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Special Series

Coastal resilience surges as living shorelines reduce lateral erosion of salt marshes

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EDITOR'S NOTE:

This article is part of the special series "Incorporating Nature-based Solutions to the Built Environment." The series documents the way in which the United Nations Sustainable Development Goal (SDG) targets can be addressed when nature-based solutions (NBS) are incorporated into the built environment. This series presents cutting-edge environmental research and policy solutions that promote sustainability from the perspective of how the science community contributes to SDG implementation through new technologies, assessment and monitoring methods, management best practices, and scientific research.

Abstract

A growing suite of research has demonstrated that nature-based shoreline stabilization methods can increase resilience of coastal ecosystems by improving their capacity to return to predisturbance states. Previous work suggests that during hurricanes, living shorelines promote vertical accretion and experience less damage than traditional shoreline stabilization alternatives. Nevertheless, there is limited research looking at the impacts of major storm events on living shorelines and most studies have investigated a small number of sites. This study used in situ real-time kinematic (RTK)-GPS surveys to quantify the resilience (via the lateral change in shore position) of 17 living shoreline sites before and after a Category 1 hurricane event (Hurricane Florence, 2018). By doing so, this study seeks to understand the capacity of living shorelines (marsh with seaward breakwater or sill) to provide storm protection as compared to unaltered natural fringing salt marshes. After Hurricane Florence, living shorelines on average experienced significantly less lateral erosion compared to unprotected control segments (shoreline change rates of 0.015 and −0.31 m year^{-1}, respectively). This study also explores how environmental siting variables (i.e., scarp presence, fetch, and bottom sediment) and sill design variables (i.e., sill material, width, and height) influence short- and long-term erosion. living shorelines were found to reduce erosion of fringing marsh edge among projects with a range of installation ages, structural materials, sill widths, and sill heights, and they were able to provide protection from erosion across a range of fetch, scarp, and bottom sediment conditions. Living shoreline siting and sill design may be suitable for broader environmental conditions than previously known. This study shows that living shorelines can increase resilience by reducing erosion of fringing salt marshes, promoting lateral building up of shoreline zones during short-term disturbance events, and from their long-term presence. *Integr Environ Assess Manag* 2022;18:82–98. © 2021 SETAC

KEYWORDS: Coastal protection, Hurricane Florence, living shorelines, Nature-based, Shoreline management

INTRODUCTION

Risks to coastal ecosystems and communities are anticipated to increase over coming decades due to natural and anthropogenic pressures that will result in accelerated sea-level rise (SLR), increased frequency and intensity of storms, coastal flooding, land subsidence, habitat conversion, and urban development (Costanza et al., 2008; Neumann et al., 2015; Zhang et al., 2004). Among 84 countries analyzed by Neumann et al. (2015), 56–245 million people are at risk of being displaced by SLR scenarios of 1–5 m, respectively. These communities will be on the front lines of impact and produce new and innovative solutions to coastal management. Moreover, coastal populations are growing (Neumann et al., 2015), which will put additional

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stressors on vulnerable coastal ecosystems and impact their capacity to adapt to natural and anthropogenic pressures. At risk are valuable ecosystem services and functions provided by coastal ecosystems, such as estuarine salt marshes, including: Nursery habitat provisioning, water quality enhancement, nutrient cycling, pollutant filtration, storm and flood amelioration, and carbon sequestration (Barbier et al., 2011; Bozek & Burdick, 2005; Costanza et al., 2008; Craft et al., 2008).

Historically, coastal communities have addressed shore zone erosion through structural hardening of the shoreline (Dugan et al., 2011). Hardened shorelines (e.g., bulkheads, seawalls, and revetments) are intended to protect upland structures by keeping shoreline positions static. Despite their broad use, hard structures eliminate the continuum between land and water, resulting in a cascade of direct and indirect consequences along and surrounding the structure. Hardened structures act as barriers to marsh migration landward, causing coastal squeeze (loss of coastal habitat in front of a landward boundary and the low water mark migrating landward due to SLR) and inevitable loss of intertidal habitat (Kirwan et al., 2016; Pontee, 2013; Titus et al., 2009). Hard structures often result in reduced faunal and floral biodiversity and abundance, reduced sediment distribution along and adjacent to the structure, erosion and scouring of bottom habitat because of wave refraction, reduced storm protection (compared to marsh plantings with and without sills), and loss of critical intertidal ecosystem services (Bozek & Burdick, 2005; Gittman et al., 2014; Gittman, Smith, et al., 2016; Meyer & Posey, 2014; Riggs, 2001).

Impacts to coastal ecosystems and communities can be mitigated by building resilience, which is the capacity, often gauged by ability or rate of recovery, of an ecosystem or community to recover to its predisturbance state (Holling, 1973). Coastal managers and researchers have highlighted the need to build resilience so that when coastal ecosystems and communities are impacted by disturbances, such as hurricanes, they can recover rapidly and with positive outcomes (Sutton-Grier et al., 2015). One way to increase coastal resilience is with nature-based infrastructure techniques that harness the ecosystem services and adaptative capacity provided by natural habitats (e.g., salt marshes, oyster reefs, and mangroves) in combination with built infrastructure (e.g., sills, breakwaters, live-walls, and fiber coirs; Sutton-Grier et al., 2015). In particular, there has been a recent focus on living shorelines, a type of nature-based infrastructure that utilizes native vegetation, often in combination with low-lying structures (e.g., sills and breakwaters), to provide shoreline stabilization while limiting impedance or disruption of intertidal habitat (NOAA, 2015; Smith et al., 2020).

Living shorelines provide a range of ecological cobenefits and have been implemented with documented instances of success in restoring habitat and ecosystem functions, such as habitat provisioning (compared to hardened structures; Gittman, Peterson, et al., 2016; Scyphers et al., 2011) and shoreline stabilization (Gittman et al., 2014; Polk & Eulie, 2018; Smith et al., 2018). With respect to habitat provisioning, various studies have observed the capacity of living shoreline sites to mimic or enhance biomass and species diversity relative to natural sites (Currin et al., 2008; Gittman, Peterson, et al., 2016). Living shorelines also support carbon sequestration capacity (Davis et al., 2015), unlike bulkheads or revetments where salt marsh habitat is often nonexistent.

A characteristic of living shorelines that is widely promoted is their capacity to build coastal resilience by adapting to SLR by transgressing landward or by building up elevation in place (Bilkovic et al., 2016). This is critical, as the first meters of marsh edge are highly vulnerable to erosion, marsh dieback, and drowning within coming decades (Barbier et al., 2011; Tonelli et al., 2010). Living shorelines provide an unimpeded continuum of the land-sea interface, allowing for dynamic movement and landward retreat of coastal marshes in response to SLR, in contrast to bulkheads or seawalls, whose placement can result in coastal squeeze (Pontee, 2013; Titus et al., 2009). The option for landward retreat is particularly important for salt marshes and other vegetated shorelines, as they tend to be particularly vulnerable to lateral (i.e., horizontal) erosion (Bendoni et al., 2016). However, even with the landward migration option, unchecked lateral marsh erosion is problematic, as many of the critical ecosystem functions and services of salt marshes are highest within the first 10 m from the salt marsh edge (Currin et al., 2008) and edge erosion will outpace landward marsh creation in many environmental contexts.

Coastal wetlands provide hurricane protection services by serving as natural "horizontal levees" to surrounding communities (Costanza et al., 2008). Living shorelines can facilitate increases in resilience by trapping sediment, reducing wave energy, and producing organic matter that enables the ecosystem to remain resilient to storms, subsidence, climate change, and SLR (Bilkovic et al., 2016). Although storm surge attenuation by salt marshes can be negligible (due to water level height and instead offer space for floodwaters to disperse), salt marshes can attenuate wind-generated waves at a rate of half a 0.9-m wave for every 200 m of marsh (Möller et al., 2014). Even narrow (>5 m) bands of salt marsh, where living shorelines are often installed, can baffle upwards of 50% of wave energy (Leonard & Croft, 2006; Morgan et al., 2009). Low-lying sill structures, often part of a living shoreline design (NOAA, 2015), can dampen wave energy; and as with marsh grasses, the energy-dampening capacity decreases with increasing water level height.

Over a long term (years), living shorelines that include a seaward breakwater or sill have been shown to reduce the rate of lateral erosion (compared to unaltered shorelines) and in some instances facilitate shore zone building via lateral accretion (Polk & Eulie, 2018). However, there are limitations on the amount of wave energy reduction that can be provided by living shoreline sills, based on water level and sill construction (Leonard & Croft, 2006; Manis et al., 2014; Safak et al., 2020). Thus, the siting (e.g., fetch [the distance wind travels across a water body generating wave height, which is critical in fetch-limited environments], sediment supply, space for landward retreat) and design (e.g., height, width, and configuration) of sills is critical (Mitchell & Bilkovic, 2019), as the primary force causing lateral and vertical erosion of salt marsh edges is wind-wave attack (Tonelli et al., 2010). Although recent work has suggested that living shorelines with sills can prevent vertical erosion and shoreline damage from hurricanes (Gittman et al., 2014; Smith et al., 2018), more research is needed investigating the performance of a range of living shoreline sill designs in preventing lateral marsh erosion during high-energy and high-water conditions observed during hurricanes. Thus, the present study quantifies the lateral change in marsh position during a short-term period encompassing Category 1 storm event (Hurricane Florence, 2018) at living shorelines and natural marsh shorelines. This study also explores how environmental siting variables (i.e., scarp [steep slope at the shore edge] presence, fetch, and bottom sediment) and sill design variables (i.e., sill material, width, and height) influence short- and long-term erosion.

SITES

The 17 living shoreline projects and seven control (natural, unaltered marsh) sites included in this study were located across North Carolina, spanning 13 study areas, and representing a reoccupation of study shoreline segments used by Polk and Eulie (2018; Figure 1). Study sites had either living shoreline projects that were constructed between 5 and 20 years ago, or unaltered controls where no shoreline modification had occurred. All living shoreline projects were located along shorelines with fringing marshes (<20 m width), with several sites having less than 10 m of marsh habitat before transitioning to upland coastal scrub or urban lawn. Control sites are those sites where no shoreline management technique is applied and no active intervention is occurring in the shore zone and have similar morphological and vegetative characteristics as living shoreline sites (Table 1). Unaltered control sites also had fringing (<20 m) marshes that transitioned to upland coastal scrub. All living shoreline projects included the planting of *Spartina alterniflora*; however, information related to the number of plugs, extent or density of coverage, or frequency of replanting were not available. All living shoreline projects had a sill structure, but the sills varied in design (i.e., structural components, height, width, configuration) and year of installation (Table 1). Sill structural components used included bagged oyster shells, rock, oyster reef balls, or a mixture of multiple materials within the same project. The placement of structural components also varied from marsh toe sills to intertidal sills that varied from 5 to 20 m from the edge of the marsh. Some projects also included the use of graded sand fill (annotated in Table 1 under sill structural component).

Study sites were located on both estuarine back-barrier islands and the continental mainland. The northern-most study sites were located within the Albemarle-Pamlico

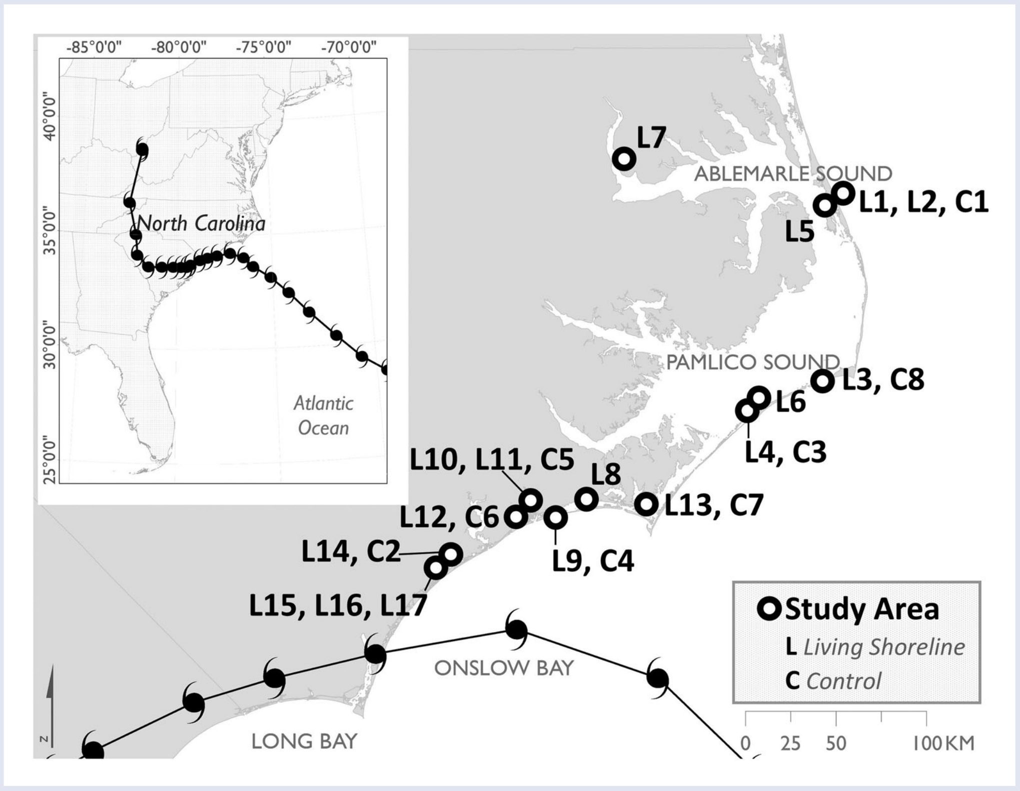

FIGURE 1 Map of North Carolina presenting the track of Hurricane Florence (September 2018), a Category 1 storm, which made landfall in at Wrightsville Beach, North Carolina (black track line and storm icon). Living shoreline (L) and control shoreline (C) segments are located across 13 shoreline study areas (outlined white circle) across the state (nomenclature aligns with Table 2)

TABLE 1 Characteristics of living shoreline design and site

Location	Installation year	Structure material	Height (m)	Width (m)	Segment length (m)	Mean fetch (km)	Max fetch (km)	Sand/muck dominant	Scarp presence	Dominant shore zone vegetation
Living Shoreline 01	2008	Oyster bag sill	0.284	2.85	152	8.8	15.7	Sand	No	*Juncus roemerianus*
Living Shoreline 02	2011	Oyster bag sill	0.1775	2.25	131	8.8	15.7	Sand	No	*J. roemerianus*
Living Shoreline 03	2011	Rock sill	–	–	113	39.6	72.9	Sand	No	*J. roemerianus*
Living Shoreline 04	2012	Rock marsh-toe sill, oyster bag sill	0.748	2.47	264	20	52.6	Mix	Yes	*Sporobolus alterniflora*
Living Shoreline 05	2002	Sand fill, rock sill	1.025	3.8	183	1.8	1.8	Muck	Yes	*J. roemerianus*
Living Shoreline 06	2009	Sand fill, rock sill, oyster bag sill	–	–	585	38.2	38.2	Sand	No	*S. alterniflora*
Living Shoreline 07	2003	Sand fill, rock sill	–	–	131	4.3	5.5	Sand	No	*S. alterniflora*
Living Shoreline 08	2002	Oyster bag sill	0.53	2.52	223	3.6	5.3	Mix	Yes	*S. alterniflora*
Living Shoreline 09	2013	Oyster bag sill	–	–	85	3.6	5.3	Mix	Yes	*S. alterniflora*
Living Shoreline 10	2008	Oyster bag sill	0.27	1.9	248	1.9	2.8	Sand	No	*S. alterniflora*
Living Shoreline 11	2011	Oyster bag sill	0.47	1.5	144	1.9	2.8	Sand	No	*S. alterniflora*
Living Shoreline 12	2000	Sand fill, rock sill	–	–	78	0.3	0.5	Mix	Yes	*J. roemerianus*
Living Shoreline 13	2004	Rock sill	–	–	397	3.1	5.7	Mix	Yes	*S. alterniflora*
Living Shoreline 14	2003	Rock sill	–	–	71	1	1.9	Mix	Yes	*S. alterniflora*
Living Shoreline 15	2005	Rock sill	0.455	2.29	170	0.9	1.5	Muck	No	*S. alterniflora*
Living Shoreline 16	2011	Sand fill, oyster bags over rock sill, oyster balls	0.3	1.6	75	0.9	1.5	Muck	No	*S. alterniflora*

(Continued)

TABLE 1 (*Continued*)

Location	Installation year	Structure material	Height (m)	Width (m)	Segment length (m)	Mean fetch (km)	Max fetch (km)	Sand/muck dominant	Scarp presence	Dominant shore zone vegetation
Living Shoreline 17	2011	Sand fill, oyster bags over rock sill, oyster balls	–	–	53	0.9	1.5	Muck	Yes	*S. alterniflora*
Control 1	–	–	–	–	127	8.8	15.7	Sand	No	*J. roemerianus*
Control 2	–	–	–	–	116	1	1.9	Mix	Yes	*S. alterniflora*
Control 3	–	–	–	–	208	20	52.6	Mix	Yes	*S. alterniflora*
Control 4	–	–	–	–	177	3.6	5.3	Mix	Yes	*S. alterniflora*
Control 5	–	–	–	–	125	1.9	2.8	Sand	No	*S. alterniflora*
Control 6	–	–	–	–	657	0.3	0.5	Mix	Yes	*J. roemerianus*
Control 7	–	–	–	–	120	3.1	5.7	Mix	Yes	*S. alterniflora*
Control 8	–	–	–	–	406	20	52.6	Mix	Yes	*S. alterniflora*

Note: All sites experienced *Sporobolus alterniflora* planting; records on number of plugs, acreage covered, and frequency of replanting were not available at the time of this study. Scarp presence annotated if scarp observed along more than 25% of shoreline. Dominant structural materials are listed first.

estuarine system, which is dominated by wind and barometric pressure tides (~0.3 m tidal amplitude). The northern coast of North Carolina is gently sloped (1 m km^{-1}) up to the Suffolk shoreline geologic formation. It is dominated by Piedmont-draining rivers with high-suspended sediment and long barrier islands with few inlets, which result in wind-tide and wave dominated systems, high salinity gradients, and irregular floods (Riggs et al., 2008). Shoreline segments located in the northern region tended to have a larger mean and maximum fetch than those in the southern portion of the state, due to the underlying geology (Table 1). The southern coast of North Carolina has steeper slopes (3 m km^{-1}) due to the Cape Fear Arch geologic formation (van de Plassche, 2014). The southern coast has coastal plain-drained rivers with low suspended sediment, shorter barrier islands with many inlets and high salt-water exchange, which result in a regularly flooded, astronomical tidal system with brackish salinity (Riggs et al., 2008; van de Plassche, 2014). The southern sites experienced a semidiurnal tidal cycle (~1.25 m tidal amplitude) along the Intracoastal Waterway and had respectively lower fetch than the Northern sites.

METHODOLOGY

Hurricane Florence impacted coastal North Carolina on September 12, 2018, making landfall as a Category 1 storm at Wrightsville Beach, New Hanover County. Hurricane Florence produced a storm surge of over 3 m and an average of 50 cm of rain over 3 days, resulting in unprecedented damage and flooding in eastern North Carolina; it is the most expensive and one of the deadliest modern disasters in North Carolina history (Stewart & Berg, 2019). To quantify the impacts of Hurricane Florence on estuarine shoreline erosion, in situ shoreline surveys were conducted using a high resolution (mm-accuracy) real-time kinematic (RTK)-GPS unit at 17 living shoreline projects and seven unaltered control shoreline segments along the North Carolina coastline. Geospatial analysis was conducted to determine shoreline change rate (SCR) relative to the North American Vertical Datum of 1988 (NAVD88; Eulie et al., 2013; Polk & Eulie, 2018). Pre-Hurricane Florence data were collected for all sites in June 2015 or in June and July 2017 (Table 2). During the pre-Hurricane Florence period, one hurricane passed North Carolina. Hurricane Matthew passed offshore of southeastern North Carolina on October 8, 2016 as a Category 1 storm, downgrading to a post-tropical storm offshore of the Outer Banks (sustained wind of 124 kph, gust of 156 kph at Nags Head, North Carolina; Stewart, 2017). Overall, Hurricane Matthew resulted in storm surge between 0.3 to 1.2 m. Beachfront erosion was prevalent in the Oak Island, NC region, where barrier islands are shore perpendicular to the storm track (Armstrong, 2017). The southernmost site was approximately 80 km northeast of Oak Island, NC and Hurricane Matthew passed approximately 80 km from the southernmost site. Post-Hurricane Florence data were collected in the 3 months following the storm event in 2018. One-year recovery data were collected for eight of the original 24 shoreline segments in August 2019—data were not collected at the remaining shorelines due to the impact of Hurricane Dorian, which made landfall at Cape Hatteras, NC as a Category 1 storm in September 2019 and impacted all study sites because of its path from south to northeast along the North Carolina coast.

The shoreline position at all sites was determined by surveying with the RTK unit along the edge of the marsh platform, line of stable vegetation, or the wet–dry line based on the type of shore habitat present (Eulie et al., 2013; Geis & Bendall, 2010; Moore, 2000; Polk & Eulie, 2018). Within North Carolina estuarine tidal marshes, peak biomass of vegetation ranges from late August to October and after the seasonal senescence of marsh grasses occurs, remnants of same-year stems can be observed into December. Accordingly, it was still possible to observe the line of stable vegetation during the fall-winter transition when the 2018 post-Hurricane Florence surveys were conducted.

The annualized shoreline position uncertainty (U) was calculated following Polk and Eulie (2018; Table 2). Real-time differential correction for the RTK-GPS (±0.025 m) was used with a conservative technician collection accuracy of ±0.25 m to calculate U (Eulie et al., 2013; Polk & Eulie, 2018). Lateral shore positions were compared between different moments in time (i.e., installation year derived from aerial imagery by Polk and Eulie (2018), pre-Hurricane Florence survey derived from in situ surveys in June 2015 or in June and July 2017, post-Hurricane Florence survey derived from no more than 3-months post storm, and recovery survey from 1-year post storm) to determine SCR for study time periods (i.e., short-term, long-term) using the software package Analyzing Moving Boundaries Using R (AMBUR), which was processed through the programming environment R (Jackson et al., 2010, 2012; R Core Team, 2017). Long-term SCR was derived from Polk and Eulie (2018) and represents the period after installation of a living shoreline project until the pre-Florence survey date (derived from in situ surveys in June 2015 or in June and July 2017; Table 2). Short-term SCR represents the annualized change in shore position from the pre-Hurricane Florence survey to the post-Hurricane Florence survey (derived from no more than 3-months post September 2018; Table 22). The 1-year recovery SCR represents the annualized change in shore position from post-Hurricane Florence survey to reoccupation of study sites in August 2019.

In addition to shoreline position data, rapid in situ observations of the presence of vertical marsh scarps (i.e., where the marsh slope reaches a maxima resulting in abrupt shoreward-edge change in elevation) were noted when more than approximately 25% of the study shoreline had a scarp (Phillips, 1986; Tonelli et al., 2010). Scarp formation in salt marshes is a common feature and is primarily caused by wind-wave attack that can be depth- or fetch-limited, depending on the system, and may switch between the two during storm events (Eulie et al., 2017; Phillips, 1986; Tonelli et al., 2010). Shorelines with scarps are more likely to experience higher erosive influences overall and during storm events than shore edges that are sloped

TABLE 2 Results of shoreline change rate (SCR; meters per year) long-term (the positional difference in SCR from project installation to before the storm), post-hurricane short-term (the positional difference in SCR from before to the hurricane to immediately after the hurricane), and 1-year recovery (2019) represented in meters per year

Shoreline segment code	Long-term SCR$^+$	Pre-Florence survey date	Post-Florence survey date	Short-term SCR	Post-Florence *U*	Post-Florence net change	One-year recovery survey date	One-year recovery SCR	One-year recovery *U*	One-year recovery net change
Living Shoreline 1	0.34	7/2015	11/2018	0.14	±0.08	0.45	8/2019	−0.74	±0.25	−0.55
Living Shoreline 2	−0.72	7/2015	11/2018	−0.53	±0.08	−1.76	8/2019	−0.32	±0.25	−0.24
Living Shoreline 3	−0.26	6/2015	11/2018	0.042	±0.08	0.14	8/2019	0.04	±0.25	0.03
Living Shoreline 4	−0.25	7/2015	11/2018	−0.11	±0.08	−0.38	8/2019	0.29	±0.25	0.22
Living Shoreline 5	−0.11	6/2017	11/2018	−0.11	±0.25	−0.15	8/2019	0.18	±0.25	0.13
Living Shoreline 6	1.44	6/2017	11/2018	−0.071	±0.25	−0.097				
Living Shoreline 7	0.019	6/2017	11/2018	0.34	±0.25	0.47				
Living Shoreline 8	−0.044	5/2017	11/2018	−0.41	±0.08	−0.64				
Living Shoreline 9	−0.16	7/2015	11/2018	−0.087	±0.08	−0.29				
Living Shoreline 10	−0.17	6/2015	11/2018	0.29	±0.08	1.00				
Living Shoreline 11	−0.33	6/2015	12/2018	0.22	±0.08	0.76				
Living Shoreline 12	0.26	5/2017	12/2018	0.047	±0.25	0.07				
Living Shoreline 13	−0.37	5/2017	12/2018	0.35	±0.25	0.54				
Living Shoreline 14	0.25	6/2017	12/2018	−0.09	±0.25	−0.14				
Living Shoreline 15	0.95	6/2015	10/2018	0.31	±0.08	1.02				

(*Continued*)

TABLE 2 (*Continued*)

Shoreline segment code	Long-term SCR$^+$	Pre-Florence survey date	Post-Florence survey date	Short-term SCR	Post-Florence *U*	Post-Florence net change	One-year recovery survey date	One-year recovery SCR	One-year recovery *U*	One-year recovery net change
Living Shoreline 16	−0.65	6/2015	10/2018	0.07	±0.08	0.22				
Living Shoreline 17	−0.13	6/2015	10/2018	−0.15	±0.08	−0.49				
Control 1	−0.93	7/2015	11/2018	−0.43	±0.08	−1.42	8/2019	−0.19	±0.25	−0.14
Control 2	0.079	6/2017	12/2018	−0.14	±0.25	−0.21				
Control 3	−0.21	7/2015	11/2018	−0.58	±0.08	−1.91	8/2019	−0.87	±0.25	−0.65
Control 4	−0.55	7/2015	12/2018	−0.28	±0.08	−0.94				
Control 5	−0.42	6/2015	12/2018	−0.46	±0.08	−1.61				
Control 6	0.18	5/2017	12/2018	0.017	±0.25	0.026				
Control 7	−0.67	5/2017	12/2018	−0.32	±0.25	−0.48				
Control 8[a]	−0.31	6/2015	11/2018	−1.63	±0.08	−5.51	8/2019	0.23	±0.25	0.17

Note: Net change represents the overall change between time periods in meters. Polk and Eulie (2018), representing the period after installation of a living shoreline project to pre-Florence survey date.

[a] This shoreline segment was not used in statistical analysis due to presence of overwash fan from Hurricane Florence.

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(Tonelli et al., 2010). Rapid in situ assessment of dominant bottom sediment texture was also conducted via the random sampling of benthos across each study site and hand-texturing sediment into sandy, mixed, or silty dominant categories. All structural materials used in project designs were also annotated from most dominant to least dominant material used. Structures were generalized by their most dominant material used (i.e., oyster bags, rock) for statistical analysis.

Data on sill structure dimensions (width and height) for nine of the 17 living shoreline projects were also collected using an RTK unit at an accuracy of ±0.025 m; these data were collected in 2018 before Hurricane Florence (Table 1). The average structure width represents the shore-perpendicular (from waterward to landward) size of the project on the day of measurement. The average structure height represents the difference of the waterward seabed-base of the structure and center point of the structure. Although this does not provide insight related to the exact sill height to water depth relationship, all structures are fully submerged or nearly fully submerged at mean high water and it does provide insight into variation in sill design performance. Data (e.g., water body depth) related to fetch and wave climate were limited; instead, back of the envelope fetch estimates were calculated using U.S. Army Corps of Engineers Waves.toolbox designed for ESRI ArcGIS software following methodology by Rohweder et al. (2008; Table 1).

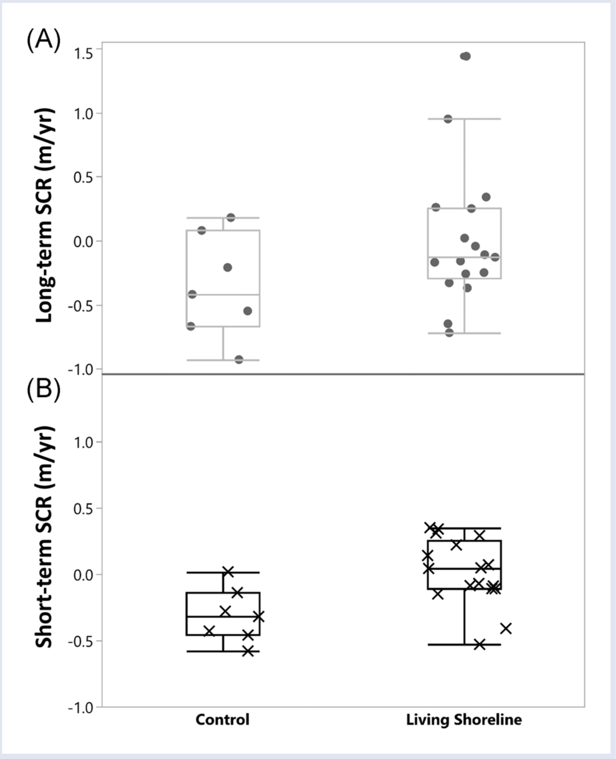

FIGURE 2 The box plot presents the minimum, quantile 1, median, quantile 3, and maximum data for control shorelines and living shorelines (A) long-term shoreline change rate (SCR) (m year^{-1}) and (B) short-term SCR (m year^{-1})

Statistical analysis

To understand how the presence of a living shoreline effects short-term SCR, a two-way analysis of variance (ANOVA) was conducted including treatment (i.e., living shoreline vs. natural reference marsh), scarp (i.e., presence vs. absence), and their interaction on post-hurricane short-term SCR (the positional difference in SCR from before the hurricane to immediately after the hurricane) as the response variable. Statistical analysis to understand how the presence of a living shoreline effects long-term SCR was conducted in Polk and Eulie (2018).

To understand the impact of different environmental siting and living shoreline design variables on SCR, we ran a series of additional tests. Among living shoreline projects, a two-way ANOVA was conducted to compare the effect of dominant sill material (oyster bag vs. rock), dominant benthic sediment type, and their interaction on post-hurricane short-term SCR, and a second two-way ANOVA was performed on long-term SCR. Additionally, a one-way ANOVA was performed comparing the age of living shoreline projects to short-term SCR as the response, and a second one-way ANOVA was performed on long-term SCR as the response. Anderson–Darling tests for normality of variables and test for homogeneity of variance were conducted to ensure that data met the assumption for normality and homogeneity.

For the analysis that included long-term SCR as a response, living shoreline 6 long-term SCR (1.44 m year^{-1}) was excluded from the analysis as an outlier (after removal Anderson-Darling: $p = 0.259$; Figure 2A). After Hurricane Florence, one shoreline segment (site: Control 8; study area in the Pamlico Sound), experienced an estuarine-side overwash fan that impacted a large portion of the shoreline segment of study. Site specific results are reported in Table 2 but was excluded from statistical analysis as an outlier. Control 8 results are reported because of the relevance of the data as there is limited availability of high-resolution SCR data 1 year after a Category 1 storm event. Specifically, the long-term SCR was −0.31 m year^{-1}, whereas after Hurricane Florence, the site appears to have eroded substantially; however, the dramatic change in SCR to −1.63 m year^{-1} was due to the formation of an overwash fan. Among those shorelines that were able to be surveyed 1 year after the storm, Control 8 experienced the only positive recovery rates among control segments, 0.23 m year^{-1}. This positive lateral change may be due to the survival and reestablishment of buried *Sporpbolus alterniflora* on the overwash fan, similarly to the effects of thin-layer sediment placement on tidal marshes (Croft et al., 2006; Walters & Kirwan, 2016).

Additionally, multiple linear regression analysis was calculated to predict post-hurricane short-term SCR based on mean fetch and maximum fetch, and a second multiple linear regression analysis was calculated to predict long-term SCR. Finally, an analysis was conducted using average height and width on a subset of the nine living shoreline projects. On this data, a multiple linear regression was

TABLE 3 Overall average of shoreline change analysis comparing living shoreline projects and control shoreline segments during long-term (the positional difference in shoreline change rate (SCR) from project installation to before the storm), post-hurricane short-term (the positional difference in SCR from before to the hurricane to immediately after the hurricane, and 1-year recovery (2019) represented in meters per year

	Long-term				Short-term				1-year recovery			
	n	Min.	Max.	Average	*n*	Min.	Max.	Average	*n*	Min.	Max.	Average
Living Shoreline	17	−0.72	1.44	0.004	17	−0.53	0.35	0.015	7	−0.97	0.23	0.18
Control	7	−0.93	0.18	−0.36	7	−0.58	0.017	−0.48	2	−0.87	−0.19	−0.53

calculated where average height and average width of sill were compared to post-hurricane short-term SCR, and a second multiple linear regression analysis was calculated to predict long-term SCR. Tests were conducted using SAS JMP 14.0 (SAS Institute, 2019).

RESULTS

Before Hurricane Florence in 2018, the long-term (the positional difference in SCR from project installation to before the storm) SCR indicated lower rates of erosion at sill-based living shorelines relative to control sites (Polk & Eulie, 2018). In short, Polk and Eulie (2018) found living shoreline long-term SCR ranged from −0.72 to 1.44 m year^{-1}, with an average gain of 0.004 m year^{-1} (Table 3; Figure 2A). The long-term SCR among control segments ranged from −0.93 to 0.18 m year^{-1} with an average lateral loss of −0.36 m year^{-1}.

After Hurricane Florence, the short-term (the positional difference from before the hurricane to immediately after the hurricane) SCR revealed an overall reduction in the rate of loss among living shoreline and control segments; short-term SCR among living shoreline projects ranged between −0.53 and 0.35 m year^{-1}, with an average gain in SCR of 0.015 m year^{-1} (Table 3). The 17 living shoreline projects experienced an average net (overall change in shore position during this period) accretion of 0.04 m. Of the 17 living shorelines, 12 experienced positive lateral shoreline change or a reduction in the rate of erosion compared to their respective long-term SCR. The short-term SCR among the 7 control segments post-Florence ranged between −0.58 and 0.017 and experienced an average lateral loss of −0.31 m year^{-1}. In contrast, during this period, three of the seven control shoreline segments experienced a reduced rate of erosion (Table 3). Although some individual study segment SCRs are within uncertainty margins, the overall results illustrate trends towards lateral erosion or accretion over time (Table 2).

Post-storm event occupation of shoreline segments showed that overall living shoreline projects experienced lateral accretion rates compared to unprotected control segments that experienced more erosion, 0.015 m year^{-1} and −0.31 m year^{-1}, respectively (Table 3). During short-term major storm events, living shorelines experienced significantly less erosion than sites without installed shore protection (two-way ANOVA: $F_{1,23} = 6.46$; $p = 0.019$; Figure 2B). Further, Cohen's effect size value (Cohen's $d = 1.192$) suggested high practical significance. There was no significance in the presence of a scarp on observed SCR ($F_{1,23} = 0.002$; $p = 0.97$), nor was there an interaction between presence of a scarp and the type of shoreline ($F_{1,23} = 0.82$; $p = 0.375$).

Living shoreline project characteristics and siting

Among living shoreline projects, sill and siting characteristics varied between projects but were generally consistent in their short- and long-term performance capacity. During the short-term (before the storm to immediately after) period, there was no significant difference between the performance of sites with sills made of oyster bags or made of rocks (two-way ANOVA: $F_{1,16} = 0.16$; $p = 0.70$; Figure 3), the dominant bottom sediment texture ($F_{2,16} = 0.042$; $p = 0.96$), or the interaction between the sill structure material and the type of bottom sediment ($F_{2,16} = 0.13$; $p = 0.88$). During the long-term (between installation and before the storm) period, there was no significant difference between the performance of sites with sills made of oyster bags or made of rocks (two-way ANOVA: $F_{1,16} = 1.50$; $p = 0.25$), the dominant bottom sediment texture ($F_{2,16.0} = 0.36$; $p = 0.71$), or the interaction between the sill structure material and the type of bottom sediment ($F_{2,16} = 1.16$; $p = 0.35$). Six of the 17 living shorelines were known to incorporate sand fill as part of the design process and this was found to not be significant in the short- or long- term performance, Welch's *t*-Test: $t(1, 13.02) = 0.38$; $p = 0.90$ and $t(1, 10.74) = 0.99$; $p = 0.007$, respectively; Table 1). Living shorelines experienced reduced erosion regardless of sill structure material or dominant bottom sediment texture (Figure 3). Long-term, there was a slightly weak positive trend in reducing erosion with the use of rock sills and in mixed benthos sediment (long-term: $R^2 = 0.34$; short-term: $R^2 = 0.03$).

No statistical difference was observed between living shoreline projects of various ages and their performance over the short-term (one-way ANOVA: $F_{1,16} = 0.44$; $p = 0.51$; Figure 4) nor long-term (one-way ANOVA: $F_{1,16} = 0.90$; $p = 0.36$). Living shorelines reduced erosion regardless of age, with a weak negative trend between site age and erosion rate—in other words, a slightly positive trend between age and accretion (long-term trend: $R^2 = 0.053$; short-term trend: $R^2 = 0.025$).

A multiple regression analysis was conducted to investigate whether mean fetch and maximum fetch could significantly predict the performance of living shorelines

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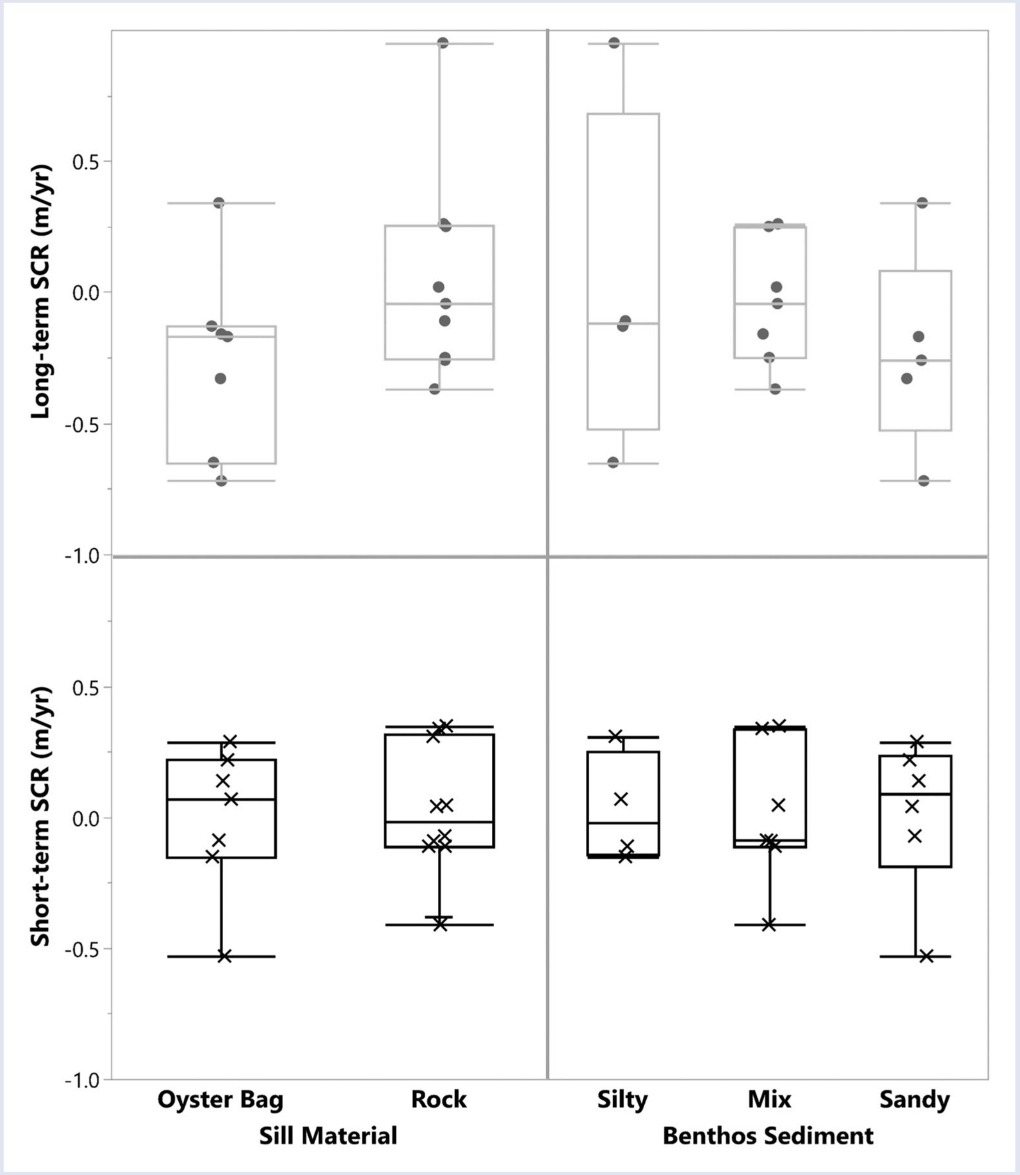

FIGURE 3 The box plot presents the minimum, quantile 1, median, quantile 3, and maximum data for dominant sill material and dominant bottom sediment characteristics among living shoreline projects during short- and long-term shoreline change rate (SCR) (m year^{-1})

over the short-term and long-term. The results of the regression indicate that the short-term performance model does not explain a significant portion of the variance (short-term: $R^2 = 0.090$). The model does not significantly predict short-term performance (short-term multiple linear regression model: $F_{3,\,16.0} = 0.42$; $p = 0.74$; Figure 5). Neither mean fetch ($\beta = -0.0051$, $t_{16} = -0.36$, $p = 0.73$) nor maximum fetch ($\beta = -0.0052$, $t_{16} = -0.57$, $p = 0.58$) contributed significantly to the model. Likewise, the long-term performance model results of the regression indicate that the model does not explain a significant portion of the variance (long-term: $R^2 = 0.080$). The model does not significantly predict post-hurricane performance (long-term multiple linear regression: $F_{3,\,15} = 0.32$; $p = 0.81$; Figure 5). Neither mean fetch ($= -0.042$, $t_{15} = -0.51$, $p = 0.62$) nor maximum fetch ($\beta = 0.0061$, $t_{15} = 0.19$, $p = 0.85$) contributed significantly to the model. Overall, living shorelines in this study reduce erosion regardless of mean and maximum fetch of the site, with a very weak trend between increased fetch and decreased erosion control performance.

A multiple regression analysis was conducted to investigate whether mean height and mean width could significantly predict the performance of living shorelines short-term and long-term on a subset of nine living shoreline projects. The results of the regression indicate that the short-term performance model does not explain a significant portion of the variance (short-term multiple linear regression model: $R^2 = 0.12$). The model does not significantly predict short-term performance (short-term multiple linear regression model: $F_{3,\,8} = 0.22$; $p = 0.88$; Figure 6). Neither mean height ($\beta = 0.18$, $t_8 = 0.25$, $p = 0.82$) nor mean width ($\beta = -0.20$, $t_8 = -0.76$, $p = 0.48$) contributed

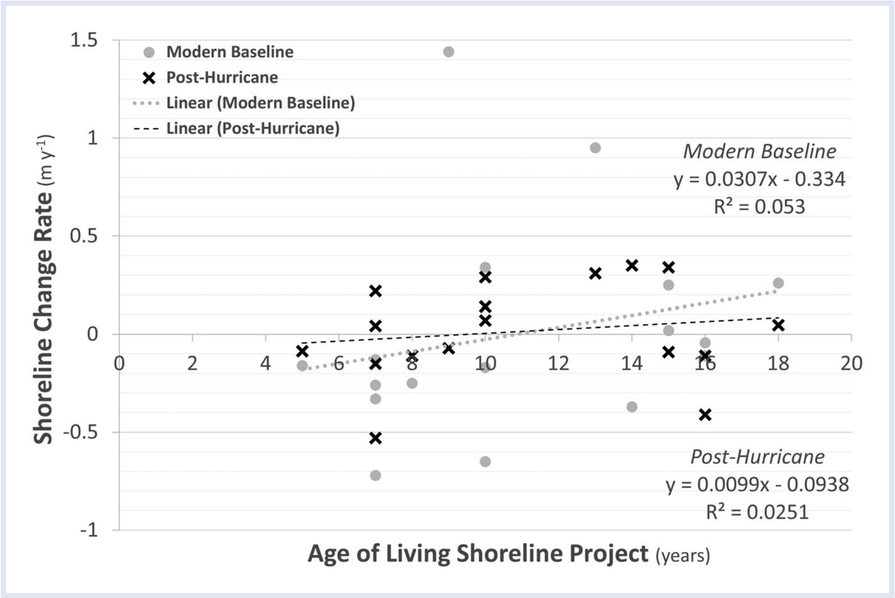

FIGURE 4 The effect of age of living shoreline projects (*x*-axis) in years on shoreline change rate (SCR; *y*-axis) in meters per year. The scatterplot shows the long-term SCR of shorelines of various ages from their installation to before Hurricane Florence (gray circles). It also shows the change in short-term SCR after Hurricane Florence (black cross). There is a slight positive correlation between age and SCR, this correlation decreased after Hurricane Florence, showing that with age there may be increasing resilience among living shoreline projects

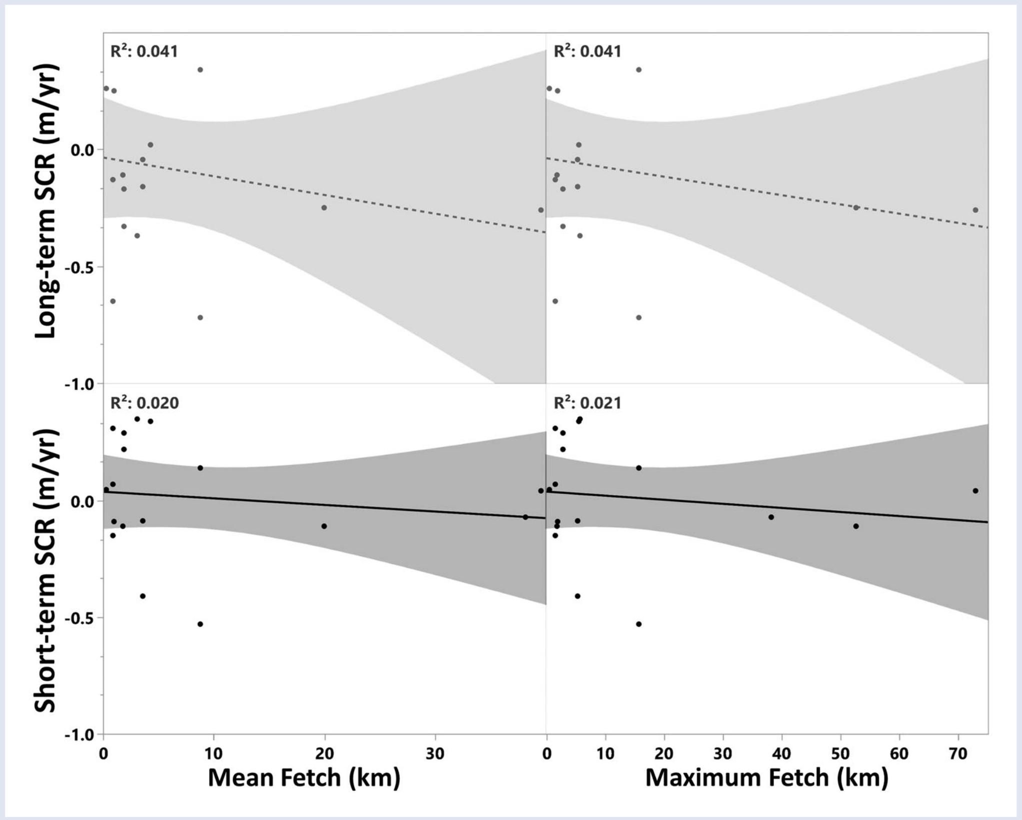

FIGURE 5 The effect of mean and maximum fetch (x-axis) in km on short- and long-term shoreline change rate (SCR) (*y*-axis) in meters per year. The scatterplot shows the long-term SCR of living shoreline projects from their installation to before Hurricane Florence (gray dash). It also shows the change in short-term SCR after Hurricane Florence (black). There is a very weak negative correlation between fetch and SCR, this correlation decreased after Hurricane Florence, showing that living shorelines protective benefits are present in a range of fetch conditions

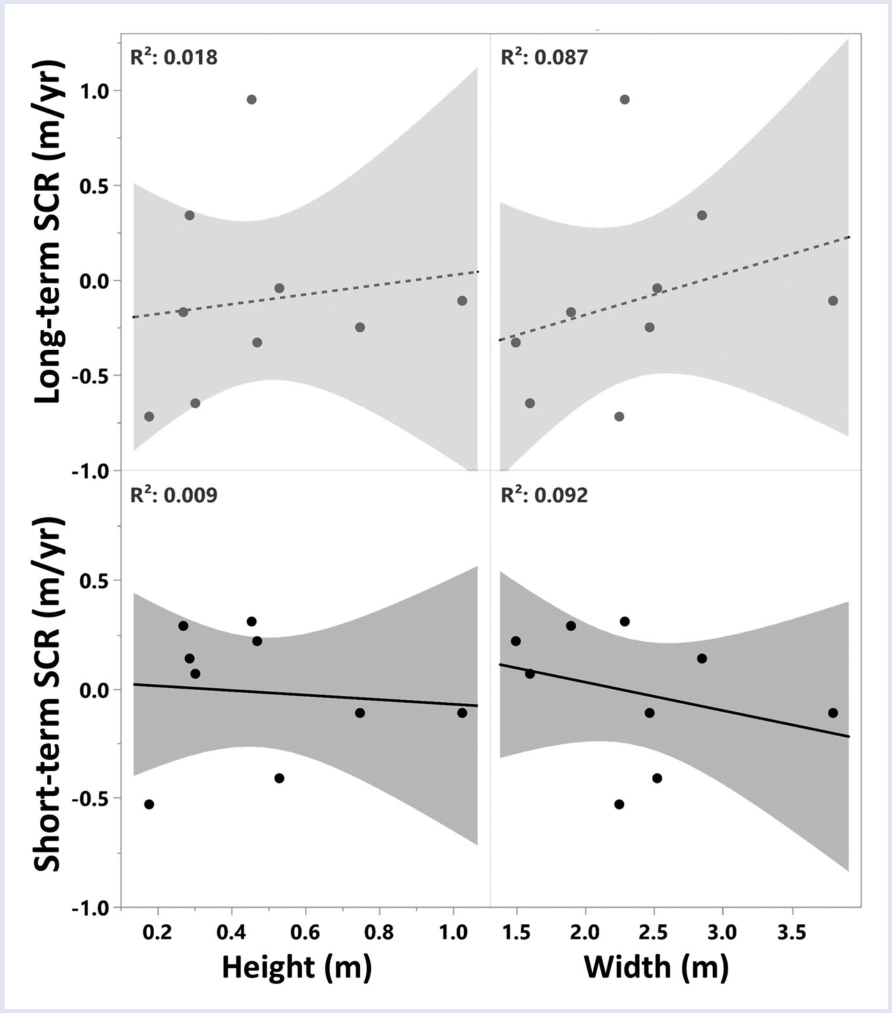

FIGURE 6 The effect of average sill height and width (*x*-axis; relative to NAVD88) in m on short- and long-term shoreline change rate (SCR) (*y*-axis) in meters per year among nine living shoreline projects. The scatterplot shows the long-term SCR of living shoreline projects from their installation to before Hurricane Florence (gray dash). It also shows the change in short-term SCR after Hurricane Florence (black). There is a very weak negative correlation between height and width and short-term SCR and a very weak positive correlation between height and width and long-term SCR. Living shorelines protective benefits are likely present in a range of height and width sill designs

significantly to the model. Likewise, the long-term performance model results of the regression indicate that the model does not explain a significant portion of the variance (long-term multiple linear regression: $R^2 = 0.30$). The model does not significantly predict post-hurricane performance (long-term multiple linear regression model: $F_{3,8} = 0.70$; $p = 0.59$; Figure 6). Neither mean height ($\beta = 0.49$, $t_8 = 0.44$, $p = 0.67$) nor mean width ($\beta = 0.42$, $t_8 = 1.08$, $p = 0.32$) contributed significantly to the model. Sill living shorelines in this study range in heights of 0.18 to 1.02 m and range in widths of 1.5 to 3.8 and are fully submerged or nearly fully submerged at mean high water. The living shorelines studied appear to be designed appropriately for their respective site conditions.

One year after Hurricane Florence

Five living shoreline projects and two control segments were surveyed 1 year after Hurricane Florence during peak growing season (August 2019); data were not collected at the remaining shorelines due to the impact of Hurricane Dorian in September 2019. Between the post-hurricane survey to the 1-year recovery (August 2019), the two control segments surveyed (Control 1, 3) had an average rate of loss of $-0.53\,\text{m year}^{-1}$ (Table 3). SCR was variable among the five living shoreline projects that were surveyed 1 year after the storm, with an average SCR of $0.18\,\text{m year}^{-1}$. Overall, 1 year after Hurricane Florence, four of five living shoreline projects experienced a positive recovery of SCR that tended to be equivalent or greater than their predisturbance SCR. Of interest is that living shoreline 1 (northern-most study area, oyster bag sill with sandy sediment) presented with a substantial change in SCR in August 2019, $-0.74\,\text{m year}^{-1}$, when comparing the long-term SCR ($0.34\,\text{m year}^{-1}$) to post-hurricane short-term SCR ($0.14\,\text{m year}^{-1}$). On the basis of available data and anecdotal evidence from site managers, this is the first known instance of erosion at this project site since the installation of the living shoreline in 2008.

DISCUSSION

By analyzing the change in lateral shore position pre- and post-Hurricane Florence, we gained a better understanding of how living shorelines can enhance coastal resilience. Our results provide evidence to suggest that living shorelines reduce erosion and, in many instances, promote lateral building of shore zones during short-term periods that include Category 1 hurricane events. The long-term (from time of installation that encompasses multiple storm events across multiple tidal frames) efficacy of sill living shorelines and short-term performance encompassing a major storm event, supported lateral growth of the shoreline (0.004 and 0.015 m year^{-1}, respectively). In contrast, unprotected control shorelines continued to see long-term (−0.36 m year^{-1}) and short-term lateral loss (−0.31 m year^{-1}). These lateral losses are consistent with North Carolina state average SCR of −0.30 to −3.35 m year^{-1}, depending on the estuarine location and overall North Carolina is experiencing a state-wide trend of erosion (Eulie et al., 2017; Polk & Eulie, 2018; Riggs, 2001). This study and findings from recent works collectively demonstrate that living shorelines with sills can promote horizontal and vertical building of shore zones (compared to unaltered marshes and bulkheaded shorelines) after a Category 1 storm (Gittman et al., 2014, Smith et al., 2018). Thus, the evidence for living shorelines enhancing resilience of coastal ecosystems, particularly salt marshes, is growing. Furthermore, our study's exploration of conditions 1-year post storm event show that living shorelines may recover better than unprotected salt marshes even when lateral erosion is initially observed immediately post storm.

Storm surge during Hurricane Florence was highly variable across eastern North Carolina, ranging regionally from 0.6 to 3.35 m above ground level and with sustained winds greater than 133 k h^{-1} (Stewart & Berg, 2019). Although storm condition extremity was variable, the living shorelines in this study still provided significant protection from the effects of severe storm events even though the low-lying sill design of the living shorelines and much of the fringing marsh vegetation in this study would have likely been submerged. Although wave energy dampening does decrease with water level height, wave dampening across a marsh system is not strictly dependent on canopy height. Instead, wave dampening is related to vegetation characteristics (including, height, stem density, stiffness, coverage, and geometry), shore morphology, and topographic variation of the marsh surface (Leonardi et al., 2018). The friction caused by these variables results in drag on a wave structure, deforming wave orbitals, and resulting in the breakdown of a wave structure. Although, living shoreline wave attenuation capacity in general and during storm surge events is thoroughly understudied, hydrodynamics across a marsh during a storm is well studied and it is known that even submerged vegetation provides wave attenuation benefits. Our study indicates that during short-term events, a range of sill design heights, widths, and materials provided protective benefits, further supporting the idea that well-designed sill structures can still prevent erosion while submerged.

The primary force causing lateral and vertical erosion of salt marsh edges is wind-wave attack (Tonelli et al., 2010). Extreme storm events are not a dominant threat to salt marsh stability, relative to other coastal environments, such as beaches and dunes (Leonardi et al., 2016). Further, a strong linear relationship exists between wave energy and unprotected salt marsh erosion, making lateral erosion of salt marshes mathematically predictable (Leonardi et al., 2016). Leonardi et al. (2016) found that extreme storms and hurricanes contribute to less than 1% of marsh edge erosion, while moderate weather conditions with wind speeds between 10 to 40 km h^{-1} were the dominant contributor to edge erosion. However, Eulie et al. (2017) found that wind direction and bathymetric conditions during a storm event can result in wave attacks that can cause significant marsh erosion that may contribute to long-term changes to rates of change, in comparison to other types of habitat (i.e., sediment banks) that have potential to recover post-storm. Further study of wind direction, bathymetry, and wave energy among our study sites may elucidate differences among study sites in contrast to system-wide (i.e., Ablemarle-Pamlico Estuary, southeastern North Carolina Intracoastal Waterway) conditions beyond site fetch limitations. Our study also suggests that living shorelines prevent ambient and small energy event erosion that typically occur over the course of a year, as shown by the SCR in the years preceding and following Hurricane Florence.

The design of a living shoreline project is critical in developing protection from erosion due to short-term storm events and long-term ambient conditions. However, this study shows that a variety of sill design (i.e., structural materials, height, width, configuration) can be used at a variety of sites (sandy to silty sediment bottoms, mean fetch range 0.3–39.6 km, maximum fetch range 0.5–72.9 km) with broad success. This study also shows that the 17 sill living shorelines in this study were well-designed to reduce erosive forces and may serve as demonstration sites. The overall success of living shoreline projects is likely in part due to forward-thinking design choices that align with individual site conditions. Our results, combined with recent findings that bulkheads are more frequently damaged during storm events and accrue more repair and maintenance costs compared to living shorelines, demonstrate the value of living shorelines for resilience building (Gittman et al., 2014; Smith et al., 2017, 2018).

Undoubtedly, there are extreme shore zone conditions, such as high wave energy areas or confined navigation channels, where other management strategies, such as increasing elevation (building up) of development or upland retreat are not possible, and the only recourse is a hardened structure. However, in suitable environmental conditions, there is a proven ecological and economic benefit to choosing a living shoreline instead of a traditional engineered management strategy. There is still limited guidance available to waterfront landowners, marine contractors, and coastal engineers on living shoreline siting and design parameter limits (Bilkovic et al., 2016; Morris et al., 2019;

Smith et al., 2020). However, a growing breadth of research is addressing this gap, including: understanding wave energy transmission through living shorelines relative to tidal frame (Safak et al., 2020), siting considerations (Mitchell & Bilkovic, 2019), and understanding how individual attitudes motivate shoreline management decisions (Scyphers et al., 2020; Smith et al., 2017). Our findings suggest that living shoreline siting and sill design may be suitable for broader conditions than previously known.

Long-term outlook of living shorelines

There is mounting evidence of living shorelines conserving and enhancing coastal habitats but there is a lack of long-term assessments of erosion protection and habitat resilience (Gittman, Peterson, et al., 2016; Sutton-Grier et al., 2015). Most published studies to date on living shorelines are short in duration, cover a small geographic area, or provide a case study perspective of individual projects rather than a generalized understanding of function (Smith et al., 2020). Spatial and temporal variabilities present in natural marshes can make it difficult to compare natural reference sites and restored sites, often necessitating larger sample sizes (Simenstad & Thom, 1996), and it can take a decade or longer for sites to reach a state where long-term trends (beyond cyclical trends) can be observed (Bouma et al., 2016; Craft et al., 1999; Morgan & Short, 2002). This limits results to “snapshots” of habitat condition rather than true assessments of restoration success and overall ecosystem resilience to short-term impacts and in the long-term (Gittman, Peterson, et al., 2016; Smith et al., 2018; Sutton-Grier et al., 2015).

A systematic review of living shoreline studies indicates that a majority of research on living shorelines has been conducted on projects that are less than 5 years old (Smith et al., 2020). Nevertheless, many ecosystem services can develop within the first 10 years at a restored marsh (Morgan & Short, 2002). For example, Bouma et al. (2016) found that economic benefits of tidal marsh restoration projects were experienced after 4 to 15 years (with years being dependent on the initial elevation of a site). Currin et al. (2008) found that after 3 years, there was slightly less biomass at a case study stone sill living shoreline compared to an adjacent natural marsh, but the difference was not significant. Other studies have shown that within a few years (<5 years) plant structure at living shorelines is comparable to natural established marshes (Bilkovic & Mitchell, 2013, Craft et al., 1999). *Crassostrea virginica* seeded loose cultch (a sill material option used in low energy living shoreline design) was found to have similar nekton utilization as natural reefs when it was surveyed 12 years after installation (Rutledge et al., 2018). After a project is 13–20 years old, carbon sequestration among living shorelines in North Carolina reaches equilibria and has been approximated to be on average between 70 and 80 $\mathrm{C\,m^{-2}\,year^{-1}}$, with the capacity of younger (<13 years old) projects having the most likelihood of sequestration because of the high amount of labile fraction of organic matter from below ground productivity (Davis et al., 2015).

Furthermore, there are several cobenefits that living shoreline projects can provide almost immediately. For example, sill or breakwater structures can reduce wave energy immediately after installation but their performance capacity for dampening wave energy can vary with design (Safak et al., 2020) and can increase over time (Manis et al., 2014). With respect to lateral shoreline protection from Hurricane Florence and since installation, the results of our study show a lack of influence of living shoreline project age, aligning with similar findings by Polk and Eulie (2018) who also found a lack of influence of project age on SCR. The youngest living shoreline projects in our study were completed in 2012 and 2013; at the time of Hurricane Florence these projects were 5 and 7 years old, respectively, and still provided similar protection to the oldest living shoreline projects (16 and 18 years old).

A distinctive need exists to understand living shorelines at varying spatial and temporal scales and their ability to improve coastal management practices (Gittman, Smith, et al., 2016; Smith et al., 2018, 2020; Sutton-Grier et al., 2015). Understanding the differences between living shoreline design and siting will be critical for informing on the utility of living shorelines to end users,particularly as our study findings indicate that these parameters may be much broader than previously thought. There is a continued need for more research on the resilience of living shorelines with robust sample sizes to understand utility of living shorelines in the wake of short-term events like hurricanes and also over the long-term.

Over the coming decades, salt marshes will continue to experience pressures from accelerated SLR, increased frequency and intensity of storms, habitat conversion, and development and hardening of coastlines. Coastal communities that rely on the ecosystem services and functions that salt marshes and other coastal habitats provide will lose resilience with the loss of these ecosystems. In an effort to protect valuable coastal resources, coastal managers have looked towards novel nature-based management strategies, like living shorelines, to provide wave energy protection and other ecosystem services. By applying living shorelines to vulnerable fringing salt marshes, resilience to lateral erosion can be built by their long-term presence at a site and short-term through their effective performance during major storm events (Polk & Eulie, 2018; Smith et al., 2018). In combination with findings by Smith et al. (2018), a quantitative and multidimensional picture is provided on the performance of living shorelines as a strategy for storm protection. The presence of living shoreline projects is effective in providing erosion protection in a range of fetch and bottom sediment conditions. Furthermore, living shorelines likely recover better 1 year post storm than their unprotected counterparts. This study adds to a growing breadth of research that present cobenefits and utility of living shorelines, where possible living shorelines should be considered as the first shoreline management strategy because of their capacity to build resilience.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available upon reasonable request from corresponding author Mariko A. Polk (map7186@uncw.edu).

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