrove wetlands occur along the coast of Florida, where the most common species are the red mangrove, *Rhizophora mangle* and the black mangrove, *Avicennia germinans.* The structure of mangrove swamps is usually attributed to topography, substrate, tidal action, and freshwater hydrology (Dame et al. 2000). As with salt marshes, mangrove wetlands provide valuable ecosystem services such as fisheries support, water filtration, nutrient cycling, habitat and shelter for a variety of species, shoreline stabilization, wave and wind energy reduction, and erosion control (Feller et al. 2010). The border between mangroves and salt marshes occurs in northern Florida, and in many areas *S. alterniflora* is intermixed with mangrove trees. The northward movement of mangroves as a consequence of climate change is an area of active research.

Although there are some examples of living shoreline projects that involve mangroves (Figure 6), we were unable to find any research specific to these projects. In the sections below we have drawn on relevant studies of naturally occurring and constructed mangroves to evaluate mangrove creation and restoration efforts.

Figure 6. Mangrove Living Shoreline

Example of the use of mangroves in a living shoreline using soft stabilization located in the Canaveral National Seashore on the east coast of Florida. This project was planted with red and black mangroves and *S. alterniflora*.

Source: Knox, Walters and Donnelly (2014)

Physical effects

Habitat distribution

Mangroves forests are highly productive ecosystems that enhance and provide habitat for a wide variety of species through the provision of food and shelter. The trees with their complex root systems add structured habitat to an area where they are planted. Although the most dramatic effect on habitat distribution would occur due to a transition from a mud flat to a mangrove forest, adding mangroves trees to an area that is currently a salt marsh also increases the 3-d complexity of the site. Some mangrove restoration projects begin by planting *S. alterniflora*, which then act as a "nurse species" by stabilizing the shoreline and creating structural habitat that will effectively trap and hold mangrove propagules. In successful situations, the transition from a created salt marsh to mangrove forest is accomplished in ten or more years (Lewis 2005).

Over decades and centuries, mangroves can alter shoreline surface elevation which, in turn, influences bathymetry and topography. They can also alter channel location and local geometry by expansion of wetland areas towards the sea (Cunniff and Schwartz 2015).

Erosion control

Much like salt marshes, mangrove vegetation controls erosion through wave attenuation and sediment accretion. They also provide protection from storm surges.

Wave attenuation

Mangrove vegetation attenuates waves through the obstruction of water flow by above-ground roots and branches. This action also reduces wave height. Factors known to affect wave height reduction include water depth, wave height, and various aspects of the mangrove tree structure, which depend on species, age, and size (McIvor et al. 2012a). Mangroves also reduce winds across the surface of the water preventing their propagation or re-formation (Spaulding 2014).

McIvor et al. (2012a) examined results from six studies measuring the attenuation of waves less than 70 cm in height in mangroves located in Vietnam, Japan, and Australia and found that wave height would be reduced by 50 to 99% across a 500 m stretch of mangrove forest. Mazda et al. (2006) showed that the rate of wave height reduction when water reached the level of the mangrove's branches and leaves was dependent on the initial wave height, with greater attenuation occurring in larger waves. Measurements were taken during a 3-hour period of constant water depth, with small waves (11 and 16 cm) passing through *Sonneratia* spp.in northern Vietnam. The rate of wave reduction over 100 m of mangrove forest was calculated as 45% when water depth was 0.2 m and 26% when the water depth was 0.6 m. Extrapolating from their data, the researchers predicted that when water depths reach the branch and leaves level, and with a wave height of 20 cm, the rate of wave reduction would be equivalent to a 50% reduction in wave height over 100 m of mangroves.

Storm surge protection

Mangroves provide protection from storm surges by slowing the inland velocity of water flow and lowering water levels. While the reduction of storm surge height may amount to centimeters over kilometers, even minor reductions in water levels can result in greatly reduced flooding of low-lying areas. The complex network of mangrove roots and branches can also trap debris, thereby reducing damage behind the mangroves (Spaulding 2014).

Krauss et al. (2009) were able to document the response of mangroves in Florida to storm surges caused by Hurricanes Charley (2004) and Wilma (2005). They calculated that during Hurricane Charley, which passed through the Ten Thousand Islands National Wildlife Refuge, peak water level reduction was 9.4 cm/km in an area that included both mangroves and salt marsh. In an area that contained only mangroves the peak reduction was even greater, at an estimated 15.8 cm/km. When Hurricane Wilma passed through mangrove forests along the Shark River in the Everglades National Park, reductions in peak water levels up to 6.9 cm/km were documented. However, it was unclear to what degree this reduction was due to the mangroves as opposed to salt marshes, open water, or other topographic relief.

The effects of Hurricane Wilma (Category 3) were also studied by Zhang et al. (2012) who analyzed field measurements of the storm surge and conducted numerical simulations using the Coastal and Estuarine Storm Tide model. Modeling results showed that the inundation area created by Wilma's storm surge would have extended more than 70% further inland without the mangrove cover. Modeling further showed that the surge height reduction rates in areas with mangroves ranged from 40-50 cm/km whereas areas with mangroves and open water had a surge reduction rate of 20 cm/km. There was a 10-30% increase in water levels in front of the mangroves due to their obstruction of the water flow. When modeling was used to explore the effects of mangrove width on storm surge, the authors found that surge attenuation was not linear, with large reduction rates (15-30%) for initial width increments and smaller rates (<5%) for subsequent width increments. A follow up study by Liu et al. (2013), using the

Coastal and Estuarine Storm Tide Model to simulate hurricanes with varying speeds, intensities, and sizes indicated that, although mangroves reduced storm surges to a greater extent for faster versus slower moving hurricanes, increasing hurricane intensity and size lowered the ability of mangroves to attenuate storm surge and reduce area flooding.

Sediment trapping

As with salt marsh plants, the presence of mangroves reduces wave energy and slows water flow over the soil surface, reducing the water's capacity to dislodge sediments while simultaneously allowing already suspended sediments to settle out (Spaulding 2014). The environment in which mangroves occur has an effect on sediment trapping. Cahoon and Lynch (1997) measured elevation change and accretion in mangroves in Rookery Bay, Florida. They identified three distinct accretionary environments based on hydro period and soil properties: fringe forests with regularly-flooded mineral soils, basin forests with irregularly-flooded organic soils, and overwash island forests that were flooded regularly and had mixed mineral-organic soils. Accretion rates were highest in the fringe forests (7.2 and 7.8 mm/yr) and lowest in the overwash forest on the sheltered island (4.4 mm/yr). The data in fringing forests may be most relevant for living shoreline projects.

Mangrove soils typically produce rich organic matter including living roots, dead leaves, and woody materials. Because mangrove soils are often waterlogged, much of this organic matter accumulates, forming a layer of peat that increases in thickness over time (Spaulding 2014). The binding of this deposited material depends on the growth of a dense network of fine roots that protects the soil from erosion and traps and binds soil particles together to form soft, moist soil layers and benthic mats (McIvor et al. 2013). The effect of benthic mats on sediment trapping was studied by McKee (2011) who found that the rates of elevation change of mangroves in Florida and Belize were positively correlated with both fine and coarse root accumulation. In this study, roots accounted for 1.2–11.8 mm/year of the total change in soil elevation. The results also indicated that turf algal mats (filamentous algae) accreted faster than leaf litter mats (filamentous algae and leaf litter) and at the same rate as microbial mats (mixtures of cyanobacteria, diatoms, other microalgae and other amorphous organic matter).

The volume of leaf litter may also affect accretion rates. Cahoon et al. (2006) found that the standing stock of leaf litter on the soil surface of a mangrove forest in southwest Florida affected vertical accretion in basin forests, with a significant positive correlation between litter biomass (g/m^2) and vertical accretion (mm/yr). However no relationship was seen in fringing mangroves where, the authors concluded, tidal action may wash leaves away and the drier conditions may allow leaves to decompose more quickly.

Biological Effects

Vegetation

There have been a few studies of vegetation characteristics in mangrove restoration projects in Florida. McKee and Faulkner (2001) evaluated two mangrove restoration sites (6 and 14 years old) in southwest Florida. They found that leaf and root inputs at each restoration site were not significantly different from that of the mixed-basin forests (> 50 years old) with which they were once contiguous. However, forest structure differed from that of reference sites. Although the younger site was typical of natural, developing forests, the older site was less well-developed, with low structural complexity. They suggest that more stressful physicochemical conditions at the older site resulting from incomplete tidal flushing (elevated salinity) and variable topography (waterlogging) apparently affected plant survival and growth. The authors concluded that local or regional factors such as salinity regime act together with site history to control primary production and turnover rates of organic matter in mangrove restoration sites.

Lewis et al. (2005) sampled a five-acre restored mangrove forest in Cross Bayou, in Pinellas County, Florida. The restoration project consisted of the removal of non-native invasive plants, re-grading the slope to favorable intertidal elevations for mangroves, restoration of the tidal creek hydrology, planting of *S. alterniflora*, and natural recruitment of mangrove propagules. Species composition, stem density, percent cover, and plant height were measured for a period of five years following installation. The density of mangrove seedlings was 208 trees/yd^2 after three months and decreased to a mean of 48 trees/yd^2 after five years. Mangrove cover increased linearly from 3.7% after grading to 94.7% after five years, and met the established cover success criterion within three years. As the mangrove canopy grew, the cordgrass was shaded out. White and black mangroves rapidly attained mean heights of 5.4 ft and 2.8 ft, respectively, within five years.

Organisms

Florida mangrove communities serve as important habitats for a wide variety of fish, reptiles, amphibians, birds, and mammals, including at least seven endangered species, five endangered sub-species, and three threatened species. They also support a diverse intertidal collection of algal epiphytes, which in turn host a variety of invertebrates (Milano 1999). Mangrove leaves and woody matter are a food supply for microorganisms such as bacteria and oomycetes, as well as some commercially important crab species that process the detritus into fragments suitable for other consumers (Hutchinson 2014). A study by Lewis and Gilmore (2007) comparing fish populations in restored and natural mangrove areas in Hollywood, FL, found statistically identical fish populations between restored and reference areas within three to five years.

Chemical Effects

Particle removal

We were unable to find any studies of Florida mangroves that evaluated their ability to remove particulates from water. However, given the information on sediment accretion (summarized above under sediment trapping), this is clearly an important function. In fact, it has been noted that the ability of mangroves to filter out sediment can also facilitate adjacent habitats that require clear water for photosynthesis, such as coral reefs and seagrasses (Hutchinson 2014). The mangroves' network of aerial roots, pneumatophores, and trunks act as a sieve, slowing water flow and causing the deposition of sediment, preventing it from reaching other habitats. Two studies in Micronesia estimate that the sediment portion trapped by mangroves can range from 15-40% (Golbuu et al. 2003, Victor et al. 2006).

Nitrogen removal

We did not find any studies of nitrogen cycling in Florida mangroves. However, a study on Twin Cays, Belize, a pair of mangrove islands, by Lee and Joye (2006) examined the rates of nitrogen fixation and denitrification in benthic microbial mats. They found that denitrification rates were broadly related to NO_3– inputs associated with land use, such as agriculture, industry, sewage and shrimp-farming, which suggests that mangrove mats, particularly those in fringe and transition habitats, may naturally mitigate anthropogenic dissolved inorganic nitrogen inputs. Of particular interest is their work on fringe mangroves, where microbial mats had high rates of denitrification and potentially limited nitrogen availability for the trees. Although previous studies have implied that denitrification is not a significant term in mangrove nitrogen budgets, they suggest that, given current data limitations, the general importance of denitrification in these ecosystems cannot be concluded at this time.

Part Six–Conclusions and Data Gaps

Living shorelines offer the possibility of combatting coastal erosion while preserving valuable ecosystem functions. As reviewed in this document, living shorelines serve as buffers and can control erosion by attenuating waves, trapping sediment, and providing protection from storm surge and flood waters. The use of natural vegetation such as marsh grasses or mangroves as well as the oysters that are often a part of living shoreline projects serve to provide habitat, filter pollutants and improve water quality. Living shorelines also maintain a link between aquatic and upland habitats, which would be lost if a hard barrier such as a bulkhead were installed.

Although there are many benefits associated with living shorelines, they are not effective in all conditions and project specific evaluations are necessary prior to design and implementation. The replacement of sub-tidal with intertidal habitat and soft-sediment with hard substrates such as sills, both of which will cause an alteration in ecosystem services is another potential disadvantage of living shoreline projects. Much of the southeastern coast is dominated by soft-bottom habitat, and natural rocky shorelines are rare to nonexistent, so installation of sills or edgings may favor recruitment of species that are normally limited by the availability of suitable substrate (Bilkovic et al. 2016).

There has been a great deal of interest in living shorelines in recent years and this is likely to increase given factors such as sea level rise and coastal development pressure. Recent reports and multi-state conferences that focused on the research gaps surrounding living shorelines on the east coast include: the 2006 Living Shoreline Summit (Erdle et al. 2006); the 2013 Mid-Atlantic Living Shoreline Summit (MD DNR et al. 2013); the 2015 report from the National Science and Technology Council's Coastal Green Infrastructure and Ecosystem Task Force (CGIES Task Force 2015); and the 2016 South Atlantic Living Shoreline Summit (GSAA 2016).

Most of these efforts included descriptions of various living shoreline projects as well as discussions of management, outreach and research needs. The consensus among these groups was that more quantitative studies of living shorelines need to be conducted in order to determine what types of techniques are most successful under a variety of conditions. Comparative assessments of living shorelines compared to more traditional methods of shore stabilization are also needed. Participants of the 2006 Living Shoreline Summit suggested that future research on living shorelines should include: "1) studying the performance of various design options and identification of optimum conditions (low, medium, high energy) for each; 2) developing more technical engineering specifications; 3) determining the effects of rising sea level on project longevity and success; 4) identifying how living shorelines affect the value of shoreline property; and 5) elucidating the sediment dynamics and how shoreline protection is affected by these processes" (Erdle et al. 2006). The CGIES Task Force (2015) reiterated many of these topics, and identified several more: "6) examination of the effects of living shorelines on water flows (from precipitation, runoff, river systems, storm surge, tides and waves), coastal erosion, damaging winds, and sediment movement; 7) comparisons of living shoreline designs (e.g., vegetative only) in various sites and conditions; and 8) quantification of the ecosystem benefits and tradeoffs associated with living shoreline approaches."

A greater understanding of the factors that affect living shoreline performance would allow for the development of clearly defined standards for monitoring success or failure. In order to accomplish this, the CGIES Task Force (2015) recommended that science-based standards which are "scalable, transferable, widely accepted, easily interpretable, and require limited resources and technical expertise to apply" should be identified for major types of living shoreline approaches and that new standards be developed for living shoreline methods for which current standards are nonexistent or inadequate.

As we synthesized information for this report we found a limited number of papers specifically focused on living shorelines in the Southeast forcing us to rely on research from Chesapeake Bay and elsewhere. Moreover, most of the living shoreline research we identified involved studies of the physical effects of living shorelines as opposed to chemical or biological characteristics, so we often had to rely on inference from restoration and natural systems. In particular, we found no studies specific to living shoreline projects that included mangroves and very few that evaluated projects that included oysters. It is probably reasonable to apply observations from natural and restored marshes and mangroves to living shorelines, as their functioning in terms of nutrient cycling or habitat provision is likely to be similar. However, it is worth keeping in mind that living shoreline projects tend to be narrow strips along the shore and so the best analog would most likely be studies of fringing marshes and mangroves. In terms of oyster reefs, studies of intertidal oysters (such as occur in Georgia) or small-scale dams in tidal creeks are probably the most relevant. Another consideration is that, although natural marshes and mangroves are appropriate controls for a living shoreline project, evaluations of living shorelines in comparison with bulkheads or other hard structures that might be used as an alternative are also important. Again, there were only a few studies that directly applied this approach (although see Gittman 2014 and Peterson and Bruno 2013).

Below is a list of additional knowledge gaps that were identified in the literature:

Living Shorelines in Salt Marshes

- The ecological impacts of installing living shorelines (Bilkovic et al. 2016)

- The regional ecological consequences of converting subtidal to intertidal habitat and existing soft-bottom intertidal habitat to artificial rocky shore (Bilkovic et al. 2016).
- Additional modeling and field observation to quantify the effectiveness of living shorelines for coastal risk reduction and quantify the effects of natural features on storm surge, wave energy, and sediment retention (NRC 2014).
- Flora and fauna species diversity in various types of living shorelines. Specifically, knowledge of vegetation composition and density change over longer time scales (USEPA 2010).
- The performance of living shorelines with respect to water quality and nutrient removal (MD DNR et al. 2013).

Living Shorelines in Mangroves

- Data to support the assumption that the density of mangrove vegetation and the diameter of aerial roots and stems affect their ability to reduce storm surge levels (McIvor et al. 2012b).
- Information necessary to determine the role of mangroves in storm surge protection (Zhang et al. 2012).
- Data quantifying successful restoration of mangrove ecosystem functions, especially data on how restored and created mangrove plant communities, soil properties, and soil-dependent ecosystem functions develop (Lewis et al. 2005).
- The specific mechanisms controlling plant influences on mangrove elevation dynamics through studies of interacting environmental (e.g. flooding, salinity) and plant (e.g. root accumulation) variables (Krauss et al. 2014).
- The study of mangrove areas undergoing disturbance (or regeneration) to assess how the presence or absence of vegetation may modify the land capacity to keep pace with sea level rise (Krauss et al. 2014).
- Longer term mangrove surface elevation datasets from more locations analyzed relative to sea level changes over the same periods of measurement (McIvor et al. 2013).

Although the questions raised above are generally relevant throughout the region, each state has its particular research needs. Studies on the use of mangroves in living shorelines are especially important for Florida since that is the only place where they occur. Information on the use and effects of natural and fabricated oyster reefs are especially applicable in North Carolina, South Carolina, and the panhandle region of Florida where restoration of dwindling historical reefs is under way. Georgia has only a limited number of projects to-date, and would benefit from studies that evaluate the efficacy of living shorelines in comparison to bulkheads.

Living shorelines are beginning to gain greater acceptance among natural resource managers and the general public as a viable alternative to traditional hard armoring methods of shore stabilization. In order to preserve this momentum, research into how living shorelines work, what makes for a successful project, and the appropriate time period for gaging success is required in various energy environments. Given the loss of natural shoreline that has already occurred, developing environmentally friendly erosion control alternatives to armoring will be important in the future for preserving and protecting the southeastern coast.

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Appendix A. Living Shoreline Projects in the Southeast

The following is a compendium of living shoreline projects in North Carolina, South Carolina, Georgia, and Florida. Each project summary includes the approximate location (if available), the reason(s) for the project, and the principle materials used in construction. A brief description of the implementation of the project is also provided where possible. Each summary ends with link(s) to further information. The page where each state begins is listed below:

North Carolina

Airlie Gardens Salt Marsh Restoration Project

Location: Airlie Botanical Gardens, Wilmington (34.2164, -77.8238)
Purpose: Shoreline stabilization; habitat enhancement
Approach: Vegetation only (phase 1)/Edging (phase 2)
Materials: Oyster shell; *S. alterniflora*
Description: Phase 1 of this project, involved clearing years of debris from the degraded shoreline, creating a wetland buffer area, and planting the shoreline with native vegetation. This project restored of 0.25 acres of wetland area. During Phase II, volunteers placed over 1,800 shell bags containing recycled oyster shells to create 4,000 square feet of oyster reef habitat along the Bradley Creek shoreline. One thousand *S. alterniflora* seedlings were then planted behind the reef to enhance the existing saltmarsh buffer.
Links: https://restoration.atlas.noaa.gov/src/html/index.html; http://www.nccoast.org/uploads/documents/factsheets/FS_AirlieGardens.pdf; https://neri.noaa.gov/neri/fullReport.html?projectId=792

Albemarle-Pamlico Peninsula

Location: Adjacent to the Alligator River National Wildlife Refuge (35.7927, -75.8766)
Purpose: Erosion control
Approach: Sill
Materials: Oyster shell; marl; *Phragmites australis*
Description: This project consisted of the construction of 400 feet of oyster shell bag reefs, 400 feet of marl reefs, three ditch plugs, a culvert upgrade and replacement, management of *Phragmites australis*, and the planting of over 40 acres of salt-tolerant hardwoods. The project resulted in 0.5 acres of restored oyster reef which are expected to: improve water quality by acting as a natural filter; create habitat for oysters, fish and other

marine animals; reduce erosion by buffering coastal lands against wave action; and provide a natural alternative to hardened shorelines.

Links:	http://www.nature.org/ourinitiatives/habitats/oceanscoasts/oyster-reef-restoration-southern-solutions-for-a-global-problem.xml; www.cakex.org/case-studies/alligator-river-national-wildlife-climate-adaptation-project

Bogue Sound Shoreline Restoration

Location:	34.7086, -76.8605
Purpose:	Shoreline stabilization
Approach:	Undetermined
Materials:	Granite; marl; wetland vegetation; submerged aquatic vegetation
Description:	500 linear feet of shoreline were stabilized through the placement of granite, marl and other alternative materials. In addition, 0.46 acres of wetland and 0.05 acres of submerged aquatic vegetation were planted.
Link:	https://restoration.atlas.noaa.gov/src/html/index.html

Bradley Oaks Shoreline Restoration Demonstration

Location:	Bradley Oaks Condominiums on Bradley Creek, Wilmington (34.2100, -77.8297)
Purpose:	Shore stabilization; enhance habitat
Approach:	Edging
Materials:	Biologs; marsh vegetation
Description:	This project was a combination of shoreline stabilization and the cultivation of an upland native vegetation buffer. The project included the use of the BIOLOG treatment (a natural alternative to bulkheads) with marsh plantings along approximately 400 feet of shoreline.
Links:	https://restoration.atlas.noaa.gov/src/html/index.html; https://neri.noaa.gov/neri/project.html?projectId=235

Carteret Community College

Location:	Morehead City on Bogue Sound (34.7227, -76.7548)
Purpose:	Stabilize and restore eroded shoreline
Approach:	Breakwater/Sill
Materials:	Oyster shell; oyster domes; oyster cultch bags; stone; submerged aquatic vegetation; marsh vegetation
Description:	This multi-faceted project involves: (1) restoration of wetland and intertidal habitat along ~1,000 linear feet of shoreline; (2) construction of offshore gapped breakwaters and stone sills for erosion control; (3) planting of submerged aquatic vegetation; (4) construction of a created wetland to help treat stormwater runoff from adjacent parking areas and roads; and (5) the placement of concrete oyster reef domes and oyster cultch bags as experimental sills.

Links: http://www.nccoast.org/uploads/documents/factsheets/FS_CCC.pdf; https://neri.noaa.gov/neri/project.html?projectId=1202

Columbia Shoreline Restoration

Location: Albemarle Sound near Columbia (36.0099, -76.2082)
Purpose: Shore stabilization
Approach: Sill
Materials: Stone; marsh vegetation
Description: The North Carolina Coastal Foundation constructed a stone sill and planted marsh vegetation on a private landowner's property. The project restored 425 linear feet of shoreline and 3,500 marsh seedlings were planted behind the sill, restoring 0.4 acres of tidal marsh.
Link: https://restoration.atlas.noaa.gov/src/html/index.html

Duke University Marine Laboratory

Location: Gallant's Channel (34.7436, -76.6731)
Purpose: Storm water control
Approach: Sill
Materials: Sand; granite; *S. alterniflora*; geotextile fabric
Description: For this project, 260 feet of degraded asbestos bulkhead at the Duke University Marine Lab was removed, and more than 700 feet of marsh along Bogue Sound was restored to create a viable oyster reef. In addition to the creation of 0.25 acres of tidal marsh, a vegetated swale and berm were constructed along the adjoining upland in order to intercept storm water from the road and university buildings and encourage filtration. Several hundred live oysters were removed from the site before construction and replaced to form reefs after the bulkhead was removed.
Link: https://restoration.atlas.noaa.gov/src/html/index.html; http://mycopri.org/node/87

Durant's Point

Location: North of Hatteras Harbor (35.2326, -75.6809)
Purpose: Erosion control
Approach: Sill
Materials: Granite; *Spartina* plants
Description: This project involved stabilizing 240 feet of eroding shore through construction of a low-profile granite sill and creation of 1.2 acres of marsh habitat through the installation of *Spartina* plants.
Link: https://restoration.atlas.noaa.gov/src/html/index.html; http://www.nccoast.org/uploads/documents/factsheets/FS_DurantsPoint%5B1%5D.pdf

Edenhouse Shoreline Restoration

Location: Edenhouse Landing along the Chowan River
Purpose: Shoreline stabilization
Approach: Undetermined
Materials: N/A
Description: Stabilization of 400 linear feet of shoreline allowed for the restoration of coastal marsh and an adjacent riparian shrub zone and forested buffer area.
Link: https://restoration.atlas.noaa.gov/src/html/index.html

Emerald Isle Property Shoreline Restoration

Location: Bogue Sound (34.6824, -76.9292)
Purpose: Enhance habitat; prevent erosion
Approach: Groin
Materials: Stone; salt marsh plants
Description: To encourage the growth of marsh in the area and to buffer the shoreline during periods of high wakes or storm activity, four stone groins were installed to hold and trap sand, creating stable cells to support newly planted marsh habitat. After installation of the groins, volunteers planted more than 3000 salt marsh plants to restore 0.1 acres of tidal wetland habitat.
Link: https://restoration.atlas.noaa.gov/src/html/index.html

Federal Point Public Boating Access Area

Location: Buzzard Bay (33.9586, -77.9417)
Purpose: Erosion protection; stormwater management
Approach: Sill
Materials: Sand; armor stone, core stone; *S. alterniflora* and *S. patens*
Description: A 200-foot rubble-mound sill was constructed of 100-200 pounds of armor stone, 10-30 pounds of core stone, 1-2 inches of bedding stone, and geotextile fabric. Three hundred cubic yards of sand was used as fill. *S. alterniflora* and *S. patens* were then planted between the structure and the MHW line. Additional ecological benefits from this project include creation of marsh and intertidal habitat and improvement of water quality.
Link: http://mycopri.org/node/1642

Green Property Shoreline Restoration

Location: Pine Knoll Shores (34.7030, -76.8105)
Purpose: Prevent erosion from high intensity wave energy and storm surge
Approach: Sill
Materials: Stone; wetland plants
Description: A stone sill was constructed along the entire 400-foot shoreline. An environmental science class from Carteret Community College then planted approximately 2000

wetland plants on the shoreline resulting in the restoration of 0.2 acres of tidal wetland habitat.

Link: https://restoration.atlas.noaa.gov/src/html/index.html

Hammock Beach State Park Wetland (Shoreline) Restoration

Location: Bogue Sound (34.6702, -77.1396)
Purpose: Shoreline stabilization
Approach: Sill
Materials: Granite; *S. alterniflora* and *S. patens*
Description: For this project, a 200-foot bulkhead was removed and coastal marsh was restored along the shoreline. A granite rubble-mound sill was constructed in front of the restored shoreline to reduce wave energy.
Links: https://restoration.atlas.noaa.gov/src/html/index.html; http://mycopri.org/node/87

Harkers Island Shoreline Restoration

Location: 34.7120, -76.5665
Purpose: Habitat enhancement
Approach: Sill
Materials: Stone; marsh vegetation
Description: The construction of a stone sill, placement of fill, regrading of substrate, and planting of marsh plants restored 400 linear feet of shoreline along Harker's Island in Bogue Sound. One acre of tidal wetland habitat was restored.
Link: https://restoration.atlas.noaa.gov/src/html/index.html

Ice Plant Island

Location: 35.7635, -79.0277
Purpose: Erosion control
Approach: Sill
Materials: Stone; trees; salt marsh plants
Description: An 810-foot stone sill and revetment was constructed in order to restore one half acre of coastal marsh, protect 3.6 acres of coastal marsh fringe, and halt further erosion. Enhancement of the upland buffer was completed with the planting of 100 Atlantic white cedar, 1,000 pine trees and 200 live oaks. The project was completed after the planting of 3,000 salt marsh plants behind the stone sill.
Link: https://restoration.atlas.noaa.gov/src/html/index.html

Jockey's Ridge State Park

Location: Roanoke Sound (35.9612, -75.6408)
Purpose: Habitat enhancement; erosion control
Materials: Oyster shell; biologs; *S. alterniflora*

Approach: Sill

Description: A low profile sill containing 4,000 bushels of bagged oyster shells and biologs was constructed. Behind the sill, *S. alterniflora* grass was planted. About 1.5 acres of marsh and riparian habitat was restored along 725 feet of shoreline.

Links: https://restoration.atlas.noaa.gov/src/html/index.html; http://www.nccoast.org/uploads/documents/factsheets/FS_JockeysRidge.pdf

Jones Island

Location: 34.6986, -77.1071

Purpose: Control shoreline and marsh erosion; enhance habitat

Approach: Sill

Materials: Recycled oyster shells; marl; cordgrass

Description: The overall goals of the project were to reestablish fringing marsh along the shoreline and to enhance oyster growth in waters just offshore. To accomplish this, 4,000 oyster shell bags were placed on the north side of the island forming temporary shoreline sills that would act to reduce wave-induced shoreline and marsh erosion. In addition to the creation of 3 acres of oyster reef/shell bottom habitat, a total of 12,000 smooth cordgrass plugs were planted, restoring 0.3 acres of salt marsh habitat.

Links: http://www.nccoast.org/uploads/documents/factsheets/FS_JonesIsland.pdf; http://mycopri.org/system/files/content/Living%20Shorelines%20Task%20Committee/Jones%20Island%20Oyster%20and%20Marsh%20Habitat%20Restoration/Jones%20Island%20Application%20for%20Permit_1.pdf; https://restoration.atlas.noaa.gov/src/html/index.html

Morris Landing

Location: South of Cape Lookout on Stump Sound (34.4695, -77.5084)

Purpose: Erosion control; habitat enhancement

Approach: Sill

Materials: Stone; oyster shell; juvenile oysters; marsh vegetation

Description: A 600-foot stone and oyster shell bag sill was installed along the shoreline, and marsh habitat was restored behind the sill. In addition, 16,000 bushels of oyster shell were deposited to create oyster reefs in Stump Sound. These reefs have been seeded with juvenile oysters to help increase the oyster population on the newly-created reefs.

Link: http://www.nccoast.org/uploads/documents/factsheets/FS_morrislanding.pdf; https://restoration.atlas.noaa.gov/src/html/index.html

Nags Head Oyster Restoration and Shoreline Protection

Location: Nags Head Woods Ecological Preserve on the Outer Banks (35.9848, -75.6651)

Purpose: Erosion control

Approach: Sill

Materials: Oyster shell; widgeon grass; submerged aquatic vegetation

Description: This project restored a highly eroding high-bank shoreline and marsh through construction of fringing oyster reef using shell bags followed by seeding over with native widgeon grass and plantings. Approximately 0.1 acres of oyster reef, 0.25 acres of submerged aquatic vegetation, and 0.5 acres of wetlands and uplands were restored.

Link: https://restoration.atlas.noaa.gov/src/html/index.html; http://projects.tnc.org/coastal/

Neuse River Property Shoreline Restoration Demonstration

Location: 35.0428, -76.9888

Purpose: Habitat enhancement

Approach: Sill

Materials: Stone; marsh vegetation

Description: A stone sill was constructed and the backfill area was graded to provide a platform for planting marsh grass. A tenth of an acre of upland habitat and tidal wetland was restored.

Link: https://restoration.atlas.noaa.gov/src/html/index.html

North Carolina Center for the Advancement of Teaching

Location: Near Silver Lake, Ocracoke Island (35.1146, -75.9810)

Purpose: Protect against erosion caused by large waves and boat wake

Approach: Sill

Materials: Granite; sand; *S. alterniflora*, *S. patens*, and *J. roemericanus*

Description: An offshore sill was constructed of granite along 725 feet of the campus' shoreline. Sand fill was brought in for surface grading, and over an acre of salt marsh was created through planting of *S. alterniflora*, *S. patens*, and *J. roemericanus*. Upland vegetation was also planted to minimize blowing sand.

Link: http://www.nccoast.org/uploads/documents/factsheets/FS_NCCAT.pdf

North Carolina Maritime Museum Shoreline

Location: Gallant's Channel, Beaufort (34.7290, -76.6677)

Purpose: Erosion control

Approach: Sill

Materials: Stone; *S. alterniflora* and *S. patens*

Description: This project involved the removal of a deteriorated steel bulkhead and discarded debris. Three stone sills were constructed to stabilize 315 feet of eroding marsh shoreline. Students and volunteers planted *S. alterniflora* and *S. patens* in three restoration areas. Two acres of tidal wetland habitat were restored.

Links: https://restoration.atlas.noaa.gov/src/html/index.html; http://mycopri.org/node/45

Oriental Shoreline Restoration

Location: Private property on the Neuse River near Oriental (35.0654, -76.6204)
Purpose: Shoreline stabilization
Approach: Sill
Materials: Stone; salt marsh vegetation
Description: This project resulted in the construction of a stone sill followed by the planting of salt marsh vegetation. Nearly 800 linear feet of shoreline was stabilized and 0.8 acres of tidal marsh was restored.
Link: https://restoration.atlas.noaa.gov/src/html/index.html

Pine Knoll Shores Aquarium Shoreline Restoration

Location: 34.7013, -76.8319
Purpose: Erosion prevention
Approach: Sill
Materials: Oyster shell; *Spartina*; stone
Description: This project restored 430 feet of coastal marsh habitat along the shoreline with the construction of a stone sill for erosion protection of the existing marsh and enhanced oyster habitat in the area. Volunteers planted 1,300 *Spartina* plants along the shoreline and spread approximately 3,000 pounds of oyster shell behind the constructed sill.
Link: https://restoration.atlas.noaa.gov/src/html/index.html

Rachel Carson National Estuarine Research Reserve (Carrot Island)

Location: 34.7128, -76.6446
Purpose: Stabilize shoreline
Approach: Sill
Materials: Oyster shell; *S. alterniflora*
Description: Twenty small patch reefs across five unique landscapes were constructed. Four 60-bushel reefs were built immediately adjacent to marsh scarps, while another six 60-bushel reefs were built on marsh ramp shorelines. Within the network of marsh creeks, eight more 60-bushel reefs were constructed: four reefs at the entrances of secondary tributaries, and four reefs along the banks of the primary creek (and at least 20 miles from a secondary creek). In addition, 3 long sills (2 shorter, 1 longer) were constructed that extend across ~230 miles of shoreline (interrupted by ~ 30 mile gaps among the three sills). Following sill construction, about 3,000 young *S. alterniflora* plants were planted.
Link: http://www.nccoastalreserve.net/c/document_library/get_file?uuid=74b7e822-1dc5-42d0-a004-1cd65b203ba4&groupId=61572

Sneads Ferry Shoreline Restoration

Location: 34.5380, -77.3782
Purpose: Shoreline stabilization
Approach: Undetermined

Materials: Marl; granite; oyster cultch and larvae

Description: The stabilization of 250 linear feet of eroding coastal marsh through the placement of marl and granite, and the seeding of oyster cultch and larvae, resulted in the restoration of 0.1 acre of tidal wetland, and protection of an additional 0.5 acres tidal wetland and 0.1 acre of oyster habitat.

Link: https://restoration.atlas.noaa.gov/src/html/index.html

Swanquarter National Wildlife Refuge Shoreline Oyster Restoration Project

Location: Bell Island Fishing Pier (36.4217, -75.9655)

Purpose: Enhance habitat; erosion protection

Approach: Undetermined

Materials: Marl

Description: This project restored 0.23 acres of oyster/shell bottom habitat adjacent to Bell Island Fishing Pier in Swanquarter National Wildlife Refuge through construction of segmented shoreline oyster reefs using marl (limestone), which was deployed along 600 linear feet of eroding shoreline. The resultant reefs measured 0.23 acres (approximately 660 feet by 15 feet total).

Link: https://restoration.atlas.noaa.gov/src/html/index.html; http://www.projects.tnc.org/coastal

Town of Southport

Location: Cape Fear River (33.9194, -78.0129)

Purpose: Erosion control

Approach: Sill

Materials: Granite; marl; *S. alterniflora* and *S. patens*

Description: A 500-foot sill was constructed out of a mix of granite, concrete riprap and marine limestone. *S. alterniflora* and *S. patens* were then planted between the structure and the MHW line to protect the area from high boat wake.

Link: http://mycopri.org/node/13

South Carolina

City of Charleston Shoreline Restoration – Plymouth Park Shoreline

Location: 32.7679, -79.9922

Purpose: Stabilize eroding shorelines

Approach: Undetermined

Materials: N/A

Description: This project, when implemented, will reduce erosion along 275 feet of eroding shoreline and demonstrate methods of stabilizing eroding shorelines, revitalizing degraded salt marsh, and increasing fisheries habitat all in recreational areas with high value to the public.

Link: https://restoration.atlas.noaa.gov/src/html/index.html

City of Charleston Shoreline Restoration –Daniel Island Trail

Location: 32.8592, -79.9012
Purpose: Stabilize eroding shorelines; enhance habitat
Approach: Undetermined
Materials: N/A
Description: This project will demonstrate methods of stabilizing eroding shorelines, revitalize a degraded salt marsh, and increase fisheries habitat. At this site, archaeological remnants of a post-Civil War freedman's settlement will be protected by an oyster reef and the sediment that collects behind it facilitating the colonization and spread of marsh grass.
Link: https://restoration.atlas.noaa.gov/src/html/index.html

ACE Basin NERR Living Shorelines and Coastal Resilience Strategy

Location: Multiple small-scale demonstration projects throughout the ACE NERR
Purpose: Erosion protection; habitat enhancement
Approach: Edging
Materials: Oyster shell; *Spartina*
Description: Between April 2013 and May 2015, this project led to 53 reef-building events at 38 discrete locations through the ACE Basin NERR, through the deployment of four different reef substrates (loose oyster shell (11 sites), bagged oyster shell (27 sites), concrete oyster castles (8 sites), and re-purposed cement crab traps (7 sites)), matched to site characteristics. All four substrates were placed directly on the shore in front of marsh vegetation. Through the deployments of these four reef substrates, this project led to the protection of 9,256 linear feet (> 1.7 miles) of shoreline.
Links: http://sagecoast.org/info/searchresults.php; http://50.87.232.11/wp-content/uploads/2015/09/project-page_overview_bringing-shorelines-to-life-in-south-carolina.pdf

Restoration of Intertidal Oyster Reefs as Habitat for Finfish in South Carolina

Location: N/A
Purpose: Habitat enhancement; erosion protection
Approach: Undetermined
Materials: N/A
Description: This project provides baseline data on the direct use of restored intertidal oyster reefs by finfish through the restoration of 0.75 acres of oyster reef/shell bottom.
Link: https://restoration.atlas.noaa.gov/src/html/index.html

South Carolina Oyster Reefs

Location: Multiple small-scale demonstration projects
Purpose: Stabilize and control erosion
Approach: Undetermined
Materials: Oyster shell; mesh
Description: NOAA's Restoration Center worked with the South Carolina Department of Natural Resources to implement an oyster restoration project along the coast of South Carolina through multiple small-scale demonstration projects. This project focused on restoring oyster habitat bordering salt marsh in tidal creeks and studied how intact oyster habitats can stabilize and control fringing marsh and mud bank erosion. Recycled oyster shell and stabilizing mesh was used to establish suitable substrate for reef development. Over a four year period this program has constructed a total of 98 volunteer-built reefs at 28 sites along the South Carolina coast.
Link: https://restoration.atlas.noaa.gov/src/html/index.html

The Nature Conservancy Living Shorelines Pilot Project

The Nature Conservancy, in partnership with the South Carolina Department of Natural Resources and many other organizations and volunteers, constructed several living shorelines as a way to promote oyster populations along South Carolina's coast and prevent shoreline erosion.

Goldbug Island

Location: 32.7742, -79.8404
Purpose: Enhancing oyster reefs; slow erosion from sea level rise; absorb impact from storm & boat wakes
Approach: Edging
Materials: Oyster castle blocks (concrete, limestone, crushed shell and pozzolan); wood; bagged (recycled) oyster shells
Description: The Goldbug Island Living Shoreline project consists of a 240' long reef and is made of wooden pallets, oyster castles, cement blocks, and bagged shell to stabilize marsh edge. Pallets were wrapped in geotextile fabric before deployment and then six oyster castles, three cement blocks and nine bags of shell were placed on top of each pallet. The reef was designed by CH2M so materials are elevated out of the mud, promote optimal oyster growth, and attenuate wave energy. All materials have all been used before, but never in this combination. TNC will be monitoring water quality, oyster recruitment, oyster growth and marsh vegetation growth. SCDNR will be assessing sediment composition and accretion behind the reef. This project is part of a two-year grant from Wildlife Conservation Society where TNC partnered with Lowcountry Land Trust to install and monitor living shoreline pilot projects adjacent to privately conserved coastal properties.
Link: http://projects.tnc.org/coastal

Expansion of Oyster Reef Enhancement on Jeremy Island

Location: Cape Romaine National Wildlife Refuge (33.0858, -79.4255)

Purpose: Slow erosion and protect shorelines; Enhance habitats for oysters, fish, crabs, and other marine life

Approach: Edging

Materials: Oyster castle blocks (concrete, limestone, crushed shell and pozzolan)

Description: The South Carolina Chapter of the Conservancy and SC DNR evaluated the effectiveness of concrete "oyster castles" to support oyster reef habitat development at two field sites around Jeremy Island during monitoring from 2011 - 2013. Reef restoration work from 2009 that showed the novel restoration structures, oyster castles, can successfully recruit larval oysters. This project resulted in the creation of an additional 0.01 acres of oyster reef built from 2 arrays of 295 stacked castles in 2011. The project demonstrated that oyster castles can provide shoreline stabilization when deployed in a single, linear three-dimensional configuration.

Link: https://restoration.atlas.noaa.gov/src/html/index.html; http://projects.tnc/coastal

Oak Point, Wadmalaw Island

Location: 32.6818, -80.1763

Purpose: Control shoreline erosion

Approach: Edging

Materials: Bagged (recycled) oyster shell

Description: The Oak Point Living Shoreline project is 100' long and made of bagged shell to stabilize marsh edge and support habitat development. The reef is four rows of bagged shell; the top row of bags is parallel to shoreline (1 bag deep) and the three rows below are perpendicular to shoreline with a double layer of bagged shell. Monitoring by the SCDNR Geological Survey showed sediments accreted quickly behind and on the reef materials. However, sedimentation precluded oyster recruitment and growth.

Link: http://projects.tnc.org/coastal/

Palmetto Plantation Restoration

Location: Along the Atlantic Intracoastal Waterway, northeast of McClellanville (33.079, -79.4515)

Purpose: Enhance habitat; control shoreline erosion and stabilize adjacent shoreline; absorb impact from boat wakes

Approach: Edging

Materials: Oyster castle blocks (concrete, limestone, crushed shell and pozzolan

Description: The Palmetto Plantation Oyster Castle Reef was installed in August 2012 by Boeing employees on the northwest bank of the Atlantic Intracoastal Waterway (ICW) northeast of McClellanville, SC. The reef is approximately 18m x 1.75m in dimension at the base and approximately 0.5m high. The reef is 60 blocks long

	(parallel to the shore) and 6 blocks wide at the base and comprises four total stacked levels. The project is Site surveys, including shoreline change analyses, sediment grainsize distributions, and oyster recruitment observations, were conducted from June 2012 through October 2013 by the College of Charleston to address the overall goal of enhancing oyster reefs in this area while stabilizing the adjacent shoreline. This goal was accomplished with the reef installation project.
Links:	http://projects.tnc.org/coastal; http://projects.tnc.org/coastal/assets/SC/PalmettoPlantationRestoration/PalmettoPlantationRestoration_FinalReport.pdf

Stono River – Phase I (James Island County Park Oyster Restoration)

Location:	32.7231, -79.9962
Purpose:	Enhancing oyster reefs; slow erosion from sea level rise; absorb impact from storm & boat wakes
Approach:	Edging
Materials:	Oyster castle blocks (concrete, limestone, crushed shell and pozzolan)
Description:	For a second year, Boeing partnered with TNC's South Carolina Chapter to install an oyster reef project around Charleston. The Conservancy partnered with Boeing, Coastal Expeditions and the Charleston County Parks & Recreation to install a continuous oyster reef configuration using oyster castle blocks on the Stono River. The reef was constructed using 600 blocks placed into three linear shapes parallel to the shoreline. The oyster castles reefs were monitored by College of Charleston interns for 12 months. Oysters have encrusted the reef and continue to grow around the castle blocks. The back side of the single configurations has accumulated sediments and is covering oysters that were growing on the lower levels of the oyster castle blocks. This was an intended result and in the spring of 2015 natural *S. alterniflora* has established itself behind the back, center portion of the front linear reef.
Link:	http://projects.tnc.org/coastal

Tibwin Creek, Francis Marion National Forest

Location:	33.0849, -79.5077
Purpose:	Control shoreline erosion
Approach:	Edging
Materials:	Bagged (recycled) oyster shell; wood pallets; coconut fiber coir logs
Description:	In 2009, the Conservancy partnered with SC DNR SCORE to help create an oyster reef in Tibwin Creek within the boundaries of the Francis Marion National Forest using mesh bags of oyster shells layered on untreated wood pallets. Coir logs were installed on the landward side of the reef to reduce sedimentation over

the shells from the eroding shoreline. The new reef covers 25 square meters, connecting two existing natural reefs.

Links: http://www.nature.org/ourinitiatives/habitats/oceanscoasts/oyster-reef-restoration-southern-solutions-for-a-global-problem.xml; http://projects.tnc.org/coastal

Winyah Bay, South Island

Location: Tom Yawkey Wildlife Center Heritage Preserve on South Island in Georgetown (33.1991, -79.2326)

Purpose: Erosion control

Approach: Edging

Materials: Oyster castle blocks (concrete, limestone, crushed shell and pozzolan); *S. alterniflora*

Description: Ten separate oyster castle groups of 100 castles each were placed approximately one mile within the intertidal zone of Winyah Bay. *S. alterniflora* was subsequently planted behind each castle group along the beach.

Links: http://projects.tnc.org/coastal/; http://projects.tnc.org/coastal/assets/SC/WinyahBaySouthIslandLivingShoreline/WinyahBaySouthIslandLivingShoreline_FinalReport.pdf

Winyah Bay, North Island

Location: 33.2511, -79.1955

Purpose: Shoreline stabilization

Approach: Edging

Materials: Oyster castle blocks (concrete, limestone, crushed shell and pozzolan)

Description: In this project, 360 oyster castle blocks (5 groups of 15 feet each) were sited along the edges of existing marsh grass populations that displayed signs of erosion.

Link: http://projects.tnc.org/coastal/

Georgia

Bellville Boat Ramp, McIntosh County

Location: north McIntosh County along the Sapelo River (31.5317, -81.3600)

Purpose: Enhance habitat for fish, birds and invertebrates; Increase viability of salt marshes

Approach: Edging

Materials: Oyster shell; oak bundles

Description: One hundred mesh bags of oyster shells were placed on a firm substrate along a stretch of an eroding vegetative edge of the river adjacent to the boat ramp. Live oak tree limbs, downed by a hurricane, were wrapped with agricultural fencing to create 125 oak bundles. Subsequently, 100 oyster spat sticks were constructed by covering 6-foot bamboo poles with resin and then dusted with cement. Researchers placed two rows of oak bundles along the intertidal zone and staked them down with spat sticks. The space between the rows was filled with the remaining spat sticks. The oyster reefs were built using both recycled oyster shell and non-traditional cultch material such as bundled wood, bamboo spat sticks, and fish attracting devices that have proven to work as oyster habitat.

Link: http://www.nature.org/ourinitiatives/habitats/oceanscoasts/oyster-reef-restoration-southern-solutions-for-a-global-problem.xml

Burton 4-H Center, Tybee Island

Location: Horse Pen Creek (32.0077, -80.8511)
Purpose: Shore stabilization; habitat enhancement
Approach: Edging
Material: Oyster shell; native plants
Description: UGA Marine Extension and Georgia Sea Grant recently completed the construction and installation of the base layer for a living shoreline project at the Burton 4-H Center on Tybee Island. The goals of this project are to stabilize an eroding bank at the Burton 4-H Center and increase the amount of oyster and marsh habitat in Horse Pen Creek. The final layer of the shoreline will be installed in 2016.
Link: http://marex.uga.edu/story/living-shoreline-on-tybee-completion/

Cannon's Point, St. Simons Island

Location: Cannon's Point Preserve, Lawrence Creek (31.2872, -81.3246)
Purpose: Habitat enhancement; shoreline stabilization
Approach: Edging
Materials: Oyster shell
Description: Completed in 2015, this project is comprised of 8,000 bags of oyster shells placed along the bank of Lawrence Creek adjacent to the former Taylor's Fish Camp site.
Link: http://www.sslt.org/news.php?id=2015_05_26

The Lodge, Little St. Simons Island

Location: The Lodge on Little St. Simons (31.2940, -81.3455)
Purpose: Stream bank stabilization; habitat enhancement
Approach: Edging
Materials: Oyster bags; recycled concrete; native plants; geo-grid
Description: This project removed a failing bulkhead on Little St. Simons Island and installed a 285-foot living shoreline in its place to provide stream bank stabilization, habitat for eastern oysters, and essential fish habitat. The project involved the shaping of the embankment and the application of oyster bags, recycled concrete, and native plants. The plan also

involved encasing the first layer of oyster bags in geo-grid (an extremely durable mesh that is a structural component in road construction) in order to create flexible cohesion and structural integrity. The geo-grid was designed to be anchored into the embankment in order to prevent the downward subsidence of materials. Islands of intertidal vegetation were planted throughout the shoreline. Approximately 25 plant species totaling more than 1,500 individual plants were installed along the intertidal and upper transitional zone of the project site.

Link: https://restoration.atlas.noaa.gov/src/html/index.html; http://gcmp.maps.arcgis.com/apps/MapTour/index.html?appid=fa83fbc0786542ff99dbf12b509ffbc5&webmap=b5e08e21085a403faec4086381edcb34#

Ashantilly - Sapelo Island

Location: Post Office Creek (31.4319, -81.2855)

Purpose: Control erosion; enhance habitat for fish, birds and invertebrates

Approach: Edging

Materials: Oyster shell – bagged and loose; rock; native trees and plants

Description: The site design and construction at Ashantilly consisted of grading the eroding embankment and placing a granite toe on the lower intertidal embankment for added support. Mesh bags of used oyster shells were then arranged in two layers along a 370-foot section of the creek bank and secured with non-treated pine stakes. Native marsh plants as well as upper transitional zone plants were also installed.

Links: http://www.nature.org/ourinitiatives/habitats/oceanscoasts/oyster-reef-restoration-southern-solutions-for-a-global-problem.xml; http://gcmp.maps.arcgis.com/apps/MapTour/index.html?appid=fa83fbc0786542ff99dbf12b509ffbc5&webmap=b5e08e21085a403faec4086381edcb34#

Long Tabby - Sapelo Island

Location: Post Office Creek (31.4319, -81.2855)

Purpose: Control erosion; enhance habitat for fish, birds and invertebrates

Approach: Edging

Materials: Oyster shell – bagged and loose; rock; native trees and plants

Description: At the Long Tabby site, gabion baskets (also called reno-mattresses) made of chain-linked welded steel measuring 6 feet by 12 feet were filled with a combination of bags of shell, loose shell, and rock. The cages were then embedded along 230 feet of creek bank in an alternating pattern.

Links: http://www.nature.org/ourinitiatives/habitats/oceanscoasts/oyster-reef-restoration-southern-solutions-for-a-global-problem.xml; http://gcmp.maps.arcgis.com/apps/MapTour/index.html?appid=fa83fbc0786542ff99dbf12b509ffbc5&webmap=b5e08e21085a403faec4086381edcb34#

Florida

A.J. Palonis Park Oyster Restoration

Location: A.J. Palonis Jr. Park in Tampa Bay (27.8917, -82.5388)
Purpose: Erosion prevention; enhance habitat
Approach: Breakwater
Materials: Oyster shell; salt marsh vegetation
Description: For this project, oyster shell material was placed on tidal flats to create oyster reefs at five sites within the park and salt marsh vegetation was planted on the shoreline behind the new oyster reefs in an effort to restore lost habitat, prevent further erosion of shorelines and improve water quality through natural filtration. Nearly 40 tons of oyster shells were used in construction of the restoration site.
Link: https://restoration.atlas.noaa.gov/src/html/index.html

Andrew's Island Oyster Bar Creation Project

Location: northern Boca Ciega Bay, St. Petersburg (27.7910, -82.7736)
Purpose: Habitat enhancement; erosion reduction
Approach: Breakwater
Materials: Oyster shell
Description: In this project, 31 tons of oyster shell in net bags was deployed to create close to 400 feet of oyster reef. The project was conducted at Andrew's Island, a mangrove-covered island, in order to restore lost oyster reefs, reduce erosion along the shoreline, improve water quality, and enhance habitat for fish and wildlife.
Link: https://restoration.atlas.noaa.gov/src/html/index.html

Bayfront Park, Sarasota

Location: Bayfront Park, Sarasota (27.3310, -82.545)
Purpose: Public education; stabilize shoreline; create habitat
Approach: Vegetation only
Materials: Native plants
Description: In 2014, the Sarasota Bay Estuary Program, in partnership with the City of Sarasota, created a living shoreline along Bayfront Park in downtown Sarasota. The project featured 150 feet of native plants within three tidal zones (lower, middle and high) intended to stabilize sediments and provide intertidal habitat. The project was designed to showcase the natural beauty and benefits of these alternatives to more traditional hardened (sea walls) shorelines. An interactive sign provided the many bayfront strollers with information on the benefits of living shorelines and a link to the SBEP website to learn more about these alternatives to hardened shorelines and how to go about considering one for themselves.
Link: http://floridalivingshorelines.com/project/bayfront-park

Bear Cut Preserve Wetlands Restoration

Location: North end of Key Biscayne (40.7127, -74.0059)
Purpose: Mangrove habitat creation/enhancement
Approach: Vegetation only
Materials: Marsh vegetation
Description: Four acres were cleared and exotic vegetation was removed following the excavation of 41,600 cubic yards of dredge spoil material. A network of intertidal flushing creeks and a 0.5 acre fresh/brackish water pool were installed. Ten acres of mangroves, 6.2 acres of high salt marsh, and 2.8 acres of tidally flushed pond were planted with 18 species of native plants. http://www.globalrestorationnetwork.org/uploads/files/LiteratureAttachments/251_restoration-of-coastal-wetlands-in-southeastern-florida.pdf

Bill Baggs Cape Florida State Park Wetlands Restoration

Location: South end of Key Biscayne (25.6797, -80.1694)
Purpose: Mangrove habitat creation/enhancement
Approach: Vegetation only
Materials: Seven species of marsh vegetation, including *Rhizophora mangle* and *S. bakeri*
Description: This project consisted of: clearing exotic vegetation; removing 30,000 cubic yards of solid waste; removing 600,000 cubic yards of dredge spoil material, creating 75 acres of tidally connected mangrove wetlands; installing 3 major flushing connections and culvert connection; installing a network of intertidal flushing creeks, and creating 10 acres of freshwater isolated wetlands. http://www.globalrestorationnetwork.org/uploads/files/LiteratureAttachments/251_restoration-of-coastal-wetlands-in-southeastern-florida.pdf

Blowing Rocks Preserve, Hobe Sound

Location: Hobe Sound
Purpose: N/A
Approach: Vegetation only
Materials: Marsh vegetation
Description: This naturally rocky Indian River Lagoon shoreline was restored by planting 1 gallon salt meadow cordgrass (*S. patens*) and red mangroves (*Rhizophora mangle*). Other native plants also successfully colonized the site.
Link: http://floridalivingshorelines.com/project/blowing-rocks-preserve/

Canaveral National Seashore

Location: Canaveral National Seashore (28.7868, -80.7546)
Purpose: Reduce erosion; stabilize shoreline
Approach: Edging

Materials: *S. alterniflora*; mangroves; oyster shell bags; oyster mats

Description: This project involved planting of emergent vegetation in the site's intertidal zone, deploying bags of oyster shells seaward of the cordgrass, and placing oyster restoration mats seaward of the bags. Plantings consisted of *S. alterniflora* in the mid-intertidal zone and *Rhizophora mangle* (red mangrove) and *Avicennia germinans* (black mangrove) in the upper intertidal zone.

Links: https://www.nps.gov/subjects/climatechange/upload/2015-11-25-FINAL-CAS-Case-Studies-LoRes.pdf; http://patimes.org/sustainable-coastal-restoration-stabilization-living-shoreline-project-floridas-east-coast/

Canaveral Tidal Pool Park

Location: 28.4105, -80.5993

Purpose: Habitat enhancement

Approach: Vegetation only

Materials: Red mangroves; black mangroves

Description: This project restored mangrove and saltmarsh grass habitat along 5,200 linear feet of shoreline at Port Canaveral. Restoration activities included planting 250 black mangrove seedlings, 20,000 rooted red mangrove propagules, and 4,000 smooth cordgrass sprigs. Approximately 30 acres of native vegetation were restored and the site now provides a source of increased recreational and educational opportunities for the community

Link: https://restoration.atlas.noaa.gov/src/html/index.html

Castillo de San Marcos National Monument Living Shoreline Project

Location: 29.8978, -81.3115

Purpose: Shoreline stabilization

Approach: Breakwater

Materials: *S. alterniflora*; coquina rock; sand

Description: In 2010, upon a recommendation from National Marine Fisheries Service, the National Park Service designed a living shoreline approach that included constructing a subtidal sheet piling wall topped and fronted with coquina rock and existing oyster rubble to act as a breakwater. The landward edge of this sediment trap was planted with smooth cordgrass to accrete sediment on the shoreline and buffer the seawall from future erosion.

https://www.dep.state.fl.us/coastal/sites/gtm/pub/ctp/living_shorelines/Castillo_de_San_Marcos_Getsinger.pdf

Charlotte Harbor Oyster Habitat Creation

Location: Adjacent to the City of Punta Gorda's Trabue Harborwalk (26.9101, -82.0957)

Purpose: Protection against erosion, sea level rise; habitat enhancement

Approach: Edging

Materials: Oyster bags; oyster mats; loose oyster shell

Description: Oyster mats, oyster bags and loose shell secured by a perimeter of oyster bags were placed in the northern portion of the Charlotte Harbor Preserve Park to help protect the mangrove shoreline.

Link: http://projects.tnc.org/coastal/

Chicken Island in Indian River Lagoon

Location: Marine Discovery Center of New Smyrna Beach (29.0299, -80.9125)

Purpose: Enhance oyster and finfish habitat; reduce shoreline erosion

Approach: Edging

Materials: Oyster mats; oyster bags

Description: Between 2008 and 2010, artificial oyster mats and oyster bags were used to restore 0.35 acres of oyster habitat in a high traffic boating area along the shoreline of Chicken Island in the Indian River Lagoon.

Link: https://restoration.atlas.noaa.gov/src/html/index.html; http://projects.tnc.org/coastal/

Chicken Key Bird Rookery Restoration

Location: Chicken Key, in the Biscayne Bay Aquatic Preserve (26.62, -80.2875)

Purpose: Habitat enhancement

Approach: Vegetation only

Materials: PVC tubes, mangrove vegetation

Description: This project consisted of: clearing and removing four acres of exotic vegetation; excavation of 33,000 cubic yards of dredge spoil from the north and central portions of the Key; planting 150 linear feet of experimental mangrove in PVC encased tubes and 3.7 acres of red mangroves on 3-foot centers; and installation of three flushing channels and a network of tidal creeks.

http://www.globalrestorationnetwork.org/uploads/files/LiteratureAttachments/251_restoration-of-coastal-wetlands-in-southeastern-florida.pdf

Chotawhatchee Bay Shoreline Restoration

Location: Eglin Air Force Base property at Okaloosa Island; private waterfront property in Destin Harbor (30.3980, -86.5977)

Purpose: Educate property owners on benefits of living shorelines

Approach: Vegetation only

Materials: Native marsh vegetation

Description: Two sites located on private property were planted with native marsh vegetation in order to educate private landowners about the importance of native marsh vegetation and how it provides an environmentally friendly alternative to seawalls, bulkheads, and riprap.

Link: https://restoration.atlas.noaa.gov/src/html/index.html

Choctawhatchee Basin Alliance's (CBA) Living Shoreline Initiative in Choctawhatchee Bay, FL & AL

Location: Intertidal habitats in various locations

Purpose: The CBA began constructing living shorelines in 2006, with the goals of providing habitat for oyster settlement, increasing intertidal salt marsh habitat, and decreasing shoreline erosion.

Approach: Breakwater

Materials: Oyster shell; *S. alterniflora*; *S. patens*

Description: CBA's living shoreline initiative is made up of two components: oyster shell breakwaters (artificial reefs) and native shoreline grass plantings. Combined, the reefs and shoreline grasses help to reduce shoreline erosion, act as habitat for marine-life, filter stormwater run-off, and improve water clarity and water quality in Choctawhatchee Bay. CBA uses recycled oyster shell to construct artificial reefs that act as a breakwater for impeding erosion. To stabilize the shoreline, CBA plants smooth cordgrass (*S. alterniflora*).

Link: http://www.basinalliance.org/page.cfm?articleID=15

Database link: http://www.basinalliance.org/page.cfm?articleID=88 (opens in Google Earth)

Projects included in CBA's Living Shoreline Initiative:

Legion Park Site: This 391-foot reef is composed of bagged fossilized oyster shell placed on sand. No shoreline restoration plants were used.

Marina Cove Site: This 530-foot reef is composed of bagged fossilized oyster shell placed on a mixture of sand and silt. No shoreline restoration plants were used.

O'Connor Site: This 120-foot reef is composed of bagged fossilized oyster shell placed on sand. Shoreline restoration plants included *S. alterniflora* and *S. patens*.

Ward Site: This 100-foot reef is composed of a mix of bagged fossilized oyster shell and bagged recycled oyster shell placed on sand. No shoreline restoration plants were used.

Wood Site: This 300-foot reef is composed of bagged fossilized oyster shell and bagged recycled oyster shell placed on sand. Shoreline restoration plants included *S. alterniflora* and *S. patens*.

Schultz Site: This 80-foot reef is composed of bagged fossilized oyster shell placed on sand. Shoreline restoration plants included *S. alterniflora*.

Cessna Park Site: This 434-foot reef is composed of bagged fossilized oyster shell placed on a mixture of sand and silt. Shoreline restoration plants included *S. alterniflora* and *Juncus roemerianus*.

Mattie Kelly Park Site: This 360-foot reef is composed of bagged fossilized oyster shell placed on sand. No shoreline restoration plants were used.

Live Oak Point Reef 1 Site: This 240-foot reef is composed of bagged fossilized oyster shell placed on a mixture of sand and silt. Shoreline restoration plants included *S. alterniflora*.

Live Oak Point Reef 2 Site: This 180-foot reef is composed of bagged fossilized oyster shell placed on silt. Shoreline restoration plants included *S. alterniflora*.

Live Oak Point Reef 3 Site: This 530-foot reef is composed of bagged fossilized oyster shell placed on silt. Shoreline restoration plants included *S. alterniflora, S. patens*, and *Juncus roemerianus*

Deadman's Island Restoration Project

Location: (27.7494, -82.7473)
Purpose: Erosion control
Approach: Breakwater
Materials: Oyster shell (Ecodisc); salt marsh planting
Description: In order to address habitat erosion on the island, a wave break was built with natural oyster shell called Ecodisc. Ecodiscs increase native oyster habitat by providing a foundation for a natural oyster reef. This project utilized the offshore placement of artificial vertical oyster reef structures along the shoreline to reduce wave energy and placed plant material to create emergent salt marsh.
Link: https://restoration.atlas.noaa.gov/src/html/index.html

E.G. Simmons Park Salt Marsh Restoration-Phase I and II

Location: 27.7438, -82.4722
Purpose: Erosion problems due to increased tidal action.
Approach: Vegetation only
Materials: Marsh/mangrove vegetation planted
Description: This project stabilized approximately two acres of eroding shoreline through the installation of 8,000 salt marsh plants and 5,000 mangrove propagules. Four acres of tidal wetland habitat was restored. During Phase II of the project, 5,000 plantings of salt marsh vegetation took place, restoring about 1.5 acres of shoreline.
Link: https://restoration.atlas.noaa.gov/src/html/index.html

Escambia Bay

Location: 30.5705, -87.1509
Purpose: Erosion control
Approach: Edging

Materials: Coconut fiber; *S. alterniflora* (smooth cordgrass), *Juncus roemerianus* (black needle rush), *S. patens* (saltmeadow cordgrass), *Baccharis halimifolia* (saltbush), and *S. bakeri* (sand cordgrass)

Description: In this project, coir logs made of coconut fiber were installed to help stabilize the sediment prior to planting. The fetch was between one and three miles, so the site needed a little more stabilization than plants alone could provide. Once secured, coir logs remain in place until they biodegrade, which happens in about one to three years. They stabilize until natural sedimentation occurs, and plants take over the stabilization role.

Link: http://floridalivingshorelines.com/project/escambia-bay-2/

Fantasy Island Salt Marsh and Oyster Restoration

Location: 27.8682, -82.4253

Purpose: Prevent erosion; provide hard bottom habitat; improve water quality

Approach: Breakwater

Materials: Salt marsh grass; unknown oyster material

Description: A series of new oyster bars were created at Fantasy Island and Green Key. In addition, 5,000 plugs of salt marsh grasses along one acre of shoreline were planted. A second planting added 2,000 plugs of smooth cordgrass.

Link: https://restoration.atlas.noaa.gov/src/html/index.html

Florida Department of Environmental Protection (FDEP), Ecosystem Restoration Section Living Shoreline Projects

FDEP is working to return public and private coastal properties to functioning estuarine habitats by working with and educating coastal property owners about the advantages and protection offered by non-hardened green stabilization techniques. By working with coastal property owners, the agency is able to gain access to private coastal properties allowing FDEP to proactively improve habitat and species diversity within northwest Florida estuaries.

Link: http://www.dep.state.fl.us/northwest/Ecosys/section/living_shorelines.htm

Sites included in the Living Shoreline Project:

Niceville 5 Oyster Reef Site

Location: Choctawhatchee Bay, Niceville (30.4552, -86.4033)

Purpose: To protect five adjacent properties from severe erosion caused by wind and wave action

Approach: Breakwater

Materials: Oyster reefs (fossilized-bagged); *S. alterniflora; Juncus roemerianus*

Description: Each property (100-feet each) received eight oyster reefs (bagged fossilized shell) to use as breakwaters. *S. alterniflora* and *Juncus roemerianus* plants were then placed above the MHW line to act as wave breaks.

Links: http://mycopri.org/node/35; http://gulfalliancetraining.com/dbfiles/Amy%20Baldwin%20%2ONW%20FL%20Living%20Shorelines.pdf

Rocky Bayou Site

Location: Choctawhatchee Bay, Niceville (30.4958, -86.4541)

Purpose: Erosion (boat wake); no sloping shoreline

Approach: Breakwater

Materials: *S. alterniflora*; oyster reefs (recycled shell/bagged)

Description: A 50-foot breakwater was constructed of five recycled oyster shell reefs to deflect seawall waves. Five hundred *S. alterniflora* plants were placed above and below the MHW line to prevent further erosion.

Links: http://mycopri.org/node/34; http://mycopri.org/system/files/content/Living%20Shorelines%20Task%20Committee/Rocky%20Bayou%20Oyster%20Reefs/Woodward_1.pdf)

Boggy Bayou Site

Location: Choctawhatchee Bay, Niceville (30.4952, -86.4838)

Purpose: To prevent further severe erosion caused by wind and boat wake

Approach: Sill

Materials: Sand; Burlap bags; *S. alterniflora* and *J. roemericanus*

Description: A 35-foot vertical sill constructed of 40 burlap sacks filled with sand was used to stabilize marsh plantings at the water's edge. A five-foot area was planted with a combination of *S. alterniflora* and *J. roemericanus*.

Links: http://mycopri.org/node/33; http://gulfalliancetraining.com/dbfiles/Amy%20Baldwin%20-%20NW%20FL%20Living%20Shorelines.pdf

Dr. Gup Site

Location: Bayou Texar, Pensacola (30.4505, -87.1986)

Purpose: Erosion from boat wake

Approach: Vegetation only

Materials: *S. alterniflora* and *J. roemericanus*

Description: Because the site was located on a low energy shoreline and no oysters were present, the owner chose to put in emergent vegetation to prevent further erosion of the property. Five vertical feet of turf grass was removed in order to create a slope. Then 350 *S. alterniflora* and 100 *J. roemericanus* were planted on 73 feet of property. A turbidity curtain (i.e., a flexible, impermeable barrier used to trap sediment in water bodies that is generally weighted at the bottom to ensure that sediment does not travel under the curtain and is supported at the top through a flotation system) was used to control wave energy post-planting and kept in place for three months.

Links: http://mycopri.org/node/31; http://gulfalliancetraining.com/dbfiles/Amy%20Baldwin%20-%20NW%20FL%20Living%20Shorelines.pdf

Orth Site

Location: Bayou Texar, Pensacola (30.4469, -87.1869)
Purpose: To maintain/retain beach in front of retaining wall
Approach: Vegetation only
Materials: *S. alterniflora* and *J. roemericanus*
Description: Because the site was located on a low energy shoreline and in order to provide habitat and stormwater filtration, the owner chose to put in emergent vegetation to retain the beach located in front of a seawall on the property. Five vertical feet of turf grass was removed in order to create a slope. Then 500 *S. alterniflora* and 200 *J. roemericanus* were planted on 130 feet of property. A turbidity curtain (i.e., a flexible, impermeable barrier used to trap sediment in water bodies that is generally weighted at the bottom to ensure that sediment does not travel under the curtain and is supported at the top through a flotation system) was used to control wave energy post-planting and kept in place for three months.
Links: http://mycopri.org/node/32; http://gulfalliancetraining.com/dbfiles/Amy%20Baldwin%20-%20NW%20FL%20Living%20Shorelines.pdf

Florida International University Bay Vista Campus Wetlands Restoration

Location: North Miami (25.9055, -80.14)
Purpose: Habitat creation/restoration
Approach: Vegetation only
Materials: Red mangrove (*Rhizophora mangle)*
Description: The project consisted of: selective clearing and removing exotic vegetation; transplanting 65 native trees; excavating and removing 10,000 cubic yards of dredge spoil; installing 4 intertidal flushing channels; and planting 2 acres of *Rhizophora mangle* on three-feet centers.
http://www.globalrestorationnetwork.org/uploads/files/LiteratureAttachments/251_restoration-of-coastal-wetlands-in-southeastern-florida.pdf

Green Key Island

Location: Mouth of the Alafia River in an area of Tampa Bay (27.8066, -82.4119)
Purpose: Erosion control; create habitat; buffer area from wave action; improve water quality
Approach: Edging
Materials: Fossilized oyster shell
Description: Five oyster bars were installed on Green Key in two separate projects. In all, 24 tons of fossilized oyster shell was deposited on the shoreline. After 2 years, the created reefs have excellent oyster growth and appear to be healthy.
Link: N/A

GreenShores Oyster Reef and Salt Marsh Creation – Phase I and II

Location: Bayfront Parkway in downtown Pensacola, Florida (30.4134, -87.2020)
Purpose: Provide habitat, improve water quality, and serve as a breakwater
Approach: Breakwater
Materials: Oyster shell; limestone; native emergent marsh vegetation; seagrasses
Description: Project GreenShores Phase I involved the creation of an oyster reef breakwater made from limestone rock and oyster shell and the formation of an intertidal salt marsh area behind the reef in a 15 acre area of Pensacola Bay. Native emergent marsh vegetation and seagrasses were planted. Phase II of the project created an additional 7 acres of oyster habitat and 5 acres of seagrass and salt marsh on the shoreline.
Link: https://restoration.atlas.noaa.gov/src/html/index.html

Guana Tolomato Matanzas NERR

Location: Guana River Marsh Aquatic Preserve (30.0714, -81.3328)
Purpose: Protect shoreline; provide nursery habitat for marine species
Approach: Edging
Materials: Oyster shell; salt marsh vegetation
Description: This project restored approximately 0.76 acres of saltmarsh and 0.071 acres of oyster habitat within the Guana River Marsh Aquatic Preserve in Northeast Florida. The project had three components: to establish an oyster shell recycling program, conduct hands-on community education and outreach, and deploy oyster mesh bags along an eroding shoreline to further protect the shoreline and adjacent marsh habitat.
Link: https://restoration.atlas.noaa.gov/src/html/index.html; http://sagecoast.org

Highland Oaks Wetlands Restoration

Location: Highland Oaks Park, Miami-Dade County (25.9583, -80.1666)
Purpose: Habitat enhancement
Approach: Vegetation only
Materials: Vegetation
Description: This project consisted of: selective removal of 8.2 acres of exotic vegetation; planting 3 acres of littoral shelf native vegetation, 3.0 acres of forested freshwater wetland, and

8.2 acres of river bank and hammock vegetation; and re-establishing 250 feet of historical riverbed of the Oleta River. http://www.globalrestorationnetwork.org/uploads/files/LiteratureAttachments/251_restoration-of-coastal-wetlands-in-southeastern-florida.pdf

Indian River Lagoon Mangrove Restoration

Location: Six sites on the Indian River shoreline
Purpose: Habitat enhancement
Approach: Vegetation only
Materials: Mangroves; native wetland and upland vegetation
Description: Mangroves and other native wetland and upland plants were planted and invasive Brazilian pepper trees were removed by volunteers at six different sites on the Indian River Lagoon shoreline. This project helped to trap sediment and filter pollution, thus preventing erosion and improving water quality.
Link: https://restoration.atlas.noaa.gov/src/html/index.html

Little Bird Key Salt Marsh and Oyster Restoration-Phase II

Location: Little Bird Key, Pinellas National Wildlife Refuge (27.6662, -82.6929)
Purpose: Habitat enhancement; shoreline stabilization
Approach: Vegetation only
Materials: Salt marsh plants
Description: In this project, 0.15 acres of marsh on Little Bird Key were planted in a previously restored area impacted by red tide in 2005. The creation of oyster bars and planting of marsh grasses helped stabilize the island and allowed for the expansion of the salt marsh.
Link: https://restoration.atlas.noaa.gov/src/html/index.html

Loblolly Community Oyster Reef and Living Shorelines Project

Location: Hobe Sound (27.0366, -80.1120)
Purpose: N/A
Approach: Breakwater
Materials: Oyster shell bags; mangrove
Description: A living shoreline breakwater was constructed by the community of Loblolly and mangrove seedlings were planted behind it. Oyster shell bags were added to the base of the breakwater to encourage oyster settlement. Cultch bag placement was performed by volunteers.
Link: http://floridalivingshorelines.com/project/loblolly-community

Lost River Preserve Restoration

Location: 27.7072, -82.4871

Purpose: Habitat enhancement
Approach: Vegetation only
Materials: Marsh vegetation
Description: This project restored 70 acres of coastal habitat through: removal of exotic Brazilian pepper and Australian pine; re-grading the disturbed portions of the site into a freshwater and estuarine marsh and planting marsh vegetation; and increasing daily tidal exchange by installing a large box culvert under the adjacent county road. This project resulted in the restoration of 23 acres of upland habitat; 4 acres of pond habitat; 8 acres of freshwater wetland habitat; 14 acres of tidal wetland habitat; and 21 acres of mangrove habitat.
Link: https://restoration.atlas.noaa.gov/src/html/index.html

MacDill Airforce Base Salt Marsh and Oyster Restoration

Location: 27.8609, -82.4866
Purpose: Erosion protection
Approach: Vegetation only
Materials: Salt marsh plants; mangroves
Description: NOAA Fisheries partnered with MacDill Air Force Base and Tampa Bay Watch to restore nearly one acre of oyster habitat and salt marsh in northeast Tampa Bay. The restoration site is located along a point of land at the Air Force base that is experiencing high rates of erosion due to wave energy. Volunteers planted approximately 2,700 salt marsh grass plugs and 500 mangroves along the shoreline immediately behind the created oyster reef.
Link: https://restoration.atlas.noaa.gov/src/html/index.html

Martin County Oyster Reef and Living Shorelines Projects

Location: Peck Lake Park (27.1069, -80.1478), Pendarvis Park and Bird Island on Hobe Sound
Purpose: N/A
Approach: Edging
Materials: Oyster shell bags; *Spartina*
Description: At all 3 sites (Peck Lake and Pendarvis Parks, Bird Island) cultch bag reefs were constructed and *Spartina* planted behind it.
Link: http://floridalivingshorelines.com/project/loblolly-community

Restoration of Intertidal Reefs in Mosquito Lagoon

Location: Mosquito Lagoon south of New Smyrna Beach (28.9836, -80.8886)
Purpose: Stabilize eroding shorelines; habitat enhancement
Approach: Edging
Materials: Oyster shell mats
Description: This project restored 12 intertidal oyster reefs in the Mosquito Lagoon Aquatic Preserve and Canaveral National Seashore. To increase the acreage of live intertidal oyster reefs,

	2,297 oyster mats were constructed and placed in the intertidal area to establish new substrates for oyster settlement. Oyster shell mats made up of 36 oyster shells were attached vertically to a small mesh mat with zip ties. The mats were later attached to each other in the water, forming a large quilt-like structure. The oyster reef sites were prepared and leveled to an appropriate elevation, the mats were deployed on site, and then the reefs were monitored for oyster growth. During Phase II of the project, an additional 24-acres of reef was restored by deploying oyster mats to help stabilize the intertidal reef system.
Links:	https://restoration.atlas.noaa.gov/src/html/index.html; http://www.nature.org/ourinitiatives/habitats/oceanscoasts/oyster-reef-restoration-southern-solutions-for-a-global-problem.xml; http://projects.tnc.org/coastal/

Naval Support Activities Shoreline Restoration Project in St. Andrews Bay

Location:	St. Andrew Bay, Panama City (30.1353, -85.6662)
Purpose:	Erosion prevention; habitat enhancement
Approach:	Edging
Materials:	Oyster shell; *S. alterniflora; J. roemerianus, S. patens*, and *B. halimifolia*
Description:	Over 15,000 square feet of emergent vegetation along the shoreline were planted with 25,000 native marsh plants, and 193 oyster reefs were constructed from loose, unconsolidated shell as part of this project. The creation of the 0.5 acre marsh will provide additional shoreline protection and nursery habitat for over 70 % of commercial and recreational finfish and shellfish species.
Links:	https://restoration.atlas.noaa.gov/src/html/index.html; http://floridalivingshorelines.com/project/820/

North Peninsula State Park Saltmarsh Restoration

Location:	(29.4416, -81.1093)
Purpose:	Shoreline stabilization; habitat enhancement
Approach:	Vegetation only
Materials:	Salt marsh vegetation
Description:	This project restored and enhanced approximately 9 acres of estuarine saltmarsh within the North Peninsula State Park in northeast Florida. The project provided direct restoration to 2 acres of historic saltmarsh habitat and enhanced an additional 7 acres of habitat. This project focused on the removal of exotic invasive species, restoration of the natural wetland elevation of the site, and stabilization of the shoreline edge habitat through planting of low marsh vegetation. The project also provided nursery habitat benefits to a variety of commercially and recreationally important fisheries species, as well as numerous other estuarine organisms.
Link:	https://restoration.atlas.noaa.gov/src/html/index.htmlc

Oleta River State Park Wetlands Restoration (Phase I)

Location:	Miami (25.9333, -80.1308)
Purpose:	Habitat enhancement
Approach:	Vegetation only
Materials:	Native wetland vegetation; mangroves (*Rhizophora mangle*)
Description:	This project consisted of clearing and mulching of exotic vegetation, predominantly *Casuarina equisetifolia,* excavation of 55,000 cubic yards of Intracoastal Waterway dredge spoil material; planting 13 acres of *Rhizophora mangle* on 3-foot centers; and installing a network of intertidal creeks. http://www.globalrestorationnetwork.org/uploads/files/LiteratureAttachments/251_restoration-of-coastal-wetlands-in-southeastern-florida.pdf

Oleta River State Park Wetlands Restoration (Phase II)

Location:	North side of the Oleta River, North Miami Beach (25.9233, -80.1394)
Purpose:	Habitat enhancement
Approach:	Vegetation only
Materials:	Native wetland vegetation; mangroves (*Rhizophora mangle*)
Description:	This project restored a 30-acre wetland along the Oleta River through removal of solid waste, soils, and exotic vegetation, the placement of grading and fill, stabilization of the shoreline, and the planting of native wetland vegetation. Abandoned concrete structures such as seawalls and fill pads were removed, while the concrete debris was moved to the canal entrance. Mangroves were planted by volunteers in the final phase of restoration.
Links:	https://restoration.atlas.noaa.gov/src/html/index.html; http://www.globalrestorationnetwork.org/uploads/files/LiteratureAttachments/251_restoration-of-coastal-wetlands-in-southeastern-florida.pdf

Port Orange Living Shoreline and Oyster Reef

Location:	Various private property sites
Purpose:	Shoreline stabilization
Approach:	Undetermined
Materials:	*Spartina*; unknown oyster shell combination
Description:	With the permission of 16 homeowners the project was able to restore 0.5 acres of shoreline habitat composed of upland, saltmarsh, and oyster reef habitat. In the course of this project, invasive species were removed, upland habitats were stabilized, *Spartina* was planted, and a variety of oyster restoration techniques were deployed.
Link:	https://restoration.atlas.noaa.gov/src/html/index.html

Project Green Shores

Location:	Pensacola Bay (30.4155, -87.1969)

Purpose: Stabilize shoreline; habitat enhancement

Approach: Breakwater

Materials: Limestone; recycled concrete; wave attenuators; sand; *S. alterniflora*, *R. maritima*, and *H. wrightii*

Description: Project Green Shores was constructed in phases and consists of two adjacent sites in Pensacola Bay. Site 1 was completed in 2003 and consists of 15 acres of estuarine habitat composed of seven acres of oyster reef and eight acres of salt marsh/seagrass habitat. Seven acres of constructed oyster reef consists of 14,000 tons of Kentucky limestone, 6,000 tons of recycled concrete and 40 wave attenuators. The eight acre salt marsh incorporated 35,000 cubic yards of sand, 40,000 *S. alterniflora* plants and 3,900 propagated seedlings of the emergent seagrass, *Ruppia maritima*.

Site 2 was completed in 2008 and consists of two submerged breakwaters constructed using 25,000 cubic yards of recycled concrete obtained from a decommissioned airfield at NAS Pensacola. The submerged breakwaters function to reduce fetch driven wave energy before it reaches the intertidal marsh islands and shoreline. In time, the breakwaters will also serve as a living oyster reef as oyster larvae settle and grow on the substrate provided. Three intertidal marsh islands were constructed using 16,000 cubic yards of spoil material from a previous dredge of the Escambia River. The islands were planted with 30,000 *S. alterniflora* plantings along with *Ruppia maritima* and *Halodule wrightii*.

Links: http://mycopri.org/node/25; http://www.dep.state.fl.us/northwest/Ecosys/section/greenshores.htm

St. Andrew Bay Shoreline Restoration

Location: Multiple properties

Purpose: Educate private property owners

Approach: Vegetation only

Materials: Salt marsh grasses

Description: A pilot study was conducted to demonstrate how salt marsh grasses were an effective shoreline stabilizer for private property owners. The goal was to encourage citizens facing bulkhead and seawall replacement to consider restoring their natural shoreline instead. Contractors worked with private land owners to remove failing bulkheads and volunteers contributed all of the labor required to transplant salt marsh grasses.

Link: https://restoration.atlas.noaa.gov/src/html/index.html

St. Lucie Estuary Oyster Reef Habitat Restoration Project

Location: 27.2009, -80.2380

Purpose: Restore historic oyster reef habitat; improve shoreline stability

Approach: Edging

Materials: Oyster shell bags; oyster domes; salt marsh planting

Description: Two acres of oyster reef habitat were restored and stretches of living shoreline were created in the St. Lucie Estuary. In addition, Martin County was able to increase the constructed oyster reef acreage to 4.52 acres during the summer of 2013.
Link: https://restoration.atlas.noaa.gov/src/html/index.html

Snook Islands Natural Area Habitat Enhancement Project

Location: Lake Worth Lagoon, Palm Beach County (26.6159, -80.0461)
Purpose: Mangrove and saltmarsh habitat enhancement
Approach: Breakwater
Materials: Spoil; red mangroves; *Spartina*; oyster shell; limestone
Description: Approximately 1.2 million cubic yards of spoil were mined and used to raise the elevation of a deep dredged hole created in 1925. Project construction resulted in creation of 10 acres of red mangroves, 2.8 acres of *Spartina* marsh, 2.3 acres of oyster reef, and nearly 50 acres of seagrass recruitment area. Constructing the offshore mangrove islands and limestone oyster reefs created valuable fish and wildlife habitat and provided a buffer against waves and boat wakes precluding the need to construct a new seawall for shoreline protection.
https://www.conservationgateway.org/ConservationPractices/Marine/crr/library/Documents/Natural20%Defenses%20in%20Southeast%20Florida_Complete%20Report_Web.pdf

Tarpon Key Salt Marsh and Oyster Restoration

Location: Tarpon Key, a small mangrove island near the mouth of Tampa Bay (27.666, -82.691)
Purpose: Erosion prevention
Approach: Undetermined
Materials: Saltmarsh plants; unknown oyster material
Description: This project replanted 2.5 acres of shoreline with marsh grasses and installed oyster reefs to prevent further erosion of the island. The original planting of 4,000 plants took place in April 2003. This was followed by a second planting of an additional 5,000 plants two years later.
Link: https://restoration.atlas.noaa.gov/src/html/index.html

Virginia Key North Point Ecosystem Restoration Project

Location: Virginia Key Island (25.7399, -80.1568)
Purpose: Shoreline stabilization
Approach: Vegetation only
Materials: Native vegetation
Description: The restoration will involve the selective clearing and grubbing of all non-native vegetation, the creation of beach dune and coastal hammock habitat by moving and grading existing fill, the enhancement of an existing isolated freshwater wetland on-site

through non-native vegetation eradication and control, and the planting of appropriate native vegetation. http://www.globalrestorationnetwork.org/uploads/files/LiteratureAttachments/251_restoration-of-coastal-wetlands-in-southeastern-florida.pdf; https://www.conservationgateway.org/ConservationPractices/Marine/crr/library/Documents/Natural%20Defenses%20in%20Southeast%20Florida_Complete%20Report_Web.pdf

Weedon Island Preserve Oyster Restoration

Location: Weedon Island, St. Petersburg (27.8453, -82.6000)
Purpose: Shoreline stabilization; habitat restoration
Approach: Breakwater
Materials: Oyster shell
Description: This 3,700 acre coastal preserve situated on Old Tampa Bay contains several different aquatic and upland ecosystems, including mangrove forests, pine flatwoods and oak hammocks. Volunteers constructed three oyster reef bars adjacent to the shoreline from 160 tons of oyster shell to absorb wave energy. In addition to shoreline protection, the reef will also provide fishery habitat and filter the water in the Bay.
Links: https://restoration.atlas.noaa.gov/src/html/index.html; http://www.estuaries.org/pdf/2012conference/room15/session2/Clark_RAE_2012_pres.pdf

Whale Island Salt Marsh Restoration

Location: 27.6625, -82.6931
Purpose: Erosion prevention
Approach: Vegetation only
Materials: Wetland plants
Description: Tampa Bay Watch joined partners to plant approximately 0.5 acres of wetland plants on Whale Island, a mangrove island and a national Wildlife refuge, near the mouth of Tampa Bay.
Link: https://restoration.atlas.noaa.gov/src/html/index.html

Whiskey Stump Key

Location: Tampa Bay area (27.8144, -82.401)
Purpose: N/A
Approach: Edging
Materials: Oyster shells
Description: Seventy tons of oyster shells were used to construct 700 linear feet of oyster bars on Whiskey Stump Key. http://www.estuaries.org/pdf/2012conference/room15/session2/Clark_RAE_2012_pres.pdf

Appendix B: Annotated Bibliography of Living Shorelines in the Southeast

The following is an annotated bibliography of information about living shorelines in the southeastern region. Sources are organized by the report headings for ease of reference. The bibliography also includes case studies of several living shoreline projects from the region, as well as information about further resources about living shorelines and databases in the Southeast. The page where each heading begins is listed below:

Overview

Bilkovic, D., M. Mitchell, P. Mason, and K. Duhring (2016). The role of living shorelines as estuarine habitat conservation strategies. *Coastal Management* 44(3): 161-174. Available at: http://dx.doi.org/10.1080/08920753.2016.1160201

Abstract: Globally, shoreline protection approaches are evolving towards the incorporation of natural and nature-based features (living shorelines henceforth) as a preferred alternative to shoreline armoring. Emerging research suggests that living shorelines may be a viable approach to conserving coastal habitats (marshes, beaches, shallows, seagrasses) along eroding shorelines. Living shorelines typically involve the use of coastal habitats, such as wetlands, that have a natural capacity to stabilize the shore, restore or conserve habitat, and maintain coastal processes. They provide stability while still being dynamic components of the ecosystem, but due to their dynamic nature, careful designs and some maintenance will be required if habitat conservation is a goal. Living shorelines may represent a singular opportunity for habitat conservation in urban and developing estuaries because of their value to society as a shoreline protection approach and resilience to sea level rise. However, enhanced public acceptance and coordination among regulatory and advisory authorities will be essential to expand their use. To fully understand their significance as habitat conservation strategies, systematic and standardized monitoring at both regional and national scales is vital to evaluate the evolution, persistence, and maximum achievable functionality (e.g., ecosystem service provision) of living shoreline habitats.

Bouma, T.J. and J. van Belzen, T. Balke, Z. Zhu, L. Airoldi, A.J. Blight, A.J. Davies, C. Galvan, S.J. Hawkins, S.P.G. Hoggart, J.L. Lara, I.J. Losada, M. Maza, B. Ondiviela, M.W. Skov, E.M. Strain, R.C. Thompson, S. Yang, B. Zanuttigh, L. Zhang, and P.M.J. Herman (2014). Identifying knowledge gaps hampering application of intertidal habitats in coastal protection: opportunities and steps to take. *Coastal Engineering* 87: 147-157. Available at: http://ac.els-cdn.com/S037838391300197X/1-s2.0-S037838391300197X-main.pdf?_tid=48e8bd34-3961-11e6-8283-00000aab0f02&acdnat=1466700248_da38fbae322eb4cd1dbd2e687bb5d1cc

Abstract: Over the last decades, population densities in coastal areas have strongly increased. At the same time, many intertidal coastal ecosystems that provide valuable services in terms of coastal protection have greatly degraded. As a result, coastal defense has become increasingly dependent on man-made engineering solutions. Ongoing climate change processes such as sea-level rise and increased storminess, require a rethinking of current coastal defense practices including the development of innovative and cost-effective ways to protect coastlines. Integrating intertidal coastal ecosystems within coastal defense schemes offers a promising way forward. In this perspective, we specifically aim to (1) provide insight in the conditions under which ecosystems may be valuable for coastal protection, (2) discuss which might be the most promising intertidal ecosystems for this task and (3) identify knowledge gaps that currently hamper application and hence need attention from the scientific community. Ecosystems can contribute most to coastal protection by wave attenuation in areas with relatively small tidal amplitudes, and/or where intertidal areas are wide. The main knowledge gap hampering application of intertidal ecosystems within coastal defense schemes is lack in ability to account quantitatively for long-term ecosystem dynamics. Such knowledge is essential, as this will determine both the predictability and reliability of their coastal defense function. Solutions integrating intertidal ecosystems in coastal defense schemes offer promising opportunities in some situations, but require better mechanistic understanding of ecosystem dynamics in space and time to enable successful large-scale application.

Bridges, T.S., P.W. Wagner, K.A. Burks-Copes, M.E. Bates, Z.A. Collier, C.J. Fischenich, J.A. Gailani, L.D. Leuck, C.D. Piercy, J.D. Rosati, E.J. Russo, D. J. Shafer, B.C. Suedel, E.A. Vexton, and T.V. Wamsley (2015*). Use of Natural and Nature-Based Features (NNBF) for Coastal Resilience*. US Army Corps of Engineers, Engineer Research and Development Center (ERDC SR-15-1), pp. 480. Available at: https://s3.amazonaws.com/nyclimatescience.org/sr-15-1.pdf

Abstract: Coastal systems are increasingly vulnerable to flooding due to the combined influence of coastal storms, development and population growth, geomorphic change, and sea level rise. This reality has given rise to efforts to make greater use of ecosystem-based approaches to reduce risks from coastal storms, approaches which draw from the capacity of wetlands, beaches and dunes, biogenic reefs, and other natural features to reduce the impacts of storm surge and waves. This report offers details regarding the use of natural and nature-based features (NNBF) to improve coastal resilience and was designed to support post-Hurricane Sandy recovery efforts under the North Atlantic Coast Comprehensive Study (NACCS). An integrative framework is offered herein that focuses on classifying NNBF, characterizing vulnerability, developing performance metrics, incorporating regional sediment management, monitoring and adaptively managing from a systems perspective, and addressing key policy challenges. As progress is made on these and other actions across the many organizations contributing to the use of NNBF, implementation of the full array of measures available will reduce the risks and enhance the resilience of the region's coastal systems.

Cheong, S.M., B. Silliman, P.P. Wong, C. van Wesenbeeck, C.K. Kim, and G. Guannel (2013). Coastal adaptation with ecological engineering. *Nature Climate Change* 3: 787-791. Available at: http://www.nature.com/nclimate/journal/v3/n9/full/nclimate1854.html

Abstract: The use of combined approaches to coastal adaptation in lieu of a single strategy, such as sea-wall construction, allows for better preparation for a highly uncertain and dynamic coastal environment. Although general principles such as mainstreaming and no- or low-regret options exist to guide coastal adaptation and provide the framework in which combined approaches operate, few have examined the interactions, synergistic effects and benefits of combined approaches to adaptation. This Perspective provides three examples of ecological engineering — marshes, mangroves and oyster reefs — and illustrates how the combination of ecology and engineering works.

Coastal Green Infrastructure and Ecosystem Services Task Force (2015). *Ecosystem-Service Assessment: Research Needs for Coastal Green Infrastructure.* Report prepared by National Science and Technology Council, Committee on Environment, Natural Resources, and Sustainability, Subcommittee on Ecological Systems, Coastal Green Infrastructure and Ecosystem Services Task Force. Office of Science and Technology Policy, Washington D.C., pp. 48. Available at: https://www.whitehouse.gov/sites/default/files/microsites/ostp/cgies_research_agenda_final_082515.pdf

Substantial knowledge and application gaps currently impede more widespread adoption of coastal green infrastructure (CGI) strategies. Green infrastructure refers to the integration of natural systems and processes, or engineered systems that mimic natural systems and processes, into investments in resilient infrastructure. The report is structured as follows. Section 2 summarizes existing information on major categories of CGI and associated ecosystem services (including co-benefits). Section 3 explains the purpose of, approaches to, and challenges associated with assessing ecosystem services, with a focus on ecosystem services provided by CGI. Section 4 discusses factors that can have significant bearing on the viability and appeal of different infrastructure-based approaches to enhancing coastal resilience, that is, factors that should be taken into account when considering if, when, and how to use CGI in a given setting. Finally, Section 5 recommends areas for prioritized Federal research to support the integration of CGI into risk reduction, resilience planning, and decision making.

Currin, C.A., Jenny Davis, Lisa Cowart Baron, Amit Malhotra, and Mark Fonseca (2015). Shoreline change in the New River Estuary, North Carolina: rates and consequences. *Journal of Coastal Research* 31(5): 1069-1077. Available at: http://api.ning.com/files/JgWHSTt60etIZlVc40jRVHr1f70Wl4eJ3VvOvvekNb6p0wD3yDkn0klO-yJ*koTH8*aYfqvtnrLjniEIGSg230R1yz72VgRq/Currinetal.2015.pdf

Abstract: This paper reviews the scientific data on the ecosystem services provided by shoreline habitats, the evidence for adverse impacts from bulkheading on those habitats and services, and describes alternative approaches to shoreline stabilization, which minimize adverse impacts to the shoreline ecosystem. Alternative shoreline stabilization structures that incorporate natural habitats, also known as living shorelines, have been popularized by environmental groups and state regulatory agencies in the mid-Atlantic. Recent data on living shoreline projects in North Carolina that include a stone sill demonstrate that the sills increase sedimentation rates, that after 3 years marshes behind the sills have slightly reduced biomass, and that the living shoreline projects exhibit similar rates of fishery utilization as nearby natural fringing marshes. Although the current emphasis on shoreline armoring in Puget Sound is on steeper, higher-energy shorelines, armoring of lower-energy shorelines may become an issue in the future with expansion of residential development and projected rates of sea level rise. The implementation of regulatory policy on estuarine shoreline stabilization in North Carolina and elsewhere is presented. The regulatory and public education issues experienced in North Carolina, which have made changes in estuarine shoreline stabilization policy difficult, may inform efforts to adopt a sustainable shoreline armoring strategy in Puget Sound. A necessary foundation for regulatory change in shoreline armoring policy, and public support for that change, is rigorous scientific assessment of the variety of services that natural shoreline habitats provide both to the ecosystem and to coastal communities, and evidence demonstrating that shoreline armoring can adversely impact the provision of those services.

Currin, C.A., W.S. Chappell and A. Deaton (2010). Developing alternative shoreline armoring strategies: the living shoreline approach in North Carolina. In: Shipman H., M.N. Dethier, G. Gelfenbaum, K.L. Fresh, and R.D. Dinicola (eds), *Pugent Sound Shorelines and the Impacts of Armoring: Proceedings of a State of the Science Workshop, May 2009*, USGS Scientific Investigations Report 2010-5254, pp. 91-102. Available at: http://pubs.usgs.gov/sir/2010/5254/pdf/sir20105254_chap10.pdf

Abstract: This paper reviews the scientific data on the ecosystem services provided by shoreline habitats, the evidence for adverse impacts from bulkheading on those habitats and services, and describes alternative approaches to shoreline stabilization, which minimize adverse impacts to the shoreline ecosystem. Alternative shoreline stabilization structures that incorporate natural habitats, also known as living shorelines, have been popularized by environmental groups and state regulatory agencies in the mid-Atlantic. Recent data on living shoreline projects in North Carolina that include a stone sill demonstrate that the sills increase sedimentation rates, that after 3 years marshes behind the sills have slightly reduced biomass, and that the living shoreline projects exhibit similar rates of fishery utilization as nearby natural fringing marshes. Although the current emphasis on shoreline armoring in Puget Sound is on steeper, higher-energy shorelines, armoring of lower-energy shorelines may become an issue in the future with expansion of residential development and projected rates of sea level rise. The implementation of regulatory policy on estuarine shoreline stabilization in North Carolina and elsewhere is presented. The regulatory and public education issues experienced in North Carolina, which have made changes in estuarine shoreline stabilization policy difficult, may inform efforts to adopt a sustainable shoreline armoring strategy in Puget Sound. A necessary foundation for regulatory change in shoreline armoring policy, and public

support for that change, is rigorous scientific assessment of the variety of services that natural shoreline habitats provide both to the ecosystem and to coastal communities, and evidence demonstrating that shoreline armoring can adversely impact the provision of those services.

Dugan, J.E., A. Airoldi, M.G. Chapman, S. Walker, and T. Schlacher (2011). Estuarine and coastal structures: environmental effects. In: Elliott, M. and J.E. Dugan (eds), *A Focus on Shore and Nearshore Structures. Treatise on Estuarine and Coastal Science.* Elsevier, New York, NY, pp. 17–41. Available at: http://www.sciencedirect.com/science/article/pii/B9780123747112008020

Abstract: Rapidly growing populations and expanding development are intensifying pressures on coastal ecosystems. Sea-level rise and other predicted effects of climate change are expected to exert even greater pressures on coastal ecosystems, exacerbating erosion, degrading habitat, and accelerating shoreline retreat. Historically, society's responses to threats from erosion and shoreline retreat have relied on armoring and other engineered coastal defenses. Despite widespread use on all types of shorelines, information about the ecological impacts of shoreline armoring is quite limited. Here we summarize existing knowledge on the effects of armoring structures on the biodiversity, productivity, structure, and function of coastal ecoystems.

Erdle, S.Y., J.L.D. Davis and K.G. Sellner (eds) (2008). *Management, Policy, Science and Engineering of Nonstructural Erosion Control in the Chesapeake Bay: Proceedings of the 2006 Living Shoreline Summit*. CRC Publ. No. 08-164, Gloucester Point, VA, pp. 136. Available at: http://www.vims.edu/cbnerr/_docs/ctp_docs/ls_docs/06_LS_Full_Proceed.pdf

The purpose of the Living Shoreline Summit was to investigate the state of the science of living shorelines, identify areas in which additional information is necessary, and investigate paths to increasing implementation of living shorelines as an alternative to hard shoreline armor, where appropriate. The Summit was intended for many audiences, including marine contractors, regulators, policy-makers, scientists, homeowners, marine engineers, consultants, and members of nonprofit groups. The goal of the information contained in these Proceedings is to encourage use of shoreline stabilization methods that serve habitat, water quality, and erosion control functions. Papers focus on the design of living shorelines and criteria to consider evaluation of the functions of living shorelines, regulatory processes and suggested ways to improve them, landowner decision-making processes and ways to incentivize living shorelines, and finally next steps in promoting living shoreline implementation in areas that are conducive to the techniques.

Governors' South Atlantic Alliance (2016). *South Atlantic Living Shorelines Summit: Summary Report*. Governors' South Atlantic Alliance. April 12-13, Jacksonville, Florida, pp. 28. Available at: http://southatlanticalliance.org/?page_id=1498

Hardaway, Scott, C. Jr., Donna A. Milligan, and Karen Duhring (2010). *Living Shoreline Design Guidelines for Shore Protection in Virginia's Estuarine Environments*. Virginia Institute of Marine Science, College of William & Mary, Gloucester Point, VA, pp. 123. Available at: http://www.vims.edu/research/departments/physical/programs/ssp/_docs/living_shorelines_guidelines.pdf

These guidelines are meant to address the need to educate consultants, contractors, and other professionals in the use of living shoreline strategies. The document provides the necessary information to determine where the guidelines are appropriate and what is involved in their design and construction. They focus on the use of created marsh fringes but also touch on the use of beaches for shore protection. The guidelines were created for the Virginia portion of the Chesapeake Bay estuarine system but may be applicable to other similar estuarine environments. These references and tools are for guidance only and should not replace professional judgments made at specific sites by qualified individuals.

Meyer, David, Felicity Burrows, Teresa McTigue, and John Foret (2005). Restoration Monitoring of Coastal Marshes. In: *Science-Based Restoration Monitoring of Coastal Habitats, Vol. 2: Tools for Monitoring Coastal Habitats*. Thayer, G.W., T.A. McTigue, R.J. Salz, D.H. Merkey, F.M. Burrows, and P.F. Gayaldo (eds). NOAA, Coastal Ocean Program Decision Analysis Series No. 23. NOAA, National Centers for Coastal Ocean Science, Silver Spring, MD, pp. 628 plus appendices. Available at: http://aquaticcommons.org/2240/1/WholeDocument.pdf

Each section of this chapter opens with a general discussion of a particular structural or functional characteristic of coastal marshes. Specific examples from salt, brackish, and/or freshwater marshes are presented to add more detail for each particular habitat type that may not be generally applied to the others. Each section concludes with recommendations on different sampling techniques or resources that can be used in monitoring restoration projects. Additional information on the ecology of coastal marshes, restoration case studies, and sampling strategies and techniques can be found in Appendix I: Annotated Bibliography of Coastal Marshes and Appendix II: Review of Technical Methods Manuals.

Miller, Jon K., Andrew Rella, Amy Williams, and Erin Sproule (2015). *Living Shorelines Engineering Guidelines*. New Jersey Dept. of Environmental Protection SIT-DL-14-9-2942, pp. 102. Available at: http://www.state.nj.us/dep/cmp/docs/living-shorelines-engineering-guidelines-final.pdf

Recently, a variety of new shoreline stabilization approaches have been developed that attempt to incorporate natural features and reduce erosion by mimicking features of the natural environment. These approaches have come to be known by a variety of names including “living shorelines”, “green shores”, and “ecologically enhanced shorelines”. Originally developed in the Chesapeake Bay area nearly two decades ago, the “living shorelines” approach has gradually gained momentum and has spread nationwide. While originally applied only to low profile stone or natural breakwaters known as marsh sills, the term “living shoreline” has evolved to take on a broader meaning which encompasses a wide variety of projects that incorporate ecological principles into engineering design.

This document provides guidance to the engineering and regulatory community on the engineering components involved in the design of living shorelines projects. While the document is intended to provide the framework for the engineering design of living shorelines projects, the nature of these projects is such that diversity and innovation should be encouraged. The document discusses the need for and the purpose of the engineering guidelines as well as the approach used to create the guidelines. A discussion of the parameters critical for the design of living shorelines projects is presented. Finally, a description of different methods for determining design parameters is given. Two appendices are also included. The first outlines the application of the engineering guidelines to five common types of living shorelines projects, while the second contains excerpts from some of the design manuals referred to throughout the document.

Moss, A.B. (N/A). *Living Shoreline Design Methodologies*. Florida Department of Environmental Protection, Ecosystem Restoration Program. Available at: http://www.gulfalliancetraining.com/dbfiles/Living%20Shoreline%20Design%20Methodology.pdf

This PowerPoint presentation reviews various types of hard shoreline stabilization techniques. It then explains what living shorelines are and lists their benefits, including the ecological Importance of salt marshes and inter-tidal reef structures. Design considerations for shoreline stabilization are described and directions for creating different types of living shorelines such as planting vegetation, vegetated retaining wall, reef/breakwater, and real world applications are provided.

National Oceanic and Atmospheric Administration (2015). *Guidance for Considering the Use of Living Shorelines*. Living Shoreline Work Group, National Oceanic and Atmospheric Administration, pp. 36. Available at: http://www.habitat.noaa.gov/pdf/noaa_guidance_for_considering_the_use_of_living_shorelines_2015.pdf

NOAA encourages the use of living shorelines as a stabilization technique along sheltered coasts (i.e., coasts not exposed to open ocean wave energy) to preserve and improve habitats and their ecosystem services at the land–water interface. NOAA has a broad interest in maintaining existing natural habitats that provide shoreline protection, like coral reefs, oyster reefs, mangroves, seagrass beds and marshes, along all coasts. This guidance document is intended to provide information on NOAA's perspective and roles regarding living shorelines implementation. It starts by describing NOAA living shorelines guiding principles, then highlights NOAA's role in providing science, tools, and training to help inform the selection of appropriate techniques. It also discusses the agency's role in reviewing living shoreline projects, depending on their location and potential effect on habitats of concern to NOAA, such as critical habitat, essential fish habitat, or protected areas. This guidance also provides a conceptual framework of 12 questions to help NOAA and its partners when planning a shoreline stabilization effort.

National Research Council (2014). *Reducing Coastal Risk on the East and Gulf Coasts*. Committee on U.S. Army Corps of Engineers Water Resources Science, Engineering, and Planning: Coastal Risk Reduction; Water Science and Technology Board; Ocean Studies Board; Division on Earth and Life Studies; National Research Council, National Academies Press, Washington D.C., pp. 208. Available at: http://www.nap.edu/catalog/18811/reducing-coastal-risk-on-the-east-and-gulf-coasts?record_id=18811

Reducing Coastal Risk on the East and Gulf Coasts reviews the coastal risk-reduction strategies and levels of protection that have been used along the United States East and Gulf Coasts to reduce the impacts of coastal flooding associated with storm surges. This report evaluates their effectiveness in terms of economic return, protection of life safety, and minimization of environmental effects. According to this report, the vast majority of the funding for coastal risk-related issues is provided only after a disaster occurs. This report calls for the development of a national vision for coastal risk management that includes a long-term view, regional solutions, and recognition of the full array of economic, social, environmental, and life-safety benefits that come from risk reduction efforts. To support this vision, *Reducing Coastal Risk* states that a national coastal risk assessment is needed to identify those areas with the greatest risks that are high priorities for risk reduction efforts. The report discusses the implications of expanding the extent and levels of coastal storm surge protection in terms of operation and maintenance costs and the availability of resources.

Reducing Coastal Risk recommends that benefit-cost analysis, constrained by acceptable risk criteria and other important environmental and social factors, be used as a framework for evaluating national investments in coastal risk reduction. The recommendations of this report will assist engineers, planners and policy makers at national, regional, state, and local levels to move from a nation that is primarily reactive to coastal disasters to one that invests wisely in coastal risk reduction and builds resilience among coastal communities.

National Research Council (2007). *Mitigating Shore Erosion along Sheltered Coasts.* Committee on Mitigating Shore Erosion along Sheltered Coasts. National Research Council, National Academies Press, Washington D.C., pp. 188. Available at: http://www.nap.edu/catalog/11764/mitigating-shore-erosion-along-sheltered-coasts

The study examines the impacts of shoreline management on sheltered coastal environments (e.g., estuaries, bays, lagoons, mudflats, deltaic coasts) and identifies conventional and alternative strategies to minimize potential negative impacts to adjacent or nearby coastal resources. These impacts include loss of intertidal and shallow water ecosystems and effects on species. The study also provides a framework for collaboration between different levels of government, conservancies, and property owners to aid in making decisions. In particular, the study addresses the following questions:

- What engineering techniques, technologies, and land management/planning measures are available to protect sheltered coastlines from erosion or inundation resulting from either natural or anthropogenic processes?
- What information is needed to determine where and when these measures are reliable and effective from an engineering and a habitat perspective? What are the likely individual and cumulative impacts of shoreline protection practices or no action on sheltered coastal habitats including public and private property?
- Over what time frame are monitoring data needed to document the effectiveness of protective coastal measures? What data are needed to predict when design criteria may be exceeded?

- Given current trends in erosion and inundation rates and a possible acceleration of relative sea-level rise, how can design criteria, the mix of technologies employed, and land use plans be implemented for the protection of the environment and property over the long term?

North Carolina Coastal Federation (2009). *North Carolina Coastal Federation Restoration and Protection Project: Living Shorelines*. Available at: http://www.nccoast.org/uploads/documents/factsheets/FS_LivShorlines.pdf

This two-page factsheet details the work the North Carolina Coastal Federation has implemented in its pilot cost share program to encourage the demonstration of "Living Shorelines" projects along the estuarine coasts of North Carolina.

North Carolina Coastal Federation (N/A). *Erosion Control: Non-Structural Alternatives: A Shorefront Property Owner's Guide*. North Carolina Coastal Federation, Newport, North Carolina, pp. 8. Available at: http://www.nccoast.org/uploads/documents/guides/ErosionBro.pdf

Shoreline erosion and landward migration of marshes are natural processes, and are important in the ecological balance found in healthy estuaries. To protect this balance, property owners should build as far landward of the shoreline as is possible to allow these natural processes to occur. Where houses are built close to the shore, the erosion process can present a problem for waterfront property owners. The alternatives selected by property owners to stabilize their shoreline can have positive or detrimental environmental implications. This publication is designed to help waterfront property owners evaluate their specific situation and select the remedy that can best protect property and benefit the environment.

North Carolina Division of Coastal Management and Division of Marine Fisheries (2014). *Living Shorelines Strategy*. North Carolina Division of Coastal Management Publication, pp. 21. Available at: https://ncdenr.s3.amazonaws.com/s3fs-public/Coastal%20Management/documents/Estuarine%20Shorelines/FINAL%20Living%20Shorelines%20Strategy%20Feb%205%202014.pdf

Over the past several years, the N.C. Coastal Resources Commission and the N.C. Division of Coastal Management (DCM) have explored the use of living shorelines, and marsh sills in particular, as alternatives to vertical stabilization measures. DCM coordinated an interagency meeting to discuss recent research and mapping projects, the offshore riprap sill General Permit, staff outreach and public awareness efforts, research needs, and short- and long-term actions for the Department to consider. The resulting discussions with agencies and partners led to the development of this Living Shorelines Strategy.

North Carolina National Estuarine Research Reserve (2005). *Living Shorelines*. Technical Paper Series, 5, pp. 2. Available at: http://portal.ncdenr.org/c/document_library/get_file?uuid=64323bf3-09dd-4ae4-ba46-a1fb389921c0&groupId=61572

This pamphlet analyzes different shoreline stabilization methods and highlights the positive effects living shorelines have on the environment (e.g., erosion control). Types of estuarine shoreline stabilization structures are described, including drawings of how each structure is built and a photograph of an existing structure.

Pilkey, O.H., R. Young, N. Longo, and A. Coburn (2012). *Rethinking Living Shorelines*. Nicholas School of the Environment, Duke University, Durham, NC, pp. 10. Available at: http://www.wcu.edu/WebFiles/PDFs/PSDS_Living_Shorelines_White_Paper.pdf

The authors of this report are concerned that the use of massive hard engineering structures in the deployment of some living shoreline projects will cause long-term environmental degradation, provide a false sense of accomplishment, and shift the focus away from trying to maintain the most natural estuarine shoreline feasible. Advocates of living shorelines should more precisely define and regulate this term so it is not misused simply to allow more unnecessary and damaging hard stabilization of estuarine shorelines.

The authors also stress the need for a renewed scientific effort to evaluate the cumulative impacts of all existing structures (bulkheads and living shorelines) on natural and physical processes and ecosystems, along with the need for a better perspective on the long-term fate of all living shorelines.

Restore America’s Estuaries (2015). *Living shorelines: from barriers to opportunities*. Restore America's Estuaries, Washington D.C., pp. 63. Available at: https://www.estuaries.org/images/stories/RAEReports/RAE_LS_Barriers_report_final.pdf

This report is an assessment of the institutional barriers that prevent the broader use of living shorelines. It is organized around the following three topics: background information about the current state of living shorelines use; barriers preventing the broader use of living shorelines; and recommended strategies to overcome these barriers.

Smith, Kevin M. (2006). Integrating Habitat and Shoreline Dynamics into Living Shoreline Applications. In: *Management, Policy, Science, and Engineering of Nonstructural Erosion Control in the Chesapeake Bay, Proceedings of the Living Shorelines Summit: Evaluation of Living Shoreline Techniques*; Erdle, S. Y., J. L. D. Davis, and K. G. Sellner (eds). CRC Publ. No. 08-164, Gloucester Point, VA, pp. 136. Available at: http://www.vims.edu/cbnerr/_docs/ctp_docs/ls_docs/06_LS_Full_Proceed.pdf

Abstract: The installation of successful living shoreline projects will consider the ecological importance of the biological and physical processes in maintaining healthy ecosystems along the shoreline. The enhancement of habitat along the shoreline and in the nearshore area in mid to high-energy environments often requires the incorporation of structural (generally rock) components. The level of habitat improvement is typically dependent on the maintenance of biologic and physical processes and the appropriate integration of structural components.

Subramanian, Bhaskaran, Gene Slear, Devin M. Smith, and Karen A. Duhring (2006). Current Understanding of the Effectiveness of Nonstructural and Marsh Sill Approaches. In: *Management, Policy, Science, and Engineering of Nonstructural Erosion Control in the Chesapeake Bay, Proceedings of the Living Shorelines Summit: Evaluation of Living Shoreline Techniques*; Erdle, S.Y., J.L.D. Davis, and K.G. Sellner (eds). CRC Publ. No. 08-164, Gloucester Point, VA, pp. 136. Available at: http://www.vims.edu/cbnerr/_docs/ctp_docs/ls_docs/06_LS_Eval.pdf

Abstract: A panel session at the Living Shorelines Summit in Williamsburg, Virginia was dedicated to the current understanding of the effectiveness of nonstructural erosion protection methods and marsh sills. Four panelists described their professional experience with either design and construction or monitoring of projects in tidal waters of Maryland and Virginia, including marsh edge stabilization (marsh toe revetments), marsh sills with sand fill, and planted marshes. Their collective experience revealed that planted tidal marshes and supporting structures can be effective alternatives to revetments and bulkheads. Site-specific engineering is required to ensure they provide functional ecological benefits, particularly in medium and high-energy settings. Another important factor for effective projects is landowner acceptance of dynamic shoreline conditions and the level of protection provided. Additional project tracking and research is needed to further investigate positive and adverse effects of created tidal marshes and supporting structures.

Sutton-Grier, Ariana, E., Kateryna Wowk, and Holly Bamford (2015). Future of our coasts: The potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. *Environmental Science & Policy* 51: 137–148. Available at: http://www.sciencedirect.com/science/article/pii/S1462901115000799

Abstract: There is substantial evidence that natural infrastructure (i.e., healthy ecosystems) and combinations of natural and built infrastructure (“hybrid” approaches) enhance coastal resilience by providing important storm and coastal flooding protection, while also providing other benefits. There is growing interest in the U.S., as well as around the world, to use natural infrastructure to help coastal communities become more resilient to extreme events and reduce the risk of coastal flooding. Here we highlight strengths and weaknesses of the coastal protection benefits provided by built infrastructure, natural ecosystems, and the innovative opportunities to combine the two into hybrid approaches for coastal protection. We also examine some case studies where hybrid approaches are being implemented to improve coastal resilience as well as some of the policy challenges that can make implementation of these approaches more difficult. The case studies we examine are largely in the U.S. but also include a couple of international examples as well. Based on this analysis, we conclude that coastal communities and other decision makers need better information in order to incorporate ecosystem protection and restoration into coastal resilience planning efforts. As additional projects are developed, it is important to capitalize on every opportunity to learn more about the cost of natural and hybrid infrastructure projects, the value of the storm and erosion protection benefits provided, and the full suite of co-benefits provided by healthy coastal ecosystems. We highlight top priorities for research, investment in, and application of natural and hybrid approaches. These data are critical to facilitate adoption of these approaches in planning and decision-making at all levels to enhance the resilience of our coasts.

Systems Approach to Geomorphic Engineering (2016*). Natural and structural measures for shoreline stabilization brochure*. National Oceanic and Atmospheric Administration and U.S. Army Corps of Engineers, pp. 7. Available at: http://sagecoast.org/docs/SAGE_LivingShorelineBrochure_Print.pdf

This brochure presents a continuum of green to gray shoreline stabilization techniques, highlighting Living Shorelines, that help reduce coastal risks and improve resiliency though an integrated approach that draws from the full array of coastal risk reduction measures.

Temmerman, S., P. Meire, T. J. Bouma, P. M. J. Herman, T. Ysebaert, and H. J. De Vriend (2013). Ecosystem-based coastal defense in the face of global change. *Nature* 504: 79-83. Available at: http://www.nature.com/nature/journal/v504/n7478/abs/nature12859.html

Abstract: The risk of flood disasters is increasing for many coastal societies owing to global and regional changes in climate conditions, sea-level rise, land subsidence and sediment supply. At the same time, in many locations, conventional coastal engineering solutions such as sea walls are increasingly challenged by these changes and their maintenance may become unsustainable. We argue that flood protection by ecosystem creation and restoration can provide a more sustainable, cost-effective and ecologically sound alternative to conventional coastal engineering and that, in suitable locations, it should be implemented globally and on a large scale.

Thomas-Blake, Jessie C. (ed) (2010). *Living Shorelines: Impacts of Erosion Control Strategies on Coastal Habitats*. Habitat Management Series #10. Atlantic States Marine Fisheries Commission, Washington D.C., pp. 70. Available at: http://www.asmfc.org/uploads/file/hms10LivingShorelines.pdf

This document provides resource managers and the general public with a concise comparative discussion of the benefits of living shorelines, and a case study of successful projects to use for reference within their own programs. This document begins with a brief overview of traditional erosion control methods, living shorelines, and the types of habitats that may be considered when creating these areas. It also discusses the impacts of some shoreline erosion control measures on the environment and provides examples of how various regulatory authorities are involved. To illustrate the value of living shorelines in a "real world" setting, a case study of their use in Maryland is included, as is a bibliography of living shorelines-related literature (Chapter 4), and a glossary of related terms (Appendix A). Appendix B suggests potential erosion control projects.

Tuttle, R.W. and Richard D. Wenberg (1996). Streambank and Shoreline Protection. In: *Engineering Field Handbook, Part 650*; Washington, D.C. 210-vi-EFH, pp. 143 with appendices. Available at: http://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=17553.wba

Streambank and shoreline protection consists of restoring and protecting banks of streams, lakes, estuaries, and excavated channels against scour and erosion by using vegetative plantings, soil bioengineering, and structural systems. These systems can be used alone or in combination. The information in this chapter does not apply to erosion problems on ocean fronts, large river and lake systems, or other areas of similar scale and complexity. Design considerations and protective measures for shoreline protection are also included.

U.S. Environmental Protection Agency (2010). *Coastal Wetlands Initiative: South Atlantic Review*. U.S. EPA (EPA-843-R-10-005B), pp. 61. Available at: http://www.epa.gov/sites/production/files/2015-05/documents/south-atlantic-review.pdf

The South Atlantic coastal wetland review is the second in a series that EPA's Coastal Wetlands Team conducted. The team was able to gain a greater understanding of coastal wetland loss in the region, including important insights into the causes of these losses. Among the several common themes that emerged from the focal watershed reviews:

- Development pressures are a growing concern for causing coastal wetland loss and degradation;
- Hydrologic alterations including water diversions, mosquito impoundments, and ditching and draining for agriculture and forestry are important past and present stressors;
- Lack of accurate characterization of coastal wetland losses;
- The impact of sea level rise and other climate change issues;
- Restoring wetlands that were impounded or converted to other land uses. Significant projects are occurring in Florida and North Carolina to restore wetlands previously impounded for mosquito control or previously converted for agricultural use. Key gaps that need to be filled to reduce the stressors and more effectively use these tools and strategies include:
    - A comprehensive central repository or database for wetland-related data, as well as a common set of metrics to allow standardization and comparison of data.
    - A better sense of how to use new and existing information to set priorities for land acquisition, design restoration projects, and implement such practices as living shorelines.

Walker, Rob, Bonnie Bendell, and Louise Wallendorf (2011). *Defining Engineering Guidance for Living Shoreline Projects*. Coastal Engineering Practice, ASCE, pp. 1064 – 1077. Available at: http://mycopri.org/system/files/content/Living%20Shorelines%20Task%20Committee/Duke%20University%20Marine%20Laboratory/Defining%20Engineering%20Guidance%20for%20Living%20Shoreline%20Projects_1.pdf

Abstract: The concept of "living shorelines" involves the use of native vegetation and low-lying structures to provide shoreline stabilization, while attempting to mimic the natural landscape. Living shorelines are frequently a desirable alternative to hard engineering structures, such as bulkheads and rock revetments, which have the potential to dramatically change shoreline conditions and can lead to a complete loss of intertidal area, as well as associated habitat, recreational, and aesthetic benefits.

The Coastal Zone Management (CZM) technical committee of the Coasts, Oceans, Ports and Rivers Institute (COPRI) has a vested interest in the research of sustainable alternatives for shoreline protection and coastal management. As the concept of living shorelines comes to the forefront in the search for alternative coastal management strategies in our ever-evolving coastal areas, the

CZM committee has set out to further develop the fundamentals of living shoreline design based on a comprehensive review of living shoreline case studies.

Whalen, Laura, Danielle Kreeger, David Bushek, Joshua Moody, and Angela Padeletti (2011). *Practitioner's Guide: Shellfish-Based Living Shorelines for Salt Marsh Erosion Control and Environmental Enhancement in the Mid-Atlantic*. Delaware Estuary Living Shorelines Institute, pp. 47. Available at: https://s3.amazonaws.com/delawareestuary/pdf/Living%20Shorelines/DELSI%20Practitioners%20Guide%20v9.7.11.pdf

In the Delaware Estuary, tidal marshes are vital to the overall health of the system but are eroding at a rapid pace. Living shorelines are a creative approach to protecting shorelines by using engineered stabilization techniques with natural habitat elements. The report states the purpose and benefits of living shorelines and goes on to inventory "bio-based" design options (e.g., vegetation management, tidal marsh creation, bank grading) and hybrid design options (e.g., breakwaters, marsh sills, marsh toe revetments). A guide to installation practices follows a description of the Delaware Estuary Living Shoreline Initiative. Finally, the report discusses recommendations for monitoring and maintenance of completed living shorelines, considerations such as cost/benefits, and permitting requirements.

Living Shorelines in Salt Marsh Habitat

Physical Effects

Ahrens, J.P., E.T. Fulford (1988). Wave energy dissipation by reef breakwaters. In: *Proceedings of the 'Oceans '88' Conference*, Baltimore, Maryland. Available at: https://www.researchgate.net/publication/251745410_Wave_energy_dissipation_by_reef_breakwaters

Abstract: Shoreline erosion has become a chronic problem around much of the US coast. E. T. Fulford (1985) has shown using segmented reef breakwaters is one of the most effective strategies for providing shoreline protection. An approach to evaluating the effectiveness of reef breakwaters based on their ability to dissipate wave energy is presented. Extensive laboratory model tests have been used to define the performance characteristics of reefs. Results from these tests have been used to develop equations that predict wave transmission and reflection characteristics, which can then be used to determine the ability of the structure to dissipate wave energy. It is concluded that the equations fit the data well, approach logical limiting values, are easy to use, and are consistent with the physics of the interaction between waves and rubble structures as it is currently understood.

Airoldi, L., M. Abbiati, M.W. Beck, S.J. Hawkins, P.R. Jonsson, D. Martin, P.S. Moschella, A. Sundelöf, R.C. Thompson, and P. Åberg (2005). An ecological perspective on the deployment and design of low crested and other hard coastal defense structures. *Coast. Eng*. 52: 1073–1087. Available at: http://www.sciencedirect.com/science/article/pii/S0378383905001158

Abstract: Coastal areas play a crucial role in the economical, social and political development of most countries; they support diverse and productive coastal ecosystems that provide valuable goods and services. Globally flooding and coastal erosion represent serious threats along many coastlines, and will become more serious as a consequence of human-induced changes and accelerated sea-level rise. Over the past century, hard coastal defense structures have become ubiquitous features of coastal landscapes as a response to these threats. The proliferation of defense works can affect over half of the shoreline in some regions and results in dramatic changes to the coastal environment. Surprisingly little attention has been paid to the ecological consequences of coastal defense. Results from the DELOS (Environmental Design of Low Crested Coastal Defense Structures, EVK3-CT-2000-00041) project indicate that the construction of coastal defense structures will affect coastal ecosystems. The consequences can be seen on a local scale, as disruption of surrounding soft-bottom environments and introduction of new artificial hard-bottom habitats, with consequent changes to the native assemblages of the areas. Proliferation of coastal defense structures can also have critical impacts on regional species diversity, removing isolating barriers, favoring the spread of non-native species and increasing habitat heterogeneity. Knowledge of the environmental context in which coastal defense structures are placed is fundamental to an effective management of these structures as, while there are some general consequences of such construction, many effects are site specific. Advice is provided to meet specific management goals, which include mitigating specific impacts on the environment, such as minimizing changes to surrounding sediments, spread of exotic species or growth of nuisance species, and/or enhancing specific natural resources, for example enhancing fish recruitment or promoting diverse assemblages for eco-tourism. The DELOS project points out that the downstream effects of defense structures on coastal processes and regional-scale impacts on biodiversity necessitate planning and management at a regional (large coastline) scale. To effectively understand and manage coastal defenses, environmental management goals must be clearly stated and incorporated into the planning, construction, and monitoring stages.

Allen, H.H., J.W. Webb, and S.O. Shirley (1984). Wetlands development in moderate wave energy climates. In: *Proceedings of the Conference Dredging '84, Waterway, Port, Coastal, and Ocean Division of American Society of Civil Engineers,* November 14-16, 1984, Clearwater Beach, Florida.

Abstract: For the last three years springs of *S. alterniflora* have been planted on portions of Theodore Island, a dredged material island in Mobile Bay, Alabama. The purpose of the planting was to stabilize the northwest side of the island and a small portion of the southwest side of the island, both of which are subject to moderate wave energies. Both the northwest and southwest sides of the island are dikes that form two of the three sides of a triangular disposal area.

Allen, H.H., J. R. Leech (eds) (1997). *Bioengineering for streambank erosion control: Report 1, Guidelines*. Technical Report EL-97-8. Report prepared for Environmental Impact Research Program, U.S. Army Corps of Engineers, Headquarters, Washington, D.C., pp. 105. Available at: http://www.engr.colostate.edu/~bbledsoe/CIVE413/Bioengineering_for_Streambank_Erosion_Control_report1.pdf

The U.S Army Corps of Engineers is often restricted from using hard structures, such as riprap or concrete-lined channels, for streambank erosion control because of environmental reasons or high cost. Bioengineering is the combination of biological, mechanical, and ecological concepts to control erosion and stabilize soil through the use of vegetation or a combination of it and construction materials. This study provides guidelines for using bioengineering treatments in a prudent manner.

This study provides guidelines for using bioengineering treatments in a prudent manner while tempering their widespread use with precautions. Precautions consist of properly designing bioengineering projects with enough hardness to prevent both undercutting the streambank toe and erosion of the upper and lower ends (flanking) of the treated project reach. This can be accomplished with one or both of (a) hard toe and flanking protection (e.g., rock riprap, refusals), and (b) deflection of water away from the target reach to be protected through deflection structures (e.g., groins, hard points, and dikes). With both of these methods, appropriate plant species should be used in a manner consistent with their natural habitats, that is, in an effort to emulate natural conditions or processes. Where possible both herbaceous and woody species are used with grass or grass-like plants in the lowermost zone that is planted; shrubby, woody vegetation is used in the middle zone; and, for the most part, larger shrubs and trees are established in the uppermost zone. These zones are respectively called the “splash, bank, and terrace zones.”

Barnhardt, W.A. (ed.) (2009). *Coastal Change along the Shore of Northeastern South Carolina - the South Carolina Coastal Erosion Study*. U.S. Geological Survey Circular 1339, pp. 77. Available at: http://pubs.usgs.gov/circ/circ1339/

The U.S. Geological Survey, in cooperation with the South Carolina Sea Grant Consortium, conducted a 7-year, multi-disciplinary study of coastal erosion in northeastern South Carolina. Shoreline behavior along the coast of Long Bay is dictated by waves, tidal currents, and sediment supply that act within the overall constraints of the regional geologic setting. Beaches are thin ribbons of sand that sit on top of layered sedimentary rocks, which have been deeply eroded by rivers and coastal processes over millions of years. Offshore of the beaches, these sedimentary rocks are exposed as hardgrounds over large expanses of shallow seafloor and are locally overlain by a discontinuous veneer of sandy sediment generally less than 1 m thick. Rates of shoreline retreat largely depend on the geologic framework of the shoreface that is being excavated by ocean processes. Mainland-attached beaches have remained relatively stable, whereas barrier islands have experienced large shifts in shoreline position. In this sediment-limited region, erosion of the shoreface and inner shelf probably contributes a significant amount of new material to the beach system. Oceanographic studies and numerical modeling show that sediment transport varies along the coast, depending on the type and travel path of storms that impact Long Bay, but the long-term net transport direction is generally from north to south. Changes in storm activity that might accompany climate change, coupled with anticipated increases in sea-level rise, are expected to strongly affect low-lying, heavily developed areas of the coast.

Bendell, B.M. (2006). *Recommendations for Appropriate Shoreline Stabilization Methods for the Different North Carolina Estuarine Shoreline Types*. The North Carolina Estuarine Biological and

Physical Processes Work Group, North Carolina Coastal Resources Commission, Estuarine Shoreline Stabilization Subcommittee, pp. 61. Available at: http://floridalivingshorelines.com/information-help-and-documents/guidance-documents/

Estuarine shorelines are dynamic features that experience continued erosion by short-term (boat wakes, storms, tides, etc.) and long-term (sea level rise) processes. The North Carolina Division of Coastal Management (DCM) formed the Estuarine Biological and Physical Processes Work Group facilitate more research and discussion between managers and researchers to effectively address and understand the impact of shoreline stabilization methods on the habitats and productivity of estuarine systems.

In order to provide recommendations to guide the development of new estuarine shoreline stabilization rules in North Carolina, the Work Group evaluated the ecological functions and values of the different North Carolina shoreline types and habitat changes due to the physical impacts associated with each shoreline stabilization structure or method. The first recommendation the Work Group gave for all estuarine shoreline types is land planning (i.e. leave the land in its natural state). Typically, the second recommendation is to use vegetation control because vegetation is a natural and environmentally beneficial stabilization method. When shoreline hardening stabilization methods are proposed, the Work Group rank sills as the most preferred option since it is a small structure that is constructed to support wetland plantings, or the conservation of existing wetland vegetation. Groins, breakwaters, sloped structures, and vertical structures vary in ranking and were determined to be shoreline type and site specific.

Berman, M., H. Berquist, J. Herman, and K. Nunea (2007). *The stability of living shorelines—An evaluation*. Final Report submitted to NOAA Chesapeake Bay Program Office, pp. 106. Available at: http://ccrm.vims.edu/livingshorelines/projects/livingshorelines_final_rpt.pdf

This project set out to determine the suitability of living shorelines as a method of erosion control along Chesapeake Bay. Using statistical tests and data that describe shoreline and environmental condition along tidal shoreline, the study found that marshes are frequently associated with stable shoreline. When investigating the erosion rates along 35 shorelines where living shoreline treatments were in place, the authors concluded that the data confirmed that erosion could be reduced using soft stabilization techniques. Finally, based on criteria evaluated in the previous two analyses, a protocol was developed to model the locations where living shoreline treatments should be considered for erosion control. Using existing GIS based databases a spatially explicit model was generated and tested in Northumberland County, Virginia. The model delineated areas as suitable, unsuitable, and suitable with design restrictions. The model was validated against random field inspections and permit reviews. The results indicate strong agreement (75%) between the modeled output and the field review when considering a site suitable (inclusive of design restrictions) and unsuitable. The model had less agreement (58%) between the output and the field assessment when considering explicit treatment types for suitable areas.

Bilkovic, D. and M. Mitchell (2013). Ecological tradeoffs of stabilized salt marshes as a shoreline protection strategy: Effects of artificial structures on macrobenthic assemblages. *Ecol. Eng*. 61 Part A: 469-481. Available at: http://www.sciencedirect.com/science/article/pii/S0925857413004278

Abstract: Armoring shorelines to prevent erosion is a long-standing global practice that has well-documented adverse effects on coastal habitats and organisms. A relatively new form of shoreline protection, referred to as hybrid stabilization, incorporates created marsh in combination with a stabilizing structure such as a low-profile stone sill and is being implemented in many US coastal states as a means to not only control erosion but also to restore coastal habitat. However, there has been limited scientific investigation of ecological benefits and impacts associated with implementation of hybrid stabilization. We evaluated relative habitat capacity of marsh-sills by comparing plant, sediment, and benthic macroinvertebrate attributes in intertidal and subtidal zones of existing marsh-sills, natural marshes, tidal flats, and riprap revetment within two sub-estuaries of Chesapeake Bay, USA. Low and high marsh plant characteristics (stem count and height) of marsh-sills were similar to or greater than natural marshes. However, sediment was coarser, total organic carbon and total nitrogen concentrations were lower, and benthic macrofaunal community structure differed in marsh-sills compared to natural marshes. Marsh-sills supported lower deposit-feeding infaunal biomass than marshes in the intertidal. Epifaunal suspension-feeders were most prevalent at sites with artificial structure (riprap and marsh-sill), but highly variable among sub-estuaries. Infaunal abundance, biomass, diversity, and proportion of suspension/interface and deposit feeding animals were greater in shallow subtidal than in intertidal environments. Conversion of existing habitat to marsh-sills may cause localized loss of benthic productivity and sediment bioturbation and nutrient-cycling functions, with the opportunity to enhance filtration capacity by epifaunal recruitment to structures. When creating marshes that require structural support, there should be a balance of minimizing loss of existing habitats while encouraging use of suitable structural habitat for suspension-feeders. If properly implemented, the addition of structural habitat could subsidize secondary productivity particularly in areas where loss of complex biogenic habitat (e.g., oyster reefs) has occurred.

Boak, E. H. and I.L. Turner (2005). Shoreline Definition and Detection: A Review. *Journal of Coastal Research* 21(4): 688-703. Available at: https://www.academia.edu/6574828/Shoreline_Definition_and_Detection_A_Review

Abstract: Analysis of shoreline variability and shoreline erosion-accretion trends is fundamental to a broad range of investigations undertaken by coastal scientists, coastal engineers, and coastal managers. Though strictly defined as the intersection of water and land surfaces, for practical purposes, the dynamic nature of this boundary and its dependence on the temporal and spatial scale at which it is being considered results in the use of a range of shoreline indicators. These proxies are generally one of two types: either a feature that is visibly discernible in coastal imagery (e.g., high-water line [HWL]) or the intersection of a tidal datum with the coastal profile (e.g., mean high water [MHW]). Recently, a third category of shoreline indicator has begun to be reported in the literature, based on the application of image-processing techniques to extract proxy shoreline features from digital coastal images that are not necessarily visible to the human eye.

Potential data sources for shoreline investigation include historical photographs, coastal maps and charts, aerial photography, beach surveys, in situ geographic positioning system shorelines, and a range of digital elevation or image data derived from remote sensing platforms. The identification of a ‘‘shoreline’’ involves two stages: the first requires the selection and definition of a shoreline indicator feature, and the second is the detection of the chosen shoreline feature within the available data source. To date, the most common shoreline detection technique has been subjective visual interpretation. Recent photogrammetry, topographic data collection, and digital image-processing techniques now make it possible for the coastal investigator to use objective shoreline detection methods. The remaining challenge is to improve the quantitative and process-based understanding of these shoreline indicator features and their spatial relationship relative to the physical land–water boundary.

Bosch, J., C. Foley, L. Lipinski, C. McCarthy, J. McNamara, A. Naimaster, A. Raphael, A. Yang, A. Baldwin, and the Maryland Department of the Environment (2006). *Shore erosion control guidelines: Marsh creation*. Maryland Department of the Environment Wetlands and Waterways Program, funded by U.S. Environmental Protection Agency State Wetland Program Development Grant CD 983379-01-0, pp. 26. Available at: http://www.mde.state.md.us/assets/document/wetlandswaterways/Shoreerosion.pdf

This document was prepared as part of the project “Shoreline and Marsh Stabilization Guidance” funded by the U.S. Environmental Protection Agency’s State Wetland Program. Background research was conducted by Dr. Andrew H. Baldwin of the University of Maryland and a research team under his direction, and reported in *Constructed Wetlands for Shoreline Erosion Control: Field Assessment and Data Management* (2006) by Bosch et al. Text for this guidance document is excerpted from the University of Maryland/MDE report. Topics covered include: understanding shore erosion including wave erosion and sediment transportation; the role of wetlands in controlling erosion; recommendations for non-structural shore erosion control projects; marsh creation for habitat and shoreline stabilization; and marsh creation with sills.

Burke, David G., E.W. Koch, and J.C. Stevenson (2005). *Assessment of hybrid type shore erosion control projects in Maryland's Chesapeake Bay, Phases I & II*. Horn Point Environmental Laboratory, University of MD Center for Environmental Science, pp. 112. Available at: http://mdstatedocs.slrc.info/cdm/ref/collection/mdgov/id/3022

In this project, a survey team assessed eight separate hybrid shore erosion control projects involving the creation and restoration of marsh fringe habitat using sand fill material and marsh plantings contained by a breakwater/rock sill system (six sites) or stone groins (two sites). Two projects were designed primarily for habitat benefits while the remaining four were primarily constructed for erosion control purposes. The “habitat first” projects experienced the greatest shoreline erosion and marsh stress or direct loss of shoreline. These sites used very low profile sills to protect the fringe marsh areas. Two “erosion first” stone groin projects experienced a moderate degree of marsh stress or loss. The remaining four “erosion first” sites had the least erosion and habitat loss. The relative success of the “erosion control first” sites was likely due, in part, to the fact that the breakwater/sills were located in sites where there was little or no bank or shoreline erosion and the marsh communities were mostly healthy. In contrast, at the "habitat first" and groin sites, variables including: bank erosion; higher average fetch; substrate conditions; boat wakes; steepness of marsh gradients; marsh shading; movement of groin structures; and littoral drift patterns placed additional stress to the marsh community, causing greater loss of overall vegetated area and shifts in plant species.

Carey, M. (2013). *Modeling Site Suitability of Living Shorelines in the Albemarle-Pamlico Estuarine System*. Master's Thesis, East Carolina University, pp. 94. Available at: http://thescholarship.ecu.edu/bitstream/handle/10342/4207/Carey_ecu_0600M_10988.pdf?sequence=1&isAllowed=y

Abstract: Shoreline erosion and associated land loss are major concerns for coastal land owners and resource managers. Traditional methods of shoreline stabilization using permanent, hard structures can have adverse environmental impacts. Living shorelines offer an alternative to these traditional methods and sometimes provide additional benefits to the surrounding environment. This study examines the suitability for living shorelines in the Albemarle-Pamlico Estuarine System (APES) by creating and testing spatial modeling for living shorelines using suitability indices. The results of this modeling show that the majority of the shoreline in the APES is suitable for living shorelines.

Cowart, L., J.P. Walsh, and D.R. Corbett (2010). Analyzing Estuarine Shoreline Change: A Case Study of Cedar Island, North Carolina. *Journal of Coastal Research* 26(5): 817-830. Available at: http://www.jcronline.org/doi/abs/10.2112/JCOASTRES-D-09-00117.1?journalCode=coas

Abstract: Continued climate change, sea-level rise, and coastal development have led to concern about shoreline dynamics beyond oceanfront areas, encompassing more sheltered coastal water bodies such as estuaries. Because estuaries are critically important ecosystems, understanding coastline changes in these areas is necessary to evaluating resource risks. A transect-based approach is commonly used to quantify shoreline change on linear (i.e., ocean) shorelines; however, due to the complex morphology of the study area, a point-based approach was developed and applied in this study. Shoreline-change rates and additional parameters (i.e., wave energy and shoreline composition) were determined using 1958 and 1998 aerial photography and available datasets. From this data, the average shoreline change in the study area is -0.24 m yr^{-1}, with 88% of the shoreline eroding. Of the parameters analyzed, shoreline composition appears to have an important control on shoreline erosion, whereas wave energy is not significantly correlated with shoreline-change rates.

Currin, C., L. Cowart, J. Davis, P. Delano, J. Fear, M. Greene, A. Hilting, J T. Morris (NA). *Natural and Stabilized Estuarine Shorelines in North Carolina Research and Policy*. Available at: http://dnr2.maryland.gov/ccs/Documents/training/currin.pdf

Researchers studied the effects of varying wave energies on erosion while using salt marsh vegetation as a natural stabilizer. Their findings include:

- Marshes are dependent upon sediment supply to maintain surface elevation.
- Stone sills increase sediment accretion and elevation gain in marsh surface elevation. This in turn results in change in marsh vegetation.
- Marsh-sills present tradeoffs in habitat types; loss of subtidal and low marsh, gain in upper marsh. Lack of design standards may contribute to use of hard structures.
- North Carolina's 'Living Shorelines', including marshes, oyster reefs, and marsh-sill hybrids, came through Hurricane Irene with no losses, and some sediment accretion; In North Carolina, intertidal oysters are a viable alternative to stone sills in many settings.
- Carbon sequestration is another important ecosystem service offered by Living Shoreline approach.

Currin, C. A., P. C. Delano, and L. M. Valdes-Weaver (2008). Utilization of a citizen monitoring protocol to assess the structure and function of natural and stabilized fringing salt marshes in North Carolina. *Wetlands Ecol. Manage*. 16: 97-118. Available at: https://coastalscience.noaa.gov/about/docs/Currinetal.WME.vol2.pdf

Abstract: Narrow fringing salt marshes dominated by *S. alterniflora* occur naturally along estuarine shorelines and provide many of the same ecological functions as more extensive marshes. These fringing salt marshes are sometimes incorporated into shoreline stabilization efforts. We obtained data on elevation, salinity, sediment characteristics, vegetation and fish utilization at three study sites containing both natural fringing marshes and nearby restored marshes located landward of a stone sill constructed for shoreline stabilization. During the study, sediment accretion rates in the restored marshes were approximately 1.5- to 2-fold greater than those recorded in the natural marshes. Natural fringing marsh sediments were predominantly sandy with a mean organic matter content ranging between 1.5 and 6.0%. Average *S. alterniflora* stem density in natural marshes ranged between 130 and 222 stems/m^2, while mean maximum stem height exceeded 64 cm. After 3 years, one of the 3 restored marshes (NCMM) achieved *S. alterniflora* stem densities equivalent to that of the natural fringing marshes, while percentage cover and maximum stem heights were significantly greater in the natural than in the restored marshes at all sites. There was no significant difference in the mean number of fish, crabs or shrimp captured with fyke nets between the natural and restored marshes, and only the abundance of *Palaemonetes vulgaris* (grass shrimp) was significantly greater in the natural marshes than in the restored ones. Mean numbers of fish caught per 5 m of marsh front were similar to those reported in the literature from marshes adjacent to tidal creeks and channels, and ranged between 509 and 634 per fishnet. Most of the field data and some of the sample analyses were obtained by volunteers as they contributed 223 h of the total 300 h spent collecting data from three sites in one season. The use of fyke nets required twice as many man-hours as any other single task. Vegetation and sediment parameters were sensitive indicators of marsh restoration success, and volunteers were capable of contributing a significant portion of the labor needed to collect these parameters.

Dame, R.F. and D.M. Allen (1996). Between estuaries and the sea. *Journal of Experimental Marine Biology and Ecology* 200(1-2): 169-185. Available at: http://www.sciencedirect.com/science/article/pii/S0022098196026421

Abstract: Dissolved and particulate materials and living organisms are exchanged between estuaries and the sea. Net material fluxes, import or export, appear to depend on physical and biological processes within both estuarine and coastal ecosystems. In temperate zone lagoonal systems, the marsh-estuarine continuum hypothesis can provide a reasonable synthetic explanation of transport based on the level of ecosystem maturity within the system. The relative importance of riverine and lagoonal material exchanges with the coastal ocean are at present entirely speculative and make the estimation of the regional influences of material transports between estuaries and the coastal ocean uncertain. Organismic exchanges depend on both passive and active behavior mechanisms and are species specific. Few quantitative estimates of organismic fluxes exist and the role of non-commercial invertebrates and fish in these fluxes are unknown.

Duhring, K. A. (2006). A Comparison of Structural and Nonstructural Methods for Erosion Control and Providing Habitat in Virginia Salt Marshes, In: *Management, Policy, Science, and Engineering of Nonstructural Erosion Control in the Chesapeake Bay, Proceedings of the Living Shorelines Summit: Evaluation of Living Shoreline Techniques*; Erdle, S. Y., J. L. D. Davis, and K. G. Sellner (eds). CRC Publ. No. 08-164, Gloucester Point, VA, pp. 136. Available at: http://www.vims.edu/cbnerr/_docs/ctp_docs/ls_docs/06_LS_Eval.pdf

Abstract: Shoreline stabilization methods that emphasize the use of tidal marshes and riparian vegetation are encouraged as a baseline defense for tidal shoreline erosion in Virginia. The effectiveness of three of these methods in preventing erosion and providing habitat was evaluated, including marsh stabilization structures (marsh toe revetments and sills), planted tidal marshes, and bank grading. This evaluation includes results from a recent field survey of 36 tidal marsh stabilization structures, permitting records, and other monitoring data. Marsh structures effectively reduced erosion of fringing and embayed marshes but were not as effective for gradually disappearing spit marshes. Adverse impacts of restricted tidal exchange were observed where the revetment height was more than one foot above the mean high water elevation. The two nonstructural methods provided both habitat and erosion protection, but were generally not as effective as marsh structures. Planted marshes were most effective where regular high tides do not reach the upland bank. Graded banks that included a flat area for marsh vegetation at the toe were more effective than banks graded steeply landward from the toe. Graded banks maintained as lawns were not as effective for preventing storm erosion as densely vegetated slopes. Additional research is needed to investigate how sand fill and fiber materials can be used beneficially to enhance tidal salt marshes and beaches for erosion protection.

Duhring, K.A., T.A. Barnard, and S. Hardaway (2006). *A survey of the effectiveness of existing marsh toe protection structures in Virginia*. Final Report to the Keith Campbell Foundation, pp. 25. Available at: http://web.vims.edu/GreyLit/VIMS/CCRMMarshToeRevtSurvey2006.pdf

Abstract: Using tidal marshes and other vegetated treatments for upland erosion control has been an accepted practice for years, yet the scientific understanding and established guidelines for this approach are limited. This survey was conducted to evaluate the efficacy of existing marsh toe protection structures, a particular type of erosion control treatment associated with tidal marshes on Chesapeake Bay shorelines. Field evaluations were conducted at 36 sites in 6 localities on the Middle Peninsula and Northern Neck of Virginia. General dimensions of each structure were recorded and observations made of erosion evidence, structural integrity, construction access impacts, and adjacent landscape settings. Most of the projects provide effective erosion protection for the tidal marsh and adjacent upland bank. Twenty projects (55%) were also determined to be effective as living shoreline treatments based on tidal marsh condition and because the riparian and wetland vegetation cover was interconnected. Common design standards from these projects have been incorporated into advisory guidelines.

Feagin, Rusty A., Nibedita Mukherjee, Kartik Shanker, Andrew H. Baird, Joshua Cinner, Alexander M. Kerr, Nico Koedam, Aarthi Sridhar, Rohan Arthur, L. P. Jayatissa, Danny Lo Seen, Manju Menon, Sudarshan Rodriguez, Md. Shamsuddoha, and Farid Dahdouh-Guebas (2010). Shelter from the storm? Use and misuse of coastal vegetation bioshields for managing natural disasters. *Conservation Letters* 3(1): 1-11. Available at: http://onlinelibrary.wiley.com/oi/10.1111/j.1755-263X.2009.00087.x/pdf

Abstract: Vegetated coastal ecosystems provide goods and services to billions of people. In the aftermath of a series of recent natural disasters, including the Indian Ocean Tsunami, Hurricane Katrina and Cyclone Nargis, coastal vegetation has been widely promoted for the purpose of reducing the impact of large storm surges and tsunami. In this paper, we review the use of coastal vegetation as a “bioshield” against these extreme events. Our objective is to alter bioshield policy and reduce the long-term negative consequences for biodiversity and human capital. We begin with an overview of the scientific literature, in particular focusing on studies published since the Indian Ocean Tsunami in 2004and discuss the science of wave attenuation by vegetation. We then explore case studies from the Indian subcontinent and evaluate the detrimental impacts bioshield plantations can have upon native ecosystems, drawing a distinction between coastal restoration and the introduction of exotic species in inappropriate locations. Finally, we place bioshield policies into a political context, and outline a new direction for coastal vegetation policy and research.

Feagin, R. A., S. M. Lozada-Bernard, T. Ravens, I. M̈oller, K. M. Yeager, and A. H. Baird (2009). Does vegetation prevent wave erosion of salt marsh edges? *Proc Natl Acad Sci USA* 106, 10101–10113. Available at: http://www.pnas.org/content/106/25/10109.full

Abstract: This study challenges the paradigm that salt marsh plants prevent lateral wave-induced erosion along wetland edges by binding soil with live roots and clarifies the role of vegetation in protecting the coast. In both laboratory flume studies and controlled field experiments, we show that common salt marsh plants do not significantly mitigate the total amount of erosion along a wetland edge. We found that the soil type is the primary variable that influences the lateral erosion rate and although plants do not directly reduce wetland edge erosion, they may do so indirectly via modification of soil parameters. We conclude that coastal vegetation is best suited to modify and control sedimentary dynamics in response to gradual phenomena like sea-level rise or tidal forces, but is less well-suited to resist punctuated disturbances at the seaward margin of salt marshes, specifically breaking waves.

Fear, J. and B. Bendell (2011). *Assessment of 27 Marsh Sills in North Carolina*. N.C. Division of Coastal Management, pp. 189. Available at: https://ncdenr.s3.amazonaws.com/s3fs-public/Coastal%20Management/documents/PDF/msfinalreport.pdf

The North Carolina Division of Coastal Management initiated a qualitative technical assessment of 27 existing marsh sills. Sills were evaluated on the basis of whether they had stabilized the shoreline of the properties where they were installed and whether the sills caused any unexpected erosion or other unanticipated problems or benefits. The feelings and perceptions of the properties' owners and the adjacent properties' owners regarding the marsh sill stabilization technique where the marsh sills are currently installed were also assessed.

The results provided the following findings:

- Marsh sills were not found by the field team to present a hazard to navigation.
- Marsh sills were observed to provide erosion protection to the property upon which they were installed.
- Marsh sills were often built in combination with other structures.
- Marsh sills that utilized the gap or overlap design were observed to provide better water, fish, and other nekton access to the area behind the sill compared to ones utilizing the dropdown design.
- It was unclear whether marsh sills cause erosional impacts on adjacent property.
- After completion of the field aspects of this project, the resource agencies still prefer to review and comment on marsh sill permits on a case-by-case basis.
- The mound material used in the marsh sills is often colonized with oysters.
- The marsh sills visited supported marsh grass and do not appear to be creating new uplands.
- Marsh sills were observed to be free from damage.
- No marsh sill related impacts to water quality were observed.

Fonseca, M., Currin, C. (2013). *Forecasting Influence of Natural and Anthropogenic Factors on Estuarine Shoreline Erosion Rates*. DCERP1 Research Project CW-2; Coastal Wetlands Module of the Defense Coastal/Estuarine Research Program. Available at: https://dcerp.rti.org/DCERPPublicSite/EcosystemModules/CoastalWetlands.aspx

This Coastal Wetlands module determines factors affecting the sustainability of coastal salt marshes on Marine Corps Base Camp Lejeune and the role of salt marsh habitats within the coastal ecosystem. The module assessed shoreline erosion rates on Camp Lejeune and the relative impacts of military training, wind, wave, and boat wake energy depending on the shoreline type. The module also examines the impact of specific military training activities on coastal wetlands habitats, calculates the contribution of eroding sediment banks to the New River Estuary sediment budget, and provides recommendations for management of the Camp Lejeune shorelines.

Gedan, K.B., M.L. Kirwan, E. Wolanski, E.B. Barbier, and B.R. Silliman (2011). The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm. *Climatic Change*, 106(1): 7-29. Available at: http://link.springer.com/article/10.1007%2Fs10584-010-0003-7

Abstract: For more than a century, coastal wetlands have been recognized for their ability to stabilize shorelines and protect coastal communities. However, this paradigm has recently been called into question by small-scale experimental evidence. Here, we conduct a literature review and a small meta-analysis of wave attenuation data, and we find overwhelming evidence in support of established theory. Our review suggests that mangrove and salt marsh vegetation afford context-dependent protection from erosion, storm surge, and potentially small tsunami waves. In biophysical models, field tests, and natural experiments, the presence of wetlands reduces wave heights, property damage, and human deaths. Meta-analysis of wave attenuation by vegetated and unvegetated wetland sites highlights the critical role of vegetation in attenuating waves. Although we find coastal wetland vegetation to be an effective shoreline buffer, wetlands cannot protect shorelines in all locations or scenarios; indeed, large-scale regional erosion, river meandering, and large tsunami waves and storm surges can overwhelm the attenuation effect of vegetation. However, due to a nonlinear relationship between wave attenuation and wetland size, even small wetlands afford substantial protection from waves. Combining manmade structures with wetlands in ways that mimic nature is likely to increase coastal protection. Oyster domes, for example, can be used in combination with natural wetlands to protect shorelines and restore critical fishery habitat. Finally, coastal wetland vegetation modifies shorelines in ways (e.g. peat accretion) that increase shoreline integrity over long timescales and thus provides a lasting coastal adaptation measure that can protect shorelines against accelerated sea level rise and more frequent storm inundation. We conclude that the shoreline protection paradigm still stands, but that gaps remain in our knowledge about the mechanistic and context dependent aspects of shoreline protection.

Gittman, R.K., A. Popowich, J. Bruno, C. Peterson (2014). Marshes with and without sills protect estuarine shorelines from erosion better than bulkheads during a Category One hurricane. *Ocean & Coastal Management* 102: 94-102. Available at: http://www.mobilebaynep.com/images/uploads/library/Bulkheads.pdf

Abstract: Acting on the perception that they perform better for longer, most property owners in the United States choose hard engineered structures, such as bulkheads or riprap revetments, to protect estuarine shorelines from erosion. Less intrusive alternatives, specifically marsh plantings with and without sills, have the potential to better sustain marsh habitat and support its ecosystem services, yet their shoreline protection capabilities during storms have not been evaluated. In this study, the performances of alternative shoreline protection approaches during Hurricane Irene (Category 1 storm) were compared by 1) classifying resultant damage to shorelines with different types of shoreline protection in three NC coastal regions after Irene; and 2) quantifying shoreline erosion at marshes with and without sills in one NC region by using repeated measurements of marsh surface elevation and marsh vegetation stem density before and after Irene. In the central Outer Banks, NC, where the strongest sustained winds blew across the longest fetch; Irene damaged 76% of bulkheads surveyed, while no damage to other shoreline protection options was detected. Across marsh sites within 25 km of its landfall, Hurricane Irene had no effect on marsh surface elevations behind sills or along marsh shorelines without sills. Although Irene temporarily reduced marsh vegetation density at sites with and without sills, vegetation recovered to pre-hurricane levels within a year. Storm responses suggest that marshes with and without sills are more durable and may protect shorelines from erosion better than the bulkheads in a Category 1 storm. This study is the first to provide data on the shoreline protection capabilities of marshes with and without sills relative to bulkheads during a substantial storm event, and to articulate a research framework to assist in the development of comprehensive policies for climate change adaptation and sustainable management of estuarine shorelines and resources in U.S. and globally.

Gray, D.H. and Sotir, R.B. (1996). *Biotechnical and soil bioengineering slope stabilization: A practical guide for erosion control*. Wiley-Interscience, Malden, Massachusetts, pp. 400. Available at: http://www.wiley.com/WileyCDA/WileyTitle/productCd-0471049786.html

This is a guide to physically attractive, environmentally compatible, and cost-effective methods of protecting slopes from erosion. This book covers the entire subject from general principles and background on the nature of soil erosion and mass movement to detailed information on root strengths, treatment selection, unit costs, critical tractive stresses, methods for harvesting and handling live cuttings, and more. This reference handbook:

- Contains four illustrated case studies, each addressing a different set of problems and solutions, demonstrate both the application of particular technologies and the site investigation, planning, scheduling, and organization required to complete these projects successfully;
- Reviews the horticultural and engineering underpinnings for biotechnical and soil engineering treatments;
- Documents and explains the role of woody plants in stabilizing slopes against both surficial erosion and mass movement;
- Provides details on a broad range of soil bioengineering methods, including live staking, live fascines, brush layering, live crib walls, branch packing, and live slope gratings;
- Describes various biotechnical methods and materials, including the incorporation of vegetation in erosion control blankets, flexible mats, cellular revetments (geocells), rock armor (rip rap), and gabion and open-front crib walls; and
- Summarizes the findings of the National Science Foundation-sponsored workshop to assess the state of the art and determine research needs.

Gutierrez, J.L., C.G. Jones, J.E. Byers, K.K. Arkema, K. Berkenbusch, J.A. Commito, C.M. Duarte, S.D. Hacker, J.G. Lambrinos, I.E. Hendriks, P.J. Hogarth, M.G. Palomo, and C. Wild (2011). Physical ecosystem engineers and the functioning of estuaries and coasts. In: Eric Wolanski and Donald McLusky (eds), *Functioning of Ecosystems at the Land-Ocean Interface, Vol. 7 of Treatise on*

Estuarine and Coastal Science, pp. 53-81. Available at: http://www.sciencedirect.com/science/article/pii/B9780123747112007051

Abstract: A great diversity of organisms modify the physical structure of estuarine and coastal environments. These physical ecosystem engineers – particularly, dune and marsh plants, mangroves, seagrasses, kelps, reef-forming corals and bivalves, burrowing crustaceans, and infauna – often have substantive functional impacts over large areas and across distinct geographic regions. Here, we use a general framework for physical ecosystem engineering to illustrate how these organisms can exert control on sedimentary processes, coastal protection, and habitat availability to other organisms. We then discuss the management implications of coastal and estuarine engineering, concluding with a brief prospectus on research and management challenges.

Hall, M. J., R.S. Young, E.R. Thieler, R.D. Priddy, and O.H. Pilkey Jr. (1990). Shoreline Response to Hurricane Hugo. *Journal of coastal research* 6(1): 211-221. Available at: http://www.jstor.org/stable/4297660?seq=1#page_scan_tab_contents

Abstract: Hurricane Hugo made landfall on the South Carolina coast on 22nd September 1989 at high tide. Maximum sustained winds near the eye of the storm were 217 kph. Maximum storm surge in areas near the eye reached 6 m. A team from the Duke University Program for the Study of Developed Shorelines observed storm response along a stretch of coastline from the North Carolina border to Folly Island.

Hurricane Hugo has provided an excellent opportunity to observe the varying responses of developed and undeveloped shorelines to a major storm event. Important processes include overwash, storm surge, storm surge ebb, beach and dune erosion, and shoreline retreat. The interaction of storm processes with developed and undeveloped shorelines was markedly different. Shoreline development intensified natural storm processes. Seawalls caused beach scour; shore perpendicular roads allowed greater penetration of overwash; and buildings channeled storm surge ebb. Post-storm beaches were narrower on developed shorelines than on undeveloped shorelines as buildings and shoreline structures impeded shoreline retreat.

Knutson P.L., R.A. Brochu, W.N. Seeling, and M.R. Inskeep (1982). Wave dampening in *Spartina alterniflora* marshes. *Wetlands* 2(1): 87–104.

Abstract: Though there is widespread agreement that *Spartina alterniflora* marshes absorb some wave energy, there is considerable question regarding the magnitude and importance of this process. It has been suggested that marshes are much like an array of vertical cylinders in a water column. Based upon empirical estimates of the fluid drag forces occurring on vertical cylinders and laboratory observations of various arrays of cylinders, a model was developed to describe wave decay in marshes. In 1981, a series of field experiments were conducted to test and calibrate this empirical model in a series of natural *S. alterniflora* marshes. The model with some modification was found to be very useful for describing wave decay in coastal marshes.

Koch, E.W., E.B. Barbier, B.R. Silliman, D.J. Reed, G.M. Perillo, S.D. Hacker, E.F. Granek, J.H. Primavera, N. Muthiga, S. Polasky, B.S. Halpern, C.J. Kennedy, C.V. Kappel, E. Wolanski (2009). Non-linearity in ecosystem services: temporal and spatial variability in coastal protection. *Front. Ecol*. 7(1), 29-37. Available at: http://onlinelibrary.wiley.com/doi/10.1890/080126/pdf

Abstract: Natural processes tend to vary over time and space, as well as between species. The ecosystem services these natural processes provide are therefore also highly variable. It is often assumed that ecosystem services are provided linearly (unvaryingly, at a steady rate), but natural processes are characterized by thresholds and limiting functions. In this paper, we describe the variability observed in wave attenuation provided by marshes, mangroves, seagrasses, and coral reefs and therefore also in coastal protection. We calculate the economic consequences of assuming coastal protection to be linear. We suggest that, in order to refine ecosystem-based management practices, it is essential that natural variability and cumulative effects be considered in the valuation of ecosystem services.

Kroeger, T. (2012). *Dollars and Sense: Economic Benefits and Impacts from Two Oyster Reef Restoration Projects in the Northern Gulf of Mexico*. The Nature Conservancy, Arlington, VA, pp. 110. Available at: http://www.nature.org/ourinitiatives/regions/northamerica/oyster-restoration-study-kroeger.pdf

Abstract: Generating quantitative estimates of the benefits that oyster reefs provide has only recently become possible. Using information from two reef restoration projects in Mobile Bay, Alabama and specific estimates of various benefits from other studies, this study is one of the first to quantify the benefits that oyster reefs provide in the northern Gulf of Mexico and calculate the social return on investment in reef restoration. In general terms, northern Gulf oyster reef restoration will generate benefits from enhanced seafood harvests, a large portion of which will accrue to the poor coastal communities highly dependent on seafood resources. In addition, large-scale reef restoration will deliver a short to medium-term output, income and employment boost during the construction period and a long-term economic boost from increased output of the seafood sector. The restoration of oyster reefs along the northern Gulf coast will also reduce the high vulnerability of many of these coastal areas to climate impacts from coastal erosion. More specifically, the two oyster reef restoration projects, with a total length of 3.6 miles, will produce the following outputs: 6,900 pounds/year of additional finfish and crab catch, with an economic value of $38,000-$46,000/year producing a total economic output of $39,000/year; 51-90% reduction in wave height and 76-99% reduction in wave energy at the shore; 280-4,160 pounds of nitrogen per year removed from Bay waters; and $8.4 million in local output, $2.8 million in earnings and 88 jobs created.

Over a 50-year timeframe, the present value of the economic net benefits from just the fishery enhancement provided by sustainably harvested oyster reefs (including oysters) is $5.6 million, giving the project a social return on investment of 2.3. If avoided damages from coastal erosion and flooding are considered, the economic rationale for reef restoration becomes even stronger. Importantly, economic benefits and impacts increase proportionally with oyster reef area.

Manis, Jennifer E., Stephanie K. Garvis, Steven M. Jachec, and Linda J. Walters (2015). Wave attenuation experiments over living shorelines over time: a wave tank study to assess recreational boating pressures. *Journal of Coastal Conservation* 19(1): 1-11. Available at: http://link.springer.com/article/10.1007%2Fs11852-014-0349-5

Abstract: With sea level rise, erosion, and human disturbances affecting coastal areas, strategies to protect and stabilize existing shorelines are needed. One popular solution to stabilize while conserving intertidal habitat is the use of “living shoreline” techniques which are designed to mimic natural shoreline communities by using native plants and animals. However, little information is available on the success of living shoreline stabilization. This project evaluated the wave energy attenuation associated with living shorelines that contained *Crassostrea virginica* (eastern oyster) and/or *Spartina alterniflora* (smooth cordgrass) in a wave tank. Four living shoreline techniques were assessed, including a control (sediment only), oysters alone, cordgrass alone, and a combination of oysters plus cordgrass. Time since deployment (newly deployed, one-year after deployment) was also assessed to see how wave energy attenuation changed with natural oyster recruitment and plant growth. Wave energy was calculated for each newly deployed and one-year old shoreline stabilization treatment using capacitance wave gauges and generated waves that were representative of boat wakes in Mosquito Lagoon, a shallow-water estuary in Florida. All one-year old treatments attenuated significantly more energy than newly-deployed treatments. The combination of one-year-old *S. alterniflora* plus live *C. virginica* was the most effective as this treatment reduced 67% of the wave energy created by a single recreational boat wake, compared to bare sediment. Natural resource managers and landowners facing shoreline erosion issues can use this information to create effective stabilization protocols that preserve shorelines while conserving native intertidal habitats.

Meyer, D.L., E.C. Townsend, and G.W. Thayer (1997). Stabilization and erosion control value of oyster cultch for intertidal marsh. *Restoration Ecology* 5(1): 93-99. Available at: http://onlinelibrary.wiley.com/doi/10.1046/j.1526-100X.1997.09710.x/abstract.

Abstract: Oyster cultch was added to the lower intertidal fringe of three created *Spartina alterniflora* marshes to examine its value in protecting the marsh from erosion. Twelve 5-m-wide plots were established at each site, with six randomly selected plots unaltered (non-cultched) and cultch added to the remaining (cultched) plots. Within each cultched plot, cultch was placed along the low tide fringe of the marsh during July 1992, in a band 1.5 m wide by 0.25 m deep. Marsh-edge vegetation stability and sediment erosion were measured for each plot from September 1992 to April 1994. Significant differences ($p < 0.05$) in marsh-edge vegetation change were detected at the only south-facing site after a major southwester storm. Significantly different rates of sediment erosion and accretion also were observed at this same site. Areas upland of the marsh edge in the cultched areas showed an average accretion of 6.3 cm, while noncultched treatment areas showed an average loss of 3.2 cm. A second site, with a northern orientation, also experienced differential sediment accretion and erosion between treatment type, caused instead by boat wakes that were magnified by the abutment of a dredge effluent pipe across the entire front fringe of the site. During this period, we observed significant differences in sediment accumulation, with the areas upland of the

marsh edge in the cultched treatment having an average accretion of 2.9 cm and the noncultched an average loss of 1.3 cm.

Milbrandt, E., Mark Thompson, Loren D. Coen, Raymond E. Grizzle, Krystin M. Ward (UNH), and Sabrina Lartz (2012). *Community-Based Restoration of Oyster Habitat: A Project to Evaluate its Success, Associated Effects on Water Quality and Seagrass Health in a Recently Modified, Substrate-Limited Southwestern Florida Embayment*. Sanibel-Captiva Conservation Foundation, National Oceanic and Atmospheric Agency and The Nature Conservancy, pp. 87 with appendices. Available at: http://www.mysanibel.us/council/agendas/Final_SCCF_Clam_Bayou_TNC_3_13_12.pdf

Abstract: A community-based oyster restoration effort in Clam Bayou, a substrate-limited back bay on Sanibel Island in southwest Florida was undertaken from October 2009 through September 2011. Under this NOAA/TNC sponsored project, three oyster reefs totaling 637 square meters were constructed using fossil shell bags placed in fringing intertidal reefs by 518 volunteers. An additional 124 square meters of reef were constructed concurrently under a grant awarded by National Association of Counties (NACo). The oyster restoration project included a robust monitoring plan consisting of periodic retrieval (8 months; 12 months post-construction) of monitoring trays from constructed and nearby natural reefs to evaluate reef development. Native oyster (*Crassostrea virginica*) density and resident reef community composition, reef relief, water quality, in situ seston uptake, and benthic submerged aquatic vegetation (SAV) surveys were measured as part of the pre-construction monitoring plan submitted to TNC. After one year, all five constructed reefs met success criteria for density, growth, recruitment, and resident reef community development. The constructed reefs had abundant initial recruitment and growth of oysters after the first season of recruitment (8 months post-construction), but suffered high mortality rates during a period of high temperature and salinity between April 2011 and August 2011. Nearby monitoring of *Perkinsus marinus* levels indicated that *Perkinsus* was prevalent (Volety, pers. comm.) and it was deduced that mortality observed during that period was likely related to *Perkinsus* infection. Separate multivariate analyses of the oyster size class distributions and invertebrate reef residents demonstrated that constructed reefs were similar to other constructed reefs. Constructed reefs were also similar to natural reefs within Clam Bayou but 4 differed from natural reefs in nearby Tarpon Bay and Pine Island Sound. In situ fluorometry (Dr. Raymond Grizzle) demonstrated that constructed reefs removed 13-44% of chlorophyll a from the adjacent water column. This finding, combined with a diverse reef resident invertebrate community, suggested that the constructed reefs were providing valuable ecosystem services (habitat and water quality improvement) in as little as one-year post reef construction. Compared to other similar restoration projects in the Northern Gulf of Mexico and South Carolina, Clam Bayou had relatively rapid development within the first year suggesting that subtropical oyster populations may develop more rapidly if suitable sites and conditions are chosen. Additional monitoring will be performed up to two years post construction to better gauge the long-term success of this project.

Narayan, Siddharth, Michael W. Beck, Borja G. Reguero, Iñigo J. Losada, Bregje van Wesenbeeck, Nigel Pontee, James N. Sanchirico, Jane Carter Ingram, Glenn-Marie Lange, Kelly A. Burks-Copes (2016). The effectiveness, costs and coastal protection benefits of natural and nature- based defenses. *PLoS*

One 11(5): e0154735. Available at: http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0154735

Abstract: There is great interest in the restoration and conservation of coastal habitats for protection from flooding and erosion. This is evidenced by the growing number of analyses and reviews of the effectiveness of habitats as natural defenses and increasing funding world-wide for nature-based defenses–i.e. restoration projects aimed at coastal protection; yet, there is no synthetic information on what kinds of projects are effective and cost effective for this purpose. This paper addresses two issues critical for designing restoration projects for coastal protection: (i) a synthesis of the costs and benefits of projects designed for coastal protection (nature-based defenses) and (ii) analyses of the effectiveness of coastal habitats (natural defenses) in reducing wave heights and the biophysical parameters that influence this effectiveness. We (i) analyze data from sixty-nine field measurements in coastal habitats globally and examine measures of effectiveness of mangroves, salt-marshes, coral reefs and seagrass/kelp beds for wave height reduction; (ii) synthesize the costs and coastal protection benefits of fifty-two nature-based defense projects and; (iii) estimate the benefits of each restoration project by combining information on restoration costs with data from nearby field measurements. The analyses of field measurements show that coastal habitats have significant potential for reducing wave heights that varies by habitat and site. In general, coral reefs and salt-marshes have the highest overall potential. Habitat effectiveness is influenced by: a) the ratios of wave height-to-water depth and habitat width-to-wavelength in coral reefs; and b) the ratio of vegetation height-to-water depth in salt-marshes. The comparison of costs of nature-based defense projects and engineering structures show that salt-marshes and mangroves can be two to five times cheaper than a submerged breakwater for wave heights up to half a meter and, within their limits, become more cost effective at greater depths. Nature-based defense projects also report benefits ranging from reductions in storm damage to reductions in coastal structure costs.

Peterson, Charles H. and John F. Bruno (2012). *Fisheries Habitat Impacts of Marsh Sills (Living Shorelines) as a Shoreline Stabilization/Restoration Alternative to Bulkheads*. University of North Carolina at Chapel Hill and Institute of Marine Sciences. Final Report in Fulfillment of N.C. Division of Marine Fisheries Coastal Recreational Fishing License Grant, pp. 37. Available at: https://ncdenr.s3.amazonaws.com/s3fs-public/Coastal%20Management/documents/PDF/Fisheries%20Habitat%20Impacts%20of%20Marsh%20Sills%20(Living%20Shorelines)%20as%20a%20Shoreline%20Stabilization%20Restoration%20Alternative%20to%20Bulkheads..pdf

In order to assess the effectiveness of marsh sills in restoring and sustaining viable shoreline habitats for fish and mobile crustaceans, the authors evaluated the ecological function of 25 marsh sill sites as well as their shoreline stabilization performance relative to traditional structures. The researchers also quantified fish and crustacean (nekton) use of coastal habitats adjacent to marsh sills and compared the abundance and species composition of epibiota and nekton associated with marsh sills, bulkheads, and control marshes to determine their relative habitat use and value. They found no difference in elevation, slope, marsh width, sediment OMC, marsh composition or seagrass density between marsh sills and control sites, a function of the presence of absence of a sill. However, between sites there was significant variation in slope, marsh width, marsh composition, and seagrass density. These differences are attributed to site age (sills only) and small-scale differences in the physical characteristics of each site. The mean change in elevation, slope, sediment OMC, and marsh stem density did not differ between marsh sill and control sites pre-and post-landfall of Hurricane Irene. No damage was observed to marsh sill or riprap shorelines, indicating that marsh sills may provide better erosion protection than bulkheads during storm events. Nekton abundance, biomass, and diversity were greater in the marsh at sill sites than control sites, but equivalent between sills and controls in seagrass/mudflat habitat. Epibiota community composition differed between bulkheads, sills and controls at upper elevations, with oysters dominating the community at sill and control sites and barnacles making up a large percentage of the cover at bulkhead sites. Habitat used by nekton directly adjacent to bulkheads was less abundant, had less biomass, and were less diverse than nekton found adjacent to sills. Sills were more structurally complex than bulkheads and were likely serving as a predation refuge for juvenile transient and small resident species.

Price, F. D. (2005). *Quantification, analysis, and management of Intracoastal Waterway channel margin erosion in the Guana Tolomato Matanzas National Estuarine Research Reserve, Florida*. National Estuarine Research Reserve Technical Report Series 2006:1, pp. 68. Available at: https://coast.noaa.gov/data/docs/nerrs/Research_TechSeries_TechSeries200601.pdf

This document reports on research completed at the Guana Tolomato Matanzas National Estuarine Research Reserve that focused on a GIS-based analysis of aerial photographs of the southern half of the reserve that revealed high rates of erosion along the margin of the Atlantic Intracoastal Waterway that runs through the reserve. From 1970/1971 to 2002 nearly 70 hectares (approximately 170 acres) of shoreline habitat were degraded by erosion along the 64.8 kilometers of channel margin analyzed. Wakes generated by vessels in the Intracoastal are hypothesized to be the primary cause of this erosion. An examination of the relationships between lateral movement of the channel margin and factors with the potential to affect erosion and accretion supports this hypothesis. Exposure to boat wakes was found to be the causal factor most strongly correlated with rate of lateral margin movement. Margin movement rates were also found to vary significantly with exposure to wind waves and with the type of channel margin eroded. A reduction in nearshore wave energy appears to be necessary to allow the recovery of impacted ecosystems. Approaches to erosion management based on nearshore stabilization and regulation of navigation are discussed, and the public policy surrounding implementation of such plans is described.

Scavia, D., J.C. Field, D.F. Boesch, R.W. Buddemeier, V. Burkett, and D.R. Cayan (2002). Climate change impacts on US coastal and marine ecosystems. *Estuaries* 25(2): 149-164. Available at: http://tenaya.ucsd.edu/~cayan/Pubs/66_Scavia_Estuaries_2002.pdf

Abstract: Increases in concentrations of greenhouse gases projected for the 21st century are expected to lead to increased mean global air and ocean temperatures. The National Assessment of Potential Consequences of Climate Variability and Change (NAST 2001) was based on a series of

regional and sector assessments. This paper is a summary of the coastal and marine resources sector review of potential impacts on shorelines, estuaries, coastal wetlands, coral reefs, and ocean margin ecosystems. The assessment considered the impacts of several key drivers of climate change: sea level change; alterations in precipitation patterns and subsequent delivery of freshwater, nutrients, and sediment; increased ocean temperature; alterations in circulation patterns; changes in frequency and intensity of coastal storms; and increased levels of atmospheric CO_2. Increasing rates of sea-level rise and intensity and frequency of coastal storms and hurricanes over the next decades will increase threats to shorelines, wetlands, and coastal development. Estuarine productivity will change in response to alteration in the timing and amount of freshwater, nutrients, and sediment delivery. Higher water temperatures and changes in freshwater delivery will alter estuarine stratification, residence time, and eutrophication. Increased ocean temperatures are expected to increase coral bleaching and higher CO_2 levels may reduce coral calcification, making it more difficult for corals to recover from other disturbances, and inhibiting poleward shifts. Ocean warming is expected to cause poleward shifts in the ranges of many other organisms, including commercial species, and these shifts may have secondary effects on their predators and prey. Although these potential impacts of climate change and variability will vary from system to system, it is important to recognize that they will be superimposed upon, and in many cases intensify, other ecosystem stresses (pollution, harvesting, habitat destruction, invasive species, land and resource use, extreme natural events), which may lead to more significant consequences.

Scyphers, B., Sean P. Powers, Denneth L. Heck Jr., and Dorothy Byron (2011). oyster reefs as natural breakwaters mitigate shoreline loss and facilitate fisheries. *PLOS ONE* 6(8): 1-12. Available at: http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0022396

Abstract: Shorelines at the interface of marine, estuarine and terrestrial biomes are among the most degraded and threatened habitats in the coastal zone because of their sensitivity to sea level rise, storms and increased human utilization. Previous efforts to protect shorelines have largely involved constructing bulkheads and seawalls which can detrimentally affect nearshore habitats. Recently, efforts have shifted towards "living shoreline" approaches that include biogenic breakwater reefs. Our study experimentally tested the efficacy of breakwater reefs constructed of oyster shell for protecting eroding coastal shorelines and their effect on nearshore fish and shellfish communities. Along two different stretches of eroding shoreline, we created replicated pairs of subtidal breakwater reefs and established unaltered reference areas as controls. At both sites we measured shoreline and bathymetric change and quantified oyster recruitment, fish and mobile macro-invertebrate abundances. Breakwater reef treatments mitigated shoreline retreat by more than 40% at one site, but overall vegetation retreat and erosion rates were high across all treatments and at both sites. Oyster settlement and subsequent survival were observed at both sites, with mean adult densities reaching more than eighty oysters m^{-2} at one site. We found the corridor between intertidal marsh and oyster reef breakwaters supported higher abundances and different communities of fishes than control plots without oyster reef habitat. Among the fishes and mobile invertebrates that appeared to be strongly enhanced were several economically-important species. Blue crabs (*Callinectes sapidus*) were the most clearly enhanced (+297%) by the presence of

breakwater reefs, while red drum (*Sciaenops ocellatus*) (+108%), spotted seatrout (*Cynoscion nebulosus*) (+88%) and flounder (*Paralichthys* sp.) (+79%) also benefited. Although the vertical relief of the breakwater reefs was reduced over the course of our study and this compromised the shoreline protection capacity, the observed habitat value demonstrates ecological justification for future, more robust shoreline protection projects.

Sharma, Shailesh, Joshua Goff, Just Cebrian, and Carl Ferraro (2016). A hybrid shoreline stabilization technique: Impact of modified intertidal reefs on marsh expansion and nekton habitat in the northern Gulf of Mexico. *Ecological Engineering* 90: 352-360. Available at: http://api.ning.com/files/jw75I-QUw-LQ9WxkoVp6vZpOR3BqrNJaUMSUDn6g9DJNEwIsDfHkiKBLYbioGYYoNIEsCxURTrQIjcXMMrCVakhv2HTmm-mj/Sharmaetal20116.pdf

Abstract: To mitigate shoreline erosion numerous armoring techniques have been employed extensively along the degrading shores of the Gulf of Mexico (GoM). Shoreline armoring strategies incorporating built vertical structures have resulted in numerous undesired ecological consequences. Bioengineering hybrid techniques consisting of "living shorelines" are emerging as an alternative option to mitigating shoreline loss and overcoming ecological shortcomings of hardened structures. Hitherto, only a few studies have assessed efficacy of hybrid techniques on shoreline stabilization and adjacent habitat enhancement. In this study, we integrated permeable intertidal reef-breakwaters (also known as wave attenuation units or WAUs) and predominantly restored native *Spartina alterniflora* marsh vegetation to mitigate erosion along severely degrading shores of a narrow peninsula in the northern GoM. Particularly, we evaluated impacts of a large-scale WAU reef deployment on a range of physical and biological parameters including erosion mitigation (shoreline stabilization), facilitation of created marsh expansion and habitat provision to marsh-utilizing nekton. We compared WAU reefs to adjacent gap areas without WAUs to evaluate the effects of tidal openings on the metrics measured. Our results of over 3 years suggest that, intertidal WAU reefs facilitate in created marsh expansion and the tidal openings between the reef complexes allow free movement of marsh-utilizing nekton fauna. Based on our results, we conclude that hybrid restoration technique is highly efficacious on erosion mitigation, adjacent marsh expansion and habitat creation. However, more works in other coastal systems are required to confirm the impacts of hybrid techniques on erosion mitigation and consequently on marshes and marsh-utilizing nekton.

Shephard, C. C., C. M. Crain, and M. W. Beck (2011). The protective role of coastal marshes: a systemic review and meta-analysis. *PLoS ONE* 6(11). Available at: http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0027374

Abstract: Salt marshes lie between many human communities and the coast and have been presumed to protect these communities from coastal hazards by providing important ecosystem services. However, previous characterizations of these ecosystem services have typically been based on a small number of historical studies, and the consistency and extent to which marshes provide these services has not been investigated. Here, we review the current evidence for the specific

processes of wave attenuation, shoreline stabilization and floodwater attenuation to determine if and under what conditions salt marshes offer these coastal protection services.

Methodology/Principal Findings: We conducted a thorough search and synthesis of the literature with reference to these processes. Seventy-five publications met our selection criteria, and we conducted meta-analyses for publications with sufficient data available for quantitative analysis. We found that combined across all studies (n = 7), salt marsh vegetation had a significant positive effect on wave attenuation as measured by reductions in wave height per unit distance across marsh vegetation. Salt marsh vegetation also had a significant positive effect on shoreline stabilization as measured by accretion, lateral erosion reduction, and marsh surface elevation change (n = 30). Salt marsh characteristics that were positively correlated to both wave attenuation and shoreline stabilization were vegetation density, biomass production, and marsh size. Although we could not find studies quantitatively evaluating floodwater attenuation within salt marshes, there are several studies noting the negative effects of wetland alteration on water quantity regulation within coastal areas.

Conclusions/Significance: Our results show that salt marshes have value for coastal hazard mitigation and climate change adaptation. Because we do not yet fully understand the magnitude of this value, we propose that decision makers employ natural systems to maximize the benefits and ecosystem services provided by salt marshes and exercise caution when making decisions that erode these services.

Swann, LaDon (2008). The use of living shorelines to mitigate the effects of storm events on Dauphin Island, Alabama, USA. *American Fisheries Society Symposium* 64: 47-57. Available at: http://livingshorelinesolutions.com/uploads/Dr._LaDon_Swann__Living_Shorelines_Paper.pdf

Abstract: Living shorelines serve multiple roles by controlling erosion, maintaining natural coastal processes, and sustaining biodiversity through land-use management, soft armoring, or combinations of soft and semi-hard armoring techniques. One type of living shoreline was used at Saw Grass Point Salt Marsh on Dauphin Island, Alabama. Chronic erosion has resulted in the loss of 0.5 ha of the marsh. This saline tidal marsh is of significant ecological importance and is one of only two on Dauphin Island. In 2004, a community-based restoration grant was used to protect and restore the marsh through the use of exposed nearshore precast concrete breakwaters called coastal havens. These structures function as detached breakwaters to minimize the effect of storm surge and boat wake through wave attenuation; they also provide suitable substrate for oyster colonization. These structures were selected over other erosion control technologies, including vertical bulkheads, rock or wooden sills, and headlands. In April 2005, 182 units were installed in two interlocking rows parallel to the east perimeter of the marsh in water approximately 1.3 m deep. Oyster density on the coastal havens, measured 19 months post-installation, was 205 oysters/m^2. Measurements behind the breakwater indicate some sediment accretion. The project cost was approximately US $335/m to protect 162/m of shoreline. The dual function of these structures has controlled the erosion behind the breakwater and has provided habitat for a wide array of National Oceanic and Atmospheric Administration trust resources, including locally important species such as spotted seatrout (also known as speckled trout) (*Cynoscion nebulosus)*, blue crabs (*Callinectes sapidus)* and Gulf stone crabs (*Menippe adina)*, eastern oyster (*Crassostrea virginica)*, red drum (*Sciaenops ocellatus)*, southern flounder (*Paralichthys lethostigma)*, and various species of commercially important shrimp (brown shrimp (*Farfantepenaeus aztecus)*, pink shrimp (*F. duorarum)*, and white shrimp (*Litopenaeus setiferus*)).

Biological Effects

Bacchiocchi, F. and L. Airoldi (2003). Distribution and dynamics of epibiota on hard structures for coastal protection. *Estuar. Coast. Shelf Sci*. 56: 1157-1166. Available at: http://www.sciencedirect.com/science/article/pii/S0272771402003220

Abstract: Hard structures for protection against erosion of shores are some of the most common human-made constructions in coastal areas. Nevertheless, little is known as to how marine organisms respond to their presence. The composition and distribution of intertidal epibiota at different positions around different types of defense structures (groynes and breakwaters) at three stations along the Emilia Romagna coast (Italy) were analyzed. Sampling covered a range of scales: meters (distance among replicate plots), hundreds of meters (distance among replicate areas) and tens of kilometers (distance among stations). The colonization and dynamics of conspicuous species over 1 year, following maintenance works on two structures, were also quantified. Assemblages on defense structures were characterized by a notably low richness of species, by strong spatial dominance of mussels and green ephemeral algae, and by high rates of colonization. Abundance of mussels, *Enteromorpha intestinalis* and filamentous algae differed significantly among nearby areas within stations. Mussels were significantly less abundant along the landward side of breakwaters compared with all other positions on both groynes and breakwaters. Overall, however, fewer differences, than expected, were observed in the distribution of species at different positions around groynes and breakwaters, probably as a consequence of the low complexity of the colonizing assemblages. Possible factors explaining the patterns of distribution observed are discussed, including the roles of harvesting of mussels and frequent maintenance works on the structures. The implications of the low richness of species observed in terms of management of defense structures and other human-made constructions are discussed.

Bahr, L.M. Jr. (1976). Energetic aspects of the intertidal oyster reef community at Sapelo Island, GA (USA). *Ecology* 57(1): 121-131. Available at: http://onlinelibrary.wiley.com/doi/10.2307/1936403/abstract?systemMessage=Wiley+Online+Library+will+be+unavailable+on+Saturday+3rd+September+2016+at+08.30+BST/+03:30+EDT/+15:30+SGT+for+5+hours+and+Sunday+4th+September+at+10:00+BST/+05:00+EST/+17:00+SGT+for+1+hour++for+essential+maintenance.+Apologies+for+the+inconvenience

Abstract: The total daily O_2 consumption rate of the intertidal oyster reef community in Georgia, USA was found to range between 0.6×10^4 and 5.0×10^4 mg O_2/m^2 of reef surface, corresponding to a seasonal range of ambient water temperature from 9^oC to 30^oC. Oysters, non-oyster macrofauna, microbiota, and chemical oxidation were estimated to account for 48.1%, 10.0%, 21.9%, and 20,0%, respectively, of total O_2 consumed.

Reef macrofaunal biomass averages 1,108 g/m^2 (ash-free dry weight) of which *Crassostrea virginica* comprises 87.5%.

Growth of individual reef oysters, and, therefore, entire reefs, appears to be extremely slow, probably due to high maintenance costs and limited inundation time characteristic of the intertidal zone.

The oyster reef community occupies only 0.06 % of total marsh-water surface area in a salt marsh estuary unit (the Duplin River marsh-estuary system), but it can theoretically degrade 1% of the estimated excess annual net primary production in the system.

Bahr, L.M. Jr. and W.P. Lanier (1981). *The ecology of intertidal oyster reefs of the South Atlantic coast: a community profile*. U.S. Fish and Wildlife Service, Office of Biological Services, Washington, D.C. FWS/OBS-81/15, pp. 105. Available at: http://www.nwrc.usgs.gov/techrpt/81-15.pdf

This oyster reef community profile is the second in a development series of profiles of coastal habitats. The purpose of this profile is to describe the structure and ecological function of intertidal oyster reefs in the salt marsh estuarine ecosystem of the Southeastern United States. The intertidal oyster reef habitat, as described here, is classified by Cowardin et al. (1979) as occurring in the Carolinian province, in the euhaline estuarine system, in the intertidal subsystem, in the reef class, and in the mollusk subclass, with the eastern oyster *Crassostrea virgirlica* as the dominance type.

This profile proceeds from a description of the estuarine setting (Chapter I), to a discussion of oyster biology (Chapter 2), to a characterization of the oyster reef per se (Chapter 3), to a discussion of the development and role of the reef system in the coastal ecosystem (Chapter 4). Chapter 5 is a summary of the role of the oyster reef as expressed in three conceptual models, and Chapter 6 includes a brief synopsis of the first five chapters, along with implications for management.

Balouskus, R.G. and T.E. Targett (2016). Fish and blue crab abundance along a riprap-sill hardened shoreline: comparisons with *Spartina* marsh and riprap shorelines. *Transactions of the American Fisheries Society* 145(4): 766-773. Available at: http://www.tandfonline.com/doi/abs/10.1080/00028487.2016.1172508?journalCode=utaf20

Abstract: Wetland managers have historically considered riprap-sill structures (a type of "living shoreline" consisting of a rock sill that is placed low in the intertidal zone, with native vegetation planted between the sill and the shore) to be more ecologically sound than the riprap that is traditionally applied for shoreline stabilization in estuaries. However, little research has been conducted to compare the macrofauna associated with riprap-sill and riprap-hardened shorelines. Density and diversity of fish and blue crabs *Callinectes sapidus* were compared via weekly sampling along a riprap-sill shoreline, a riprap shoreline, and a shoreline fringed with smooth cordgrass *S. alterniflora* marsh in the Delaware Coastal Bays during summer 2010. Seining was conducted to quantitatively sample the shore zone and shallow subtidal regions, and minnow traps were used to determine the presence or absence of fishes in the mid- to upper-intertidal zone of each shoreline type. Temporally persistent differences in macrofaunal density and diversity were evident among the three shoreline types. In terms of fish density and diversity metrics, riprap-sill was more similar to the smooth cordgrass shoreline than to the traditional riprap shoreline. These results provide evidence for the biological advantage of riprap-sill over traditional riprap as a shoreline modification structure; spatial confirmation by further studies at different locations is warranted.

Broome, S.W., S.M. Rogers, E.D. Seneca, and C.B. Burgess (1992). *Shoreline erosion control using marsh vegetation and low-cost structures*. North Carolina Sea Grant Program Publication UNC-SG-92-12, North Carolina State University Press, Raleigh, North Carolina, pp. 23. Available at: http://nsgl.gso.uri.edu/ncu/ncuh92002.pdf

This short book is a manual for coastal property owners who are experiencing shoreline erosion and would like to use vegetation as an alternative erosion-control method. Chapters include topics such as: how marsh vegetation reduces shoreline erosion; judging site suitability (e.g., tides and shore slope); and structural aids (e.g., breakwaters or sills). The book also provides information about appropriate marsh plant species and how to transplant and establish a healthy vegetative cover.

Broome, S.W., E.D. Seneca and W.W. Woodhouse, Jr. (1988). Tidal salt marsh restoration. *Aquatic Botany* 32(1-2): 1-22. Available at: http://ac.els-cdn.com/030437708890085X/1-s2.0-030437708890085X-main.pdf?_tid=a79c7c06-f2cd-11e5-99b2-00000aab0f01&acdnat=1458940260_f10cbcb91d5abff69253b9f6683cc2c5

Abstract: Coastal salt marshes occur in the intertidal zone of moderate to low energy shorelines along estuaries, bays and tidal rivers. They have ecological value in primary production, nutrient cycling, as habitat for fish, birds and other wildlife and in stabilizing shorelines. Disturbance by development activities has resulted in the destruction or degradation of many marshes. Awareness of this loss by scientists and the public has led to an interest in restoration or creation of marshes to enhance estuarine ecosystems. Recovery of marshes after human perturbation such as dredging, discharges of wastes and spillage of petroleum products or other toxic chemicals is often slow under natural conditions and can be accelerated by replanting vegetation. The basic techniques and procedures have been worked out for the propagation of several marsh angiosperms. Factors which affect successful revegetation include elevation of the site in relation to tidal regime, slope, exposure to wave action, soil chemical and physical characteristics, nutrient supply, salinity and availability of viable propagules of the appropriate plant species. Marsh restoration technology has been applied at a variety of locations to vegetate intertidal dredged material disposal sites, stabilize shorelines, mitigate damage to natural marshes and to revegetate one marsh destroyed by an oil spill. Contractual services for marsh establishment are now available in some regions. Further research is needed to determine the success of marsh restoration and creation in terms of ecological function, including the faunal component.

Cahoon, D.R., M.A. Ford and P.F. Hensel (2004). Ecogeomorphology of *Spartina patens* dominated tidal marshes- soil organic matter accumulation, marsh elevation dynamics, and disturbance. In: *The Ecogeomorphology of Tidal Marshes, Coastal Estuarine Studies Vol. 59*, Fagherazzi, S., M. Marani, and L.K. Blum (eds), AGU, Washington, D.C., pp. 247-266. Available at: https://www.researchgate.net/publication/272294622_Ecogeomorphology_of_Spartina_patens-Dominated_Tidal_Marshes_Soil_Organic_Matter_Accumulation_Marsh_Elevation_Dynamics_and_Disturbance

Abstract: Marsh soil development and vertical accretion in *Spartina patens* (Aiton) Muhl. –dominated tidal marshes is largely dependent on soil organic matter accumulation from root-rhizome production and litter deposition. Yet there are few quantitative data sets on belowground production and the relationship between soil organic matter accumulation and soil elevation dynamics for this marsh type. *Spartina patens* marshes are subject to numerous stressors, including sea-level-rise, water level manipulations (i.e., flooding and draining) by impoundments, and prescribed burning. These stressors could influence long-term sustainability by their effect on root production, soil organic matter accumulation, and soil elevation dynamics. In this review, we summarize current knowledge on the interactions among vegetative production, soil organic matter accumulation and marsh elevation dynamics, or the ecogeomorphology, of *Spartina patens*-dominated tidal marshes. Additional studies are needed of belowground production/decomposition and soil elevation change (measured simultaneously) to better understand the links among soil organic matter accumulation, soil elevation change, and disturbance in this marsh type. From a management perspective, we need to better understand the impacts of disturbance stressors, both lethal and sub-lethal, and the interactive effect of multiple stressors on soil elevation dynamics in order to develop better management practices to safeguard marsh sustainability as sea level rises.

Craft, C., P. Megonigal, S. Broome, J. Stevenson, R. Freese, J. Cornell, L. Zheng, and J. Sacco (2003). The pace of ecosystem development of constructed *Spartina alterniflora* marshes. *Ecological Applications* 13: 1417-1432. Available at: http://onlinelibrary.wiley.com/doi/10.1890/02-5086/abstract

Abstract: Ecological attributes were measured along a chronosequence of 1- to 28-yr-old, constructed *Spartina alterniflora* marshes to identify trajectories and rates of ecosystem development of wetland structure and function. Attributes related to biological productivity and diversity (*Spartina*, epiphytic and sediment algae, benthic invertebrates), soil development (sediment deposition, organic C, N, P, organic matter quality), and microbial processes (C mineralization) were compared among eight constructed marshes and eight paired natural reference marshes. Most ecological attributes developed in a predictable manner over time, and most achieved equivalence to natural marshes 5–15 yr after marsh construction. An exception was soil organic C and N pools (0–30 cm) that, after 28 yr, were significantly lower in constructed marshes. Development of habitat structure (*Spartina* stem height and density) and biodiversity (algae and invertebrates) developed concurrently with functional characteristics such as biomass, chlorophyll *a,* and invertebrate density. Processes related to hydrology, sediment deposition and soil C and N accumulation, developed almost instantaneously with the establishment of *Spartina*, and young (1- to 3-yr-old), constructed marshes trapped sediment and sequestered N at higher rates than comparable reference marshes. Development of heterotrophic activity (C mineralization, invertebrate density) was strongly linked to surface (0–10 cm) soil organic C content. Ecosystem development of constructed (and natural) salt marshes depended on a minimum of 100 g N/m^2 (0.05–0.1% N) to support emergent vegetation and 1000 g C/m^2 (0.5–1% C) to sustain the heterotrophic community.

Craft, C., S. Broome, and C. Campbell (2002). Fifteen years of vegetation and soil development after brackish-water marsh creation. *Restoration Ecology* 10: 248-258. Available at: http://onlinelibrary.wiley.com/doi/10.1046/j.1526-100X.2002.01020.x/abstract

Abstract: Aboveground biomass, macro-organic matter (MOM), and wetland soil characteristics were measured periodically between 1983 and 1998 in a created brackish water marsh and a nearby natural marsh along the Pamlico River estuary, North Carolina to evaluate the development of wetland vegetation and soil dependent functions after marsh creation. Development of aboveground biomass and MOM was dependent on elevation and frequency of tidal inundation. Aboveground biomass of *Spartina alterniflora*, which occupied low elevations along tidal creeks and was inundated frequently, developed to levels similar to the natural marsh (750 to 1,300 g/m^2) within three years after creation. *Spartina cynosuroides*, which dominated interior areas of the marsh and was flooded less frequently, required 9 years to consistently achieve aboveground biomass equivalent to the natural marsh (600 to 1,560 g/m^2). Aboveground biomass of *Spartina patens*, which was planted at the highest elevations along the terrestrial margin and seldom flooded, never consistently developed aboveground biomass comparable with the natural marsh during the 15 years after marsh creation. MOM (0 to 10 cm) generally developed at the same rate as aboveground biomass. Between 1988 and 1998, soil bulk density decreased and porosity and organic C and N pools increased in the created marsh. Like vegetation, wetland soil development proceeded faster in response to increased inundation, especially in the streamside zone dominated by *S. alterniflora.* We estimated that in the streamside and interior zones, an additional 30 years (nitrogen) to 90 years (organic C, porosity) are needed for the upper 30 cm of created marsh soil to become equivalent to the natural marsh. Wetland soil characteristics of the *S. Patens* community along upland fringe will take longer to develop, more than 200 years. Development of the benthic invertebrate-based food web, which depends on organic matter enrichment of the upper 5 to 10 cm of soil, is expected to take less time. Wetland soil characteristics and functions of created irregularly flooded brackish marshes require longer to develop compared with regularly flooded salt marshes because reduced tidal inundation slows wetland vegetation and soil development. The hydrologic regime (regularly vs. irregularly flooded) of the "target" wetland should be considered when setting realistic expectations for success criteria of created and restored wetlands.

Craft, C., J. Reader, J.N. Sacco, and S.W. Broome (1999). Twenty-five years of ecosystem development of constructed *Spartina alterniflora* (Loisel) marshes. *Ecological Applications* 4: 1405-1419. Available at: http://onlinelibrary.wiley.com/doi/10.1890/1051-0761%281999%29009%5B1405:TFYOED%5D2.0.CO;2/full

Abstract: Wetland creation and restoration are frequently used to replace ecological functions and values lost when natural wetlands are degraded or destroyed. On many sites, restoration of ecological attributes such as secondary production, habitat/species diversity, and wetland soil characteristics do not occur within the first decade, and no long-term studies exist to document the length of time required to achieve complete restoration of wetland dependent functions and values. Characteristics of community structure (macrophyte aboveground biomass, macro-organic matter [MOM], benthic invertebrates) and ecosystem processes (soil development, organic C, N, and P accumulation) of two constructed *Spartina alterniflora* (Loisel) marshes (established 1971 and 1974) and paired natural *S. alterniflora* marshes in North Carolina were periodically measured during the past 25 yr. On constructed marshes, the macrophyte community developed quickly, and within 5 to 10 yr, aboveground biomass and MOM were equivalent to or exceeded corresponding values in natural marshes. After 15–25 yr, benthic infauna density and species richness were greater than in the natural marshes. Soil bulk density decreased, and organic C and total N increased over time in constructed marshes, but after 25 yr, soil organic C and N reservoirs were much smaller than in a 2000-yr-old natural marsh. Organic C accumulation was similar in constructed and natural marshes with 12–24% of the net primary production buried annually. Nitrogen accumulation was much higher in constructed marshes (7–12 $g \cdot m^{-2} \cdot yr^{-1}$) than in natural marshes (2–5 $g \cdot m^{-2} \cdot yr^{-1}$), reflecting the open biogeochemical cycles and paucity of N in these young ecosystems. Different ecological attributes develop at different rates, with primary producers achieving equivalence during the first 5 yr, followed by the benthic infauna community 5–10 yr later. Accumulation of soil nutrients to levels similar to those of reference marshes may require more time.

Currin, C. A., P. C. Delano, and L. M. Valdes-Weaver (2008). Utilization of a citizen monitoring protocol to assess the structure and function of natural and stabilized fringing salt marshes in North Carolina. *Wetlands Ecol. Manage*. 16: 97-118. Available at: https://coastalscience.noaa.gov/about/docs/Curinetal.WME.vol2.pdf

Abstract: Narrow fringing salt marshes dominated by *Spartina alterniflora* occur naturally along estuarine shorelines and provide many of the same ecological functions as more extensive marshes. These fringing salt marshes are sometimes incorporated into shoreline stabilization efforts. We obtained data on elevation, salinity, sediment characteristics, vegetation and fish utilization at three study sites containing both natural fringing marshes and nearby restored marshes located landward of a stone sill constructed for shoreline stabilization. During the study, sediment accretion rates in the restored marshes were approximately 1.5- to 2-fold greater than those recorded in the natural marshes. Natural fringing marsh sediments were predominantly sandy with a mean organic matter content ranging between 1.5 and 6.0%. Average *S. alterniflora* stem density in natural marshes ranged between 130 and 222 stems/m^2, while mean maximum stem height exceeded 64 cm. After 3 years, one of the three restored marshes (NCMM) achieved *S. alterniflora* stem densities equivalent to that of the natural fringing marshes, while percentage cover and maximum stem heights were significantly greater in the natural than in the restored marshes at all sites. There was no significant difference in the mean number of fish, crabs or shrimp captured with fyke nets between the natural and restored marshes, and only the abundance of *Palaemonetes vulgaris* (grass shrimp) was

significantly greater in the natural marshes than in the restored ones. Mean numbers of fish caught per 5 m of marsh front were similar to those reported in the literature from marshes adjacent to tidal creeks and channels, and ranged between 509 and 634 per fishnet. Most of the field data and some of the sample analyses were obtained by volunteers as they contributed 223 h of the total 300 h spent collecting data from three sites in one season. The use of fyke nets required twice as many man-hours as any other single task. Vegetation and sediment parameters were sensitive indicators of marsh restoration success, and volunteers were capable of contributing a significant portion of the labor needed to collect the separameters.

Davis, J. L. D., R. L. Takaes, and R. Schnabel (2006). Evaluating Ecological Impacts of Living Shorelines and Shoreline Habitat Elements: An Example from the Upper Western Chesapeake Bay. In: *Management, Policy, Science, and Engineering of Nonstructural Erosion Control in the Chesapeake Bay, Proceedings of the Living Shorelines Summit: Evaluation of Living Shoreline Techniques*; Erdle, S. Y., J. L. D. Davis, and K. G. Sellner (eds). CRC Publ. No. 08-164, Gloucester Point, VA, pp. 36. Available at: http://www.vims.edu/cbnerr/_docs/ctp_docs/ls_docs/06_LS_Eval.pdf

Abstract: Living shorelines, or use of natural habitat elements in shoreline protection rather than hard shoreline armor, have been used in the Chesapeake Bay for decades due to anticipated habitat and water quality benefits. The goal of this work is to begin to quantify how quickly living shorelines assume “natural” ecological function. On the upper Western Shore of the Chesapeake Bay, macrofauna at control marsh sites and bulkhead sites slated for living shoreline installation were sampled before and after construction (before-after control-impact design). Species with higher densities at marsh than bulkhead sites prior to bulkhead removal (e.g., mummichog (*Fundulus heteroclitus*), grass shrimp (*Palaemonetes pugio*), and spot (*Leiostomus xanthurus*) were expected to increase after living shoreline installation, and those with higher densities at bulkheads (e.g., white perch (*Morone americana*)) were expected to decrease. Two months after restoration, densities of mummichog, grass shrimp, and pumpkinseed (*Lepomis gibbosus*) had increased at the experimental site relative to the control marsh, though densities of some marsh species had not. Results suggest that certain species can respond almost immediately to installation of living shorelines. Results also suggest that incorporation of multiple structural habitat elements may expand the functional value of living shorelines. In a second study element comparing assemblage structure in several structural habitat types (riprap, oyster shell, vegetation, woody debris), vegetation served the greatest nursery function, oyster reef provided the greatest refuge for species like blue crabs, riprap hosted the greatest proportion of older life-history stages, and all four hosted different suites of species. Work to optimize living shoreline design relative to erosion control function is on-going in the management and engineering arenas. Similar efforts to correlate design elements to ecological function by the scientific and restoration communities will serve to maximize the benefits of living shorelines to estuarine biota.

Gittman, R.K., C.H. Peterson, C.A. Currin, F.J. Fodrie, M.F. Piehler, and J.F. Bruno (2016). Living shorelines can enhance the nursery role of threatened estuarine habitats. *Ecological Applications* 26(1): 249–263. Available at: http://api.ning.com/files/D3oar*BqtaXHe8SIvZ-

6MA75ZsclrQu16xpw3ccHyzzUrEXannkrwnWcvb1H7vLBFWpfukUeaiLDWVQYPWjH-7j4ks5WgfmR/Gittmanetal.2016EcologicalApplications.pdf

Abstract: Coastal ecosystems provide numerous services, such as nutrient cycling, climate change amelioration, and habitat provision for commercially valuable organisms. Ecosystem functions and processes are modified by human activities locally and globally, with degradation of coastal ecosystems by development and climate change occurring at unprecedented rates. The demand for coastal defense strategies against storms and sea-level rise has increased with human population growth and development along coastlines worldwide, even while that population growth has reduced natural buffering of shorelines. Shoreline hardening, a common coastal defense strategy that includes the use of seawalls and bulkheads (vertical walls constructed of concrete, wood, vinyl, or steel), is resulting in a “coastal squeeze” on estuarine habitats. In contrast to hardening, living shorelines, which range from vegetation plantings to a combination of hard structures and plantings, can be deployed to restore or enhance multiple ecosystem services normally delivered by naturally vegetated shores. Although hundreds of living shoreline projects have been implemented in the United States alone, few studies have evaluated their effectiveness in sustaining or enhancing ecosystem services relative to naturally vegetated shorelines and hardened shorelines. We quantified the effectiveness of (1) sills with landward marsh (a type of living shoreline that combines marsh plantings with an offshore low-profile breakwater), (2) natural salt marsh shorelines (control marshes), and (3) unvegetated bulkheaded shores in providing habitat for fish and crustaceans (nekton). Sills supported higher abundances and species diversity of fishes than unvegetated habitat adjacent to bulkheads, and even control marshes. Sills also supported higher cover of filter-feeding bivalves (a food resource and refuge habitat for nekton) than bulkheads or control marshes. These ecosystem- service enhancements were detected on shores with sills three or more years after construction, but not before. Sills provide added structure and may provide better refuges from predation and greater opportunity to use available food resources for nekton than unvegetated bulkheaded shores or control marshes. Our study shows that unlike shoreline hardening, living shorelines can enhance some ecosystem services provided by marshes, such as provision of nursery habitat.

Guannel, G., P. Ruggiero, J. Faries, K. Arkema, M. Pinsky, G. Gelfenbaum, A. Guerry, and C-K Kim (2015). Integrated modeling framework to quantify the coastal protection services supplied by vegetation. *Journal of Geophysical Research - Oceans* 120(1): 324–345. Available at: http://onlinelibrary.wiley.com/doi/10.1002/2014JC009821/abstract

Abstract: Vegetation can protect communities by reducing nearshore wave height and altering sediment transport processes. However, quantitative approaches for evaluating the coastal protection services, or benefits, supplied by vegetation to people in a wide range of coastal environments are lacking. To begin to fill this knowledge gap, we propose an integrated modeling approach for quantifying how vegetation modifies nearshore processes—including the attenuation of wave height, mean and total water level—and reduces shoreline erosion during storms. We apply the model to idealized seagrass-sand and mangrove-mud cases, and illustrate its potential by quantifying how those habitats reduce water levels and sediment loss beyond what would be

observed in the absence of vegetation. The integrated modeling approach provides an efficient way to quantify the coastal protection services supplied by vegetation and highlights specific research needs for improved representations of the ways in which vegetation modifies wave-induced processes.

Hardaway, Scott, C. Jr., G. R. Thomas, B. K. Fowler, C. L. Hill, J. E. Frye, and N. A. Ibison (1985). Results of vegetative erosion control project in the Virginia Chesapeake Bay system. In: *Proceedings of the twelfth annual conference on wetlands restoration and creation*. F. J. Webb, Jr. (ed). Hillsborough Community College, Tampa, Florida, pp. 144-158. Available at: http://images.library.wisc.edu/EcoNatRes/EFacs/Wetlands/Wetlands12/reference/econatres.wetlands12.i0020.pdf

Abstract: Reestablishing a marsh grass fringe for estuarine shoreline erosion control is an accepted alternative to construction of bulkheads, revetments, and groins. The physical limit of creating a marsh grass fringe is mainly the severity of wave climate acting on a given shore. The main variables used to determine the relative intensity of wave climate are (1) average fetch exposure, (2) shore geometry, and (3) shore orientation.

In the Virginia Chesapeake Bay system, 24 planted marsh grass fringes were monitored from 1981 to 1983. These sites were selected to include a variety of average fetch exposures. Results of the planting project showed that (1) establishing a marsh grass fringe can be accomplished with little or no maintenance planting on relatively low wave energy shores (average fetch exposure less than 1.0 nautical mile). (2) Along medium wave energy shorelines exposed to 1.0 to 3.5 nautical miles average fetch, the establishment of a combination fringe of smooth cordgrass and salt meadow hay is necessary. (3) On straight shorelines with average fetch exposures of 3.5 to 5.5 nautical miles it will be impractical to try and establish a marsh fringe without some type of permanent offshore wave stilling device (i.e., a breakwater). (4) Shorelines exposed to an average fetch greater than 5.5 nautical miles should not be considered for marsh grass implantation unless well protected by a headland, island, or spit. The use of offshore breakwaters in combination with marsh implantation is a consideration but further research is needed.

La Peyre, M.K., A.T. Humphries, S.M. Casas, and J.F. La Peyre (2014). Temporal variation in development of ecosystem services from oyster reef restoration. *Ecological Engineering* 63: 34-44. Available at: http://www.sciencedirect.com/science/article/pii/S0925857413004916

Abstract: Restoration ecology relies heavily on ecosystem development theories that generally assume development of fully functioning natural systems over time, but often fail to identify the time-frame required for provision of desired functions, or acknowledge different pathways of functional development. In estuaries, a decline of overall habitat quality and functioning has led to significant efforts to restore critical ecosystem services, recently through the creation and restoration of oyster reefs. Oyster reef restoration generally occurs with goals of (1) increasing water quality via filtration through sustainable oyster recruitment, (2) stabilizing shorelines, and (3) creating and enhancing critical estuarine habitat for fish and invertebrates. We restored over 260 m^2

of oyster reef habitat in coastal Louisiana and followed the development and provision of these ecosystem services from 2009 through 2012. Oysters recruited to reefs immediately, with densities of oysters greater than 75 mm exceeding 80 in dm^2 after 3 years, and provision of filtration rates of 1002 ± 187 L h−1m−2; shoreline stabilization effects of the created reefs were minimal over the three years of monitoring, with some evidence of positive shoreline stabilization during higher wind/energy events only; increased nekton abundance of resident, but not larger transient fish was immediately measurable at the reefs, however, this failed to increase through time. Our results provide critical insights into the development trajectories of ecosystem services provided by restored oyster reefs, as well as the mechanisms mediating these changes. This is critical both ecologically to understand how and where a reef thrives, and for policy and management to guide decision-making related to oyster reef restoration and the crediting and accounting of ecosystem services.

Meyer. D. L. and E. C. Townsend (2000). Faunal utilization of created intertidal eastern oyster (*Crassostrea virginica*) reefs in the southeastern United States. *Estuaries* 23(1), 34–35. Available at: http://www.jstor.org/stable/1353223

Abstract: Oyster cultch was added to the lower intertidal marsh-sandflat fringe of three previously created *Spartina alterniflora* salt marshes. Colonization of these created reefs by oysters and other select taxa was examined. Created reefs supported numerous oyster reef-associated faunas at equivalent or greater densities than adjacent natural reefs. Eastern oyster (*Crassostrea virginica*) settlement at one site of created reef exceeded that of the adjacent natural reefs within 9 mo of reef creation. After only 2 yr, harvestable-size *C. virginica* (>75 mm) were present in the created reefs along with substantial numbers of C. virginica clusters. The created reefs also had a higher number of molluscan, fish, and decapod species than the adjacent natural reefs. After 2 yr the densities of *C. virginica*, striped barnacle (*Balanus amphitrite*), scorched mussel (*Brachidontes exustus*), Atlantic ribbed mussel (*Geukensia demissa*), common mud crab (*Panopeus herbstii*), and flat mud crab (*Eurypanopeus depressus*) within the created reefs were equivalent to that of adjacent natural reefs. From these data it is evident that created oyster reefs can quickly acquire functional ecological attributes of their natural counterparts. Because the demand for oysters continues to increase in the face of dwindling natural resources, habitat creation techniques need to evolve and these approaches need to consider the ancillary ecological benefits reef creation may provide. Reef function as well as physical and ecological linkages of oyster reefs to other habitats (marsh, submerged aquatic vegetation, and bare bottom) should be considered when reefs are created in order to provide the best use of resources to maintain the integrity of estuarine systems.

O'Conner, M.I., C.R. Violin, A. Anton, L.M. Ladwig and M.F. Piehler (2011). Salt marsh stabilization affects primary producers at the marsh edge. *Wetlands Ecology and Management* 19: 131-140. Available at: http://link.springer.com/article/10.1007/s11273-010-9206-y

Abstract: As sea level rise and human activities erode coastal wetlands, managers rebuild or preserve wetlands that can perform the ecosystem services of a natural system. One increasingly common mitigation activity is the construction of rock sills in the low marsh zone to stabilize marsh

elevation. Sills dramatically alter the physical structure of marshes by changing elevation, adding hard substrate and potentially altering the spatial structure of benthic algal communities in and adjacent to the low marsh. We documented differences in benthic algal abundance at the seaward marsh edge in silled and unsilled marshes in North Carolina. We found that sills were associated with reduced standing stocks of benthic algal primary production and reduced macroalgal taxonomic richness, and this difference was driven primarily by differences in macroalgal abundance. We experimentally tested the effect of macroalgal abundance on cordgrass (*Spartina alterniflora*) growth in the low zone of an unmanipulated marsh, and found that macroalgal removal had no effect on final cordgrass abundance. Our study suggests that salt marsh management through the construction of sills in low marsh zones impacts benthic primary production in the low marsh zone, but that benthic algal production does not affect cordgrass growth over a growing season.

Peterson, Charles H. and John F. Bruno (2012). *Fisheries Habitat Impacts of Marsh Sills (Living Shorelines) as a Shoreline Stabilization/Restoration Alternative to Bulkheads*. University of North Carolina at Chapel Hill and Institute of Marine Sciences. Final Report in Fulfillment of N.C. Division of Marine Fisheries Coastal Recreational Fishing License Grant, pp. 37. Available at: https://deq.nc.gov/document/fisheries-habitat-impacts-marsh-sills-living-shorelines-shoreline-stabilization-restoration

In order to assess the effectiveness of marsh sills in restoring and sustaining viable shoreline habitats for fish and mobile crustaceans, the authors evaluated the ecological function of 25 marsh sill sites as well as their shoreline stabilization performance relative to traditional structures. The researchers also quantified fish and crustacean (nekton) use of coastal habitats adjacent to marsh sills and compared the abundance and species composition of epibiota and nekton associated with marsh sills, bulkheads, and control marshes to determine their relative habitat use and value. They found no difference in elevation, slope, marsh width, sediment OMC, marsh composition or seagrass density between marsh sills and control sites a function of the presence of absence of a sill. However, between sites there was significant variation in slope, marsh width, marsh composition, and seagrass density. These differences were attributed to site age (sills only) and small-scale differences in the physical characteristics of each site. The mean change in elevation, slope, sediment OMC, and marsh stem density did not differ between marsh sill and control sites pre-and post-landfall of Hurricane Irene. No damage was observed to marsh sill or riprap shorelines, indicating that marsh sills may provide better erosion protection than bulkheads during storm events. Nekton abundance, biomass, and diversity were greater in the marsh at sill sites than control sites, but equivalent between sills and controls in seagrass/mudflat habitat. Epibiota community composition differed between bulkheads, sills and controls at upper elevations, with oysters dominating the community at sill and control sites and barnacles making up a large percentage of the cover at bulkhead sites. Habitat used by nekton directly adjacent to bulkheads was less abundant, had less biomass, and were less diverse than nekton found adjacent to sills. Sills were more structurally complex than bulkheads and were likely serving as a predation refuge for juvenile transient and small resident species.

Peterson, C.H., J. Grabowski, and S. Powers (2003). Estimated enhancement of fish production resulting from restoring oyster reef habitat: quantitative valuation. *Marine Ecology Progress Series* 264: 249 – 264. Available at: http://www.northeastern.edu/grabowskilab/wp-content/uploads/2012/04/peterson-et-al-2003-MEPS.pdf

Abstract: We reviewed studies providing quantitative measurements of abundance of fishes and large mobile crustaceans on oyster reefs and on nearby sedimentary habitat in the southeast United States. For each species, we compared density by size (age) class on oyster reefs and sedimentary bottom as a means of estimating the degree to which restoration of oyster reef on sedimentary bottom could augment abundances. By applying published information on growth rates of each species and a combination of empirical data and published information on age-specific survivorship, we calculated the per-unit-area enhancement of production of fishes and large mobile crustaceans expected from the addition of oyster reef habitat. For this calculation, we gave the reef habitat full credit for the expected lifetime production of species whose recruitment was judged to be limited by the area of oyster reefs based on nearly exclusive association of recruits to reefs. For species that were only modestly enhanced in abundance by oyster reefs, we gave the reef credit for the fraction of production that is derived from consumption of reef-associated prey, using a combination of gut content data and natural history information. This combination of analyses and calculations revealed that 10 m2 of restored oyster reef in the southeast United States is expected to yield an additional 2.6 kg/yr of production of fish and large mobile crustaceans for the functional lifetime of the reef. Because the reef is biogenic and self-sustaining, the lifetime of a reef protected from bottom-disturbing fishing gear is limited by intense storms or sedimentation. A reef lasting 20 to 30 yr would be expected to augment fish and large mobile crustacean production by a cumulative amount of 38 to 50 kg 10 m⁻2, discounted to present-day value. This set of calculations assumes that oyster reef habitat now limits production of reef-associated fish and crustaceans in the southeast United States. This assumption seems reasonable based on the tight associations of so many fishes with reef-dependent prey, and the depletion of reef habitat over the past century.

Peterson, M.S., B.H. Comyns, J.R. Hendon, P.J. Bond, and G.A. Duff (2000). Habitat use by early life-history stages of fishes and crustaceans along a changing estuarine landscape: differences between natural and altered shoreline sites. *Wetlands Ecology and Management* 8(2-3): 209-219. Available at: http://link.springer.com/article/10.1023%2FA%3A1008452805584

Abstract: The recent population explosion along the coastal zone of the southeast United States and the Gulf of Mexico has accelerated the development rate of waterfront property, and particularly along the Gulf Coast of Mississippi. We compared use of pristine and altered shoreline habitat by early life-history stages of fish and crustaceans to assess the potential effects of this development. Monthly beam trawls were taken at 13 sites along shoreline habitats characterized by *Juncus/Spartina* marsh, natural beach, and areas altered by bulkheads and rubble. A total of 52,068fish (n = 48 taxa) and 288,715 crustaceans (n = 24taxa) were collected during a two year study. The most abundant fish groups included gobiids, sciaenids, clupeids, and engraulids. Crustaceans, excluding the copepods, were numerically dominated by mysids, both caridean and penaeid shrimps, and crabs (*Callinectes*spp.). Demersal residents were dominated by *Gobiosoma*

bosc and *Palaemonetes* sp. whereas clupeiformes, sciaenids and penaeid shrimps were dominant among the nektonic and demersal transient species. These taxa were least abundant along stretches of shoreline altered with bulkheads or rubble, and were generally most abundant in shoreline habitats fringed with *Juncus/Spartina* grasses. This general pattern in nekton relative abundance parallel the low diversity (reciprocal of Simpson's Dominance Index) values adjacent to altered marsh to high values adjacent to pristine marsh or beach habitats, suggesting that habitats adjacent to altered marsh sites are less frequently used as nursery habitat compared to natural sites. These data support the hypothesis that shorelines adjacent to marsh habitat are critical to various life history stages of ecologically- and commercially-important species, illustrate the influence of altering natural marsh habitat on resident/transient nekton, and provide quantitative data for resource managers in the continued efforts to preserve the complex estuarine marsh landscape.

Rogers, S.M. (1994). *Marsh Grass Protection with Low-Cost Breakwaters, Shoreline Erosion Control Demonstration: Final Project Report for Albemarle-Pamlico Estuarine Study*. UNC Sea Grant College Program and the Department of Civil Engineering, North Carolina State University, Raleigh, North Carolina, pp. 65. Available at: http://digital.ncdcr.gov/cdm/ref/collection/p249901coll22/id/206079

Abstract: Previous research with the use of marsh grasses for the control of shoreline erosion has produced excellent short-term (one to five years) results. Unfortunately, use of the method on moderately exposed shorelines in our estuaries has shown limited long-term (20 to 30 years) success. This report describes the design and construction of erosion control demonstration projects using a combination of planted marsh grasses and low-cost wooden breakwaters. The breakwaters can extend the effective lifetime of planted marshes to that of bulkheads and other common erosion-control methods. Since it entails to creating a marsh where none previously existed, significant environmental advantages are apparent over most other erosion-control methods. The method can be attractive to property owners because the marsh/breakwater is significantly less costly than other alternatives offering the same level of protection and useful lifetime.

Scyphers, B., Sean P. Powers, and Denneth L. Heck Jr. (2015). Ecological value of submerged breakwaters for habitat enhancement on a residential scale. *Environmental Management* 55: 383-391. Available at: http://link.springer.com/article/10.1007%2Fs00267-014-0394-8

Abstract: Estuarine shorelines have been degraded since humans arrived in the coastal zone. In recent history, a major cause of habitat degradation has been the armoring of shorelines with vertical walls to protect property from erosive wave energy; however, a lack of practical alternatives that maintain or enhance ecological function has limited the options of waterfront residents and coastal zone managers. We experimentally investigated the habitat value of two configurations of submerged breakwaters constructed along an eroding shoreline in northwest Mobile Bay, AL (USA). Breakwaters comprised of bagged oyster shell or Reef Ball™ concrete domes were built by a community-based restoration effort. Post-deployment monitoring found that: bagged oyster breakwaters supported much higher densities of live ribbed mussels than Reef Ball breakwaters; both breakwater configurations supported increased species richness of juvenile and smaller fishes compared to controls; and that larger fishes did not appear to be affected by breakwater presence.

Our study demonstrates that ecologically degraded shorelines can be augmented with small-scale breakwaters at reasonable cost and that these complex structures can serve as habitat for filter-feeding bivalves, mobile invertebrates, and young fishes. Understanding the degree to which these structures mitigate erosive wave energy and protect uplands will require a longer time frame than our 2-year-long study.

Seitz, R.D., R.N. Lipcius, N.H Olmstead, M.S. Seebo, and D.M. Lambert (2006). Influence of shallow-water habitats and shorelines development on abundance, biomass, and diversity of benthic prey and predators in Chesapeake Bay. *Marine Ecology Progressive Series* 326: 11-27. Available at: http://www.int-res.com/abstracts/meps/v326/p11-27/

Abstract: Within the coastal zone, waterfront development has caused severe loss of shallow water habitats, such as salt marshes and seagrass beds. Although the effects of habitat degradation on community structure within intertidal marshes have been well studied, little is known about the impact of habitat degradation on, and the ecological value of, subtidal shallow-water habitats, despite the prevalence of these habitats in coastal ecosystems. In coastal habitats, bivalves are dominant benthic organisms that can comprise over 50% of benthic prey biomass and are indicative of benthic production. We quantified bivalve diversity, density, and biomass in deep and shallow (<1.5 m MLW) unstructured subtidal habitats in 2 tributaries of lower Chesapeake Bay (Elizabeth-Lafayette River system and York River). We also examined the effects of shoreline alteration in shallow habitats by contrasting the benthos of the subtidal areas adjacent to natural marsh, bulkhead, and rip-rap shorelines. Bivalve diversity, density, and biomass were significantly higher in shallow than in deep benthic habitats in both systems. Benthic abundance and diversity were higher in subtidal habitats adjacent to natural marsh than those adjacent to bulkhead shorelines; abundance and diversity were intermediate in rip-rap shorelines, and appeared to depend on landscape features. Predator density and diversity tended to be highest adjacent to natural marsh shorelines, and density of crabs was significantly higher in natural marsh than in bulkhead habitats. There is thus a crucial link between natural marshes, infaunal prey in subtidal habitats, and predator abundance. Consequently, the indirect effects of coastal habitat degradation upon secondary production in the shallow, subtidal habitats adjacent to salt marshes may be as great as or greater than direct habitat effects.

Sharma, Shailesh, Joshua Goff, Just Cebrian, and Carl Ferraro (2016). A hybrid shoreline stabilization technique: Impact of modified intertidal reefs on marsh expansion and nekton habitat in the northern Gulf of Mexico. *Ecological Engineering* 90: 352-360. Available at: http://api.ning.com/files/jw75I-QUw-LQ9WxkoVp6vZpOR3BqrNJaUMSUDn6g9DJNEwIsDfHkiKBLYbioGYYoNIEsCxURTrQIjcXMMrCVakhv2HTmm-mj/Sharmaetal20116.pdf

Abstract: To mitigate shoreline erosion numerous armoring techniques have been employed extensively along the degrading shores of the Gulf of Mexico (GoM). Shoreline armoring strategies incorporating built vertical structures have resulted in numerous undesired ecological consequences. Bioengineering hybrid techniques consisting of “living shorelines” are emerging as an

alternative option to mitigating shoreline loss and overcoming ecological shortcomings of hardened structures. Hitherto, only a few studies have assessed efficacy of hybrid techniques on shoreline stabilization and adjacent habitat enhancement. In this study, we integrated permeable intertidal reef-breakwaters (also known as wave attenuation units or WAUs) and predominantly restored native *Spartina alterniflora* marsh vegetation to mitigate erosion along severely degrading shores of a narrow peninsula in the northern GoM. Particularly, we evaluated impacts of a large-scale WAU reef deployment on a range of physical and biological parameters including erosion mitigation (shoreline stabilization), facilitation of created marsh expansion and habitat provision to marsh-utilizing nekton. We compared WAU reefs to adjacent gap areas without WAUs to evaluate the effects of tidal openings on the metrics measured. Our results of over 3 years suggest that, intertidal WAU reefs facilitate in created marsh expansion and the tidal openings between the reef complexes allow free movement of marsh-utilizing nekton fauna. Based on our results, we conclude that hybrid restoration technique is highly efficacious on erosion mitigation, adjacent marsh expansion and habitat creation. However, more works in other coastal systems are required to confirm the impacts of hybrid techniques on erosion mitigation and consequently on marshes and marsh-utilizing nekton.

Stevenson, Carrie Shannon Tomlinson (1998). *Enhancement of Recruitment and Nursery Function by Habitat Creation in Pensacola Bay, Florida*. Thesis to the Dept. of Biology, College of Arts and Sciences, University of West Florida, pp. 95.

Abstract: Urban impacts to estuarine nursery habitats can limit larval recruitment affecting fisheries production and carrying capacity. A community-sponsored habitat creation effort, Project GreenShores, in Pensacola Bay, Florida, USA, consists of a limestone oyster reef/breakwater placed seaward of intertidal areas planted with *Spartina alterniflora*. For this thesis, fish and epibenthic crustacean populations were sampled monthly using a 15.24 m beach seine for fifteen months during and after placement of the reefs and intertidal marsh to monitor changes. The study used an adjacent open water area separated by a point of land with similar pre-project characteristics to the marsh creation area as a control. Dominant fish and crustacean species in both locations were *Mugil cephalus, Leiostomus xanthurus*, and *Callinectes sapidus.* Overall, there were statistically significant differences between abundance of frequently occurring species and the community structures in Sites 1 and 2. Diversity was nearly indistinguishable between sites, but species richness was higher within the developed site. Fish size was similar between the sites and was consistent with expected presence of juvenile fish based on seasonal spawning patterns and net avoidance capability of larger fish. The results are relevant to communities and fisheries managers considering investments in large-scale habitat development projects.

Swann, LaDon (2008). The Use of Living Shorelines to Mitigate the Effects of Storm Events on Dauphin Island, Alabama, USA. *American Fisheries Society Symposium* 64: 47-57. Available at: http://livingshorelinesolutions.com/uploads/Dr._LaDon_Swann__Living_Shorelines_Paper.pdf

Abstract: Dauphin Island's Fort Gaines Harbor was constructed in the 1950s by removing approximately 3 ha from Saw Grass Point Salt Marsh. The harbor now serves as one of Dauphin

Island's two primary access points for recreational and commercial boats to the Gulf of Mexico. Chronic erosion has resulted in the loss of 0.5 ha of the remaining marsh. This saline tidal marsh is of significant ecological importance and is one of only two on Dauphin Island. In 2004, exposed nearshore precast concrete breakwaters called coastal havens were used to protect and restore the marsh. These structures function as detached breakwaters to minimize the effect of storm surge and boat wake through wave attenuation; they also provide suitable substrate for oyster colonization. In April 2005, 182 units were installed in water approximately 1.3 m deep. Oyster density on the coastal havens, measured 19 months post-installation, was 205 oysters/m^2. Measurements behind the breakwater indicate some sediment accretion. The dual function of these structures has controlled erosion behind the breakwater and provided habitat for a wide array of locally important species such as: spotted seatrout (also known as speckled trout), blue and Gulf stone crabs, eastern oyster, red drum, southern flounder, and various species of commercially important shrimp.

Utomo, H.S., I. Wenefrida, M.D. Materne, and .J.T Linscombe (2010). Polycross seed of genetically diverse smooth cordgrass (*Spartina alterniflora*) for erosion control and habitat restoration. *Restoration Ecology* 18(2): 170-172. Available at: http://onlinelibrary.wiley.com/doi/10.1111/j.1526-100X.2009.00623.x/abstract

Abstract: Although seed-based planting is common in crop systems, it is relatively a new concept in coastal erosion control and habitat restoration. This paper discusses the potential use of seed-based revegetation to accommodate large-scale erosion control using a highly diverse population of smooth cordgrass (*Spartina alterniflora*) from controlled polycross to attain desirable genetic diversity suitable for habitat restoration. Seed-based restoration provides a more versatile alternative approach to the current clonal revegetation technique in many regions, including the Gulf Coast of the United States. The objectives of this study were to (1) describe seed production and cultural aspects of the polycross population and (2) discuss the potential use of polycross seeds for direct seeding applications and other innovative restoration approaches using seed-derived planting materials. The polycross population was produced using 15 genetically diverse and high-seed producing smooth cordgrass lines selected from native populations. The average seed set of the polycross population was 58.5 ± 6.3% with an average germination rate of 82.2 ± 9%. As comparison, Vermilion, the only available smooth cordgrass cultivar, has a seed set of 20.6 ± 5% and a germination rate of 35 ± 8%. The average yield of *S. alterniflora* seed from the polycross population was 277.5 kg/ha, which is equivalent to approximately 26 million viable seeds. Seed can be stored in 100% humidity at a temperature of 2 ± 1°C for 6–9 months.

Woodhouse, W.W. Jr., E.D. Seneca and S.W. Broome (1976). *Propagation of Spartina alterniflora for shoreline erosion abatement*. USACE, Coastal Engineering Research Center Technical Memorandum No. 76-2, Fort Belvoir, VA, pp. 75. Available at: http://nsgl.gso.uri.edu/ncu/ncut76010.pdf

Abstract: Experimental plantings to stabilize eroding shorelines in Bogue Sound, NC in 1974 were successful. Better stands were produced on sites subject to severe wave stress by reducing transplant spacing to 1.5 to 2.0 feet apart. Rhizomes without well-developed culms attached were

worthless as propagules within the intertidal zone. Seeding was unsuccessful do to exposure to excessive wave energy.

Differences between plants from different sources decreased with time but a local plant stock was superior to an introduced stock under stressed conditions through the first growing season. Greenhouse-grown plants were more costly but no better than field-grown plants.

Some of the adaption of *Spartina alterniflora* to the low oxygen supply and the ammonium form of nitrogen characteristic of the intertidal zone were confirmed by laboratory studies. Plants were detrimentally affected by forced aeration of roots and the substitution of nitrate for ammonium. Stands of *Spartina alterniflora* continued to respond to high inputs of nitrogen and phosphorus through the fourth year.

Woodhouse, W.W. Jr., E.D. Seneca and S.W. Broome (1974). *Propagation of Spartina alterniflora for substrate stabilization and salt marsh development*. USACE, Coastal Engineering Research Center Technical Memorandum No. 46, Fort Belvoir, VA, pp. 170. Available at: https://archive.org/details/propagationofspa00wood

Abstract: Techniques were developed for propagation of *Spartina alterniflora* Loisel., smooth cordgrass, in the intertidal zone on dredge spoil and eroding shorelines. Both seeding and transplanting methods were successful. Trans- plants proved to be more tolerant of rigorous conditions such as storm waves and blowing sand, but seeding was more economical and was successful on protected sites. Vegetative development of seeded and transplanted areas was rapid with primary production equal to that of a long established marsh by the second growing season. At the end of the first growing season, more plant cover was produced from seeding at the rate of 100 viable seeds per square meter than from transplanting single-stem plants on 0.9-meter spacing.

The relationship of mineral nutrition to productivity of *S. alterniflora* was determined. Plants and soils in natural stands were sampled and analyzed for productivity interrelationships using multiple regression techniques. Salinity of the soil solution, plant and soil manganese concentrations, and plant sulfur concentrations were negatively associated with aboveground production. Variables positively associated with production included phosphorus concentration in the plant tissue and in the soil. Fertilizer experiments showed that the production of a natural stand of *S. alterniflova* growing on sand was increased significantly by additions of nitrogen and increased three-fold when both nitrogen and phosphorus were added. The production of natural marsh growing on finer-textured sediments doubled when nitrogen was added, but there was no response to phosphorus. Nitrogen and phosphorus fertilizers also enhanced growth of transplants and seedlings on sandy dredge material.

Chemical Effects

Dame, R. F. and D. M. Allen (1996). Between estuaries and the sea. *Journal of Experimental Marine Biology and Ecology* 200(1-2): 169-185. Available at: http://www.sciencedirect.com/science/article/pii/S0022098196026421

Abstract: Dissolved and particulate materials and living organisms are exchanged between estuaries and the sea. Net material fluxes, import or export, appear to depend on physical and biological processes within both estuarine and coastal ecosystems. In temperate zone lagoonal systems, the marsh-estuarine continuum hypothesis can provide a reasonable synthetic explanation of transport based on the level of ecosystem maturity within the system. The relative importance of riverine and lagoonal material exchanges with the coastal ocean are at present entirely speculative and make the estimation of the regional influences of material transports between estuaries and the coastal ocean uncertain. Organismic exchanges depend on both passive and active behavior mechanisms and are species specific. Few quantitative estimates of organismic fluxes exist and the role of non-commercial invertebrates and fish in these fluxes are unknown.

Grizzle, R. E., J. K. Greene and L. D. Coen (2008). Seston removal by natural and constructed intertidal eastern oyster (*Crassostrea virginica*) reefs: A comparison with previous laboratory studies, and the value of in situ methods. *Estuaries and Coasts* 31: 1208-1220. Available at: http://link.springer.com/article/10.1007%2Fs12237-008-9098-8

Abstract: An important ecological role ascribed to oysters is the transfer of materials from the water column to the benthos as they feed on suspended particles (seston). This ecosystem service has been often touted as a major reason for many oyster restoration efforts, but empirical characterization and quantification of seston removal rates in the field have been lacking. Changes in chlorophyll a (chl a) concentrations in the water column were measured in May 2005 and June 2006 in South Carolina using in situ fluorometry and laboratory analysis of pumped water samples taken upstream and downstream as water flowed over natural and constructed intertidal oyster reefs. Both methods gave similar results overall, but with wide variability within individual reef datasets. In situ fluorometer data logged at 10 to 30-s intervals for up to 1.3 h over eight different reefs (three natural and five constructed) showed total removal (or uptake) expressed as % removal of chl a ranging from−9.8% to 27.9%, with a mean of 12.9%. Our data indicate that restored shellfish reefs should provide water-quality improvements soon after construction, and the overall impact is probably determined by the size and density of the resident filter feeder populations relative to water flow characteristics over the reef. The measured population-level chl a removal was converted to mean individual clearance rates to allow comparison with previous laboratory studies. Although direct comparisons could not be made due to the small size of oysters on the study reefs (mean shell height, 36.1 mm), our calculated rates (mean, 1.21 L h^{-1}) were similar to published laboratory measured rates for oysters of this size. However, the wide variability in measured removal by the oyster reefs suggests that individual oyster feeding rates in nature may be much more variable than in the laboratory. The proliferation of ecosystem-level models that simulate the impacts of bivalves on water quality based only on laboratory-feeding measurements underscores the importance of further research aimed at determining ecologically realistic feeding rates for oysters in the field. Because in situ methods provide many replicate measurements quickly, they represent a potentially powerful tool for quantifying the effects of oyster reefs, including all suspension-feeding taxa present, on water quality.

Kellogg, Lisa M., Jeffrey C. Cornwell, Michael S. Owens, and Kennedy T. Paynter (2013). Denitrification and nutrient assimilation on a restored oyster reef. *Marine Ecology Progress Series* 480: 1-19. Available at: http://www.int-res.com/articles/feature/m480p001.pdf

Abstract: At a restored reef site and a control site in the Choptank River, Maryland, USA, we partially quantified the effect of oyster reef restoration on the removal of nutrients from the water column by determining seasonal fluxes of oxygen (O2), ammonium (NH4+), combined nitrate and nitrite (NO2+3), di-nitrogen (N2) and soluble reactive phosphorus (SRP) and by assessing the assimilation of nutrients by macrofauna. Fluxes of O2, NH4+, NO2+3 and SRP at the restored site were enhanced by at least one order of magnitude during all seasons. Seasonal denitrification rates at the restored site, measured as flux of N2-N, ranged from 0.3 to1.6 mmol N2-N m–2 h–1, with August rates among the highest ever recorded for an aquatic system. In addition to oysters (131 oysters m–2; average shell height = 114 mm; age = 2 to 7 yr), the restored reef provided habitat for 24 585 other microbenthic organisms per square meter compared to 2265 organisms m–2 at the control site. Restoration enhanced the average standing stock of assimilated nutrients by 95 g N m–2 and 15 g P m–2. Nitrogen and phosphorus in shells of live oysters and mussels accounted for 47 and 48% of total nitrogen and phosphorus standing stocks, respectively. Our results demonstrate that oyster reef restoration can significantly increase denitrification rates and enhance nutrient sequestration via assimilation into bivalve shells.

Leonard, Lynn A., P, Ansley Wren, and Rebecca L. Beavers (2002). Flow dynamics and sedimentation in *Spartina alterniflora* and *Phragmites australis* marshes of the Chesapeake Bay. *Wetlands* 22(2): 415–424. Available at: http://link.springer.com/article/10.1672%2F0277-5212(2002)022%5B0415%3AFDASIS%5D2.0.CO%3B2#page-1

Abstract: The introduction of invasive species such as *Phragmites australis* in the Chesapeake Bay has been viewed to be deleterious to habitat quality. Little is known, however, on the extent to which the replacement of *Spartina alterniflora* by *Phragmites* affects hydrodynamics and sediment trapping on the surface of impacted marshes. This study examined sediment deposition, sediment mobility, and flow conditions in adjacent *Phragmites australis* and *Spartina alternifora* marshes in Prospect Bay, Maryland, USA in order to determine if differences in plant morphology affect surficial flow properties and particle dispersion patterns. Measures of fine-scale flow dynamics, total suspended sediment (TSS) concentration, and particulate deposition were obtained at various distances from open water across the marsh surface over four sequential tidal cycles in Fall 1999. The hydrodynamic data indicate that both the gross and fine-scale properties of tidal flows were similar in both types of vegetation and that flow conditions were conductive to particle deposition. TSS concentrations did not differ between canopy types and decreased over time in both systems. There was no difference in TSS reduction over distance between *Spartina* and *Phragmites*. The sediment trap data indicate that maximum deposition occurs closer to open water in both *Spartina* and *Phragmites* and that the organic content of deposited matter increased with distance into the marsh interior. This study provides the first *in situ*, high resolution, over-marsh flow data for marshes dominated by *Phragmites*. The data provided herein suggest that differences in vegetative

cover do not significantly affect flow regime, sediment transport, and sediment deposition patterns in the marsh systems examined.

O'Meara, T., S.P. Thompson, and M.F. Piehler (2015). Effects of shoreline hardening on nitrogen processing in estuarine marshes of the U.S. mid-Atlantic coast. *Wetlands Ecol. Manage*. 23: 385-394. Available at: http://link.springer.com/article/10.1007/s11273-014-9388-9

Abstract: Multiple stressors affect estuarine shorelines including erosion, sea level rise and impacts from human development of adjacent lands. Increasingly common features of coastal development are vertical shoreline stabilization structures such as bulkheads. Bulkheads are designed to prevent land loss and flooding through the construction of a vertical wall anchored to the land. However, they break the connection between land and water and are barriers to upland plant migration. This disconnect can affect hydrology, alter nutrient and sediment supplies, and lead to marsh loss. We measured the effects of bulkheads on sediment nitrogen fluxes, including denitrification (DEN), at three representative estuarine shoreline types: natural marsh (no bulkhead), bulkhead without marsh, and bulkheads with marshes of varying widths. Sediment cores were taken mid-marsh or, 2 m seaward of bulkhead in sites lacking marsh in northern, central and southern coastal regions of North Carolina. Concentrations of N_2 and O_2 were measured using a membrane inlet mass spectrometer. In addition, sediment organic matter and inorganic nitrogen concentrations were quantified. Average DEN rate was 93.1 ± 7.0 µmol N m−2 h−1 with the highest rates in the summer and lowest rates in the winter. Sediment oxygen demand was positively correlated with DEN rate (R2 = 0.43, p < 0.01), which suggests that DEN is affected by carbon lability. DEN was not affected by bulkhead presence (R2 = 0.01, p = 0.52), but marsh presence significantly affected yearly DEN rates (R2 = 0.13, p < 0.01). These data indicate that bulkheads do not directly affect nitrogen processing, but indirectly reduce cycling rates through marsh loss.

Piehler, M.F. and A.R. Smyth (2011). Habitat-specific distinctions in estuarine denitrification affect both ecosystem function and services. *Ecosphere* 2(1): article 12. Available at: http://onlinelibrary.wiley.com/doi/10.1890/ES10-00082.1/pdf

Abstract: Resource limitation controls the base of food webs in many aquatic ecosystems. In coastal ecosystems, nitrogen (N) has been found to be the predominant limiting factor for primary producers. Due to the important role nitrogen plays in determining ecosystem function, understanding the processes that modulate its availability is critical. Shallow-water estuarine systems are highly heterogeneous. Intemperate estuaries, multiple habitat types can exist in close proximity to one another, their distribution controlled primarily by physical energy, tidal elevation and geomorphology. Distinctions between these habitats such as rates of primary productivity and sediment characteristics likely affect material processing. We used membrane inlet mass spectrometry to measure changes in N_2 flux (i.e., denitrification) in multiple shallow-water estuarine habitats through an annual cycle. We found significantly higher rates of denitrification (DNF) in structured habitats such as submerged aquatic vegetation, salt marshes and oyster reefs than in intertidal and subtidal flats. Seasonal patterns were also observed, with higher DNF rates occurring in the warmer seasons. Additionally, there was an interaction between habitat type and season that

we attributed to the seasonal patterns of enhanced productivity in individual habitat types. There was a strong correlation between denitrification and sediment oxygen demand (SOD) in all habitats and all seasons, suggesting the potential to utilize SOD to predict DNF. Denitrification efficiency was also higher in the structured habitats than in the flats. Nitrogen removal by these habitats was found to be an important contributor to estuarine ecosystem function. The ecosystem service of DNF in each habitat was evaluated in US dollars using rates from a regional nutrient-offset market to determine the cost to replace N through management efforts. Habitat-specific values of N removal ranged from approximately three thousand U.S. dollars per acre per year in the submerged aquatic vegetation to approximately four hundred U.S. dollars per acre per year in the subtidal flat. Because of the link between habitat type and processes such as DNF, changes in habitat area and distribution will have consequences for both ecosystem function and the delivery of ecosystem services.

Sparks Eric L., Just Cebrian, Craig R. Tobias, and Christopher A. May (2015). Groundwater nitrogen processing in Northern Gulf of Mexico restored marshes. *Journal of Environmental Management* 150(1): 206–215. Available at: http://www.sciencedirect.com/science/article/pii/S0301479714005453

Abstract: Groundwater nitrogen processing was examined in a restored black needlerush (*Juncus roemerianus*) marsh to assess its potential for removing land-derived nitrogen pollution. Two restoration designs, one initially planted at 50% cover (half density plots) and the other one at 100% cover (full density plots), were compared with non-vegetated controls. The introduction via groundwater of a NO3− solution with a conservative tracer (Br^-) and labeled isotopically (^{15}N) allowed calculation of nitrogen removal in the plots following two methods. The first method used changes in the ratio $[NO_x]:[Br^-]$ as the groundwater plume traveled through the plot, and the second method relied on balancing ^{15}N input with ^{15}N export. Both methods showed ≈97% of the N from the simulated groundwater plume was removed (i.e. not delivered to the open waters of the adjacent estuary) in vegetated plots and ≈86% was removed in non-vegetated controls. The most dominant routes of N removal from the introduced solution were N_2 production and assimilation into macrophyte biomass, which were similar in magnitude for the vegetated plots, whereas N_2 production dominated in the unvegetated plots. The majority of N removed from the introduced solution occurred in the first 30 cm the solution traveled in the vegetated treatments. In addition, ambient porewater concentrations of dissolved inorganic nitrogen (DIN) were similar between full and half density plots, but lower than the non-vegetated control (≈8.5× and 7.5×), suggesting full and half density plots removed more DIN than non-vegetated plots. These results suggest that restoring marshes by planting 50% of the area may be a more cost-effective restoration design in terms of mitigating land-derived nutrient pollution than planting 100% of the area since it requires less effort and cost while removing similar quantities of N.

Living Shorelines in Mangrove Habitat

Burrows, Felicity and Perry Gayaldo (2005). Restoration Monitoring of Mangroves. In *Science-Based Restoration Monitoring of Coastal Habitats, Vol. 2: Tools for Monitoring Coastal Habitats*. Thayer, G.W., T.A. McTigue, R.J. Salz, D.H. Merkey, F.M. Burrows, and P.F. Gayaldo (eds). NOAA, Coastal

Ocean Program Decision Analysis Series No. 23. NOAA National Centers for Coastal Ocean Science, Silver Spring, MD, pp. 628 plus appendices. Available at: http://aquaticcommons.org/2240/1/WholeDocument.pdf

This section presents the structural characteristics of mangroves that are applicable to restoration monitoring. The characteristics described in this section refer to the biological, physical, hydrological, and chemical features of the habitat that may be potential parameters used to gather baseline information and for monitoring restoration efforts and abiotic factors that may influence the restoration process. Additional information provided is intended to help educate the reader on the ecology of mangroves such as the role each characteristic plays in supporting the structure of the habitat and plant and animal life.

Dame, R., M. Alber, D. Allen, M. Mallin, C. Montague, A. Lewitus, A. Chalmers, R. Gardner, C. Gilman, B. Kjerfve, J. Pinckney, and N. Smith (2000). *Estuaries* 23(6): 793-819. Available at: http://link.springer.com/article/10.2307%2F1352999

Abstract: Estuaries of the southeastern Atlantic coastal plain are dominated by shallow meso-tidal bar-built systems interspersed with shallow sounds and both low flow coastal plain and high flow piedmont riverine systems. Three general geographical areas can be discriminated: the sounds of North Carolina; the alternating series of riverine and ocean dominated bar-built systems of South Carolina, Georgia, and northeast Florida, and the subtropical bar-built estuaries of the Florida southeast coast. The regional climate ranges from temperate to subtropical with sea level rise and hurricanes having a major impact on the region's estuaries because of its low and relatively flat geomorphology. Primary production is highest in the central region. Seagrasses are common in the northern and southern most systems, while intertidal salt marshes composed of *Spartina alterniflora* reach their greatest extent and productivity in South Carolina and Georgia. Nuisance blooms (cyanobacteria, dinoflagellates, and cryptomonads) occur more frequently in the northern and extreme southern parts of the region. Fishery catches are highest in the North Carolina and Florida areas. Human population growth with its associated urbanization reaches a maximum in Florida and it is thought that the long-term sustainability of the Florida coast for human habitation will be lost within the next 25 years. Tidal flushing appears to play an important role in mitigating anthropogenic inputs in systems of moderate to high tidal range, i.e., the South Carolina and Georgia coasts. The most pressing environmental problems for the estuaries of the southeastern Atlantic coast seem to be nutrient loading and poor land use in North Carolina and high human population density and growth in Florida. The future utilization of these estuarine systems and their services will depend on the development of improved management strategies based on improved data quality.

Feller, I.C., C.E. Lovelock, U. Berger, K.L. McKee, S.B. Joye, and M.C. Bal (2010). Biocomplexity in Mangrove Ecosystems. *Annual Review of Marine Science* 2: 395-417. Available at: http://www.annualreviews.org/doi/pdf/10.1146/annurev.marine.010908.163809

Abstract: Mangroves are an ecological assemblage of trees and shrubs adapted to grow in intertidal environments along tropical coasts. Despite repeated demonstration of their economic and societal value, more than 50% of the world's mangroves have been destroyed, 35% in the past two decades to aquaculture and coastal development, altered hydrology, sea-level rise, and nutrient over enrichment. Variations in the structure and function of mangrove ecosystems have generally been described solely on the basis of a hierarchical classification of the physical characteristics of the intertidal environment, including climate, geomorphology, topography, and hydrology. Here, we use the concept of emergent properties at multiple levels within a hierarchical framework to review how the interplay between specialized adaptations and extreme trait plasticity that characterizes mangroves and intertidal environments gives rise to the biocomplexity that distinguishes mangrove ecosystems. The traits that allow mangroves to tolerate variable salinity, flooding, and nutrient availability influence ecosystem processes and ultimately the services they provide. We conclude that an integrated research strategy using emergent properties in empirical and theoretical studies provides a holistic approach for understanding and managing mangrove ecosystems.

Physical Effects

Cahoon, D.R. (2006). A review of major storm impacts on coastal wetland elevations. *Estuaries and Coasts* 29(6): 889-898. Available at: http://www.pwrc.usgs.gov/prodabs/pubpdfs/6702_cahoon.pdf

Abstract: Storms have long been recognized as agents of geomorphic change to coastal wetlands. A review of recent data on soil elevation dynamics before and after storms revealed that storms affected wetland elevations by storm surge, high winds, and freshwater flushing of the estuary (inferred). The data also indicate that measures of sediment deposition and erosion can often misrepresent the amount and even direction of elevation change because of storm influences on subsurface processes. Simultaneous influence on both surface and subsurface processes by storms means that soil elevation cannot always be accurately estimated from surface process data alone. Eight processes are identified as potentially influencing soil elevation: sediment deposition, sediment erosion, sediment compaction, soil shrinkage, root decomposition (following tree mortality from high winds), root growth (following flushing with freshwater, inferred), soil swelling, and lateral folding of the marsh root mat. Local wetland conditions (e.g., marsh health, tide height, groundwater level) and the physical characteristics of the storm (e.g., angle of approach, proximity, amount of rain, wind speed, and storm surge height) were apparently important factors determining the storm's effect on soil elevation. Storm effects on elevation were both permanent (on an ecological time scale) and short-lived, but even short-term changes have potentially important ecological consequences. Shallow soil subsidence or expansion caused by a storm must be considered when calculating local rates of relative sea level rise and evaluating storm effects on wetland stability.

Cahoon, D. and Lynch, J.C. (1997). Vertical accretion and shallow subsidence in a mangrove forest of southwestern Florida, U.S.A. *Mangroves and Salt Marshes* 1: 173-186. Available at: http://link.springer.com/article/10.1023%2FA%3A1009904816246

Abstract: Simultaneous measurements of vertical accretion from artificial soil marker horizons and soil elevation change from sedimentation-erosion table (SET) plots were used to evaluate the processes related to soil building in fringe, basin, and overwash mangrove forests located in a low-energy lagoon which receives minor inputs of terrigenous sediments. Vertical accretion measures reflect the contribution of surficial sedimentation (sediment deposition and surface root growth). Measures of elevation change reflect not only the contributions of vertical accretion but also those of subsurface processes such as compaction, decomposition and shrink-swell. The two measures were used to calculate amounts of shallow subsidence (accretion minus elevation change) in each mangrove forest. The three forest types represent different accretionary environments. The basin forest was located behind a natural berm. Hydroperiod here was controlled primarily by rainfall rather than tidal exchange, although the basin flooded during extreme tidal events. Soil accretion here occurred primarily by autochthonous organic matter inputs, and elevation was controlled by accretion and shrink-swell of the substrate apparently related to cycles of flooding-drying and/or root growth-decomposition. This hydrologically-restricted forest did not experience an accretion or elevation deficit relative to sea-level rise. The tidally dominated fringe and overwash island forests accreted through mineral sediment inputs bound in place by plant roots. Filamentous turf algae played an important role in stabilizing loose muds in the fringe forest where erosion was prevalent. Elevation in these high-energy environments was controlled not only by accretion but also by erosion and/or shallow subsidence. The rate of shallow subsidence was consistently 3–4 mm y^{-1} in the fringe and overwash island forests but was negligible in the basin forest. Hence, the vertical development of mangrove soils was influenced by both surface and subsurface processes and the processes controlling soil elevation differed among forest types.

The mangrove ecosystem at Rookery Bay has remained stable as sea level has risen during the past 70 years. Yet, lead-210 accretion data suggest a substantial accretion deficit has occurred in the past century (accretion was 10–20 cm < sea-level rise from 1930 to 1990) in the fringe and island forests at Rookery Bay. In contrast, our measures of elevation change mostly equaled the estimates of sea-level rise and our short term estimates of vertical accretion exceeded the estimates by the amount of shallow subsidence. These data suggest that (1) vertical accretion in this system is driven by local sea-level rise and shallow subsidence, and (2) the mangrove forests are mostly keeping pace with sea-level rise. Thus, the vulnerability of this mangrove ecosystem to sea-level rise is best described in terms of an elevation deficit (elevation change minus sea-level rise) based on annual measures rather than an accretion deficit (accretion minus sea-level rise) based on decadal measures.

Cunniff, S. and A. Schwartz (2015). *Performance of Natural Infrastructure and Nature-based Measures as Coastal Risk Reduction Features*. Environmental Defense Fund, pp. 35. Available at: https://www.edf.org/sites/default/files/summary_ni_literature_compilation_0.pdf

Abstract: This EDF report represents a review of the state of knowledge on the performance of natural and nature-based infrastructure as compiled from existing literature and participant input obtained during an expert workshop. An accessible summary of the most current state of understanding of the risk reduction performance of natural infrastructure is provided in table form.

It is important to note that non-structural approaches, such as zoning, building codes and evacuation planning, also play critical roles in increasing coastal resilience.

Hutchison, J., M. Spalding, and P. zu Ermgassen (2014). *The Role of Mangroves in Fisheries Enhancement*. The Nature Conservancy and Wetlands International, pp. 54. Available at: http://www.mangroverestoration.com/pdfs/Hutchinson%20et%20al%202014%20The%20Role%20of%20Mangroves%20in%20Fisheries%20Enhancement%20%20WI.pdf

This review of the scientific literature demonstrates the importance of mangroves for wild capture fisheries. A fuller understanding of this ecosystem service and its value in both social and economic terms will help enhance the sustainable management of both mangroves and fisheries. Key findings of the report include:

- Fish productivity from mangroves will be highest where mangrove productivity is high, where there is high freshwater input from rivers and rainfall, and where mangroves are in good condition.
- Fish productivity will increase with an increase in total area of mangroves and also with the length of mangrove margin since generally it is the fringes of mangroves where fish populations are enhanced.
- Mangroves with greater physical complexity both in terms of patterns of channels, pools and lagoons, as well as root structure, which is an important area for shelter and for growth of some bivalves, will enhance fisheries.

Krauss, Ken W., Karen L. McKee, Catherine E. Lovelock, Donald R. Cahoon, Neil Saintilan, Ruth Reef, and Luzhen Chen (2014). How mangrove forests adjust to rising sea level. *New Phytologist* 202: 19–34. Available at: http://www.mangroverestoration.com/pdfs/Krauss%20et%20al%202014%20SLR%20and%20mangroves.pdf

Abstract: Mangroves are among the most well described and widely studied wetland communities in the world. The greatest threats to mangrove persistence are deforestation and other anthropogenic disturbances that can compromise habitat stability and resilience to sea-level rise. To persist, mangrove ecosystems must adjust to rising sea level by building vertically or become submerged. Mangroves may directly or indirectly influence soil accretion processes through the production and accumulation of organic matter, as well as the trapping and retention of mineral sediment. In this review, we provide a general overview of research on mangrove elevation dynamics, emphasizing the role of the vegetation in maintaining soil surface elevations (i.e. position of the soil surface in the vertical plane). We summarize the primary ways in which mangroves may influence sediment accretion and vertical land development, for example, through root contributions to soil volume and upward expansion of the soil surface. We also examine how hydrological, geomorphological and climatic processes may interact with plant processes to influence mangrove capacity to keep pace with rising sea level. We draw on a variety of studies to describe the important, and often under-appreciated, role that plants play in shaping the trajectory of an ecosystem undergoing change.

Krauss, K. W., T. W. Doyle, T. J. Doyle, C. M. Swarzenski, A. S. From, R. H. Day, and W. H. Conner (2009). Water level observations in mangrove swamps during two hurricanes in Florida. *Wetlands* 29(1); 142-149. Available at: http://link.springer.com/article/10.1672%2F07-232.1

Abstract: Little is known about the effectiveness of mangroves in suppressing water level heights during landfall of tropical storms and hurricanes. Recent hurricane strikes along the Gulf Coast of the United States have impacted wetland integrity in some areas and hastened the need to understand how and to what degree coastal forested wetlands confer protection by reducing the height of peak water level. In recent years, U.S. Geological Survey Gulf Coast research projects in Florida have instrumented mangrove sites with continuous water level recorders. Our ad hoc network of water level recorders documented the rise, peak, and fall of water levels (± 0.5 hr) from two hurricane events in 2004 and 2005. Reduction of peak water level heights from relatively in-line gages associated with one storm surge event indicated that mangrove wetlands can reduce water level height by as much as 9.4 cm/km inland over intact, relatively unchannelized expanses. During the other event, reductions were slightly less for mangroves along a river corridor. Estimates of water level attenuation were within the range reported in the literature but erred on the conservative side. These synoptic data from single storm events indicate that intact mangroves may support a protective role in reducing maximum water level height associated with surge.

Liu, H., Keqi Zhang, Yuepeng Li, and Lian Xie (2013). Numerical study of the sensitivity of mangroves in reducing storm surge and flooding to hurricane characteristics in southern Florida. *Continental Shelf Research* 64: 51–65. Available at: http://www.sciencedirect.com/science/article/pii/S0278434313001994

Abstract: The sensitivity of the mangrove effect on reducing storm surge flooding to hurricane characteristics is investigated by using the numerical model Coastal and Estuarine Storm Tide (CEST). First, the attenuation of storm surge by mangroves is incorporated into the model by updating Manning's coefficient based on the National Land Cover Dataset (NLCD) 2001. Then CEST is verified by comparing the model results with field observations in South Florida for Hurricane Wilma. Secondly, a set of numerical experiments using synthetic hurricanes with different intensity, forward speed, radius of maximum wind speed and travel direction are conducted for the sensitivity study. Results indicate that storm surge magnitudes and flooding areas are reduced by the mangrove zone more for fast moving hurricanes than slow moving hurricanes in the west coast of South Florida. In addition, increasing hurricane intensity and hurricane size lower the effect of mangroves on attenuating storm surge and reducing the flooding area. The mangrove zone plays a more effective role in reducing flooding areas from hurricanes that travel from east to west than from hurricanes that travel from west to east. The mangrove reduction effect is most sensitive to changes in hurricane forward speed. A 6.7 m/s to 2.2 m/s decrease in forward speed can result in a decrease in flood area reduction by mangroves that is equivalent to the decrease in flood area reduction by mangroves from Category 3 to 5 hurricanes.

Mazda, Y., M. Magi, Y. Ikeda, T. Kurokawa, and T. Asano (2006). Wave reduction in a mangrove forest dominated by *Sonneratia* sp. *Wetlands Ecology and Management* 14(4): 365-378. Available at: http://link.springer.com/article/10.1007%2Fs11273-005-5388-0

Abstract: Based on a field observation at the Vinh Quang coast in northern Vietnam, the characteristics of wave reduction due to the drag force of one mangrove species, *Sonneratia* sp., were quantitatively analyzed. The reduction rate of sea waves in this area changed substantially with the tidal phase, due to the unique vertical configuration of *Sonneratia* sp. At the shallow range of water depth, since the shape of pneumatophores of *Sonneratia* sp. tapers off upward, the effect of drag force by these roots on the wave reduction decreased with the increase in the water level, resulting in a decrease in the rate of wave reduction. On the other hand, when water levels rose above the height of thickly spread branches and leaves of these trees, the rate of wave reduction increased again with an increase in the water level. Further, at this high range of water level, the rate of wave reduction depended strongly on the incident wave height. These results indicate that the thickly grown mangrove leaves effectively dissipate huge wave energy which occurs during storms such as typhoons, and protect coastal areas. Referring to the past studies, our results suggest that the hydrodynamic knowledge in various mangrove conditions such as the vertical configuration of mangrove species, their vegetation conditions, water depth, incident wave condition and the relationships between these factors should be further accumulated and then quantitatively formulated in order to protect coastal areas from severe sea waves

McIvor, A. L., T. Spencer, I. Möller, and M. Spalding (2013). *The response of mangrove soil surface elevation to sea level rise*. Natural Coastal Protection Series: Report 3. Cambridge Coastal Research Unit Working Paper 42. The Nature Conservancy and Wetlands International, pp. 59. Available at: http://coastalresilience.org/science/mangroves/surface-elevation-and-sea-level-rise

This report explores the capacity of mangrove soil surfaces to respond to local rises in sea level through elevation increase. The report describes the processes that influence surface elevation change in mangroves including: sedimentation/resuspension; accretion/erosion; faunal processes (e.g. burrowing of crabs); growth/decomposition of roots; shrinkage/swelling of soils in the presence/absence of water; and compaction/compression/rebound of soils over time and under the weight of soil/water above. A variety of factors affect the rates of these processes, including the supply of external sediment, the types of benthic mats that bind surface sediments together, vegetation characteristics (tree density, aerial root structure), nutrient availability to sub-surface roots, storm impacts, and several hydrological factors (e.g., river levels, rainfall and groundwater pressure). The sum of these processes results in surface elevation change. The report discusses historical and recent evidence suggesting the ability of mangrove surfaces to rise at similar rates to sea level in a number of locations. However, current measurements are only available for a relatively small number of sites, and most records span short time periods. The report concludes that longer-term datasets are needed from more locations, and these need to be analyzed relative to sea level changes over the same periods of measurement and recommends that monitoring and management of mangrove areas be used to ensure continued provision of coastal defense services into the future.

McIvor, A. L., T. Spencer, I. Möller, and M. Spalding (2012). *Reduction of wind and swell waves by mangroves*. Natural Coastal Protection Series: Report 1. Cambridge Coastal Research Unit Working Paper 40. The Nature Conservancy and Wetlands International, pp. 27. Available at: https://www.conservationgateway.org/ConservationPractices/Marine/crr/library/Documents/wind-and-swell-wave-reduction-by-mangroves.pdf

This report describes the role mangrove forests can play in reducing wind and swell waves. While mangrove forests are usually found on shores with little incoming wave energy, they may receive larger waves during storms, hurricanes and periods of high winds. Large wind and swell waves can cause flooding and damage to coastal infrastructure. By reducing wave energy and height, mangroves can potentially reduce associated damage. The report analyses the effect of mangroves on reducing wave height over distance as well as several experimental models that are able to predict typical levels of wave attenuation given knowledge of the mangrove characteristics, the wave parameters, and the local bathymetry and topography. The report states that further research is needed of the ability of mangroves to attenuate larger waves associated with greater water depths, as are more datasets to test the wider validity of the existing wave models under different wave conditions and in areas with different types of mangrove forest and different topographies.

McIvor, A. L., T. Spencer, I. Möller, and M. Spalding (2012). *Storm surge reduction by mangroves*. Natural Coastal Protection Series: Report 2. Cambridge Coastal Research Unit Working Paper 41. The Nature Conservancy and Wetlands International, pp. 35. Available at: https://www.conservationgateway.org/ConservationPractices/Marine/crr/library/Documents/storm-surge-reduction-by-mangroves-report.pdf

This report describes the role mangrove forests play in reducing storm surge water levels by slowing the flow of water and reducing surface waves. Storm surges occur when high winds and low atmospheric pressure raise water levels at the coast, causing seawater to surge onto the land. Few data are available on surge reduction rates through mangroves because of the difficulties associated with measuring water levels during storm surges. All data currently available are from the southeastern United States, where networks of recorders have been placed in wetland areas. Numerical models and simulations, validated using this data, provide the only means of exploring the importance of different factors in reducing storm surge heights.

Several topics relating to storm surge reduction by mangroves are yet to be explored, such as the effect of mangrove density, species composition and vegetative morphology. Further data on storm surge reduction by mangroves and further refinements to numerical models and simulations will improve our ability to understand and quantify the coastal defense services provided by mangrove forests against storm surges. Such information is needed to ensure that the coastal defense functions of mangroves are utilized appropriately, either alone or in combination with other measures, to reduce risk to people and infrastructure from storm surges.

McKee K. L. (2011). Biophysical controls on accretion and elevation change in Caribbean mangrove ecosystems. *Estuarine, Coastal and Shelf Science* 91:475–483. Available at: http://www.sciencedirect.com/science/article/pii/S0272771410001691

Abstract: Habitat stability of coastal ecosystems, such as marshes and mangroves, depends on maintenance of soil elevations relative to sea level. Many such systems are characterized by limited mineral sedimentation and/or rapid subsidence and are consequently dependent upon accumulation of organic matter to maintain elevations. However, little field information exists regarding the contribution of specific biological processes to vertical accretion and elevation change. This study used biogenic mangrove systems in carbonate settings in Belize (BZ) and southwest Florida (FL) to examine biophysical controls on elevation change. Rates of elevation change, vertical accretion, benthic mat formation, and belowground root accumulation were measured in fringe, basin, scrub, and dwarf forest types plus a restored forest. Elevation change rates (mm yr^{-1}) measured with Surface Elevation Tables varied widely: BZ-Dwarf (−3.7), BZ-Scrub (−1.1), FL-Fringe (0.6), FL-Basin (2.1), BZ-Fringe (4.1), and FL-Restored (9.9). Root mass accumulation varied across sites (82–739 g m^{-2} yr^{-1}) and was positively correlated with elevation change. Root volumetric contribution to vertical change (mm yr^{-1}) was lowest in BZ-Dwarf (1.2) and FL-Fringe (2.4), intermediate in FL-Basin (4.1) and BZ-Scrub (4.3), and highest in BZ-Fringe (8.8) and FL-Restored (11.8) sites. Surface growth of turf-forming algae, microbial mats, or accumulation of leaf litter and detritus also made significant contributions to vertical accretion. Turf algal mats in fringe and scrub forests accreted faster (2.7 mm yr^{-1}) than leaf litter mats in basin forests (1.9 mm yr^{-1}), but similarly to microbial mats in dwarf forests (2.1 mm yr^{-1}). Surface accretion of mineral material accounted for only 0.2–3.3% of total vertical change. Those sites with high root contributions and/or rapid growth of living mats exhibited an elevation surplus (+2 to +8 mm yr^{-1}), whereas those with low root inputs and low (or non-living) mat accumulation showed an elevation deficit (−1 to −5.7 mm yr^{-1}). This study indicates that biotic processes of root production and benthic mat formation are important controls on accretion and elevation change in mangrove ecosystems common to the Caribbean Region. Quantification of specific biological controls on elevation provides better insight into how sustainability of such systems might be influenced by global (e.g., climate, atmospheric CO_2) and local (e.g., nutrients, disturbance) factors affecting organic matter accumulation, in addition to relative sea-level rise.

Spalding M, A. McIvor, F. H. Tonneijck, S. Tol, and P. van Eijk (2014). *Mangroves for coastal defence. Guidelines for coastal managers & policy makers*. Wetlands International and The Nature Conservancy, pp. 42. Available at: http://www.mangroverestoration.com/pdfs/Coastal%20defence%20with%20mangroves%202014%20WI%20%20TNC.pdf

The Nature Conservancy and Wetlands International together with the University of Cambridge set out to map the current state of knowledge about the role of mangroves in coastal defense. The conclusion is that mangroves can indeed reduce the risk from a large number of hazards. This practical guidebook summarizes the findings of the reviews and provides practical management recommendations to coastal zone managers and policymakers. Among key messages:

- The importance of mangroves in coastal defense depends on the site characteristics and the local hazard context.
- Wind and swell waves are rapidly reduced as they pass through mangroves, lessening wave damage during storms.
- Wide mangrove belts (i.e., thousands of meters) can be effective in reducing the flooding impacts of storm surges occurring during major storms However, narrower mangrove belts, hundreds of meters wide, are still be able to reduce wind speed, the impact of waves on top of the surge and flooding impact to some degree.
- The dense roots of mangroves help to bind and build soils. The aboveground roots slow down water flows, encourage deposition of sediments and reduce erosion.
- Over time, mangroves can actively build up soils, increasing the thickness of the mangrove soil, which may be critical as sea level rise accelerates.

Zhang, K., Huiqing Liu, Yuepeng Li, Hongzhou Xu, Jian Shen, Jamie Rhome, and Thomas J. Smith III (2012). The role of mangroves in attenuating storm surges. *Estuarine, Coastal and Shelf Science* 102-103: 11-23. Available at: http://ac.els-cdn.com/S0272771412000674/1-s2.0-S0272771412000674-main.pdf?_tid=43e503d8-22be-11e6-8122-00000aab0f02&acdnat=1464211306_5791f8dc89cf2ae1d3a23b92a14d2db1

Abstract: Field observations and numerical simulations indicate that the 6-to-30-km-wide mangrove forest along the Gulf Coast of South Florida effectively attenuated storm surges from a Category 3 hurricane, Wilma, and protected the inland wetland by reducing an inundation area of 1800 km^2 and restricting surge inundation inside the mangrove zone. The surge amplitude decreases at a rate of 40-50 cm/km across the mangrove forest and at a rate of 20 cm/km across the areas with a mixture of mangrove islands with open water. In contrast, the amplitudes of storm surges at the front of the mangrove zone increase by about 10-30% because of the "blockage" of mangroves to surge water, which can cause greater impacts on structures at the front of mangroves than the case without mangroves. The mangrove forest can also protect the wetlands behind the mangrove zone against surge inundation from a Category 5 hurricane with a fast forward speed of 11.2 m/s (25 mph). However, the forest cannot fully attenuate storm surges from a Category 5 hurricane with a slow forward speed of 2.2 m/s (5 mph) and reduced surges can still affect the wetlands behind the mangrove zone. The effects of widths of mangrove zones on reducing surge amplitudes are nonlinear with large reduction rates (15-30%) for initial width increments and small rates (<5%) for subsequent width increments.

Biological Effects

Lewis III, Roy R. and R. Grant Gilmore (2007). Important considerations to achieve successful mangrove forest restoration with optimum fish habitat. *Bulletin of Marine Science* 80(3): 823–837. Available at: http://mangroverestoration.com/pdfs/Lewis%20and%20Gilmore%202007.pdf

Abstract: Mangrove forest restoration projects commonly fail to achieve significant plant cover for two reasons: because there is a misunderstanding of mangrove forest hydrology, or, acceptance of

the false assumption that simply planting mangroves is all that is required to establish a fully-functional mangrove ecosystem. Even restoration projects that meet a restoration goal within 3–5 yrs often fail to provide adequate habitat for fish and invertebrates. Here we discuss how fish and mangrove ecosystems are coupled in time and space, offer several restoration strategies that match these couplings, and provide simple sequential checklist of design tasks to use to prevent most failures. Tidal hydrology must be carefully designed to incorporate fish habitat, including tidal creeks, to provide access and low tide refuge for mobile nekton because the mangrove forest floor is generally flooded by tidal waters less than 30% of the time. A fully successful restoration design must mimic tidal stream morphology and hydrology along an estuarine gradient across a heterogeneous mixture of mangrove ecosystem communities.

Lewis III, Roy R. (2005). Ecological engineering for successful management and restoration of mangrove forests. *Ecological Engineering* 24: 403–418. Available at: http://www.mangroverestoration.com/Ecol_Eng_Mangrove_Rest_Lewis_2005.pdf

Abstract: Great potential exists to reverse the loss of mangrove forests worldwide through the application of basic principles of ecological restoration using ecological engineering approaches, including careful cost evaluations prior to design and construction. Previous documented attempts to restore mangroves, where successful, have largely concentrated on creation of plantations of mangroves consisting of just a few species, and targeted for harvesting as wood products, or temporarily used to collect eroded soil and raise intertidal areas to usable terrestrial agricultural uses. I document here the importance of assessing the existing hydrology of natural extant mangrove ecosystems, and applying this knowledge to first protect existing mangroves, and second to achieve successful and cost-effective ecological restoration, if needed. Previous research has documented the general principle that mangrove forests worldwide exist largely in a raised and sloped platform above mean sea level, and inundated at approximately 30%, or less of the time by tidal waters. More frequent flooding causes stress and death of these tree species. Prevention of such damage requires application of the same understanding of mangrove hydrology.

Lewis, R.R., A.B. Hodgson, and G.S. Mauseth (2005). Project facilitates the natural reseeding of mangrove forests (Florida). *Ecol. Rest*. 23(4): 276–277. Available at: http://www.mangroverestoration.com/LEWISH_1.PDF

This paper describes the authors' facilitation of the natural reseeding of five acres of mangrove forest in Florida. The project consisted of clearing the site of all invasive plants and the removal of ~190,000 cubic yards of dredged material. The site was regraded and two tidal creek systems were excavated through the site to enhance flushing within the developing forest. *Spartina alterniflora* was planted to trap mangrove seeds from adjacent forests at high tide and allow rapid secondary succession to mangroves. The species composition, stem density, percent cover, and plant height were measured over time. Mangrove cover increased linearly from 3.7% after grading to 94.7% after five years. As the mangrove canopy grew, the *Spartina* was shaded out. White and black mangroves rapidly attained mean heights of 5.4 feet and 2.8 feet, respectively, within five years.

McKee, K.L. and P. L. Faulkner (2001). Restoration of biogeochemical function in mangrove forests. *Restoration Ecology* 8(3): 247–259. Available at: http://onlinelibrary.wiley.com/doi/10.1046/j.1526-100x.2000.80036.x/abstract

Abstract: Forest structure of mangrove restoration sites (6 and 14 years old) at two locations (Henderson Creek [HC] and Windstar [WS]) in southwest Florida differed from that of mixed-basin forests (>50 years old) with which they were once contiguous. However, the younger site (HC) was typical of natural, developing forests, whereas the older site (WS) was less well developed with low structural complexity. More stressful physicochemical conditions resulting from incomplete tidal flushing (elevated salinity) and variable topography (waterlogging) apparently affected plant survival and growth at the WS restoration site. Lower leaf fall and root production rates at the WS restoration site, compared with that at HC were partly attributable to differences in hydroedaphic conditions and structural development. However, leaf and root inputs at each restoration site were not significantly different from that in reference forests within the same physiographic setting. Macrofaunal consumption of tethered leaves also did not differ with site history, but was dramatically higher at HC compared with WS, reflecting local variation in leaf litter processing rates, primarily by snails (*Melampus coffeus*). Degradation of leaves and roots in mesh bags was slow overall at restoration sites, however, particularly at WS where aerobic decomposition may have been more limited. These findings indicate that local or regional factors such as salinity regime act together with site history to control primary production and turnover rates of organic matter in restoration sites. Species differences in senescent leaf nitrogen content and degradation rates further suggest that restoration sites dominated by *Laguncularia racemosa* and *Rhizophora mangle* should exhibit slower recycling of nutrients compared with natural basin forests where *Avicennia germinans* is more abundant. Structural development and biogeochemical functioning of restored mangrove forests thus depend on a number of factors, but site-specific as well as regional or local differences in hydrology and concomitant factors such as salinity and soil waterlogging will have a strong influence over the outcome of restoration projects.

Milano, G.R. (1999). Restoration of Coastal Wetlands in Southeastern Florida. *Wetland Journal* 11(2): 15-24. Available at: http://globalrestorationnetwork.org/uploads/files/LiteratureAttachments/251_restoration-of-coastal-wetlands-in-southeastern-florida.pdf

Abstract: Rapid urbanization and associated coastal development in southeastern Florida over the last 100 years have virtually eliminated the low coastal wetlands along approximately 21 miles (34 kilometers) of mainland shoreline and approximately 12 miles (19 kilometers) of barrier island shoreline bordering Biscayne Bay. These wetland communities, which are essential to the general health of the estuarine ecosystem, were replaced by eroding, unconsolidated shorelines, and bulkheads. Historical wetlands are being restored on publicly owned lands through cooperative efforts of federal, state, and local agencies. The restoration process has involved removing fill and bulkheads, establishing species-specific elevation grades, creating flushing channels, removing exotic trees, and planting wetlands vegetation. In addition, unconsolidated shorelines are being stabilized and enhanced with mangroves and associated lime-rock protection barriers. This paper

reviews ten coastal wetlands restoration projects in Miami-Dade County, Florida. In the first decade of implementing of the Biscayne Bay Restoration and Enhancement Program, Miami-Dade Department of Environmental Resources Management (DERM) has restored and enhanced approximately 300 acres (121.5 hectares) of wetlands, using cost-effective techniques learned from the experience of implementing these successful projects.

Chemical Effects

Feller, I.C., K.L. McKee, D.F. Whigham, and J.P. O'Neill (2003). Nitrogen vs. phosphorus limitation across an ecotonal gradient in a mangrove forest. *Biogeochemistry* 62:145–175. Available at: http://www.serc.si.edu/labs/animal_plant_interaction/pubs/Feller%20et%20al.%20Biogeo_2003.pdf

Abstract: Mangrove forests are characterized by distinctive tree-height gradients that reflect complex spatial, within-stand differences in environmental factors, including nutrient dynamics, salinity, and tidal inundation, across narrow gradients. To determine patterns of nutrient limitation and the effects of nutrient availability on plant growth and within-stand nutrient dynamics, we used a factorial experiment with three nutrient treatment levels (control, N, P) and three zones along a tree-height gradient (fringe, transition, dwarf) on offshore islands in Belize. Transects were laid out perpendicular to the shoreline across a mangrove forest from a fringe stand along the seaward edge, through a stand of intermediate height, into a dwarf stand in the interior of the island. At three sites, three trees were fertilized per zone for 2 yr. Although there was spatial variability in response, growth by *R. mangle* was generally nitrogen (N) -limited in the fringe zone; phosphorus (P) -limited in the dwarf zone; and, N- and/or P-limited in the transition zone. Phosphorus-resorption efficiency decreased in all three zones, and N-resorption efficiency increased in the dwarf zone in response to P enrichment. The addition of N had no effect on either P or N resorption efficiencies. Belowground decomposition was increased by P enrichment in all zones, whereas N enrichment had no effect. This study demonstrated that essential nutrients are not uniformly distributed within mangrove ecosystems; that soil fertility can switch from conditions of N to P limitation across narrow ecotonal gradients, and; that not all ecological processes respond similarly to, or are limited by, the same nutrient.

Lee, Rosalynn Y. and Samantha B. Joye (2006). Seasonal patterns of nitrogen fixation and denitrification in oceanic mangrove habitats. *Mar Ecol Prog Ser* 307: 127–141. Available at: http://www.int-res.com.proxy-remote.galib.uga.edu/articles/meps2006/307/m307p127.pdf

Abstract: Mangrove peat soils are home to a variety of microbial communities that may play a vital role in system-level elemental cycling. We examined rates of nitrogen fixation and denitrification in benthic microbial mats on Twin Cays, Belize, a pair of oceanic mangrove islands. A tree-height gradient across the islands created distinct habitats for benthic microbes. Seawater flushing of the benthos and tree height decreased landward from tall, dense trees on the island fringe through a transition zone of high elevation and intermediate tree heights. In the center of the islands, microbial mats with dense communities of cyanobacteria and purple sulfur bacteria covered the

benthic surface of shallow ponds and around dwarf trees. Wet-dry seasonality, tidal cycles and elevation controlled the extent of mat exposure to desiccation and UV radiation. Nitrogen fixation was controlled primarily by the sensitivity of nitrogenase to oxygen inhibition, whereas denitrification was limited by oxidant (nitrate) availability. Diel patterns of nitrogen fixation varied with the type of cyanobacteria dominant in each mat. Dissolved inorganic nitrogen concentration influenced both nitrogen fixation and denitrification rates. Redox conditions contributed to variability in mat nitrogen fixation and denitrification response to nutrient addition, while dissolved organic carbon did not. Microbial mat nitrogen cycling likely contributes to the nutrient (nitrogen and phosphorus) limitation patterns observed in the mangrove trees; in dwarf habitats, mats serve as a source of nitrogen via nitrogen fixation, while in fringe and transition habitats, mats compete with the trees for nitrogen via denitrification.

Osland, M.J., A.C., Spivak, J.A. Nestlerode, J.M. Lessmann, AE Almario, P.T. Heitmuller, M.J. Russell,K.W. Krauss, F. Alarez, D.D. Dantin, J.E. Harvey, A.S. From, N. Cormier, and C.L. Stagg (2012). Ecosystem development after mangrove wetland creation: plant-soil change across a 20-year chronosequence. *Ecosystems* 15(5): 848-866. Available at: http://link.springer.com/article/10.1007%2Fs10021-012-9551-1

Abstract: Mangrove wetland restoration and creation efforts are increasingly proposed as mechanisms to compensate for mangrove wetland losses. However, ecosystem development and functional equivalence in restored and created mangrove wetlands are poorly understood. We compared a 20-year chronosequence of created tidal wetland sites in Tampa Bay, Florida (USA) to natural reference mangrove wetlands. Across the chronosequence, our sites represent the succession from salt marsh to mangrove forest communities. Our results identify important soil and plant structural differences between the created and natural reference wetland sites; however, they also depict a positive developmental trajectory for the created wetland sites that reflects tightly coupled plant-soil development. Because upland soils and/or dredge spoils were used to create the new mangrove habitats, the soils at younger created sites and at lower depths (10–30 cm) had higher bulk densities, higher sand content, lower soil organic matter (SOM), lower total carbon (TC), and lower total nitrogen (TN) than did natural reference wetland soils. However, in the upper soil layer (0–10 cm), SOM, TC, and TN increased with created wetland site age simultaneously with mangrove forest growth. The rate of created wetland soil C accumulation was comparable to literature values for natural mangrove wetlands. Notably, the time to equivalence for the upper soil layer of created mangrove wetlands appears to be faster than for many other wetland ecosystem types. Collectively, our findings characterize the rate and trajectory of above- and below-ground changes associated with ecosystem development in created mangrove wetlands; this is valuable information for environmental managers planning to sustain existing mangrove wetlands or mitigate for mangrove wetland losses.

Proffit, C. E. and D. J. Devlin (2005). Long-term growth and succession in restored and natural mangrove forests in southwestern Florida. *Wetl. Ecol. Manage*. 13: 531–551. Available at: http://link.springer.com/article/10.1007%2Fs11273-004-2411-9

Abstract: We compared colonization, growth and succession from 1989 to 2000 in a restored mangrove site and in gap and closed canopy sites in a natural mangrove forest. The restored site was created in 1982 and planted with *Rhizophora mangle* (≈2 m^{-2}) propagules. By 1989, *Laguncularia racemosa*, with densities up to 12.9 tree m^{-2}, was a dominant in all plots, although densities were greater at edge plots relative to inner plots, and near open water (west plots) relative to further inland (east plots), and in tall mangrove plots relative to scrub plots. *Rhizophora mangle* (1989 tree densities about 2 m^{-2}) was a codominant in inner and scrub plots, while *Avicennia germinans* had the lowest densities (<1 tree m^{-2}) in all plots. From 1989 to 2000 *L. racemosa* experienced reduced recruitment and apparent density-dependent mortality of canopy individuals in plots with high initial densities. Scrub plots experienced high rates of colonization by *R. mangle* and *L. racemosa*, rapid growth in height of all species (1989–1996), followed by a die off of *L. racemosa* in later years (1997–2000) as the canopy came to resemble that of tall mangrove plots. Colonization and growth rates were lower in gap and closed canopy regions of the natural forest relative to rates in the restored site. After 11 years, densities of *L. racemosa* were 10–20× lower and *R. mangle* slightly less in the gap relative to densities in tall mangrove plots in the restored site at the same age. Although the restored stand had converged with the natural forest by 2000 in terms of some factors such as species richness, vegetation cover, litter fall, and light penetration, trees were still much smaller and stem densities much higher. Full development of mature structure and ecological function will likely require decades more development.

Case Studies

Atlantic Coastal Fish Habitat Partnership: Funded Projects (2011). *On-the-Ground-Projects: Spotlight on Shoreline and Spartina Marsh Stabilization along the Atlantic Intracoastal Waterway*. Available at: http://www.atlanticfishhabitat.org/wp-content/uploads/2012/10/ACFHP-project-factsheet-FY11-SC-updated.pdf

This project rehabilitated tidal marsh areas experiencing degradation from boat traffic along the Intracoastal Waterway (AIWW), by constructing natural breakwaters using oyster reefs. The project engaged over 1,000 community volunteers in shoreline habitat restoration; constructing approximately 0.08 acres of oyster habitat to protect 150 meters of shoreline; and over time creating approximately 0.3 acres of adjacent tidal marsh. Results over time include: increased fish habitat (oyster reef, tidal salt marsh), stabilized shoreline, and improved water quality.

Atlantic Coastal Fish Habitat Partnership: Funded Projects (2013). *On-the-Ground-Projects: Spotlight on Restoring Coastal Fish Habitat Using Oysters, Mussels, and Marsh Grass at Guana Peninsula*. Available at: http://www.atlanticfishhabitat.org/wp-content/uploads/2012/10/ACFHP-project-factsheet-FY13-FL-updated1.pdf

This project, located specifically at Wright's Landing, in the Guana Tolomato Matanzas National Estuarine Research Reserve, aimed to restore and enhance fish habitat by preventing shoreline erosion and promoting shoreline accretion using a combination of mussel and oyster-based living shorelines. Combined with *Spartina alterniflora* planting, living shorelines have stopped or reversed

erosion and provided critical habitats for plants, fishes, and invertebrates. Specifically, restored marsh and reef provide nursery and feeding habitat for forage fishes (mummichog, silversides) that utilize emergent salt marsh habitats, as well as juvenile commercial and recreational species (drum, shrimp) that utilize oyster reef and shallow nearshore habitats.

Created oyster shell reefs, and coir fiber logs with ribbed mussels were established separately and in combined fashion to examine their relative effectiveness on erosion reduction, sediment capture and enhancement of success of *Spartina* plantings. Marsh accretion, fish and invertebrate habitat usage, and *Spartina* seedling success were monitored by researchers and volunteers.

Atlantic Coastal Fish Habitat Partnership: Funded Projects (2012). *On-the-Ground-Projects: Spotlight on Restoring the Mangroves of the Indian River Lagoon*. Available at: http://www.atlanticfishhabitat.org/wp-content/uploads/2012/10/ACFHP-project-factsheet-FY12-FL-v2-updated.pdf

A unique aspect of this project is the restoration of mangrove forests, which in addition to providing nursery habitat for commercial and game fish species are critical to maintaining the overall health of the coastal ecosystem by helping to trap and cycle organic materials, chemical elements, and nutrients. The project involved removing 10 acres of invasive plants and planting over 8,500 linear feet of shoreline with wetland species such as mangroves and *Spartina* grass to create new fish nursery habitat. Volunteers helped remove invasives, plant natives, and removed trash and monofilament line for recycling.

BLUE: Land, Water, Infrastructure (2006). *Hammocks beach shoreline stabilization and wetland restoration project: 2005 annual monitoring report*. Prepared by BLUE: Land, Water, Infrastructure for submission to the NCDENR's Ecosystem Enhancement Program. PN 050033) pp. 25. Available at: http://www.nceep.net/gis_data/Hammocks%20Beach%20%23163%20%28EEP%29/MONITORING%20REPORTS/2005%20Report/HammocksBeach_163_2005_MY5.pdf

The Hammocks Beach shoreline stabilization and wetland restoration project is located at the Hammocks Beach State Park, in Onslow County, near Swansboro, N.C. The project was a cooperative effort between the State Parks of North Carolina, the NC Coastal Federation and the NC Ecosystem Enhancement Program. The project demonstrated the use of a rock sill and provided for the restoration of 0.3 acres of regularly flooded salt marsh, *Spartina alterniflora* and *Spartina patens*. The site was planted in the year 2000. This report represents the fifth year of vegetative monitoring.

With no specific monitoring criteria to meet for either vegetation or hydrology, success is determined by vegetative growth and regular flooding of the vegetative zones. Growth in the marsh appears to be good. Stem counts of the *Spartina alterniflora* have doubled since the previous report. Height and percent cover of both species are comparable. Observed hydrology is in accordance to maintaining the vegetation and is similar to the adjacent natural stands.

Problems areas are few. There is some presence of *Typha* sp. and *Phragmites australis* which could be controlled with spraying. Most impacts of vegetative loss are in the shrub/scrub zone during repairs to the bulkhead.

Clark, P., Serra Herndon, and Kevin Misiewicz (2012). *Community Oyster Reef Enhancement in Tampa Bay.* Tampa Bay Watch. Available at: http://www.estuaries.org/pdf/2012conference/room15/session2/Clark_RAE_2012_pres.pdf

This PowerPoint presentation describes Tampa Bay Watch's project, Community Oyster Reef Enhancement. It explains the importance of oyster reefs in the environment and the beneficial ecosystem functions they provide. The presentation describes the oyster restoration efforts at the Weedon Island Preserve, Whiskey Stump Key, and the MacDill Shoreline Stabilization Project.

Fodrie, J., T. Rodriguez, and N. Lindquist (2012). *Final Report: 2012 UNC Chapel Hill Institute of Marine Sciences portion of: Sustainable Estuarine Shoreline Stabilization: Research, Education and Public Policy in North Carolina (Carrot Island Demonstration Project)*, pp.8. Available at: http://portal.ncdenr.org/c/document_library/get_file?uuid=c9dbe939-6f3e-4fe7-b564-b25e04c9e412&groupId=61572

This project involved constructing reefs of two distinct types: small patch reefs constructed to understand how to protect existing marsh. and larger reef sills built to protect a section of shoreline in which new marsh planting would occur. Since planting, monitoring of restored marsh patches (e.g., plant condition, faunal densities, and sediment characteristics) has occurred monthly. Barnacles, marsh periwinkles, mud snails, and fiddler crabs have recruited to both *S. alternaflora* and mimic stem patches and new shoot growth is evident in a majority of the *S. alternaflora* patches both of which are key indicators of successful marsh restoration.

For the small patch reefs, shell cover and spat density were considerably higher at restored sites relative to non-restored reference sites. Among restored reefs, however, spat settlement was greatest on the reefs constructed along the marsh ramp, with 2-3 times fewer spat per-unit-area on the reefs built along marsh scarps or creek banks. Variability was also apparent at smaller scales, with spat density 2 times higher on the creek reefs at the entrance of tributaries relative to those on creek banks, and spat density on "blowout" reefs only 1/5 of that observed on adjacent ramp reefs. On the sill reefs, spat and associated faunal densities were greatest on the seaward side of the sills, and decreased across the crest and to the landward side of the sills.

Getsinger, G. (2010). *Castillo de San Marcos National Monument Living Shoreline Project*. National Marine Fisheries Service, Southeast Regional Office, Habitat Conservation Division, Atlantic Branch. Available at: https://www.dep.state.fl.us/coastal/sites/gtm/pub/ctp/living_shorelines/Castillo_de_San_Marcos_Getsinger.pdf

This PowerPoint presentation describes the formation of a living shoreline in order to stabilize two sections of shoreline contiguous to the Castillo de San Marcos National Monument. The project originally called for the placement of concrete riprap covered with coquina stone at the base of two sections of the historic seawall of the Castillo. On the recommendation of the National Marine Fisheries Service, this plan was modified to include a living shoreline consisting of a breakwater using coquina and existing oyster rubble, sand placement, oyster relocation, and the planting of smooth cordgrass on the landward side.

Georgia Department of Natural Resources (2013). *Living Shorelines along the Georgia Coast: A Summary Report of the First Living Shoreline projects in Georgia*. Coastal Resources Division, Brunswick, GA, pp. 46 plus appendix. Available at: http://www.oyster-restoration.org/wp-content/uploads/2012/06/LivingShorelinesAlongtheGeorgiaCoastweb.pdf

This guidance document focuses on the design, methods, application, viability, and effects of living shorelines in coastal Georgia, with specific reference to the construction and monitoring of living shorelines on Sapelo Island and Little St. Simons Island.

Harris, D. (N/A). *Sapelo Living Shoreline Project*. Marine Extension, UGA. Available at: https://www.dep.state.fl.us/coastal/sites/gtm/pub/ctp/living_shorelines/Sapelo_Harris.pdf

The PowerPoint presentation describes the planning, designing, and implementation of two living shorelines on Sapelo Island, Georgia.

Harris, Scott M. and Sonja L. Tyson (2014). *Palmetto Plantation Oyster Castle Reef Survey: Final Report*. College of Charleston. pp. 17. Available at: http://projects.tnc.org/coastal/assets/SC/PalmettoPlantationRestoration/PalmettoPlantationRestoration_FinalReport.pdf

The overall goal of this project was to enhance oyster reefs while stabilizing the adjacent shoreline in the Palmetto Plantation area. Oyster castle reefs were installed in August 2012 on the northwest bank of the Atlantic Intracoastal Waterway northeast of McClellanville, SC. Site surveys, including shoreline change analyses, sediment grainsize distributions, and oyster recruitment observations, were conducted from June 2012 through October 2013.

Detailed shoreline studies from this project indicate consistent erosion before installation of the reef, and accretion behind the reef in two lobes. Oyster recruitment was almost immediate, with clear oyster growth in the second month after installation. The most important colonization and subsequent growth areas were on the front of the reef, the ends of the reef, and on the protected platforms on the front of the reef. Flat surfaces on overturned block ends did not recruit oysters. Oyster growth was highest on the merlons, and in some cases completely closed the gabs between them in just over a year.

Kingsley-Smith, Peter, John W. Leffler, and Blaik Keppler (2015). *Expanding Living Shorelines within the ACE Basin NERR to Protect Habitat and to Reduce Climate Change Vulnerability through the Application of Collaborative Science-Based Habitat Restoration*. A Final Report Submitted to the National Estuarine Research Reserve System Science Collaborative, pp. 36. Available at:

http://50.87.232.11/wp-content/uploads/2015/09/project-page_final-report_bringing-shorelines-to-life-in-south-carolina.pdf

The overall goal for this project was to address three of the four ACE Basin NERR priority management issues, “Habitat Conservation”, “Water Quality”, and “Community Resilience”, by expanding living shorelines in the ACE Basin through a community-based, intended user-driven collaboration with the South Carolina Department of Natural Resources. To accomplish this, 53 reef-building events at 38 discrete locations through the ACE Basin NERR were held between April 2013 and May 2015.

Mackinnon, J. (2010). Alternative shoreline armoring techniques along Georgia's high energy coast. *Proceedings from the 5th National Conference on Coastal and Estuarine Habitat Restoration: Preparing for Climate Change: Science, Practice, and Policy*, November 13-17, 2010. Available at: https://www.estuaries.org/pdf/2010conference/wednesday17/galleon3/session2/mackinnon-j.pdf

This PowerPoint presentation describes the planning, designing, and implementation of two living shorelines on the Georgia coast. The goals of these projects was to: study the feasibility of alternative techniques to traditional shoreline hardening in tidal wetlands (i.e. alternatives to riprap and bulkheads); and determine the effectiveness of alternative erosion control methods that will protect and enhance ecosystem function. The construction of living shorelines on Sapelo Island (Ashantilly and Long Tabby) is discussed as is the initial monitoring criteria.

McCall, Aaron and Kate Murray (2013). *Final Report: Demonstrating the value of natural communities for shoreline protection: Restoration of oyster reefs, submerged aquatic vegetation, coastal wetlands, and maritime salt shrubs along a high energy, high bank shoreline*. 2010-2013 Grant Awarded through the National Partnership between the NOAA Community-Based Restoration Program and The Nature Conservancy, pp. 27. Available at: http://projects.tnc.org/coastal/assets/NC/NagsHeadWoodsEcologicalPreserveShorelineRestoration/NagsHeadWoodsEcologicalPreserveShorelineRestoration_FinalReport.pdf

Nags Head Woods Ecological Preserve on the Outer Banks of North Carolina, a 1,200 acre nature preserve managed by The Nature Conservancy, is currently experiencing significant shoreline erosion along the southern boundary of the preserve. Sea-level rise, wave action, and storm surges have effectively extirpated the protective fringing marsh, converting the vegetated shoreline into an eroding high sediment bank void of wetland and maritime salt shrub vegetation. We undertook a comprehensive ecosystem restoration pilot project to: 1) stabilize the high-bank shoreline and prevent further erosion using natural materials; 2) restore native maritime salt shrub, coastal marsh, and shallow water habitats 3) build ecosystem resilience to sea-level rise, and 4) demonstrate natural alternatives to hard shoreline stabilization to neighboring property owners.

McColl, David and Joy Brown (Alana Sweatt (ed)). *Yawkey Living Shorelines Pilot Project Oyster Recruitment & Erosion Control on South Island*. Available at: http://projects.tnc.org/coastal/assets/SC/WinyahBaySouthIslandLivingShoreline/WinyahBaySouthIslandLivingShoreline_FinalReport.pdf

Populations of eastern oyster, (*Crassostrea virginica*) and sedimentation erosion along the southeast coast are becoming a concern for society and many researchers. Oysters are an important species for estuaries, bays and shorelines of the southeast. Yawkey Preserve in Georgetown, SC is an ideal location for this type of restoration effort. Winyah Bays' high energy can provide challenges for preserving these shorelines naturally and expand populations of oysters. Utilizing man-made materials and native plants may provide beneficial results for continuing research. Using patented interlocking blocks for recruitment of oysters, natural marsh grass (*Spartina alterniflora*), planted for erosion control, may determine if these efforts will continue and what adjustments need to be made for future projects.

Ray-Culp, M. (2010). *Living Shorelines 101: Teaching and Achieving the Softer Approach*. Presented at the 5th National Conference on Coastal and Estuarine Habitat Restoration: Preparing for Climate Change: Science, Practice, and Policy. Available at: https://www.estuaries.org/pdf/2010conference/monday15/schooner/session1/ray-culp.pdf

This PowerPoint presentation discusses living shorelines in general and the Florida Living Shoreline Initiative in particular.

Ray-Culp, M. (2007). A Living Shoreline Initiative for the Florida Panhandle: Taking a Softer Approach. *National Wetlands Newsletter*, 29(6): 9-11 & 19. Environmental Law Institute. Washington D.C., USA. Available at: http://www.dep.state.fl.us/northwest/ecosys/section/LSDocs/Living%20Shoreline%20Initiative%20for%20the%20Panhandle.pdf

Property owners often harden their shorelines to combat coastal erosion. Ironically, this tends to increase erosion. It also prevents the shoreline from functioning naturally and destroys established habitat for many species. The Florida Panhandle Coastal Program and its partners have established a Living Shoreline Initiative to provide landowners and contractors a "softer" alternative to shoreline armoring.

Reed, Heather (N/D). *Deadman's Island: Appreciation for past, present and future*. Ecological Consulting Services Inc. Available at: http://www.oyster-restoration.org/wp-content/uploads/2013/03/Deadmans%20Island2%20012.pdf

This PowerPoint presentation includes a history of Deadman's Island beginning with European settlement in the 17th century. It then goes on to describe restoration efforts beginning in the mid-2000's when erosion caused by Hurricane Ivan exposed historic archaeological artifacts. Phase I of these efforts included construction of a breakwater, shoreline stabilization, and fill/renourishment. Phase II involved the placement of "ecodiscs" along the shoreline.

Rogers, Spencer (1994). *Marsh Grass Protection with Low-Cost Breakwaters, Shoreline Erosion Control Demonstration: Final Project Report for Albemarle-Pamlico Estuarine Study*. UNC Sea Grant College Program and the Department of Civil Engineering, North Carolina State University, Raleigh, North

Carolina, 65 pp. Available at: http://portal.ncdenr.org/c/document_library/get_file?uuid=e38d00bd-a684-43c9-805f-2ed424137d7b&groupId=61563

Previous research with the use of marsh grasses for the control of shoreline erosion has produced excellent short-term (one to five years) results. Unfortunately, use of the method on moderately exposed shorelines in our estuaries has shown limited long-term (20-30 years) success. This report describes the design and construction of erosion-control demonstration projects using a combination of planted marsh grasses and low-cost wooden breakwaters. The breakwaters can extend the effective lifetime of planted marshes to that of bulkheads and other common erosion-control methods. Since this entails creating a marsh where none previously existed, significant environmental advantages are apparent over most other erosion-control methods. The method can be attractive to property owners because the marsh/breakwater is significantly less costly than other alternatives offering the same level of protection and useful lifetime.

Shoreline Resilience Working Group (2012). *Nature-Based Coastal Defenses in Southeast Florida*. The Nature Conservancy; Southeast Florida Regional Climate Change Compact's Shoreline Resilience Working Group, Washington D.C. pp. 19. Available at: http://www.nature.org/media/florida/natural-defenses-in-southeast-florida.pdf

The Nature Conservancy and the Southeast Florida Regional Climate Change Compact, in order to spotlight the role of natural and nature-based approaches to coastal defense, compiled the seven case studies included in this packet. A diverse set of project types and sizes was selected from locations across the region. Case study project leaders include county and municipal governments and a not-for-profit conservation organization working with a consortium of public and private players. These case studies are representative of numerous other excellent projects that have been completed in southeast Florida.

Skrabal, T.E. (2013). *Living Shoreline Projects in North Carolina*. North Carolina Coastal Federation. Available at: http://www.dnr.state.md.us/ccs/pdfs/ls/2013summit/skrabal.pdf

This presentation gives an overview of a few of the living shoreline projects in North Carolina conducted by the North Carolina Coastal Federation, including: Carrot Island, N.C. NERRS, Rachel Carson Reserve; Edenhouse Boat Ramp – Chowan River; Roanoke Island Festival Park, Manteo, N.C.; Carteret Community College, Bogue Sound; and Morris Landing Preserve, Stump Sound.

Thompson, M.A., E. Milbrandt, R.E. Grizzle, L. Coen, and R. Bartleson (2014). *Long-term Monitoring of a Community-Based Oyster Reef Restoration Project in Calm Bayou, Southwest FL*. Sanibel-Captiva Conservation Foundation. Available at: http://www.chnep.org/Events/Summit2014/Thompson_oysterreef.pdf

This presentation describes the oyster reef restoration efforts conducted at Clam Bayou, Sanibel Island in Southeastern Florida.

Resources

Center for Coastal Resources Management; Virginia Institute of Marine Science

The Center for Coastal Resources Management develops and supports integrated and adaptive management of coastal zone resources. To fulfill this mission, the Center undertakes research, provides advisory service, and conducts outreach education. The Center's website is a rich source of information about living shorelines, including material concerning design and building criteria for living shorelines, permitting, research, policy and legislation. In addition, the site has links to vendors and plants appropriate for living shorelines, demonstration sites and photos, a glossary, and links to relevant publications and helpful state and federal agencies in the Virginia, North Carolina, and Maryland area.

Available at http://ccrm.vims.edu/livingshorelines/index.html

Florida Department of Environmental Protection, Northwest District

This website provides general information about living shorelines, common problems with shoreline armoring and a short explanation of the Department's living shoreline projects and permitting status, as well as links to additional information.

Available at: http://www.dep.state.fl.us/northwest/ecosys/section/living_shorelines.htm

Florida Department of Environmental Protection, Project Greenshores

Project GreenShores is a multi-million dollar habitat restoration and creation project located in Downtown Pensacola along the urban shoreline of Pensacola Bay. This habitat restoration effort was a community based effort to restore oyster reef, salt marsh and seagrass habitat within the Pensacola Bay System in order to stabilize shorelines and provide essential habitat for wildlife propagation and conservation. The site contains a description of both phases of the project with pictures and links to other information relevant to the project including monitoring data.

Available at: http://www.dep.state.fl.us/northwest/Ecosys/section/greenshores.htm

Florida Living Shorelines

The purpose of the Florida Living Shorelines website is to make it easier for coastal property owners and managers to take a more environmentally-friendly and cost-effective approach to shoreline stabilization wherever needed and appropriate. This website shows how to use plants and other natural materials to help protect eroding shorelines from wave and storm damage in the bays and estuaries of coastal Florida. The living shoreline techniques described on this site can be used in relatively low wave energy areas instead of traditional coastal armoring systems such as seawalls and bulkheads. The site also provides examples of different types of living shorelines used in Florida along with photos of actual projects. Links to guidance documents, permitting information, and reference articles as well as contact information for Florida is also included.

Available at: http://www.floridalivingshorelines.com

Georgia Department of Natural Resources, Coastal Resources Division

This website gives general information about what living shorelines are and the benefits they provide. It also includes a link to the report, "Living Shorelines along the Georgia Coast."

Available at: http://coastalgadnr.org/LivingShorelines

LinkedIn Living Shoreline Erosion Control Forum

The purpose of this group, hosted by the website, LinkedIn, is to provide a forum for the discussion of Living Shorelines and improving their effectiveness and public acceptance. Topics may include: design, innovation, construction, implementation problems, problem solving, monitoring, maintenance, etc. It is administered by Kevin R. Du Bois, and as of 2016, has 205 members.

Available at: http://www.linkedin.com/groups/Living-Shoreline-Erosion-Control-Forum-4157277/about

Living Shoreline Academy

The Living Shoreline Academy's website offers an online resource promoting the exchange of information, research, training modules, policies, and practices to advance the use of living shorelines. Its goals are to increase the abundance of coastal wetlands, advance the policy, science, and practice of living shorelines and enhance collaboration among governmental and private stakeholders by providing tools to elevate the understanding, importance, and practice of using living shorelines. In particular, the website provides:

- Living shorelines training modules that take advantage of proven training and education strategies used by the EPA for years to engage, train and learn from stakeholders
- A peer-reviewed database of white papers and reports on the subject of living shorelines
- A database of existing living shorelines project databases
- A map of highlighted living shorelines projects across the US
- A directory of living shorelines professionals
- An online forum where the living shorelines community can collaborate by sharing research, ideas and photos

Available at: http://www.livingshorelinesacademy.org/index.php

National Oceanic and Atmospheric Agency, Habitat Conservation, Restoration Center

NOAA's Restoration Center's webpage provides information about the planning and implementation steps that must take place in the course of a living shoreline project. It also includes descriptions of habitat zones and suggested living shoreline treatments suitable for each zone.

Available at: http://www.habitat.noaa.gov/restoration/techniques/lsimplementation.html

North Carolina Coastal Federation: Living Shorelines

This webpage details the Federation's work with living shorelines including the state's problem with coastal erosion and the benefits of using living shorelines to help alleviate it.

Available at: http://www.nccoast.org/protect-the-coast/restore/living-shorelines/

Oyster Restoration Workgroup

The Oyster Restoration Workgroup was established to address questions related to shellfish restoration success, especially all pertinent issues associated with the restoration of both intertidal and subtidal oyster reefs. The Living Shoreline webpage provides general information about living shorelines and links to many research publications and groups that are involved in living shorelines regionally, nationally, and internationally.

Available at: http://www.oyster-restoration.org/living-shorelines/

Restore America's Estuaries

Restore America's Estuaries' 11 member organizations restore coastal habitats in 11 estuaries and 16 states nationwide. The group's projects restore coastal wetlands, open fish passages, remove invasive species, build living shorelines, transplant seagrasses, re-plant salt marshes, and restore shellfish habitat. Living shorelines is one of four RAE initiatives, and their webpage provides general information about living shorelines as well as links to group sponsored reports and conferences.

Available at: https://www.estuaries.org/living-shorelines

Systems Approach to Geomorphic Engineering (SAGE)

SAGE is an initiative that brings together experts and practitioners from the federal, academic, non-profit and private sectors to pursue and advance a comprehensive view of shoreline change. This community of practice will facilitate the development and application of hybrid engineering approaches that link 'soft' ecosystem-based approaches with 'hard' infrastructure approaches to enhance the resiliency of coastal communities and shorelines. The intent is to reduce impacts from the consequences of land cover and climate change through prevention, mitigation and/or adaptation. This community of practice will build on the "living shoreline" concept and identify combinations of natural ecosystems and built infrastructure that best protect coastal communities and shorelines, while also improving economic outcomes and provision of ecosystem services.

Available at: http://sagecoast.org

The Nature Conservancy's Oyster Reef Restoration Project

This webpage links to information about oyster reef restoration projects The Nature Conservancy has been involved with in the Southeast including two in North Carolina, two in South Carolina, three in Georgia, and two in Florida. The site also has information about TNC projects in Alabama, Mississippi, Louisiana, and Texas.

Available at: http://www.nature.org/ourinitiatives/habitats/oceanscoasts/oyster-reef-restoration-southern-solutions-for-a-global-problem.xml

Living Shoreline Databases

Coasts, Oceans, Ports and Rivers Institute (COPRI)

COPRI hosts a database of existing living shoreline projects around New York, Maryland, Virginia, North Carolina, Georgia, Florida, Alabama, Mississippi, Louisiana, and Texas. It is searchable by primary wetland species below the MHW, design criteria, structure presence, or other criteria.

Available at: http://mycopri.org/

NOAA Habitat Restoration Projects Database

NOAA's Restoration Center's Restoration Atlas is a one-stop review of NOAA's collective restoration efforts around the country. The Atlas can be searched by habitat type, location or congressional district, and many other topics. Alternatively, users can choose the drop down menus and sort through a more comprehensive list.

Available at: https://restoration.atlas.noaa.gov/src/html/index.html

NOAA National Estuaries Restoration Inventory

The National Estuaries Restoration Inventory (NERI) houses information on estuary habitat restoration projects from across the country. The Inventory is searchable by location, habitat type, and restoration technique and contains over 2,500 project records. It focuses on estuarine restoration projects funded by federal agencies, such as NOAA, USFWS, and ACOE.

To be included in the National Estuaries Restoration, restoration projects must meet the following requirements:

- provide ecosystem benefits for estuaries and their associated ecosystems and
- include monitoring to gauge the success of restoration efforts.
- have been implemented on or after November 7, 2000
- have a monitoring plan that meets ERA Council Monitoring Standards
- not be required by state or federal law (compensatory)

Available at: https://neri.noaa.gov/neri/searchInventory.html

SAGE Searchable Project Database

This database contains multiple coastal resilience projects around the nation, including living shorelines for shoreline stabilization, habitat restoration, and floodplain management. Each project includes a variety of site, design, and partner information. Searches can be conducted using the pull-down lists or by key word to find certain project names, partners, and other unique information.

Available at: http://sagecoast.org/info/sagesearch.html

The Nature Conservancy's Coastal Restoration and Natural Infrastructure Project Database

This database was built and is maintained by TNC's North America Region's Oceans and Coasts Program. It allows users to search and find information on any of TNC's North American Coastal Restoration and Natural Infrastructure Projects which are designed to restore important habitats, reduce flood risks and protect communities, and to conserve land and water.

With this tool, users can get information on an individual project, download final project reports, fact sheets and photos from that project, or roll-up information across multiple projects. Users can search for projects by habitat type, data collected, restoration technique, congressional district, and partners. When available, the contact information for TNC Field Office or the lead organization is another way to find out more about a project and other ongoing work.

Available at: http://projects.tnc.org/coastal/