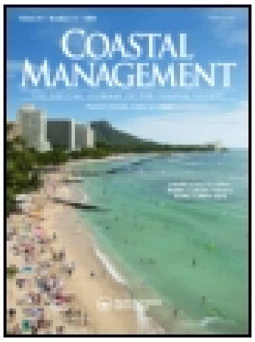

Coastal Management

ISSN: 0892-0753 (Print) 1521-0421 (Online) Journal homepage: http://www.tandfonline.com/loi/ucmg20

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COASTAL MANAGEMENT
2016, VOL. 44, NO. 3, 161–174
http://dx.doi.org/10.1080/08920753.2016.1160201

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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.

KEYWORDS
climate adaptation; coastal management; estuarine shoreline protection; marsh; wetland restoration

History of estuarine shoreline management in the United States

The world's estuaries are centers for human settlement and in the modern era growing populations have intensified pressures on these coastal ecosystems. Urbanized estuaries are characterized by expansive infrastructure, land development, and alterations to intertidal and shallow subtidal areas to accommodate societal needs. Historically, estuarine shorelines were chiefly managed for human uses. Armoring structures including seawalls, bulkheads, and revetments were placed in attempts to reduce erosion and flooding threats to coastal communities (Charlier, Chaineux, and Morcos 2005) and the prevalence of armoring shorelines increased substantially in the second half of the 20th century (Dugan et al. 2011). In Chesapeake Bay, 18% of tidal shorelines have been armored with more than 50% armoring of urban subwatersheds (CCRM 2013). Similarly, 17% of New Jersey (Lathrop and Love

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2007), 21% of Florida (Florida DEP 1990), and 30% of southern California (Griggs 1998) coastlines were armored with higher values (45–50%) along developed shores.

More recently, the ecological consequences of shoreline armoring have been documented globally. Armoring has been associated with habitat loss and fragmentation (Peterson and Lowe 2009; Dugan et al. 2011), alterations to sediment characteristics and dynamics affecting adjacent properties (Bozek and Burdick 2005; NRC 2007), increased scouring and turbidity (Bozek and Burdick 2005), deepening of nearshore waters (Bilkovic and Roggero 2008; Toft et al. 2013), subsequent declines in diversity or abundance of fish, invertebrates, birds, and diamondback terrapin (*Malaclemys terrapin*) (Peterson et al. 2000; Chapman 2003; King et al. 2005; Moschella et al. 2005; Bilkovic et al. 2006; Bilkovic and Roggero 2008; Morley, Toft, and Hanson 2012; Isdell et al. 2015), increases in invasive species, such as *Phragmites australis* (Chambers, Meyerson, and Saltonstall 1999), and prevention of the landward migration of coastal habitats in response to sea-level rise (Titus et al. 2009; Bilkovic 2011). In addition, armoring acts as an ecological barrier, separating upland and wetland functions, reducing filtration capacity and nutrient uptake, increasing the rate of wetland loss, and changing the character of the nearshore ecosystem (Peterson and Lowe 2009 and references within; Patrick et al. 2014). Shoreline development has the potential to alter species distribution and diversity at both local and broader landscape/watershed scales. The cumulative effect of incremental shoreline alteration on natural habitats and associated living resources may lead to large-scale disruption and loss of a range of ecosystem functions and services (e.g., Bilkovic et al. 2006; Bilkovic and Roggero 2008; Jennings et al. 1999; Patrick et al. 2014). A growing body of scientific evidence indicating that armoring reduces ecosystem services has led to substantive changes in how shorelines are managed.

Living shorelines are created or enhanced shorelines that make the best use of nature's ability to abate shoreline erosion while maintaining or improving habitat and water quality. Living shoreline treatments address erosion by providing protection, restoration, enhancement, or creation of vegetated shoreline habitats through strategic placement of plants, stone, sand fill, and other structural or organic materials. While some living shoreline projects seek to restore lost habitat to its original condition, others act to enhance existing habitat or to create habitats that were not naturally supported. In the latter instances, consideration of the potential tradeoffs of habitat conversion is particularly important. If properly designed with a system-level approach, living shoreline treatments reflect the best scientific understanding of how shoreline systems work, and how the benefits they provide can be sustained. For these reasons, promoting the use of living shorelines is seen as desirable by resource managers and scientific advisors across the nation. Public policy actions to promote the use of living shorelines have been implemented by many local, state, and federal governmental entities. A few states have opted for legislative requirements (Maryland and Connecticut), while more popular options employ fiscal and procedural incentives in the form of an expedited permit process (North Carolina, Mississippi, and Virginia), or fiscal aid (low interest loans have been or are offered in Maryland, Virginia, and Texas, while fee waivers operate in Maryland and tax incentives are an option in Oregon and Virginia) (CCRM 2010; Pace 2010). Likewise, federal agencies including the National Oceanic and Atmospheric Administration (NOAA), Environmental Protection Agency (EPA), and Army Corps of Engineers (USACE) have indicated via funding and planning initiatives a preference for living shorelines to promote wetland sustainability and community resilience. The NOAA Fisheries Office of Habitat Conservation offers grant and design assistance for living shorelines, partnering with governmental and non-governmental groups. On the Coastal Wetlands Initiative, NOAA and EPA partnered to promote living shorelines to curb the trend of coastal wetlands loss (see http://water.epa.gov/type/wetlands/cwt.cfm). The EPA considers living shorelines a green infrastructure approach in their education, planning, and funding programs. The USACE and NOAA helped initiate a Community of Practice (along with Federal Emergency Management Agency, Virginia Institute of Marine Science, and The Nature Conservancy among others) called Systems Approach to Geomorphic Engineering (SAGE) which includes living shorelines as a tool to achieve larger-scale community resilience.

Here, we review case studies and information to synthesize the current understanding on the use of living shorelines as both shoreline protection and habitat conservation strategies along eroding shorelines. We focus on living shoreline approaches that include created salt marsh, a prevalent living shoreline technique found in many U.S. settings but notably along the east and Gulf coasts.

Living shorelines defined

Various definitions of living shorelines have been used across the nation with common elements and intentions. These include:

- Erosion risk reduction—unacceptable erosion risk is present and some type of shoreline management action is deemed necessary
- Wave attenuation—rough surfaces to reduce wave height and energy of approaching waves
- Habitat heterogeneity—Diverse habitats similar to natural shorelines in local area
- Habitat continuum—unimpeded migration of fish and wildlife along the shoreline and between aquatic and terrestrial habitats, plus the import and export of organic matter between habitats
- Habitat migration allowance—buffer zone to allow movement of habitat features within shore zone in response to storm events, to promote vertical sediment accretion, and/or landward wetland migration in response to rising sea levels.

Organic techniques and materials are the dominant elements in living shoreline project designs, such as wetland, riparian, and dune plantings, beach nourishment, shellfish reefs, biodegradable fiber logs, and emplaced large woody debris. These "soft" non-structural elements alone can be successful in low-energy estuarine settings. Higher energy sites may require a hybrid approach in which engineered, shore-parallel structures constructed of low-rising granite, or oyster shell, termed sills or breakwaters, provide the requisite wave attenuation to sustain planted vegetation and habitats. To meet the definition of a living shoreline, engineered structures should be used only when necessary to support vegetated and beach habitats and designed to avoid overwhelming the living habitat features they are supporting.

The science of living shorelines

Natural estuarine habitats including salt marshes, oyster reefs, seagrasses, beaches, and shallow waters provide a diverse suite of ecosystem services. Capitalizing on their ability to stabilize shorelines, one or more of these habitats may be incorporated into living shoreline designs, but the enhancement or creation of salt marsh is often a dominant feature. One important distinction of living shorelines from other marsh creation efforts is that living shorelines are often narrow fringing marshes (Currin, Delano, and Valdes-Weaver 2008), not the extensive meadow marsh systems that were the focus of most previous tidal marsh creation research. Fringing marshes of living shorelines are typically less than 20 m wide and are usually comprised of narrow bands of low marsh *Spartina alterniflora* and high marsh *Spartina patens* vegetation for the Gulf and Atlantic coastal states.

Marsh creation science, primarily based on meadow marshes, reveals that most ecological attributes follow a predictable trajectory toward structural or functional equivalence to natural marshes. Within 5–15 years, primary producers and macrobenthic infaunal communities typically reach equivalence, while biogeochemical processes such as organic carbon and nitrogen accumulation may require in excess of 25 years (Craft et al. 2003). The potential differences between fringe and extensive meadow marsh functions, and the introduction of supporting structures and/or placement of sand fill for hybrid designs, may cause living shoreline marshes to deviate from these established trajectories. Although uncertainty remains regarding the benefits, impacts, and restoration trajectories associated with many living shoreline designs due to the lack of long-term studies, varying designs and environments, and potential ecological tradeoffs from habitat conversion, some patterns have begun to emerge. A limited but growing number of studies have evaluated the ecological attributes (e.g., faunal community structure, sediment composition, plant characteristics) of living shorelines in relation to natural marshes to gain a better understanding of the performance of living shorelines as a form of habitat restoration (e.g., Burke, Koch, and Stevenson 2005; Davis, Takacs, and Schnabel 2006; Currin, Delano, and Valdes-Weaver 2008; Wong, Peterson, and Piehler 2011; Bilkovic and Mitchell 2013).

When evaluating living shorelines as a form of habitat conservation, three important questions should be considered: (1) do fringing marshes, which typify living shorelines, provide a similar suite of ecosystem services as extensive meadow marshes?, (2) are fringing marsh living shorelines providing comparable function as natural fringing marshes?, and (3) what are the ecological tradeoffs associated with converting existing habitat to construct living shorelines?

Value of fringing marshes

Narrow fringing marshes are able to perform many of the desired ecosystem services provided by more extensive meadow marshes, including wave attenuation, fish and invertebrate utilization, sediment trapping, and groundwater nitrate removal. Marsh vegetation provides erosion control via above and below-ground plant biomass which act to attenuate waves, reduce erosive energy from surface flow, slow floodwaters and storm waves, as well as retain sediment and organic matter (Knutson, Seeling, and Inskeep 1982; Morgan, Burdick, and Short 2009). Wave attenuation and sediment retention by marshes depend on marsh width, stem height, water depth, tidal amplitude, vegetation type, and soil composition (Morris et al. 2002). However, wave reduction may occur within a short distance of a marsh, signifying that even fringe marshes are effective at wave dampening. In Chesapeake Bay, 64% of wave energy was dissipated within the first 2.5 m of cordgrass marsh and minimal wave energy persisted beyond 30 m (Knutson et al. 1982). Similarly, in New England, measurements within 7 m of both fringe and meadow marshes showed the height of the waves reduced by 63%, while there was only 33% reduction in areas without marsh (Morgan, Burdick, and Short 2009). A meta-analysis concluded that marshes less than 10 m in width can reduce wave heights by 50–80% (Shepard, Crain, and Beck 2011).

Wave and flow reduction are related to sediment and nutrient removal by marshes. Sediment deposition is higher at the marsh edge near the sediment source than within the marsh interior (Neubauer et al. 2002), which suggests fringe marshes may have similar sediment retention capabilities as extensive marshes if the amount of edge habitat is comparable. Up to 90% of groundwater nitrate load has been shown to be taken up within the first 50 cm of the marsh on the upland border (Tobias, Harvey, and Anderson 2001). Likewise, Burke, Koch, and Stevenson (2005) suggest that fringe marshes are capable of filtering nutrients from managed lands with up to 80% groundwater nitrate removal within 5 m.

Preferential utilization of marsh edge habitat by fish and crustaceans has been observed in several studies, suggesting that even narrow fringing marshes will serve as habitat (Minello, Zimmerman, and Medina 1994; Peterson and Turner 1994; Micheli and Peterson 1999). Further, in North Carolina fish utilized fringing marshes in similar numbers as extensive marshes (Currin, Delano, and Valdes-Weaver 2008).

Taken together, these studies suggest that fringing marsh and extensive marsh can have similar wave attenuation, nutrient removal, sediment accretion, and habitat values for nekton.

Living shoreline fringing marshes

Generally, properly constructed living shoreline marshes possess similar structural attributes as natural fringing marshes. Marsh plant structure (stem density and height) in living shoreline marshes are comparable to natural fringing marshes in most settings within a few growing seasons (Currin, Delano, and Valdes-Weaver 2008; Bilkovic and Mitchell 2013). In many cases, living shoreline *S. alterniflora* stem densities (which can affect sediment trapping capacity; Gleason et al. 1979) are similar to natural fringing and more extensive marshes. Living shoreline marshes with and without sills may also be more protective of estuarine shorelines than bulkheads during major storm events (Gittman et al. 2014).

There is some suggestion that sediment accretion rates are higher in newly created living shoreline marshes with sills than in natural marshes (Currin, Delano, and Valdes-Weaver 2008). However, because of the construction practice of using clean sand fill to create suitable elevations for marsh plantings, sediment characteristics often vary from natural marshes. Living shoreline intertidal sediments are predominantly coarse sand with low organic matter content (Bilkovic and Mitchell 2013; Currin, Delano, and Valdes-Weaver 2008). As with any created marsh, this low soil organic matter content may limit infauna colonization in recently constructed marshes (Levin, Talley, and Thayer 1996). In addition to sediment characteristics, living shoreline design features and local physical conditions regulate associated faunal assemblages. In hybrid living shorelines, benthic community structure differs from natural fringing marshes, because the addition of a sill structure can result in an invertebrate community dominated by fouling organisms (e.g., barnacles, oysters) with fewer subsurface deposit-feeders, which is atypical for marsh shorelines (Wong, Peterson, and Piehler 2011; Bilkovic and Mitchell 2013).

Invertebrate and fish diversity and abundance are often enhanced along living shorelines compared to armored shorelines, and comparative studies of fish utilization in living shorelines suggest they are providing valuable refuge and forage habitat (Davis, Takacs, and Schnabel 2006; Currin, Delano, and Valdes-Weaver 2008; Scyphers et al. 2011). Hybrid living shorelines may also introduce habitat diversity in select estuarine landscapes. Sill structures can support relatively high epibenthic community production compared to habitats without hard structures (Wong, Peterson, and Piehler 2011; Bilkovic and Mitchell 2013). Hardaway et al. (2007) observed higher resident marsh minnow (*Fundulus heteroclitus*) catches behind marsh sills than in offshore sites. Further characterization of fish utilization over time using empirical measures of performance (growth, condition, and diet) are needed to more fully understand the magnitude of the value of living shorelines as nursery habitat.

Ecological tradeoffs of habitat conversion

The potential benefit of constructing a living shoreline and the ecological tradeoffs therein will depend in part on what existing habitat is being replaced. Unfortunately, there is often limited information on the types of habitats being converted making it difficult to evaluate net benefits or losses. In Virginia, the most frequently converted habitat types were eroding relict fringe marshes and/or unvegetated tidal flats (98% of marsh-sill projects from 2009–2011), suggesting a net gain in structural vegetative habitats for these shorelines and concomitant services. Further, the placement of marsh-sills provided a net positive ecological benefit because the addition of structural habitat subsidized secondary productivity by enhancing biomass of native filter-feeding epifauna (e.g., oysters, mussels) (Bilkovic and Mitchell 2013). However, the adverse effects of artificial structures on macrofauna in adjacent habitats may diminish these reported benefits. This may occur in instances where large areas of existing habitat (mudflats, shallows) are converted, when sufficient offshore shallows are not maintained for nekton refuge habitat, or if the introduction of artificial substrates enhances recruitment of species that are normally limited by the availability of suitable substrate including native and non-native species (Wong et al. 2011; Bilkovic and Mitchell 2013). Scientific insights on the net ecological effect of habitat conversion can help resolve conflicts among regulatory agencies that are charged with managing specific resources (e.g., subaqueous lands, wetlands).

Balancing science, management, and societal needs

As human presence in coastal systems continues to grow unabated, the demands for protection of the built environment will also grow. Ironically, the very shoreline habitats that are threatened by human pressures can act as natural barriers from rising waters and storm events (Gedan et al. 2011; Shepard, Crain, and Beck 2011). Traditional shoreline armoring eliminates estuarine habitats and erodes ecosystem services. Missing from the shoreline management decision-making process is a consideration of the long-term value or future ecosystem services yet to be provided by the at-risk marsh or estuarine habitat. Living shorelines have the potential to allow us to maximize the benefits of coastal habitats for the next few decades as we face rising seas and intensified development. Efforts to quantify successful living shoreline approaches in economic and ecological terms have been underway for the past couple of decades. Example case studies that integrated both human and natural considerations for the application of living shoreline approaches are highlighted below.

Perception of living shoreline effectiveness to protect shorelines

Living shorelines implementation has been hampered because of the perception that these approaches are inferior to armoring for protection from erosion and storm damage. Gittman et al. (2014) demonstrated that living shorelines (planted marshes with and without sills as a stabilizing structure) in North Carolina were more effective than bulkheads at protecting shorelines from a hurricane event. In addition, they provided cost-comparison information on different shoreline approaches showing that the average construction costs were similar among armoring and marsh-sills with lower replacement costs associated with marsh-sills. Noted limitations to the analysis were that maintenance costs were not incorporated nor were considerations for the availability of qualified contractors. This study is one example of how research can inform coastal management policy because it provides information coastal managers may use to reassure property owners that living shorelines are viable options in some settings for shoreline protection.

Shoreline enhancements in urban settings—benefits to fisheries

On the west coast in highly urbanized areas, habitat enhancements as a form of living shoreline have been applied along armored shorelines. Falling short of restoration to natural conditions, modifications or additions of natural elements to armored shorelines may be the only practicable approach in some urban settings. The goal of such enhancements is to improve the nearshore conditions for fishes and invertebrates (Toft et al. 2013). In Puget Sound, Seattle, WA urban shoreline enhancements were constructed to simulate shallow water habitat and a pocket beach. Following these enhancements, larval and juvenile salmon (*Oncorhynchus* spp.) densities increased and prey assemblages were more diverse than armored shorelines without enhancements (Toft et al. 2013). This suggests that the enhancement of important estuarine habitats along armored shorelines can benefit economically important fish species and may be a strategy to consider in heavily urbanized settings.

Living shorelines as estuarine habitat conservation strategies

There is growing interest in nature-based solutions to societal issues. Appropriate nature-based solutions should function dynamically, provide the same ecosystem services as their natural counterparts, and protect human life and infrastructure (Tobey et al. 2010). Living shorelines are especially suited to addressing issues of shoreline stability and climate change due to their natural resiliency, which can protect property from erosion and reduce flood impacts to communities (Gedan et al. 2011). Appropriately placed, living shorelines can enhance ecosystem services capacity by more than 90% compared to their previous status (Rodríguez-Calderón 2014), thereby providing a myriad of services to human communities beyond flood and erosion protection. This suggests that expansion of living shoreline projects within urbanized or developing coastal localities may be a viable adaptation to preserve ecosystem services.

Living shorelines are of particular interest as an adaptation to sea-level rise. The primary concern with rising sea level is an increase in flooding impacts due in part to more intense storm surges and storm waves. Sea-level rise in areas with hardened shorelines can increase flooding and erosion of adjacent shorelines and tidal amplitudes (Holleman and Stacey 2014), while natural and living shorelines provide water storage areas, help attenuate waves (Barbier et al. 2011), and reduce tidal amplification (Holleman and Stacey 2014). Living shorelines and other nature-based solutions help support the economy by supporting fish species, providing tourist venues with attractive natural shorelines (e.g., Beckon 2005), and providing communities with recreation opportunities and wildlife habitat. Living shorelines can also act as CO_2 sinks, potentially mitigating future climate change and sea-level rise (Duarte et al. 2013; Mcleod et al. 2011).

Living shorelines have some ability to accumulate sediment, building their elevation (Hardaway et al. 1984). Thus, living shorelines could potentially keep pace with sea-level rise, making them a more sustainable option than engineered structures (Vandenbruwaene et al. 2011). However, this capacity is dependent on an adequate sediment supply (Kirwan et al. 2010) and wind or wave energy conditions conducive to sediment capture. Although marshes have been shown to significantly reduce wave energy (e.g., Barbier et al. 2013), the amount of wave reduction is dependent on the width of the marsh and the height and density of the vegetation (Hardaway et al. 1984). Therefore, living shorelines will be most successful as long-term adaptations if they are situated to allow landward migration of the wetlands with sea-level rise rather than depending on marsh accretion.

Experimentation with nature based strategies for flood defense has shown that they can be more sustainable, cost-effective, and have fewer side effects than conventional adaptation strategies (Temmerman et al. 2013). Many states are actively promoting or trying to incentivize the use of living shorelines as a management strategy (Pace 2010). In Virginia, more than 80% of shorelines are appropriate for living shorelines based on fetch conditions (CCRM 2013). This makes living shorelines a viable alternative for climate change adaptation and habitat conservation. However, at this time, only about 20% of Virginia shoreline permit requests are for living shorelines compared to traditional armoring. This suggests that identifying a "missing link" of either policy or public education is needed to truly make living shorelines a successful form of adaptation.

Best practices and key challenges for living shorelines

To be considered a coastal habitat conservation strategy living shorelines must demonstrate functional equivalence to natural shorelines as is expected of traditional conservation practices (e.g., tidal marsh). Best practices for living shorelines should embody: (1) science-based management and policy, (2) streamlined regulatory oversight to minimize habitat restoration or creation hurdles, (3) improved public perception and acceptance of living shorelines as a shoreline protection approach, (4) appropriate design and maintenance to ensure persistence of living shoreline habitats and ecosystem service provision, and (5) standardized monitoring and application of adaptive management.

Science-based policy

Successful coastal resource management is a complex process necessitating engagement of all sectors of the community, home-owners, commerce, military, public utilities, and fishing interests, all within a dynamic environmental setting. Coastal management programs have a longstanding history of using the best available science to inform decision-making and this should be the case with living shorelines best practices. Research and monitoring of existing living shoreline programs should be reviewed to convert lessons learned into policy and guidance, including criteria to support an expedited permit process. To ensure the effectiveness of living shorelines and maximize potential ecological benefits, proper siting and design guidance to identify the most appropriate shoreline protection approaches for specific physical settings (e.g., shoreline orientation and morphology, fetch, position in estuary) should be improved and made available to local decision-makers (Bilkovic and Mitchell 2013). Increasing functional fringe marsh habitat through living shoreline applications may also be a means to reduce nutrients. Efforts are underway in the Chesapeake Bay Program to assign nutrient load reduction values based on the scientific literature to shoreline erosion best management practices (BMPs), including living shorelines. This may result in the use of these values for total maximum daily load (TMDL) credits (CBP Urban Stormwater Workgroup, Expert Panel on Shoreline Management 2014).

Reduction in regulatory complexity

Implementation of living shorelines can be problematic, given the regulatory complexity of shoreline management programs in most coastal states. While not all living shoreline designs are identical, creating the necessary conditions can involve:

- grading the riparian area, disrupting or removing the natural vegetation and the associated pollutant removal capacity, and creating a conflict with local water quality or habitat code requirements; or
- moving design elements channelward to preserve an existing vegetated riparian area, impacting wetlands and creating a conflict with tidal wetlands regulations and possibly raising navigation concerns; or
- filling nearshore waters to create intertidal wetlands, creating significant conflicts with subaqueous land proprietary code. State regulatory guidelines may require demonstration of "positive aquatic resource benefits" in order to obtain permits for subaqueous encroachment.

For a living shoreline design to be implemented, one or more of the agencies involved in shoreline management may have to accept impacts within targeted resources. This means successful promotion of living shorelines will require cooperative efforts by the regulatory and advisory authorities. Development and implementation of science-based coordinated regulatory processes such as expedited permits and integrated guidance that coordinates these programmatic interests would be a necessary component.

Design and maintenance for habitat persistence

Regulatory programs and policies only address initial design and construction. Project owners and third parties are responsible for tracking and maintaining living shoreline projects long term. Best maintenance practices include frequent inspections and adjustments as needed during the establishment period. Only periodic inspection and maintenance is necessary once there is evidence of a "well-established" marsh, with occasional re-planting after storm events if the gradual recovery of vegetation from local root stock and seed sources is not sufficient. Natural ecological succession and physical changes should be tolerated, such as lateral and landward migration in response to accretion or storm event recovery.

Both design and setting of a living shoreline project may limit its restoration potential. For example, a persistent shallow water environment may be essential if the goal is to enhance fish and shellfish habitat. Certain design elements, such as lower profile sills with tidal gaps, allow greater access to the marsh habitat by aquatic organisms and encourage faunal colonization. Ribbed mussel (*Geukensia demissa*) densities on the marsh surface behind sills in Virginia were significantly lower than densities on the sill or within natural fringing marshes suggesting sills restricted access by mussel larvae to the marsh behind the sill (Bilkovic and Mitchell in press). Improper grading or placement of sills too close to the shore will reduce tidal flushing and cause the loss of low marsh and aquatic habitat (Bosch et al. 2006), effectively turning the marsh sill into a revetment. Insufficient tidal gaps will restrict flushing, causing elevated temperatures and reduced access by mobile aquatic species (Burke, Koch, and Stevenson 2005). In Maryland, a little over half of the living shoreline marsh projects assessed had an associated sill structure (43 of 80 sites) but only 35% of the sills had gaps for tidal exchange and habitat access (Bosch et al. 2006). Hardaway et al. (2007) observed that in addition to tidal gaps, marsh access for fish was maintained through macro-pores in the sill stone and by overtopping of the sill by tidal waters. A tradeoff exists between protection of the shore from wave climate and access to the marsh via tidal gaps that may allow pockets of shoreline erosion. However, innovative vent designs (e.g., staggered system), porosity in sill stone, and overtopping by tidal waters are potential balancing mechanisms to ensure the coexistence of erosion control with desired ecological functions.

Performance standards for living shorelines

Progress has been slowed by the lack of resources dedicated to assessing and monitoring the performance of living shorelines. Most living shoreline projects do not include mandatory long-term monitoring and the data that are collected (e.g., visual inspection of plants) are not standardized or readily available to coastal managers, engineers, or scientists. Contractors or regulators may monitor projects following construction to ensure the integrity, but in many cases this effort is voluntary and inconsistently applied. Systematic and standardized monitoring at both regional and national scales will be vital to fully evaluate living shoreline effectiveness as an estuarine habitat conservation strategy. In addition, monitoring information must be made available to better inform project designs and to shorten the time frame until a living shoreline is functioning as designed. Developing a network of users and guidance on universal, standardized metrics to evaluate habitat success and support adaptive management should be a top priority moving forward.

Key challenges to expanding the use of living shorelines as conservation approaches include: (1) coordination and cooperation of regulatory agencies and advisory authorities, (2) enhanced public acceptance through incentives, demonstration sites in multiple settings, outreach, or other methods, and (3) securing dedicated long-term resources for research and monitoring to support science-based policy.

The future recommended path for science, management, and policy

Application of an adaptive management approach is considered the best scenario for management of natural and naturalized systems subject to change from human uses and dynamic environmental conditions. The process, "learning by doing," intentionally engages stakeholders to affect management changes in response to performance criteria data collection assessed relative to a set of clear goals (Thom 2000). Successful adaptive management is linked with system flexibility and resilience (Gunderson 1999; Tompkins and Adger 2004). However, adaptive management success is limited by reliance on linear models that oversimplify managed systems, discounting non-scientific knowledge from the managed community, and dependence on flexibility in non-flexible policy processes (McLain and Lee 1996).

Elements of adaptive management can be immediately adopted and implemented to improve coastal decision-making. One clear option is to create stakeholder engagement opportunities for coastal managers, regulators, project designers and builders, funders, academia, and property owners to identify a common suite of intended project goals for living shorelines. Networking and communication of project successes and failures will enable future efforts to avoid pitfalls and improve project performance. By using systematic and standardized monitoring at both regional and national scales to gain a better understanding of ecosystem services gained and their persistence over time, living shorelines can be an adaptation strategy that will conserve ecologically important estuarine habitat.

Acknowledgments

We thank our colleagues at the Center for Coastal Resources Management at VIMS and the living shoreline community for insights and discussions supporting this paper. This article is Contribution No. 3490 of the Virginia Institute of Marine Science, College of William & Mary.

References

Barbier, E. B., S. D. Hacker, C. Kennedy, E. W. Koch, A. C. Stier, and B. R. Silliman. 2011. The value of estuarine and coastal ecosystem services. *Ecological Monographs* 81:169–193.

Barbier, E. B., I. Y. Georgiou, B. Enchelmeyer, and D. J. Reed. 2013. The value of wetlands in protecting southeast Louisiana from hurricane storm surges. *PloS ONE* 8 (3):e58715.

Beckon, S. 2005. Harmonizing climate adaptation and mitigation: The case of tourist resorts in Fiji. *Global Environmental Changes* 15:381–393.

Bilkovic, D. M. 2011. Response of tidal creek fish communities to dredging and coastal development pressures in a shallow-water estuary. *Estuaries and Coasts* 34:129–147.

Bilkovic D. M., and M. Mitchell. 2013. Ecological tradeoffs of stabilized salt marshes as a shoreline protection strategy: Effects of artificial structures on macrobenthic assemblages. *Ecological Engineering* 61:469–481.

Bilkovic, D. M., and M. M. Mitchell. In press. Designing living shoreline salt marsh ecosystems to promote coastal resilience. In *Living Shorelines: The Science and Management of Nature-based Coastal Protection* to be published by CRC Press/Taylor & Francis Group in 2017.

Bilkovic, D. M., and M. M. Roggero. 2008. Effects of coastal development on nearshore estuarine nekton communities. *Marine Ecology Progress Series* 358:27–39.

Bilkovic, D. M., M. M. Roggero, C. H. Hershner, and K. Havens. 2006. Influence of land use on macrobenthic communities in nearshore estuarine habitats. *Estuaries and Coasts* 29:1185–1195.

Bosch, J., C. Foley, L. Lipinsky, C. McCarthy, J. McNamara, A. Naimaster, A. Raphael, A. Yang, and A. Baldwin. 2006. Constructed wetlands for shoreline erosion control: Field assessment and data management. Prepared for Maryland Department of the Environment for submittal to the U.S. Environmental Protection Agency.

Bozek, C. M., and D. M. Burdick. 2005. Impacts of seawalls on saltmarsh plant communities in the Great Bay Estuary, New Hampshire USA. *Wetlands Ecology and Management* 13:553–568.

Burke, D. 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. Final Report for Chesapeake Bay Trust, Annapolis, MD, 112 p.

CBP Urban Stormwater Workgroup, Expert Panel on Shoreline Management. 2014. Recommendations of the expert panel to define removal rates for shoreline management projects. http://www.chesapeakebay.net/channel_files/21151/attachment_c–uswg_shoreline_management_041414.pdf (accessed 4 April 2016).

CCRM (Center for Coastal Resources Management). 2010. Study of Tidal Shoreline Management in Virginia: Recommendations for living shorelines and tidal resources sustainability. Report to the Governor and Virginia General Assembly in Response to Senate Joint Resolution No. 35.

CCRM (Center for Coastal Resources Management). 2013. Comprehensive Coastal Inventory. http://ccrm.vims.edu/gis_data_maps/shoreline_inventories/index.html (accessed April 2016).

Chambers, R., L. A. Meyerson, and K. Saltonstall. 1999. Expansion of *Phragmites australis* into tidal wetlands of North America. *Aquatic Botany* 64:261–273.

Chapman, M. G. 2003. Paucity of mobile species on constructed seawalls: effects of urbanization on biodiversity. *Marine Ecology Progress Series* 264:21–29.

Charlier, R. H., M. C. P. Chaineux, and S. Morcos. 2005. Panorama of the history of coastal protection. *Journal of Coastal Research* 21:79–111.

Craft, C., P. Megonigal, S. W. Broome, J. Stevenson, R. Freese, J. Cornell, and J. Sacco. 2003. The pace of ecosystem development of constructed *Spartina alterniflora* marshes. *Ecological Applications* 13:1417–1432.

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 Ecology Management* 16:97–118.

Davis, J. L. D., R. L. Takacs, 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*, ed. S. Y. Erdle, J. L. D. Davis, and K. G. Sellner, 55–61. Gloucester Point, VA: CRC Publication No. 08-164.

Duarte, C. M., I. J. Losada, I. E. Hendriks, I. Mazarrasa, and N. Marbà. 2013. The role of coastal plant communities for climate change mitigation and adaptation. *Nature Climate Change* 3 (11):961–968.

Dugan, J. E., L. Airoldi, M. G. Chapman, S. J. Walker, and T. Schlacher. 2011. Estuarine and coastal structures: Environmental effects, a focus on shore and nearshore structures. In Treatise on Estuarine and Coastal Science, ed. E. Wolanski and D. McLusky, pp. 17–41. New York: Elsevier Press.

Florida DEP, Department of Environmental Protection Bureau of Beaches and Coastal Systems. 1990. Coastal armoring in Florida. Final Status Report. Tallahassee, Florida.

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* 106:7–29.

Gittman, R. K., A. M. Popowich, J. F. Bruno, and C. H. Peterson. 2014. Marshes with and without sills protect estuarine shorelines from erosion better than bulkheads during a Category 1 hurricane. *Ocean & Coastal Management* 102:94–102.

Gleason, M. L., D. Elmer, N. C. Pien, and J. S. Fisher. 1979. Effects of stem density upon sediment retention by salt marsh cord grass, *Spartina alterniflora* Loisel. *Estuaries* 2:271–273.

Griggs, G. B. 1998. The armoring of California's coast. In *California and the World Ocean '97, Conference Proceedings*, ed. O. T. Magoon, H. Converse, B. Baird, and M. Miller-Henson, 515–526. Reston, VA: American Society of Civil Engineers.

Gunderson, L. 1999. Resilience, flexibility and adaptive management—Antidotes for spurious certitude? *Conservation Ecology* 3 (1):7. [online] http://www.consecol.org/vol3/iss1/art7/

Hardaway, C. S., G. R. Thomas, A. W. Zacherle, and B. K. Fowler. 1984. Vegetative Erosion Control Project: Final Report. Prepared for Virginia Division of Soil and Water. Technical Report. Virginia Institute of Marine Science, Gloucester Point, VA, 275 p.

Hardaway, C. S., J. Shen, D. Milligan, C. Wilcox, K. O'Brien, W. Reay, and S. Lerberg. 2007. Performance of Sill, St. Mary's City, St. Mary's River, Maryland. Technical Report prepared by Virginia Institute of Marine Science, Gloucester Point, Virginia.

Holleman, R. C., and M. T. Stacey. 2014. Coupling of sea level rise, tidal amplification, and inundation. *Journal of Physical Oceanography* 44 (5):1439–1455.

Isdell, R., R. Chambers, D. M. Bilkovic, and M. Leu. 2015. Effects of terrestrial–aquatic connectivity on an estuarine turtle. *Diversity and Distributions* 21 (6):643–653.

Jennings, M. J., M. A. Bozek, G. R. Hatzenbeler, E. E. Emmons, and M. D. Staggs. 1999. Cumulative effects of incremental shoreline habitat modification on fish assemblages in north temperate lakes. *North American Journal of Fisheries Management* 19 (1):18–27.

King, R. S., A. H. Hines, F. D. Craige, and S. Grap. 2005. Regional, watershed, and local correlates of blue crab and bivalve abundances in subestuaries of Chesapeake Bay, USA. *Journal of Experimental Marine Biology and Ecology* 319:101–116.

Kirwan, M. L., G. R. Guntenspergen, A. D'Alpaos, J. T. Morris, S. M. Mudd, and S. Temmerman. 2010. Limits on the adaptability of coastal marshes to rising sea level. *Geophysical Research Letters* 37 (23):1–5.

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

Lathrop, R. G., Jr., and A. Love. 2007. Vulnerability of New Jersey's coastal habitats to sea level rise. Grant F. Walton Center for Remote Sensing & Spatial Analysis Rutgers University and the American Littoral Society. Highlands, NJ. 17 p.

Levin, L. A., D. Talley, and G. Thayer. 1996. Succession of macrobenthos in a created salt marsh. *Marine Ecology Progress Series* 141:67–82.

McLain, R. J. and R. G. Lee. 1996. Adaptive management: Promises and pitfalls. *Environmental Management* 20 (4):437–448.

Mcleod, E., G. L. Chmura, S. Bouillon, R. Salm, M. Björk, C. M. Duarte, C. E. Lovelock, W. H. Schlesinger, and B. R. Silliman. 2011. A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. *Frontiers in Ecology and the Environment* 9 (10):552–560.

Micheli, F., and C. H. Peterson. 1999. Estuarine vegetated habitats as corridors for predator movements. *Conservation Biology* 13 (4):869–881.

Minello, T. J., R. J. Zimmerman, and R. Medina. 1994. The Importance of edge for natant macrofauna in a created salt marsh. *Wetlands* 14 (3):184–198.

Morgan, P. A., D. M. Burdick, and F. T. Short. 2009. The functions and values of fringing salt marshes in Northern New England, USA. *Estuaries and Coasts* 32:483–495.

Morley, S. A., J. D. Toft, and K. M. Hanson. 2012. Ecological effects of shoreline armoring on intertidal habitats of a Puget Sound urban estuary. *Estuaries and Coasts* 35:774–784.

Morris, J. T., P. V. Sudareshwar, C. T. Nietch, B. Kjerfve, and D. R. Cahoon. 2002. Responses of coastal wetlands to rising sea level. *Ecology* 83:2869–2877.

Moschella, P. S., M. Abbiati, P. Åberg, L. Airoldi, J.M. Anderson, F. Bacchiocchi, F. Bulleri, et al. 2005. Low-crested coastal defence structures as artificial habitats for marine life: using ecological criteria in design. *Coastal Engineering* 52:1053–1071.

National Research Council (NRC). 2007. *Mitigating shore erosion on sheltered coasts*. Washington, DC: The National Academies Press.

Neubauer, S., I. C. Anderson, J. A. Constantine, and S. A. Kuehl. 2002. Sediment deposition and accretion in a mid-Atlantic (U.S.A.) tidal freshwater marsh. *Estuarine Coastal and Shelf Science* 54:713–727.

Pace, N. L. 2010. Wetlands or seawalls-adapting shoreline regulation to address sea level rise and wetland preservation in the Gulf of Mexico. *Journal of Land Use and Environmental Law* 26:327.

Patrick, C. J., D. E. Weller, X. Li, and M. Ryder. 2014. Effects of shoreline alteration and other stressors on submerged aquatic vegetation in subestuaries of Chesapeake Bay and the Mid-Atlantic coastal bays. *Estuaries and Coasts* 37:1516–1531.

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 8:209–219.

Peterson, M. S., and M. R. Lowe. 2009. Implications of cumulative impacts to estuarine and marine habitat quality for fish and invertebrate resources. *Reviews in Fisheries Science* 17:505–523.

Peterson, G. W., and R. E. Turner. 1994. The value of salt marsh edge vs. interior as a habitat for fish and decapod crustaceans in a Louisiana tidal marsh. *Estuaries* 17:235–262.

Rodríguez-Calderón, C. 2014. Forecasting ecosystem service capacity: Effects from sea level rise and management practices, Chesapeake Bay, Virginia. Dissertation. College of William & Mary.

Scyphers, S. B., S. P. Powers, K. L. Heck Jr., and D. Byron. 2011. Oyster reefs as natural breakwaters mitigate shoreline loss and facilitate fisheries. *PloS ONE* 6 (8):e22396.

Shepard, C. C., C. M. Crain, and M. W. Beck. 2011. The protective role of coastal marshes: A systematic review and meta-analysis. *PloS ONE* 6:e27374.

Temmerman, S., P. Meire, T. J. Bouma, P. M. Herman, T. Ysebaert, and H. J. De Vriend. 2013. Ecosystem-based coastal defence in the face of global change. *Nature* 504 (7478):79–83.

Titus, J. G., D. E. Hudgens, D. L. Trescott, M. Craghan, W. H. Nuckols, C. H. Hershner, J. M. Kassakian, et al. 2009. State and local governments plan for development of most land vulnerable to rising sea level along the US Atlantic coast. *Environmental Research Letters* 4:4.

Thom, R. M. 2000. Adaptive management of coastal ecosystem restoration projects. *Ecological Engineering* 15:365–372.

Tobey, J., P. Rubinoff, D. Robadue Jr., G. Ricci, R. Volk, J. Furlow, and G. Anderson. 2010. Practicing coastal adaptation to climate change lessons from integrated coastal management. *Coastal Management* 38 (3):317–335.

Tobias, C. R., J. W. Harvey, and I. C. Anderson. 2001. Quantifying groundwater discharge through fringing wetlands to estuaries: Seasonal variability, methods comparison, and implications for wetland-estuary exchange. *Limnology and Oceanography* 46 (3):604–615.

Toft, J. D., A. S. Ogston, S. M. Heerhartz, J. R. Cordell, and E. E. Flemer. 2013. Ecological response and physical stability of habitat enhancements along an urban armored shoreline. *Ecological Engineering* 57:97–108.

Tompkins, E. L., and W. N. Adger. 2004. Does adaptive management of natural resources enhance resilience to climate change? *Ecology and Society* 9 (2):10.

Vandenbruwaene, W., T. Maris, T. J. S. Cox, D. R. Cahoon, P. Meire, and S. Temmerman. 2011. Sedimentation and response to sea-level rise of a restored marsh with reduced tidal exchange: comparison with a natural tidal marsh. *Geomorphology* 130:115–126.

Wong, M., C. Peterson, and M. Piehler. 2011. Evaluating estuarine habitats using secondary production as a proxy for food web support. *Marine Ecology Progress Series* 440:11–25.