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Embracing dynamic design for climate-resilient living shorelines

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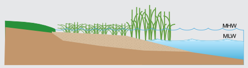
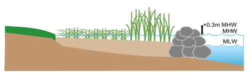
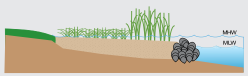
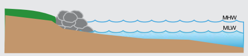
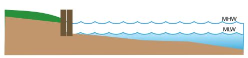
1 | INTRODUCTION

As natural marshes are lost to erosion, sea level rise, and human activity, small created marshes, (sometimes with ancillary stabilization structures, and frequently called living shorelines) have gained interest as a replacement habitat; providing both shoreline stabilization and restoration of important ecological functions. These living shorelines enhance ecological function while reducing erosion through the use of marsh plants (Table 1). In all but the lowest energy settings, oyster reefs, low rock structures, or other stabilizing material are frequently used to enhance marsh establishment. Due to their ability to stabilize the shoreline with minimal impact to the ecology, living shorelines are considered a method to increase coastal community resilience to sea level rise (e.g., Sutton-Grier, Wowk, & Bamford, 2015; Van Slobbe et al., 2013) but little consideration is being given to living shoreline resilience under changing climate. Although it has been stated that living shorelines have the capacity to adapt to rising sea levels (e.g., Moosavi, 2017; Sutton-Grier et al., 2015; Toft, Bilkovic, Mitchell, & La Peyre, 2017), their ability to fulfill this potential relies on being designed to incorporate all the processes occurring in natural systems. The extent to which living shorelines can mimic the resiliency of natural marshes and oyster reefs will depend on their setting, design and the type of human maintenance provided. Truly resilient projects will require engineers and ecologists to work together to describe the dynamics of shoreline processes under sea level rise and translate this understanding into living shoreline design.

The potential for living shorelines to self-adapt to rising sea levels comes from their biotic components. When properly constructed, living shorelines provide a plethora of ecological services through their biotic components, including: nursery, nesting and feeding habitat (Bilkovic & Mitchell, 2017; Davis, Takacs, & Schnabel, 2006; Gittman et al., 2015); filtering of sediments and nutrients from waterways (Beck, Chambers, Mitchell, & Bilkovic, 2017); reduction of wave energy (Gedan, Kirwan, Wolanski, Barbier, & Silliman, 2011; Gittman, Popowich, Bruno, & Peterson, 2014); and carbon storage (Davis, Currin, O'Brien, Raffenburg, & Davis, 2015). In this respect, they have the potential to provide ecological functions that are similar to natural marshes and it is tempting to assume that living shorelines incorporate all the same dynamic processes. However, living shorelines are engineered systems which frequently differ from natural coastal marshes in a few key elements: (a) Plantings are done on a grid, so initial plant density is controlled by design, not inundation; (b) living shorelines typically have a gradual, constant slope while natural shorelines (particularly in erosional areas) often have a scarped edge and complex microtopography; (c) living shorelines frequently have associated engineered structures designed to mitigate wave energy, which can affect sedimentation and faunal settlement patterns. These differences can translate into a system which is stable in the short term, but may have difficulty adapting to a changing environment.

Much of the monitoring or assessment of living shorelines is related to ensuring ecological functions (habitat, nutrient transformations) are equivalent to those of natural marshes; however, assessments of living shoreline sustainability are equally important. Natural coastal marshes are dynamic systems, with some natural adaptation to sea level rise realized through feedback loops (Morris, 2007) involving plant production and sediment capture that result in marsh vertical growth (accretion) and migration into adjacent lands

TABLE 1 Comparison of different shoreline stabilization methods

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

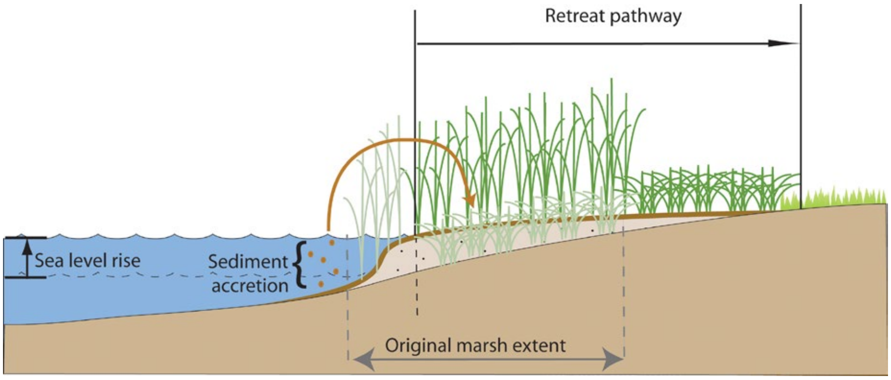


FIGURE 1 Dynamic processes help natural marshes adapt to rising sea level. Tall, dense marsh plants dissipate wave energy and collect sediment, allowing the marsh surface elevation to increase. Their roots also contribute to accretion. Natural, low elevation lands allow marshes to retreat into upland areas as sea level rises. This maintains marsh extent under changing conditions

where possible (Figure 1). In contrast, living shorelines are typically engineered as static systems that reduce erosion and mimic the flora (primarily) and the fauna (secondarily) of natural marshes, but with little emphasis on creating the characteristics of natural marshes that allow for self-evolution under changing water levels. Appropriate design of living shorelines should enhance longevity by embracing the dynamic characteristics of natural marshes and leveraging natural feedback loops to maximize sediment accretion and stabilization (Bilkovic & Mitchell, 2017). In this article, we draw on scientific literature and practical experience with living shoreline design and application to make recommendations for how living shorelines can be sited, built and maintained to be resilient to sea level rise.

2 | LIVING SHORELINE SITING IS CRITICAL FOR ENHANCED LONGEVITY

Longevity of living shorelines under sea level rise is largely dependent on their location in the coastal system. There are three siting factors that affect persistence: (a) wave energy at the site, (b) the potential for upland marsh retreat, and (c) the sediment supply (which is critical for marsh accretion). Ideally, living shorelines should be placed to minimize wave energy and maximize the other two factors (Figure 2). Rock sill or oyster reef structures can be used to mitigate high wave energy and maximize sediment capture, but cannot completely compensate for poor siting.

Living shorelines are most appropriate in low to moderate energy settings since plants have difficulty establishing and thriving in high energy areas (Currin, Davis, & Malhotra, 2017). This means that most estuarine, riverine or creek settings should be appropriate, assuming that the shorelines are not subject to high wave energy. The exception is the outer bends of river meanders, where water flow can be swift and natural processes lead to erosion and migration of the bend. With appropriately-sized structures, living shorelines have been built in open coastal areas. However, their long-term prognosis under sea level rise may be difficult to predict. These areas are subject to high wave energy and although structures placed channelward of the marsh can reduce wave energy somewhat, coastal sediment dynamics can also be very different from the more sheltered coastlines where natural marshes are typically found. Alongshore sand movement and barrier island migration are both important processes on open coasts that are critical components of coastal resilience but are not compatible with stabilized living shoreline design. The development of dynamic living shoreline designs specifically for high-energy coastal areas, such as barrier islands, would have enormous resilience potential.

Marsh retreat potential is linked to local land use and surrounding elevations (Mitchell, Herman, Bilkovic, & Hershner, 2017). Living shorelines built in low elevation areas will naturally be able to migrate landward, as long as the surrounding land use is compatible. The adjacent upland/riparian area should be preserved as natural lands, ideally populated with native grass or shrubs. Marshes can migrate into forested riparian areas, but shade from the trees can slow migration and competition from invasive species (e.g. Smith, 2013) can alter the floral community. There may be plants that enhance the migration of marsh flora that could be planted in riparian zones and research on this topic would be timely. Steeper elevations or impervious surfaces (roads, driveways, buildings, etc.) interrupt the marsh retreat corridor and should be avoided where possible. In areas where there are sharp inclines, elevation breaks, or retaining walls in the riparian zone, grading of the land may be possible to create a gentle slope and ensure that the marsh isn't compressed during migration. Where living shorelines are backed by bluffs, migration won't be a viable process and significant accretion (equivalent to sea level rise rates) will be crucial to maintain the marsh.

Another important siting factor for living shoreline persistence is local sediment supply. This is particularly critical where marsh retreat is limited. Sediment from both the waterway and the surrounding upland can be captured, contributing to marsh accretion. Accretion slowly raises the surface of the marsh over time, and can keep it in the proper position in the tidal frame. Accretion increases with time of submergence (Temmerman, Govers, Wartel, & Meire, 2004) and with increased plant productivity (Kirwan & Murray, 2007; Morris, Sundareshwar, Nietch, Kjerfve, & Cahoon, 2002), both processes increase with sea level rise. Together these processes can contribute significantly to marsh persistence under moderate sea level rise (Gedan et al., 2011). However, in areas where sea level rise is accelerating (Boon & Mitchell, 2015), high sediment supply will be an important consideration when

FIGURE 2 Comparison of retreat potential for living shorelines. (a) This living shoreline was constructed adjacent to natural marshes and on a low elevation shoreline with ample opportunity for retreat. However, the somewhat sparse grass may limit its ability to accrete sediment. (b) This marsh is in front of a bluff, which cuts off the retreat pathway but provides sediment for accretion. (c) This living shoreline is built in front of a block retaining wall that cuts off the retreat pathway. Survival under sea level rise will require sufficient sediment accretion to maintain its elevation within the tidal frame

migration potential is limited, so consideration should be given to the surrounding shorelines. Local sediment supply can be greatly reduced by shoreline and bank stabilization, such as retaining walls or bulkheads; therefore, living shorelines in front of or adjacent to unstablilized banks should be more resilient than those where bulkheads and revetments are pervasive. It is also important to consider local conditions that might lead to high subsidence at the marsh location. Marshes persist in areas where the surface accretion is higher than the subsidence rate plus the local sea level rise rate. Some subsidence rates, such as subsidence due to glacial isostatic rebound, are widespread with reliable estimates of magnitude (Piecuch et al., 2018). However, subsidence rates can vary greatly on small scales (20–30 m, Bekaert, Hamlington, Buzzanga, & Jones, 2017) due to local processes such as groundwater withdrawals. In marsh sediments, some subsidence is due to the breakdown of organic material (Morris, 2007); this should be a minor issue for living shorelines since most of them are built on inorganic sediment surfaces and take years (>8 year) to develop typical marsh sediments (Beck et al., 2017). Locally high subsidence rates result in an increased rate of relative sea level rise in the affected area. Living shorelines in these areas will require higher accretion rates to compensate for the sea level rise and this should be taken into account during project design.

3 | DYNAMIC DESIGN CONSIDERATIONS

Living shorelines can be designed to take advantage of natural processes that enhance sediment accretion, marsh surface elevation, marsh stability and adaptability. Plant growth is an important moderator of all of these characteristics; therefore marsh plantings are integral to living shoreline sustainability. Plant height and density are positively related to the marshes ability to dissipate wave energy (Gedan et al., 2011), which can increase sediment capture (as long as there is sufficient sediment supply) and stimulate accretion. Plants also contribute organic matter to the sediment through root production, taking up space in the sediment and raising the surface elevation (Baustian, Mendessohn, & Hester, 2012). Maximizing plant height and root growth requires appropriate nutrient availability. Adding fertilizer to the initial plantings may help maximize plant productivity (Priest, 2017), at least in the early years (2–3 year) after creation. Living shorelines that are partially groundwater-fed may benefit from natural fertilization since they have been shown to remove nitrogen from the groundwater (Beck et al., 2017). Maximizing plant density could be achieved through denser initial planting or encouraging plant spread. Adjusting planting configurations, such as planting marsh vegetation in clumps rather than evenly dispersed, may promote high density plant growth and rapid expansion (Silliman et al., 2015).

Sediment stability is important to prevent marsh erosion and create a stable base for accretion. Edge stabilization is frequently achieved through the use of a rock or oyster sill structures. Sill inclusion in living shorelines can enhance sediment deposition and accretion, given sufficient sediment supply and wave reduction capacity (Currin, Delano, & Valdes-Weaver, 2008), and therefore may help increase their resilience. Marsh-wide, sediment stability can be enhanced by root production which helps to bind the sediment together. In some living shorelines, there may also be fauna that can help bind sediments, such as ribbed mussels (*Geukensia demissa*), which are considered important components of natural marsh stability (Bertness, 1984). Encouraging the settlement of these species may increase marsh stability; however, the construction of ancillary stabilization structures (e.g., rock sills) in living shorelines is likely one contributing factor to observed low recruitment of mussels in living shoreline by reducing larval access to the marsh surface (Bilkovic & Mitchell, 2017). This suggests that using sills to increase edge stability has the potential to affect marsh-wide stability. However, with careful design, impacts from sills can be minimized; enhancing overall marsh resilience. When sills are necessary or desirable to promote sediment accretion and reduce erosion, the use of low elevation sills or low elevation "windows" in the sills should be considered to maximize faunal access to the marsh. Although sills can enhance living shoreline resilience, their effectiveness may decline over time. Rock sills are static structures; as sea level rises, their elevation in the tidal frame and their effectiveness in reducing wave energy will be reduced. Adding biotic components (e.g. oysters) can create a dynamic reef sill (Hall, Beine, & Ortego, 2017) that maintains its elevations under rising sea levels. The oysters also add roughness and complexity to sills, creating natural habitat and dissipating wave energy (Whitman & Reidenbach, 2012).

The slope of the living shoreline marsh and the way in which water enters and leaves the marsh may also affect its resilience. Living shorelines typically have more "perfect" slopes than natural marshes and the high and low marsh widths are controlled by design, not natural feedback loops. Water access may be through more constricted channels than in natural marshes, leading to changes in inundation periods, sedimentation patterns and plant species distributions. All of these factors can affect the living shoreline's response to sea level rise. At this time, there is little research addressing this issue. One model, which looked at the persistence of a created marsh under sea level rise, suggested that a consistent slope and controlled inundation can lead to a problematic response to sedimentation under accelerated sea level (Vandenbruwaene et al., 2011). As mentioned above, accretion is expected to increase with increasing inundation (under sea level rise); if this is not happening, the living shoreline will eventually drown. More studies of this issue should be done, both models and field tests of different grading plans (e.g. flatter gradients or more microtography) and water access designs should be studied.

Ultimately, achieving the dynamic design necessary for sea level rise resilience requires a change in attitude by engineers and property owners. Since shoreline stabilization is typically meant to "hold the line" against changing coastal boundaries, there is an expectation that the initial design is also the final design of the project. To truly incorporate sea level rise into a living shoreline requires acceptance and tolerance by the property owners for a dynamic stabilization technique—i.e. their sand and plants may move around over time by design. These shifts are necessary for the living shorelines to be resilient to storms and long-term changes in sea level. Natural succession of plant and animal species and landward retreat of marsh plants should be expected and part of the initial design (Bilkovic, Mitchell, Mason, & Duhring, 2016).

4 | MAINTENANCE

Although the goal is to design living shorelines that naturally accrete and retreat with rising sea levels, it is unrealistic to think this can be achieved in all places and human maintenance of living shorelines may be necessary. Studies of natural marshes show that sea level rise is accelerating at stressful rates in some areas, leading to marsh loss (Mitchell et al., 2017); this is likely also going to be a problem for the living shorelines in the absence of intervention. Long-term augmentation of living shoreline accretion rates may be possible through thin-layer dredge disposal. This is one method that has been used to raise natural marsh elevations (Croft, Leonard, Alphin, Cahoon, & Posey, 2006; Ford, Cahoon, & Lynch, 1999), and may be applicable to living shoreline resilience. In this process, a thin deposit of sediment is sprayed over the marsh surface, with the idea that it will be captured by the vegetation, enhancing marsh accretion. The transferability of this technique to living shorelines needs more research. Even if technically feasible, thin layer dredge disposal may be too expensive and labor intensive for smaller projects. In addition, the depth of the sediment deposit and frequency of application would need to be assessed for each project since local rates of sea level rise and subsidence can vary on small spatial scales.

5 | CONCLUSIONS

Tidal marshes are naturally adaptive systems that alter their location and elevation to fit changing sea levels. Embracing the dynamic characteristics of these systems when designing living shorelines will result in more resilient shoreline designs. Considering longevity in both project siting and project design is critical to ensuring shoreline protection and the continuation of ecological services from living shorelines. Key considerations include:

- Siting that allows for landward marsh retreat with rising sea levels, wherever possible
- Healthy and appropriate plant communities that can stabilize and accrete sediments with consideration of species diversity and density of plantings to maximize productivity and sediment accretion
- Sill structures designed to enhance sedimentation while not limiting faunal use of the marsh, including the use of "windows" in the sill to promote faunal movement; and which include biotic components, such as oysters, allowing adaptation to rising sea levels
- An improved societal understanding of the benefits of dynamic shoreline protection designs

Living shorelines are rapidly populating our coasts, and are increasingly being considered critical components of flood wave reduction and erosion protection for coastal communities (Sutton-Grier et al., 2015). The resilience of these coastal communities is reliant on the resilience of their living shorelines. A key element mentioned in this paper is the need for the integration of ecologist and engineers in the design of living shorelines. This need has been recognized (e.g. Airoldi et al., 2005; Bilkovic & Mitchell, 2017; Moosavi, 2017) and there are a few examples of it being put into practice (Chapman & Blockley, 2009; Firth et al., 2014). However, there is room for improvement. We recommend three steps towards achieving this goal. First, as mentioned in Toft et al. (2017) the creation of "virtual" forums can help facilitate discussion across disciplines. Second, funding agencies can promote transdisciplinary research through their funding programs. Third, universities can break down barriers between their educational tracks and make cross-disciplinary learning more accessible. These actions could help change the landscape of living shoreline design, resulting in more sustainable coastlines.

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AUTHORS' CONTRIBUTIONS

M.M. and D.M.B. conceived the ideas for this manuscript. M.M. led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

DATA ACCESSIBILITY

Data have not been archived because this article does not contain data.

BIOSKETCHES

M. Mitchell is an ecologist who researches wetlands, how they change and adapt under sea level rise, and how we can create systems that mimic the important processes of the natural wetland systems, with a particular emphasis on the plant communities.

D.M. Bilkovic is an ecologist and associate professor at Virginia Institute of Marine Science. She has worked on multiple aspects of the ecology of coastal habitats and assemblages. She does research on improving the understanding of social-ecological feedbacks that erode or strengthen coastal resilience, and the role of living shorelines as habitat conservation strategies.

Together they have co-edited a book on living shorelines, authored papers on living shoreline management and both have been lecturers on living shoreline at numerous educational and outreach venues. They also provide advice to state, local and public entities about the impacts of different shoreline solutions on the natural system.

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