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Living shorelines enhanced the resilience of saltmarshes to Hurricane Matthew (2016)

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Abstract. Nature-based solutions, such as living shorelines, have the potential to restore critical ecosystems, enhance coastal sustainability, and increase resilience to natural disasters; however, their efficacy during storm events compared to traditional hardened shorelines is largely untested. This is a major impediment to their implementation and promotion to policy-makers and homeowners. To address this knowledge gap, we evaluated rock sill living shorelines as compared to natural marshes and hardened shorelines (i.e., bulkheads) in North Carolina, USA for changes in surface elevation, *Spartina alterniflora* stem density, and structural damage from 2015 to 2017, including before and after Hurricane Matthew (2016). Our results show that living shorelines exhibited better resistance to landward erosion during Hurricane Matthew than bulkheads and natural marshes. Additionally, living shorelines were more resilient than hardened shorelines, as they maintained landward elevation over the two-year study period without requiring any repair. Finally, rock sill living shorelines were able to enhance *S. alterniflora* stem densities over time when compared to natural marshes. Our results suggest that living shorelines have the potential to improve coastal resilience while supporting important coastal ecosystems.

Key words: bulkhead; coastal resilience; erosion; green infrastructure; hardened shoreline; hurricane; living shoreline; marsh sill; rock sill; saltmarsh; Spartina alterniflora; *storm.*

Introduction

The issues of resilience and sustainability are critically important along coastlines, which are home to some of the most valuable habitats on Earth but also the densest human settlements (Small and Nicholls 2003, MEA 2005). Anthropogenic pressure along shorelines has historically led to degradation and decline of critical ecosystems (Lotze et al. 2006), loss of biodiversity (Worm et al. 2006), and a reduction in the ability of natural habitats to protect against and recover from disasters like hurricanes and floods (Arkema et al. 2013). As such, enhancing coastal resilience, especially to storms and sea level rise, has become a global priority (Barbier 2014, IPCC Working Group II 2014).

Resilience has been defined as the ability of an ecosystem or community to "bounce back" from or adjust flexibly to an external disturbance (Timmerman 1981). While salt marshes have been well recognized for their coastal hazard mitigation value (Shepard et al. 2011), a variety of natural and human-induced stressors (e.g., hydrological alterations, boat wakes, rapid sea level rise, landward development; Kennish 2001) can undermine their capacity for long-term resilience. Similarly, traditional hard coastal protection infrastructure, like seawalls and bulkheads, are designed to protect against erosion and enhance resistance to storms, but they fundamentally lack capacity for resilience because they weaken with time, experience high rates of damage (Thieler and Young 1991, Gittman et al. 2014), and require frequent maintenance and repairs (Sutton-Grier et al. 2015, Smith et al. 2017). Furthermore, hardened shorelines have been shown to have adverse effects on the sustainability of coastal habitats and on the biological communities that rely on them (Dugan et al. 2011, Gittman et al. 2016*b*).

Nature-based solutions, such as living shorelines (also known as hybrid infrastructure), combine some of the best characteristics of natural and engineered shorelines and they have the potential to improve coastal resilience while restoring critical ecosystems or maintaining ecosystems in areas where they might otherwise be lost (e.g., saltmarshes and oyster reefs; Sutton-Grier et al. 2015). Living shorelines have been shown to enhance services like wave amelioration, carbon sequestration, and nursery provision for juvenile fish (Scyphers et al. 2011, Davis et al. 2015, Gittman et al. 2016*a*), but successful promotion of living shorelines as an alternative to hardened shorelines will likely rely on demonstrating their effectiveness and durability first, and then promoting their ecological advantages as co-benefits (Scyphers et al. 2015, Smith et al. 2017). An impediment to this promotion is that data on living shoreline resilience to hurricane impacts (as directly compared to traditional hardened shorelines) are extremely limited (Sutton-Grier et al. 2018,

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but see Gittman et al. 2014). Accordingly, in this study we evaluated the resilience of living shorelines compared to bulkheads and natural marshes over the course of two years (2015–2017), including before and after Hurricane Matthew (2016).

Methods

Description of study sites

We investigated a common living shoreline design in the United States that combines restored salt marsh with an offshore sill (i.e., a shore-parallel, low-rising breakwater) constructed of granite rocks, which is designed to protect landward vegetation and encourage oyster recruitment (USACE 2016). Alternate designs using loose or bagged oyster shell were not the focus of this study. The sills in our study were situated below mean high water just offshore of the marsh.

From 2015 to 2017, we conducted detailed surveys at 12 sites across coastal North Carolina, USA. Each shore protection approach, including bulkhead, rock sill living shoreline, and natural marsh (Fig. 1A), was replicated within each of four regions in North Carolina (Fig. 1B). When selecting and grouping sites within regions, we maximized proximity and environmental similarities, such as shoreline orientation, fetch, and bathymetry (Fig. 1C–F). Bulkheads in all regions were constructed of vinyl sheet pile and had no marsh vegetation. Dates of bulkhead construction are unknown, but rock sills were constructed between 1991 and 2006 (Appendix S1: Table S1). Living shorelines and natural marshes were all dominated by *Spartina alterniflora*. The natural marsh sampled in the Morris Landing region in 2015 was modified by the property owner in spring of 2016; therefore, we selected a different natural marsh along the same stretch of shoreline and we sampled it before and after the hurricane (but we lack 2015 data for that site).

Field sampling

All 12 sites were initially visited and sampled in May–July 2015. On this first visit, we established five to seven (depending on shoreline length) shore-perpendicular transects at each site that ran landward and waterward of the structure or marsh edge. We established landward sampling plots at 3- or 5-m increments depending on the width of the marsh (sensu Currin et al. 2008 and Gittman et al. 2014), but this paper reports on results only to 6 m. Landward transects ran from the inside edge of the structure (or the edge of the marsh shoreline) toward upland vegetation. Waterward transects extended 6 m offshore from the waterward edge of the structure (or the edge of the marsh shoreline; see Appendix S2: Fig. S1 for sampling schematics). Transects were always resampled according to their location in 2015 (i.e., if the marsh edge migrated landward, the plot locations did not move).

Within each plot along the landward transects, we measured surface elevation and *S. alterniflora* stem densities within a 0.25-m^2 quadrat. To measure elevation, we established a semi-permanent benchmark at each site (e.g., stainless steel screw in a piling) and used a leveling rod and rotary laser level to measure elevation in the bottom left-hand corner of each plot relative to that benchmark ($\pm$5 mm/100 m; Currin et al. 2008). At the end of our first sampling period, in August 2015, we used a Real-Time Kinematic Virtual Reference Station (RTK-VRS; Trimble Inc., Sunnyvale, California, USA) to determine the elevation of the benchmark at each site relative to the North American Vertical Datum of 1988 (NAVD88) and from there we referenced the laser-leveled elevations of the plots to NAVD88 ($\pm$2 cm). *S. alterniflora* stem densities were quantified by counting each individual shoot within a 0.25-m^2 quadrat and then converting that density to 1 m^2. Stem density was not measured at bulkhead sites, because marsh vegetation was never present. For waterward transects, the -3 and -6m waterward plots were added in summer 2016.

For the subsequent rounds of sampling in May–June 2016, October 2016, and May–June 2017, we resampled every site according to the methodology above, with the exceptions that *S. alterniflora* stem densities were not quantified in summer 2016 and plot elevations were often taken directly with an RTK GPS rather than the laser level. For the Hurricane sampling in October 2016, we resampled all of our sites within 3 weeks of Hurricane Matthew, which was a Category 1 Hurricane that did not make direct landfall in North Carolina, but it hovered off the North Carolina coastline for approximately 24 h and caused severe flooding and estuarine shoreline damage in many areas of the state (Stewart 2017, Fig. 1B; see Appendix S1: Table S1 for maximum storm tides for each region).

Statistical analyses

We averaged values across transects at each site to get a mean value for stem density and elevation at each plot distance and then we calculated absolute change for each response variable from: (1) before to after Hurricane Matthew; and, (2) from 2015 to 2017 (or 2016 to 2017 for -3 and -6 m waterward plots). Landward and waterward transects were evaluated separately. We present all the vegetation data we collected, but due to the seasonality of *S. alterniflora* stem densities, we only calculated a change value from the beginning of the study to the end (summer 2015 to summer 2017). While planning this study, we expected that the greatest vegetation change would occur in the edge plots (Koppel et al. 2004), so we additionally used an *a priori* planned comparison to look at differences between stem densities exclusively at the edge plot.

For the elevation and vegetation data, we used two-way analysis of variance (ANOVA), with treatment (i.e., shoreline type) and plot distance (i.e., inside edge, 3 m, and 5/6 m for landward transects; outside edge, -3, and -6 m for waterward transects) as fixed factors and absolute change as the response variable (i.e., five separate tests). There were no significant interactions between factors, thus the interaction terms were dropped from the models (Crawley 2012). When the two-way ANOVA was significant, we ran Tukey's post-hoc tests to determine pairwise differences. The *a priori* planned comparison was evaluated using one-way ANOVA, with treatment as a fixed factor. The data required no transformations to meet the assumptions of normality or homogeneity of variance (Levene's Test, $P > 0.05$). All statistical

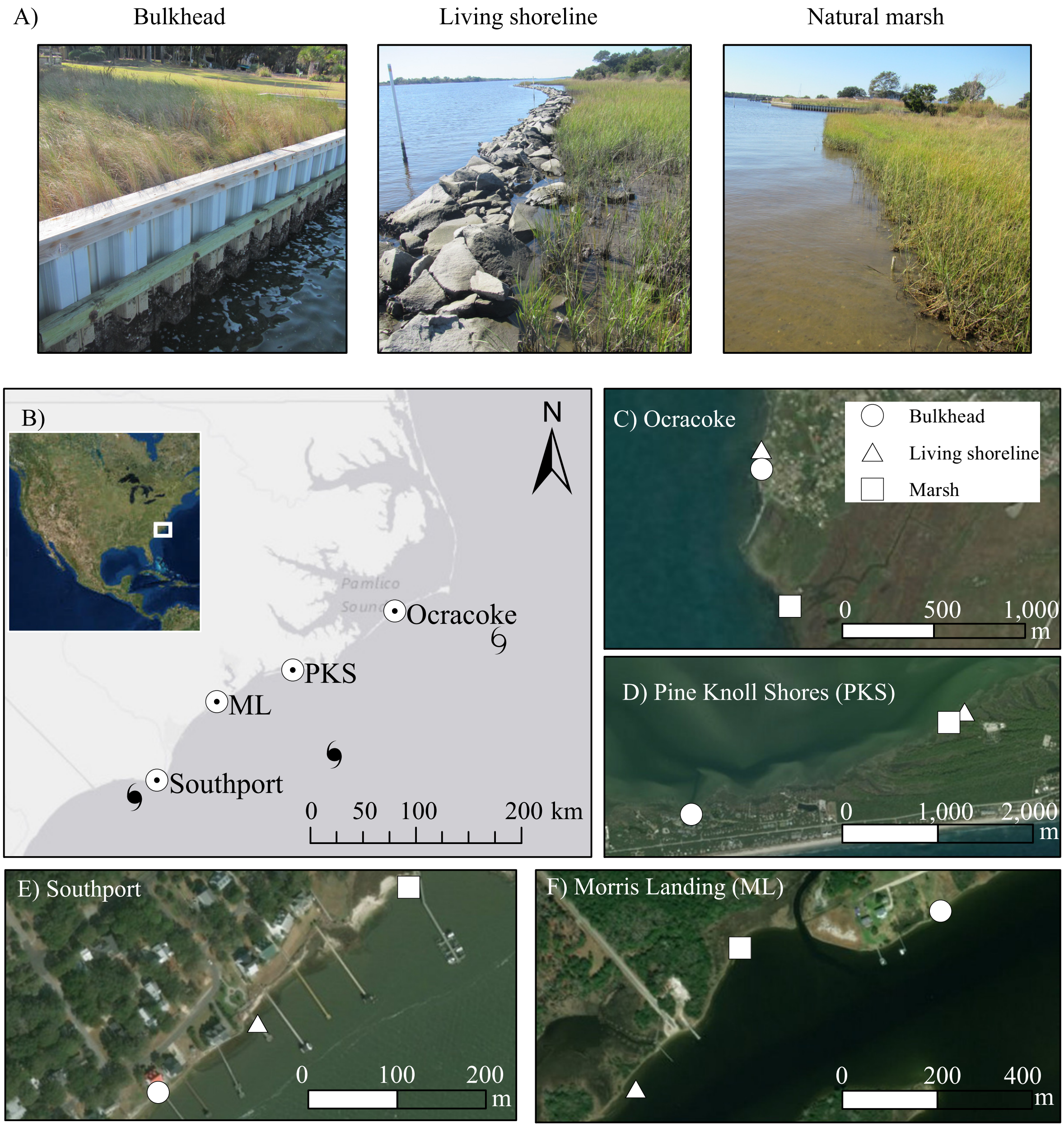

FIG. 1. (A) Photographs of each shoreline type included in this study and (B) map of all four study regions in North Carolina, USA. (C) The northernmost region located on Ocracoke Island along the Outer Banks bordering Pamlico Sound. (D) The second region located in the town of Pine Knoll Shores (PKS) along Bogue Sound. (E) The third region, Morris Landing (ML), located in Holly Ridge bordering Stump Sound. (F) The final region located in the town of Southport situated along the Cape Fear River and the Intracoastal Waterway. Hurricane symbols show the location of the eye of Hurricane Matthew at roughly 6-h intervals, and the fill indicates storm status (i.e., filled symbols indicate hurricane and open symbols indicate tropical storm).

analyses were performed in RStudio Version 0.98.1028 (RStudio Team 2016).

RESULTS

From before to after Hurricane Matthew, significantly more sediment accreted waterward of rock sills than waterward of bulkheads (two-way ANOVA, $F_{2,31} = 4.8$, $P = 0.015$; Tukey's post-hoc tests, $P = 0.04$) and natural marshes ($P = 0.02$; Fig. 2A). Plot distance was not a significant factor ($F_{2,31} = 1.5$, $P = 0.2$). Across all landward plots, natural marshes and bulkheads lost elevation during Hurricane Matthew, whereas living shorelines roughly maintained elevation (two-way ANOVA, $F_{2,29} = 3.6$, $P = 0.04$; Fig. 2B); this difference was significant between living shorelines and natural marshes (Tukey's post-hoc tests, $P = 0.04$), but not between living shorelines and bulkheads ($P = 0.16$). There were no differences in landward elevation change across plot distances ($F_{2,29} = 0.9$, $P = 0.4$). Additionally, three of the four bulkheads we sampled showed visual evidence of some kind of storm damage, ranging from minor landward scour directly inside of the bulkhead in Southport to structural

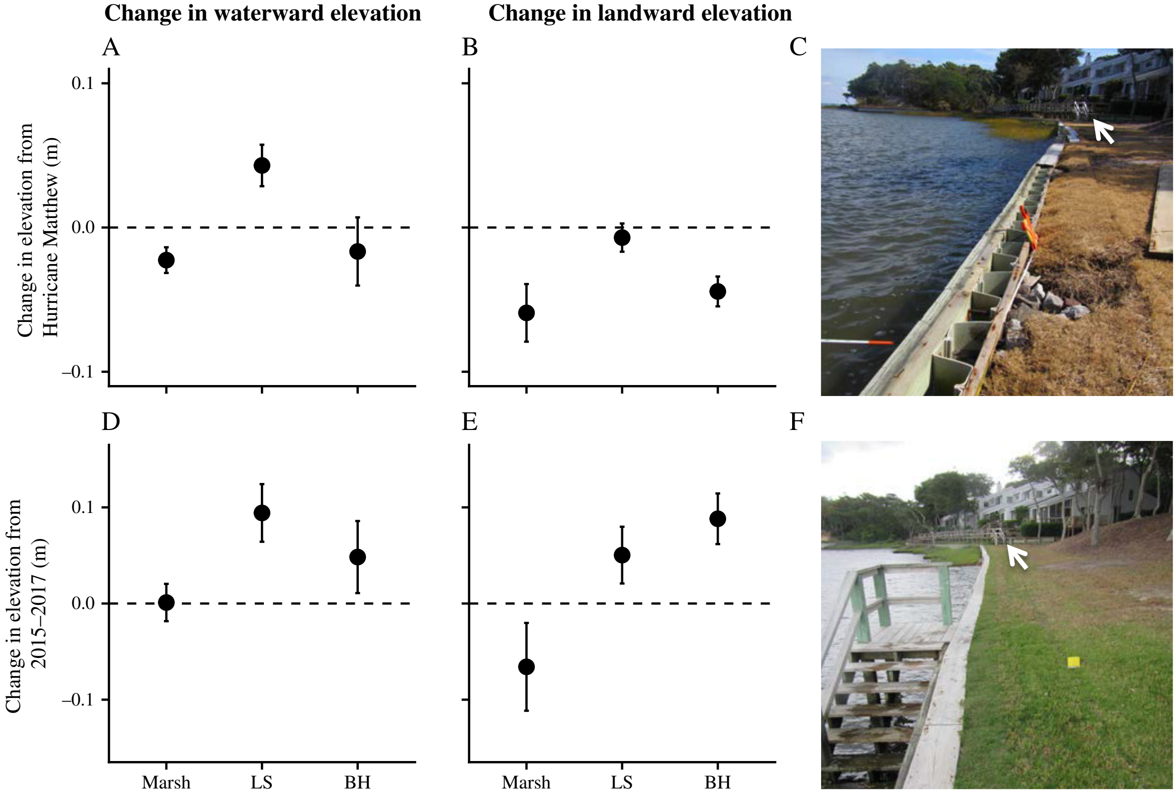

FIG. 2. (A, B) Change (mean ± SE) in absolute elevation by shoreline type from before (May/June 2016) to after Hurricane Matthew (October 2016) in (A) waterward plots and (B) landward plots. (C) Photograph taken in October 2016 documenting hurricane damage at the bulkhead site in Pine Knoll Shores (PKS). (D, E) Change (mean ± SE) in absolute elevation by shoreline type from the beginning to the end of the study (2015–2017) in (D) waterward plots and (E) landward plots. (F) Photograph taken in June 2017 documenting bulkhead repair and re-sodding at PKS (the white arrows indicate the same reference point within the two photographs). *X*-axis labels correspond to treatment: Marsh = natural marsh; LS = living shoreline; BH = bulkhead.

damage and landward erosion at the Ocracoke and Pine Knoll Shores bulkheads (Fig. 2C). Living shorelines showed no visual signs of damage or erosion from the hurricane.

Over the entire study period, there were no significant differences in waterward elevation change among shore types (two-way ANOVA, $F_{2,31} = 2.4$, $P = 0.1$) or plot distances ($F_{2,31} = 0.7$, $P = 0.5$; Fig. 2D). In landward plots, however, rock sill living shorelines and bulkheads both maintained landward elevation better than natural marshes (two-way ANOVA, $F_{2,28} = 5.0$, $P = 0.01$); this difference was significant between bulkheads and natural marshes (Tukey's post-hoc test, $P = 0.01$), but only marginally significant between living shorelines and marshes ($P = 0.07$; Fig. 2E). Elevation change was not significantly different across plot distances ($F_{2,28} = 0.2$, $P = 0.8$). Gains in landward elevation at bulkhead sites over the course of the study were primarily due to homeowner repair following Hurricane Matthew (e.g., the bulkhead that was damaged in Pine Knoll Shores during Hurricane Matthew was repaired and re-sodded by the summer of 2017 [Fig. 2F] and we suspect that the bulkhead in Southport had sand added behind the structure).

The change in *S. alterniflora* stem densities over the entire study period was not significantly different between marshes and living shorelines (two-way ANOVA, $F_{1,18} = 1.9$, $P = 0.2$) or among plot distances ($F_{2,18} = 1.5$, $P = 0.3$; Fig. 3A). However, there was a significant difference between shoreline type at the edge plot alone (planned comparison, one-way ANOVA, $F_{1,6} = 6.2$, $P = 0.048$), with stem density at the landward edge of rock sills exhibiting an increase over the course of the study and marshes exhibiting a decrease (Fig. 3B).

DISCUSSION

Our results suggest that rock sill living shorelines can be more resilient to the impacts of a category 1 hurricane than traditional hardened shorelines and natural marshes, while still maintaining coastal habitats. Living shorelines have the potential to increase not just ecological but also socioeconomic resilience, because they have the capacity for self-sustaining recovery from damage and rebuilding of elevation after storm events (Sutton-Grier et al. 2015). This is in contrast to hardened shorelines, which necessarily weaken over time and require the continual investment of money for maintenance and repair (Smith et al. 2017). Furthermore, the benefits of living shorelines extend beyond their ability to prevent erosion; unlike hardened shorelines, living shorelines come with a suite of ecological co-benefits, such as maintaining coastal saltmarsh, enhancing the nursery value of coastal habitats for fish and crustaceans (Gittman et al. 2016*a*), and increasing benthic infaunal biomass (Davenport et al. 2017). There are certainly coastal areas where vertical

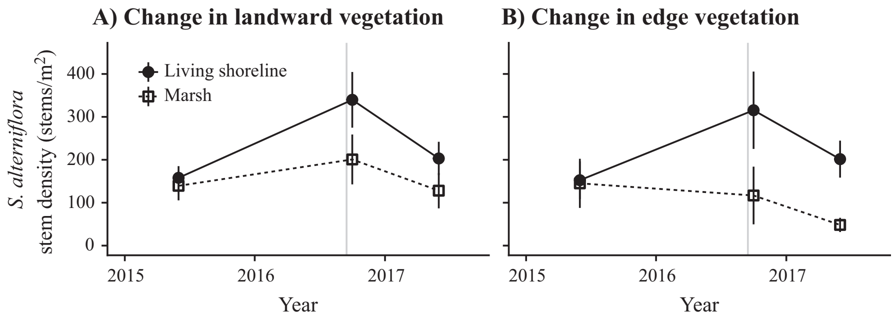

FIG. 3. Change in *Spartina alterniflora* stem density (mean ± SE) at marsh and living shoreline sites from 2015 to 2017. (A) The change in stem density across all landward plots. (B) The change in stem density at the edge plot only. The vertical gray lines indicate when Hurricane Matthew passed.

walls are the only feasible shoreline stabilization option (e.g., man-made canal systems, regions of extremely high wave action), but in areas where either a bulkhead or living shoreline would suffice, living shorelines may be more economically and ecologically sustainable in the long term.

The express purpose of a living shoreline or bulkhead structure, as permitted by the U.S. Army Corps of Engineers (USACE), is to prevent landward erosion and protect upland infrastructure, particularly during storm events (USACE 2016, 2017). During Hurricane Matthew, living shorelines were more effective at preventing landward erosion than bulkheads or natural marshes. Previous studies have shown that bulkheads can rapidly lose landward elevation during storms when over-topped or breached (Thieler and Young 1991), because the elevation landward of bulkheads is often 1–2 m above mean sea level. The elevation behind bulkheads is on average much higher than the elevation of marshes and living shorelines, and therefore a bulkhead that loses landward elevation may still have a higher ending elevation than a living shoreline or marsh. Nevertheless, there is no major mechanism other than human repair for sediment to reaccumulate behind a bulkhead, thus limiting their resilience. It is worth mentioning that aeolian redistribution of sand may be an occasional (but probably uncommon) mechanism by which some bulkheads regain landward elevation. We suspect this may have occurred at the bulkhead in Ocracoke (which had an eroding beach right next to it), because we saw minor landward elevation gains after Hurricane Matthew but homeowner repair was unlikely.

In addition to landward elevation loss, we also documented visual damage at three out of the four bulkheads that we surveyed and at least one of those bulkheads was definitively repaired by homeowners within nine months of the storm. Construction firms often claim that vinyl bulkheads have a lifespan of 50+ yr. While the precise dates of bulkhead construction in our study are unknown, we believe that they were all constructed after 1983 (D. Govoni, *personal communication*). With that said, a 50+ yr lifespan claim may belie the fact that bulkheads often require frequent repairs and maintenance (Gittman et al. 2014, Smith et al. 2017). In the last decade alone, an extraordinary amount of human and monetary resources have been spent cleaning up after natural disasters. In fact, 2017 is expected to be the most expensive hurricane season on record in the United States because of damages associated with Hurricanes Harvey, Irma, and Maria (NOAA 2017). These costs can be attributed in part to shoreline infrastructure that failed or was damaged during the storms, which could represent a significant financial burden to coastal property owners and municipalities over time. A notable limitation of our study is that we only investigated damage to shoreline structures themselves and changes in elevation and vegetation within a relatively small swath of shoreline (i.e., −6 to 6 m). It is possible that while bulkheads are experiencing high rates of damage and loss of elevation directly behind the structure, that they are still doing a superior job at protecting upland infrastructure. Many more data are needed that actually look at the rates of damage to infrastructure behind different built defenses in order to answer this question.

We documented scour occurring at the waterward edge of bulkheads from before to after Hurricane Matthew. Scour could undermine the structural integrity of a bulkhead and, when combined with landward erosion, may contribute to its failure during a storm or make it more vulnerable to a subsequent storm (Camfield 1994). Furthermore, persistent scour at the toe of a bulkhead has long been considered as a mechanism leading to the loss of important intertidal habitat such as saltmarsh (Currin et al. 2008). In contrast to bulkheads, rock sills accreted sediment waterward of the structure. If waterward sediment accretion continues, it could lead to shallowing along the shoreline, which may increase intertidal habitat, but could also ultimately restrict boat access or necessitate dredging.

On average, both living shorelines and bulkheads increased in landward elevation from 2015 to 2017, whereas natural marshes lost elevation, though most bulkhead elevation gains were necessarily the result of homeowner repair. This suggests that living shorelines with an offshore breakwater can be effective at trapping sediments. Currin et al. (2008) similarly found that rock sill living shorelines in North Carolina had accretion rates 1.5–2.0 times higher than natural marshes, and attributed these differences in sedimentation rates to the presence of the breakwater. Under future climate change scenarios, high sediment accretion behind the sill may increase the ability of marshes to keep pace with sea level rise. Furthermore, living shorelines enable saltmarsh to transgress landward unimpeded with rising water levels, unlike hardened shorelines, which create a barrier to migration and can ultimately contribute to saltmarsh loss in areas where sediment accretion is low. Relatedly, over the course of our two-year study, the edge vegetation at natural marshes was almost completely lost, whereas *S. alterniflora* stem densities at the inside edge of living shorelines increased. This suggests that living shorelines may be able to maintain coastal saltmarsh and its associated ecosystem services in areas where saltmarsh might otherwise be lost. This is in contrast to hardened shorelines sampled in this study where saltmarsh vegetation was never present. Finally, the construction of rock sill living shorelines should not be considered a direct substitute for marsh restoration and conservation. In lower-energy environments and at larger scales, traditional strategies like marsh replanting, hydrological restoration, or thin-layer deposition are just a few approaches that may be more cost-effective and appropriate (Raposa et al. 2016).

The hardening of natural shorelines may result in the creation of distinct shoreline environments that are governed by different forces. For example, Leonardi et al. (2016) found that hurricane events contributed to less than 1% of long-term saltmarsh erosion in the United States, suggesting that average wave climate is the most important erosive force in salt marshes. On the other hand, hardened shorelines are likely to be quite resistant to average wave climate, but they have been shown to be vulnerable to extreme weather events (Thieler and Young 1991, Gittman et al. 2014, Smith et al. 2017) and they lack resilience after storms because they cannot regularly reaccumulate landward elevation that has been lost. Living shorelines may be a rare win-win solution, whereby they help to reduce saltmarsh loss over the long term by buffering waves and increasing rates of sediment accretion, but also offer increased resistance during storms without the high rates of damage that have been attributed to traditional hardened infrastructure. A key component of any plan designed to enhance resilience and maintain a myriad of critical ecosystem services will be developing and promoting sustainable solutions that meet multiple social, economic, and ecological goals. Living shorelines have the potential to be such a solution, by bridging the gap between the priorities of affordable coastal erosion protection, sustainable ecosystem service delivery, and enhanced coastal resilience.

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Supporting Information

Additional supporting information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/eap.1722/full

Data Availability

Data available from the Dryad Digital Repository: https://doi.org/10.5061/dryad.nh71t5c

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