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Effectiveness of Living Shorelines as an Erosion Control Method in North Carolina

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Abstract

Living shorelines are a shoreline stabilization strategy encompassing a range of vegetative to structural materials and serve as an alternative approach to the use of structures like bulkheads, which are known to aggravate erosion. Living shorelines are often installed with little to no long-term monitoring for effectiveness; specifically, there is a lack of quantitative data regarding their performance as a shoreline stabilization strategy. This study sought to assess the performance of living shorelines with sills, with respect to shoreline protection, by determining shoreline change rates (SCR) using geospatial analysis. Shoreline surveys were conducted using a real-time kinematic (RTK)-GPS unit at a total of 17 living shoreline projects and nine control segments at 12 sites along the coast of North Carolina. Current shoreline position was compared to historic (pre-installation) shoreline positions obtained from aerial imagery, dating to 1993. The average SCR among northern sites before installation was -0.45 ± 0.49 m year^{-1}, and in southern sites, it was -0.21 ± 0.52 m year^{-1}. After installation, average SCR was significantly less erosive at northern and southern sites with living shorelines, 0.17 ± 0.47 and -0.01 ± 0.51 m year^{-1}, respectively. Of the 17 living shoreline project segments, 12 exhibited a reduction in the rate of erosion; of those 12, six were observed to be accreting. This study supports the convention that living shorelines can reduce the rate of erosion and potentially restore lost shore zone habitat.

Keywords Coastal management · Living shoreline · Shoreline change rate · Geographic information systems (GIS) · Shoreline protection

Introduction

Coastal zones are dynamic systems that are affected by natural and anthropogenic processes. Severe weather events, tidal cycles, sea level rise, boat wakes, and urban development aggravate erosion and result in the loss of sensitive coastal ecosystems (Riggs and Ames 2003; Dahl and Stedman 2013). The coastal zone provides a wide range of ecosystem services, such as carbon sinks, erosion protection for development, nursery habitat, recreational and commercial activities, and water filtration (Rogers and Skrabal 2001; Bozek and

Burdick 2005; Roland and Douglass 2005; Craft et al. 2008). These ecosystem services are critical to coastal resiliency and the economic viability of coastal communities but are at risk due to erosion of coastal zone habitats.

To mitigate shoreline erosion, hard structures, such as revetments and bulkheads, have conventionally been used as a strategy for shoreline stabilization. These armored shorelines are meant to remain static but can impact the estuarine shore zone ecosystem (Davis et al. 2006; Currin et al. 2010; Morley et al. 2012). Hard structures alter sediment transport and deposition and can cause the loss of shallow and intertidal habitat. They can also result in increased erosion of the shoreline adjacent to the structure (Pilkey and Wright 1988; Douglass and Pickel 1999; Rogers and Skrabal 2001; Yozzo et al. 2003; Bozek and Burdick 2005). Additionally, the area in front of a hard structure, where a beach, sandbar, or marsh would be present, can be eroded by wave energy reflecting off of the structure (DeLaune et al. 1983; Pilkey and Wright 1988; Riggs 2001; Rogers and Skrabal 2001; Bozek and Burdick 2005). Marshes are highly responsive to wave energy and tidal regime, which affects their morphology, sediment

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accumulation, and assemblage of biota (Friedrichs and Perry 2001; Bendoni et al. 2016). Hard structures landward of marshes can cause shoreline recession and impede marsh retreat, resulting in the loss of marsh habitat due to coastal squeeze (Rogers and Skrabal 2001; Riggs and Ames 2003; Bendoni et al. 2016). Additionally, hard structures support lower biodiversity and do not perform as well during storm events, often leading to further shoreline erosion and structural failure (Morley et al. 2012; Toft et al. 2013; Gittman et al. 2014, 2016b).

An alternative shoreline management strategy to using hard structures is living shorelines. The National Oceanic and Atmospheric Administration (NOAA) defines living shorelines as being composed of "…mostly of native material. It incorporates vegetation or other living, natural "soft" elements alone or in combination with some type of harder shoreline structure (e.g., oyster reefs or rock sills) for added stability. Living shorelines maintain continuity of the natural land–water interface and reduce erosion while providing habitat value and enhancing coastal resilience" (*Guidance for considering the use of living shorelines* 2015). In North Carolina, the primary vegetation planted during installation is smooth cordgrass (*Spartina alterniflora*; Currin et al. 2010). Marsh vegetation is effective at wave attenuation and is a critical design element in the development of a living shoreline structure (Knutson et al. 1982; Roland and Douglass 2005; Riffe et al. 2011; Gedan et al. 2011). Structural components range from fiber logs, sand, oyster shells, marl rock, crab pots, concrete, or hybrid structures, which combine vegetation and structural components (Currin et al. 2010; *Guidance for considering the use of living shorelines* 2015). Structural components are used to dampen wave energy, while allowing coastal processes to continue and serve as a substrate for oyster spat recruitment and encouraging the establishment of marsh habitat (*Guidance for considering the use of living shorelines* 2015). Living shorelines are not intended to eliminate the movement of water or sediment, which is critical as coastal marshes rely on sediment accumulation to keep pace with sea level (Redfield 1972; DeLaune et al. 1983). Additionally, it is important to note that not all living shorelines are installed with the primary goal of limiting erosion. Living shorelines can also be used for habitat restoration and to increase coastal resiliency to climate change.

Of North Carolina's 17,152 km of estuarine shoreline (12,070 km of marsh), over 1486 km of the shoreline consists of hard structures. Structures within North Carolina primarily consist of bulkheads (838 km; the remaining consists of rip-rap, groins or jetties, and breakwaters; McVerry 2012; North Carolina Estuarine Shoreline Mapping Project 2012 Statistical Reports 2015). Only 8 km of shoreline are sills, which can be indicative of a structural component of a living shoreline projects. The disparity between hard structures and living shoreline usage is due to a variety of issues, including public policy impediments, slow permitting process, and a lack of education and awareness of living shorelines as an alternative shoreline management strategy to hard structures (Fear and Currin 2012).

Qualitative data and practiced methodology exists on various measures of the efficacy of living shorelines, particularly on biological measures; however, quantitative data is limited (Currin et al. 2007; Scyphers et al. 2011; La Peyre et al. 2014; Gittman et al. 2016a). At the 2013 Mid-Atlantic Living Shorelines Summit (Maryland DNR 2013), professionals and academics in the field noted a need for expanded scientific data to reaffirm the effectiveness of living shorelines. Three years later, professionals and academics in the field reemphasized the need for quantitative studies during the 2016 South Atlantic Living Shorelines Summit. An increased understanding of this strategy will enable agencies, marine contractors, non-governmental organizations, and scientists to further promote living shoreline methodologies to enhance marsh habitat while addressing erosion.

Without understanding the effects of living shoreline projects to shore zone habitat, it is difficult to quantify the effectiveness of projects to manage erosion. Conceptually, if the intent of a living shoreline is to alleviate the impact of erosion, shoreline change rates (SCRs) along areas with living shoreline projects should be less than the surrounding average SCR; this is supported by anecdotal evidence, but little quantitative data. This study seeks to understand the general performance of living shoreline projects with sills as a form of erosion control.

Study Area

This case study takes place along the estuarine coast of North Carolina at 12 study sites, encompassing 9 control shoreline segments and 17 living shoreline project segments (Fig. 1). Some sites encompass multiple living shoreline projects that were installed at different times or utilize different structural methods. Of the roughly 8000 m of potential living shorelines within North Carolina, this study surveyed 3428 m of living shoreline (North Carolina Estuarine Shoreline Mapping Project 2012 Statistical Reports 2015). Additionally, 2017 m of control shoreline segments, where no living shoreline or alteration existed within the segment, was surveyed. The sites within this study were chosen based on accessibility. All control segments were located directly adjacent to a living shoreline, so they would be subject to the same environmental conditions as the project shoreline segments.

The living shoreline projects vary in site characteristics, sill design components (i.e., structural materials used), and year of installation (Table 1). Study sites are located on both the estuarine coastline and the back-barrier shore of barrier islands. Structural components used include sand fill, loose and bagged oyster shells, rock marl, oyster reef balls, wood-metal breakwater, or a mixture of multiple materials within

Fig. 1 Map representing the location of the 12 study sites. The study includes 17 living shoreline projects with sills (some sites contain multiple living shorelines) and nine accompanying control sites across North Carolina, represented by squares and circles respectively. Control segments were located immediately adjacent to the living shoreline project
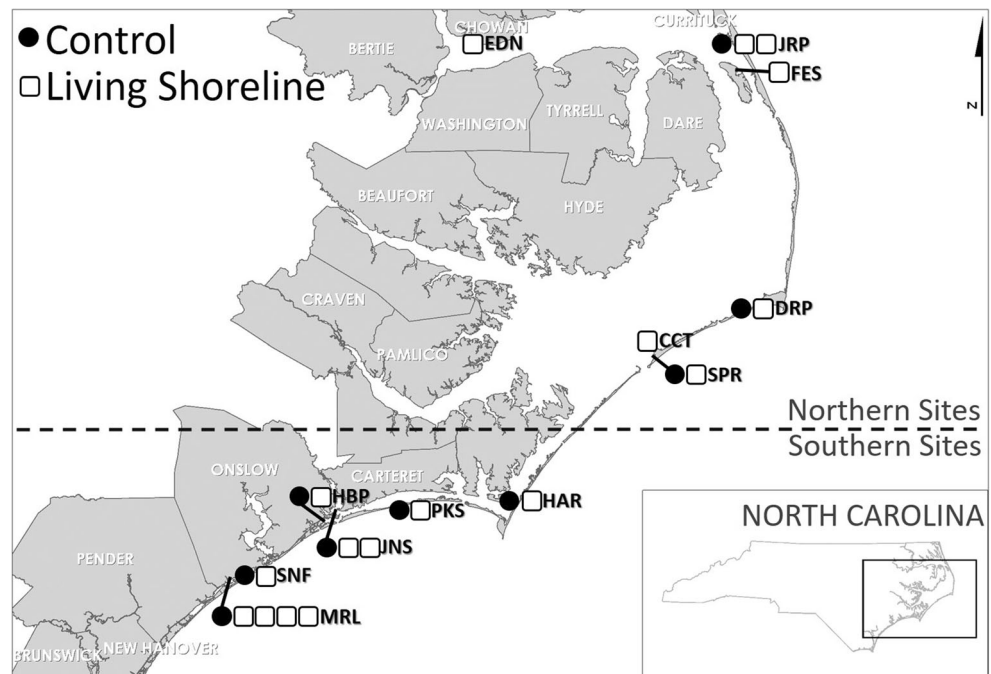
the same project; ten sites utilized oyster bags as one or the primary structural component (Table 1). All structural sill components were part of an intertidal or subtidal offshore structure. All project segments include the planting of vegetation (primarily *S. alterniflora* plugs). Accurate records could not be obtained with regard to planting and replanting regimes, initial acreage covered, and other planting characteristics. Accurate records could also not be obtained for all sites regarding the original primary intent of installation (i.e., whether it was installed primarily as an erosion control mechanism or for habitat or to meet other goals). Additionally, the geomorphology, surrounding land use practices, level of anthropogenic activity, hydrology, and total length of the living shoreline project, varies at each of the 17 projects. Sites are grouped by region throughout the rest of this study as statistical analysis indicated location by region was significant. Northern and southern regions also represent different hydrologic and geomorphic conditions. Characteristics of fetch, site slope, and predominate wind direction are reported for all sites in Table 2.

The seven northern study sites are located within the Albemarle-Pamlico estuarine system (APES). This is a larger, shallow, compound estuary that is dominated by two main lagoons (Albemarle Sound and Pamlico Sound) and fed by several drowned river tributaries. Water-level changes in system are primarily driven by a wind and barometric pressure tide (0.3 m; Pilkey et al. 1998). The dominant wind directions are from the northeast and southwest during winter and summer, respectively. Of the seven study sites located in the APES, five are back-barrier sites along the Outer Banks barrier island system that encloses the sounds (Jockey's Ridge

State park [JRP], Festival Park [FES], Hatteras Village private residence [DRP], NC Center for Advancement of Teaching [CCT], and Springer's Point Preserve [SPR]; Fig. 1). Another site is located on the inner bank, estuarine mainland shore in Dare County (The Nature Conservancy at Point Peter Road [TNC]; Fig. 1). The final site, Edenton (EDN), is located at the upper reach of Albemarle Sound (Fig. 1).

The seven southern study sites are located along the estuarine shores of Carteret and Onslow counties in the southern coastal plain region. These sites all experience a semidiurnal tidal cycle (1 m; Pilkey et al. 1998; *NOAA tide predictions* 2017). These sites are primarily located along the intracostal waterway and some of the smaller, narrow, back-barrier sounds such as Bogue Sound and Core Sound (Fig. 1). Two of the study sites are located in the back-barrier, Pine Knoll Shores Aquarium (PKQ), and a private church camp in Pine Knoll Shores (PKS; Fig. 1). One site is located on a small marsh island at the White Oak River inlet, Jones Island (JNS; Fig. 1). The remaining sites are located along the mainland estuarine shoreline (Cape Lookout National Seashore on Harker's Island [HAR], Hammock's Beach State Park [HBP], a private farm in Sneads Ferry [SNF], and Morris Landing Clean Water Preserve [MRL]; Fig. 1).

Method

Shoreline Position

In situ surveys of shoreline position were conducted initially during the summer of 2015 with additional sites surveyed in

Table 1 Living shoreline project characteristics

Site code	Install year	Location along estuarine shoreline	Structural component	Shore zone morphology		Dominant shore zone vegetation
				Sand/muck dominant	Scarp presence	
North						
JRP 1	2008	Barrier Island	Oyster bag sill	Sand	No	*J. roemerianus*
JRP 2	2011	Barrier Island	Oyster bag sill	Sand	No	*J. roemerianus*
EDN	2003	Mainland	Sand fill, rock sill	Sand	No	*S. alterniflora*
FES	2002	Barrier Island	Sand fill, rock sill	Muck	Yes	*J. roemerianus*
DRP	2011	Barrier Island	Rock sill	Sand	No	*J. roemerianus*
CCT	2009	Back Barrier Island	Sand fill, rock sill, oyster bag sill	Sand	No	*S. alterniflora*
SPR	2012	Barrier Island	Rock marsh-toe sill, oyster bag sill	Mix	Yes	*S. alterniflora*
South						
HAR	2004	Barrier Island	Rock sill	Mix	Yes	*S. alterniflora*
PKS	2013	Barrier Island	Oyster bag sill	Mix	Yes	*S. alterniflora*
JNS 1	2008	River Delta Island	Oyster bag sill	Sand	No	*S. alterniflora*
JNS 2	2011	River Delta Island	Oyster bag sill	Sand	No	*S. alterniflora*
HBP	2000	Mainland	Sand fill, rock sill	Mix	Yes	*J. roemerianus*
SNF	2003	Mainland	Rock sill	Mix	Yes	*S. alterniflora*
MRL 1	2005	Mainland	Rock sill	Muck	No	*S. alterniflora*
MRL 2	2011	Mainland	Sand fill, oyster bags over rock sill, oyster balls	Muck	No	*S. alterniflora*
MRL 3	2011	Mainland	Sand fill, oyster bags over rock sill, oyster balls	Muck	Yes	*S. alterniflora*
MRL 4	2013	Mainland	Oyster bag sill, oyster balls, PVC-wood breakwater sill	Sand	No	*S. alterniflora*

Projects listed in order from north to south. All sites experienced *S. alterniflora* planting; records on number of plugs, acreage covered, and frequency of replanting were not available at the time of this study. Scarp presence was annotated if scarp observed at more than 30% of shoreline

the summer of 2017 to expand the project sample size. Shoreline position was mapped using a Trimble real-time kinematic (RTK)-GPS unit using a 5-m continuous survey interval. The shoreline position was determined by surveying along the edge of the marsh platform, line of stable vegetation, or the wet/dry line based on the type of shoreline (Crowell et

Table 2 Living shoreline site characterization

Site code	Total length (m)	Mean fetch (km)	Max fetch (km)	Shoreline slope	Maximum fetch orientation[1]
North					
JRP	467	8.8	15.7	–	270° W
DRP	517	39.6	72.9	0.90	270° W
SPR	464	20	52.6	0.96	270° W
FES	487	1.8	1.8	0.93	45° NE
CCT	584	38.2	38.2	0.95	315° NW
EDN	131	4.3	5.5	0.87	180° S
South					
PKS	136	3.6	5.3	–	45° NE
JNS	745	1.9	2.8	–	0° N
HBP	559	0.3	0.5	0.93	90° E
HAR	514	3.1	5.7	0.92	45° NE
SNF	198	1	1.9	–	90° S
MRL	601	0.9	1.5	–	90° S

[1] This represents the maximum fetch orientation from the reported degrees

al. 1991; Moore 2000; Limber et al. 2004; Geis and Bendall 2010; Eulie et al. 2013; Eulie et al. 2016). Real-time differential correction for the RTK-GPS was combined with a conservative horizontal accuracy of ± 0.5 m (Eulie et al. 2013).

Historical shoreline positions were digitized utilizing aerial imagery in the software program ArcGIS 10.3. The baseline year was established as the year prior to living shoreline project installation (actual image year used for baselines were limited to availability of historic aerial imagery; Table 1). Georeferenced aerial imagery collected in 1993 was obtained from the North Carolina Department of Transportation (pixel resolution 1 m; NCDOT) GIS portal. Orthoimagery for 1998 (res. 1 m), 2006 (res. 0.15 m), 2010 (res. 0.15 m), and 2012 (res. 0.15 m) was obtained from the N.C. OneMap GeoSpatial Portal. Orthoimagery from 2008 (res. 0.15 m) was obtained from the National Oceanic and Atmospheric Administration (NOAA).

Shoreline Change Analysis

The shorelines were compared in two eras, pre- and post-installation of living shoreline projects, using the software package Analyzing Moving Boundaries Using R (AMBUR), which was processed through the programming environment R (Jackson et al. 2010; Jackson et al. 2011). AMBUR quantifies shoreline change by generating shore perpendicular transects between two baselines (Jackson et al. 2010; Jackson et al. 2011). Transects were generated at 1 m intervals, and change is calculated using the end-point rate (EPR) method, which is reported in this study as the SCR (Dolan et al. 1991). The resulting SCR represents the calculated change between two shoreline positions. The annualized shoreline position uncertainty (U_t) was calculated following the method of Eulie et al. (2013) and is reported in Table 3.

Statistical Analysis

SCR was analyzed to determine statistical significance between living shoreline versus control segments utilizing statistical software program SAS JMP 10.0. Non-parametric analysis was selected based on lack of normality within the dataset. Sites were grouped by region (north, south) to account for the two distinct hydrologic systems (APES in the north and the Intracoastal Waterway and sounds in the south). Mann–Whitney U analysis were conducted to determine if significance existed between control and living shoreline segments prior to the installation of living shoreline projects in each region. Finally, Wilcoxon signed-rank test was conducted comparing pairs of controls to living shorelines in each region. The U value of the Mann–Whitney U analysis represents the number of observations in one sample that are greater than the comparison sample ranking; this is reported as U. Mean,

standard deviation, P value, and z score are reported as M, SD, P, and z, respectively, when appropriate.

Results

The observed SCR across all sites (encompassing all 17 living shoreline and 9 control segments) ranged between − 3.69 and 5.12 m year^{-1}. Sites were grouped by region as regionality was found to be significant (refer to Table 1; $U = 15,472,190$, $z = 3.68$, $P > 0.002$).

Pre-installation Shoreline Change

The average SCR of all segment at northern sites prior to the installation of a living shoreline project was − 0.45 ± 0.49 m year^{-1} ($n = 2619$; Table 3). The SCR range across all northern segments varied between − 3.35 and 0.67 m year^{-1}. Along future control segments, SCR ranged between − 1.68 and 0.67 m year^{-1} with an average SCR of − 0.45 ± 0.46 m year^{-1}. At future living shoreline segments, SCR ranged between − 3.35 and 0.59 m year^{-1} with an average SCR of − 0.43 ± 0.79 m year^{-1}. No significant difference was found between northern future control segments ($M = −0.45$, $SD = 0.49$) and future living shoreline segments ($M = −0.43$, $SD = 0.65$).

In comparison, average SCR along all southern shoreline segments was − 0.21 ± 0.52 m year^{-1} ($n = 2344$). The SCR range across all southern segments varied between − 2.13 and 2.68 m year^{-1}. Along future control segments, SCR ranged between − 1.58 and 1.52 m year^{-1} with an average SCR of − 0.26 ± 0.97 m year^{-1}. At future living shoreline segments SCR ranged between − 1.36 and 0.96 m year^{-1} with an average SCR of − 0.36 ± 0.84 m year^{-1}. No significant difference was found between southern control segments ($M = −0.26$, $SD = 0.49$) and southern living shoreline segments ($M = −0.36$, $SD = 0.35$) prior to the installation of a project.

Post-installation Shoreline Change

After installation, the average SCR at northern segments with living shoreline projects was 0.17 ± 0.47 m year^{-1}, while at control segments, it was − 0.50 ± 0.51 m year^{-1}. The average SCR after the installation of a living shoreline project in the north was significantly different from control segments ($z = −17.92$, $P < 0.0001$). After installation, average SCR at southern segments with living shoreline projects was − 0.01 ± 0.51 m year^{-1}, while at control segments, it was − 0.20 ± 0.48 m year^{-1}. The average SCR after the installation of a living shoreline project in the south was significantly different from control segments ($z = 3.35$, $P < 0.0008$). While these averages are within the annualized uncertainty, the difference between SCRs at project shoreline segments and control

Table 3 Results of shoreline change analysis pre- and post-installation of the living shoreline projects among all segments

Site code	Installation year	Before installation SCR	Annualized uncertainty	After installation SCR	Annualized uncertainty
JRP 1	2008	− 1.37	± 0.50	0.34	± 0.36
JRP 2	2011	− 0.26	± 0.50	− 0.72	± 0.36
JRP control	–	− 0.05	± 0.50	− 0.93	± 0.36
DRP	2011	− 0.018	± 0.50	− 0.26	± 0.36
DRP control	–	− 0.74	± 0.50	− 0.31	± 0.36
SPR	2012	− 0.041	± 0.39	− 0.25	± 0.82
SPR control	–	0.037	± 0.39	− 0.21	± 0.82
FES	2002	− 0.39	± 2.0	− 0.11	± 0.37
CCT	2009	− 0.71	± 0.61	1.44	± 0.67
EDN	2003	− 0.16	± 2.0	0.019	± 0.37
PKS	2013	− 0.58	± 0.39	− 0.16	± 0.82
PKS control	–	− 0.40	± 0.39	− 0.55	± 0.82
JNS 1	2008	− 0.057	± 0.50	− 0.17	± 0.36
JNS 2	2011	− 0.38	± 0.50	− 0.33	± 0.36
JNS control	–	− 0.41	± 0.50	− 0.42	± 0.36
HBP	2000	− 0.12	± 2.0	0.26	± 0.37
HBP control	–	− 0.16	± 2.0	0.18	± 0.37
HAR	2004	− 0.46	± 0.54	− 0.37	± 0.16
HAR control	–	− 0.14	± 0.54	− 0.67	± 0.16
SNF	2003	− 0.88	± 2.0	0.25	± 0.37
SNF control	–	− 0.73	± 2.0	0.079	± 0.37
MRL 1	2005	− 0.69	± 0.54	0.95	± 0.16
MRL 2	2011	0.0015	± 0.39	− 0.65	± 0.82
MRL 3	2011	− 0.30	± 0.39	− 0.13	± 0.82
MRL 4	2013	− 0.54	± 0.39	− 0.40	± 0.82
MRL control	–	0.34	± 0.39	− 0.0082	± 0.82

SCR and total uncertainty presented as meter per year

segments illustrates an overall trend of reduced erosion from the presence of projects. Additionally, within individual shoreline segments, there were SCRs calculated that exceeded the annualized uncertainty and supported the trend illustrated by the regional averages.

SCR for all project and control segments were analyzed pre- and post-installation eras (Table 1). There was a significant difference in SCR between shorelines with living shoreline projects and control segments in both the northern and southern regions. Across all study sites in the north and south, the control shoreline segments all continued to experience erosion, except for southern HBP and SNF control segments, which had an average SCR of 0.18 ± 0.37 and 0.08 ± 0.37 m year^{-1}, respectively, after the adjacent living shorelines were installed (Table 3). The other control segments exhibited variable changes in SCR post-installation of nearby living shoreline projects. One of the control segments had a decrease in erosion rate (but was not accreting; DRP). Finally, at the remaining six (JRP, SPR, PKS, JNS, HAR, and MRL) control segments, the rate of erosion increased after the

adjacent site received a living shoreline project; of these six, three exceeded the uncertainty margin (JRP, JNS, HAR).

The living shoreline project segments showed a mix of accretion and erosion during the post-installation era (Table 3). Overall, five of the 17 project segments (JRP 2, DRP, SPR, JNS 1, and MRL 2) experienced an increase in the rate of erosion despite the installation of a living shoreline (Table 3). Of these five, only SPR and MRL 2 had living shoreline segments that experienced a higher rate of erosion compared to adjacent controls, and only JRP 2 exhibited an increase in erosion beyond the annualized uncertainty (-0.72 ± 0.36 m year^{-1}). In contrast, the other 12 projects segments experienced a decrease in the rate of erosion. Of these, six exhibited a reduction in the rate of erosion compared to regional controls and regional pre-installation SCR, and six had a positive SCR (indicating they were accreting post-installation). Three of these living shoreline segments exhibited a decrease in erosion beyond the annualized uncertainty (CCT, HAR, MRL), and two more were within annualized uncertainty by only ± 0.03 m year^{-1}.

Discussion

Effectiveness as Shoreline Stabilization

This study sought to quantitatively assess the widely held view that living shorelines can be used as a shoreline protection strategy. It was determined that areas with living shoreline projects experienced mixed results when SCR was compared pre- and post-installation; however, those shorelines did experience significantly less erosion than sites without living shoreline projects (controls). The average SCR before installation was -0.45 ± 0.49 m year^{-1} at northern sites and -0.21 ± 0.52 m year^{-1} at southern sites—previous studies have found that estuarine shoreline erosion in North Carolina ranges between -0.5 and -3.0 m year^{-1} (Stirewalt and Ingram 1974; Bellis et al. 1975; Riggs and Ames 2003; Eulie et al. 2016). After installation of a living shoreline, average SCR in the north was 0.17 ± 0.47 and -0.01 ± 0.51 m year^{-1} in the south. Of the 17 living shoreline project segments, 12 exhibited a reduction in the rate of erosion from before to after installation; of those 12, six were observed to be accreting. These results support the convention that living shorelines can reduce the rate of erosion and potentially restore lost shore zone habitat. Some of the adjacent control shorelines (three of the control segments) also exhibited a reduced rate of erosion during the post-installation period, while three control segments also experienced an increase in erosion. This could be due to a variety of environmental factors, study limitations (such as not having non-adjacent control sites, more living shoreline projects, more controls in general, elevation, and dimensions of structures), which potentially can be an artifact from the adjacent living shoreline, or processes that were not quantified within the present study. Further exploration and expansion of this study will be examined in future planned studies of living shorelines in North Carolina.

However, five living shoreline projects experienced an increase in erosion from before to after installation: JRP 2, DRP, SPR, JNS 1, and MRL 2. Of these, the rate of erosion at JRP 2 and SPR exceeds that of their adjacent control segments. However, only JRP 2 exhibited an increase in erosion beyond the annualized uncertainty (-0.72 ± 0.36 m year^{-1}). Both JRP 2 and SPR have adjacent, high-traffic, pedestrian trails. Analysis of SPR by individual transects indicated that erosion is highest near the trail head of the preserve. This may be due to high levels of human activity affecting the retention of vegetation along the shoreline at these areas or the failure of the oyster bag sill in this area. Site managers have indicated multiple vegetation plantings have been attempted in these areas. At JRP 2, the bulk of erosion is concentrated along the southern portion of the project (Fig. 2). This area is a sandy beach and past plantings of *S. alterniflora* in combination with the bagged oyster shell sill have not been as successful at

halting erosion as at the adjacent JRP 1 segment. This area coincides with two gaps (necessary per regulation) and a visible decrease in the height of the intertidal oyster sill structure. The structure may be too low to dampen wave energy. The structural design was also referenced by site managers as the most likely explanation for the poor results of the project installation at JRP 2. Although the other sites that experienced an increase in erosion (DRP, SPR, JNS 1, and MRL 2) are within the margin for annualized uncertainty, an increase in erosion post-installation could be an indication of insufficient design or environmental processes that have not been fully explored.

Overall, results suggest that living shoreline projects are more likely to exhibit a positive increase in SCR the longer a project has been installed. Of the 12 living shoreline projects with a positive increase in SCR, six are experiencing accretion, all of which had been installed between 7 and 17 years at the time of sampling. While all five projects that experienced an increase in erosion were between 3 and 7 years old, which could be indicative of these projects not equilibrating or installing design issue. Variability in the spatial and temporal development of salt marshes, and thus the various matrices, such as biota assessments and sediment assessments, used to measure functionality can make it difficult to compare reference and restored sites, necessitating larger sample sizes (Simenstad and Thom 1996). Dolan et al. (1991) and Eliot and Clarke (1983) have found that at a minimum, an era of at least 10 years was needed to delineate long-term trends that go beyond cyclical trends along oceanfront beaches. Studies in other coastal environments, including salt marshes, also indicate that it can take a decade or longer for sites to reach a stable equilibrium with the surrounding environment and biophysical processes (Craft et al. 1999; Morgan and Short 2002; Boerma et al. 2016). However, many ecosystem services can be seen within the first 10 years at a restored marsh (Simenstad and Thom 1996; Morgan and Short 2002). Additionally, Boerema et al. (2016) found that the ecosystem services of tidal marsh restoration projects were experienced after 4 to 15 years (with years being dependent on the initial elevation pre-installation). These previous studies and the observations from sampled sites indicate that living shoreline projects may take up to 7 years (or longer) before average SCR stabilizes. Continued monitoring of these sites will be necessary to affirm this in the years to come.

The Role of Environmental and Installation Characteristics

Like all estuarine shoreline protection strategies, the living shoreline projects studied were installed in complex estuarine systems, where a variety of environmental forcings drive shoreline change. This study attempted to analyze modern characteristics of the sites and installations utilizing a mix of

Fig. 2 Shoreline change analysis of two living shoreline project segments (installed in 2008 and 2011) and control segment at Jockeys Ridge State Park. Shoreline envelope indicates pre- and post-installation era envelopes; the SCR is indicated by the color of the transect line, which was used to calculate the SCR. The gray, black, and hashed lines indicate installment year or control segment, and the position of the lines indicates shore position
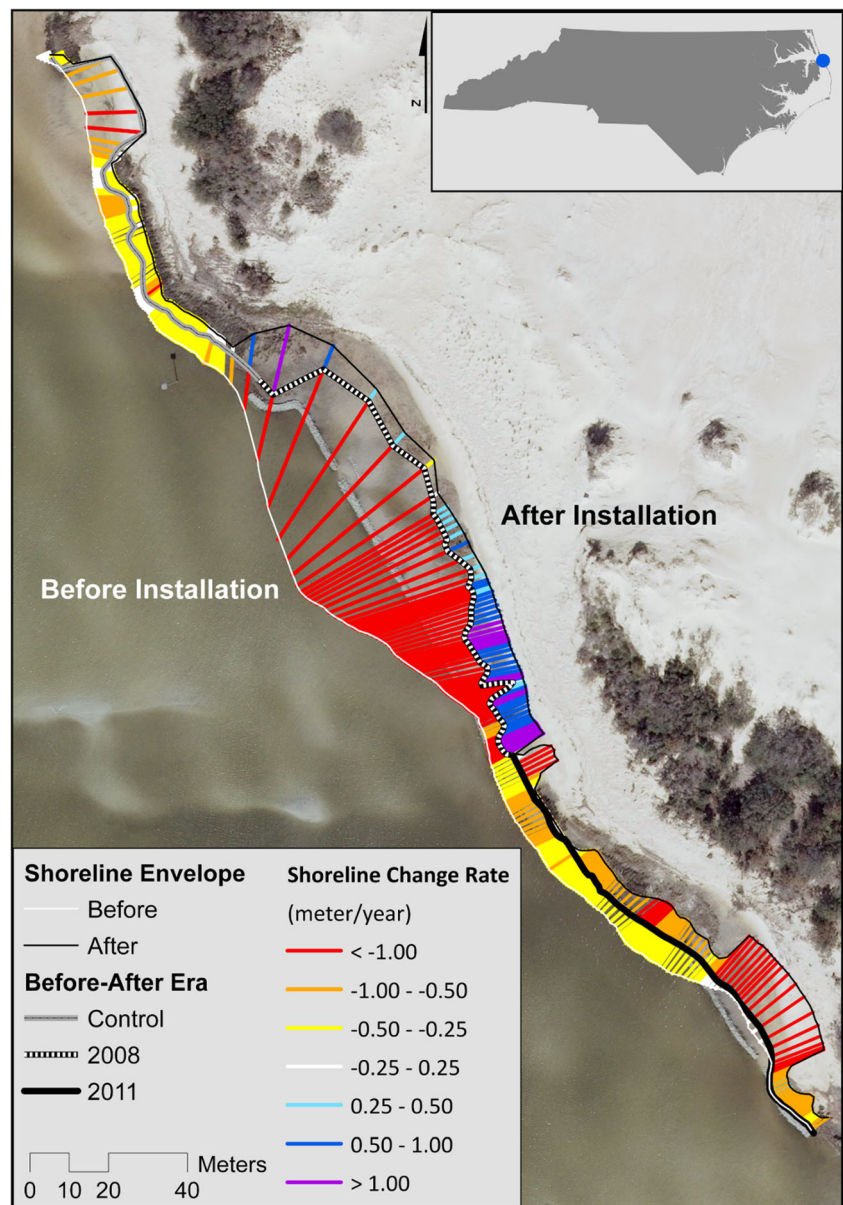
qualitative and quantitative observations of shore zone composition (sandy, mucky, or mix), morphology (presence of a scarp in more than 30% of the shoreline segment, slope), dominant shore zone vegetation, installation material, mean fetch, maximum fetch, and maximum fetch orientation. Other studies (including some in North Carolina) have observed a relationship between several of these characteristics and rates of shoreline change (Riggs and Ames 2003, Eulie et al. 2016, Bendoni 2016). However, few trends were observed between these characteristics and changes in SCR after the installation of living shoreline projects. Future work will include a combination of more detailed in situ measures of these characteristics, as well as modeling efforts.

Overall, no significant trends were recognized between erosion rates and present day shore zone morphology (edge

morphology and slope) and shore composition at living shoreline projects overall or by region. However, some trends (not statistically significant) were observed across the study sites. Overall, 89% of individual segments at control sites presented with scarps, while only 41% of segments with living shorelines presented with scarps. Only one control site (JNS Control) did not have scarps along 30% or more of the shoreline. Four living shorelines (FES, PKS, HAR, and SNF) presented with scarping, yet still showed a reduction in erosion. Scarp features develop from edge erosion and are often associated with wind-wave action (Rogers and Skrabal 2001; Tonelli et al. 2010). Shore composition was also found to not be a significant control of the erosion rate. However, it is of note that living shoreline projects that had been installed the longest (> 10 years) were all either mucky or of mixed muck/

sand composition. This may be indicative that the project installations are successfully reducing wave energy landward of the structural components, allowing finer sediments and organic matter to deposit and accumulate along the shoreline.

Six of 17 living shoreline projects had sand fill brought in to regrade the shoreline slope during initial installation; only one of those projects (MRL 2) experienced an increase in erosion. Sites with sand fill were located equally in the northern (FES, CCT, EDN) and southern (HBP, MRL 2, MRL 3) region. Modern slope was collected for FES, CCT, EDN, and HBP, the average slope for these projects was 0.92 (range 0.87 to 0.95). In contrast, control slope was 0.93 and at living shoreline projects that did not receive sand fill slope was 0.93. This points to the original amount of fill and grading placed at the projects that received sand fill being appropriate during installation. A larger sample size would be necessary to determine whether sand fill is a significant factor to success.

Most sites presented with *S. alterniflora* as the dominant vegetation type. Only three sites (JRP, FES, and HBP) had a predominance of black needlerush (*Juncus roemerianus*). Both species are common in natural estuarine marshes, both in North Carolina and the larger southeast region of the USA. There is not enough sample variation within the current study to determine trends or significance based on dominant vegetation, and no measures of biomass or species diversity were conducted.

A variety of structural materials were utilized for the living shoreline projects included in this study. Five of these projects were constructed with a mixture of different structural components, but all contained rock sills or oyster bag sills (Table 1). While installations of mixed structural components were not unexpected, it did complicate attempts to assess the role of different structural components in reducing erosion. Many of these living shoreline sites contain multiple structural methods as they were often installed as pilot projects. Early installations were attempts to address shoreline habitat loss, while simultaneously exploring the most effective "soft" stabilization strategies (per site managers). Guidance from agencies such as NOAA and other stakeholders have pushed for application of the least structural installation designs that still reduce shoreline erosion; consequently, some of these mixed project sites attempted to address this by implementing multiple strategies. To garner a better understanding of the implications of various structural materials would require a larger sample size with more single-material projects.

Finally, fetch was measured at the study sites as a proxy for wave energy (as in situ measures and modeling were not available for the study). In the northern region, mean fetch averaged 19.0 km (range of 1.8 to 39.6 km) and in the southern region mean fetch averaged 1.6 km (range of 0.3 to 3.7 km). No trend was observed between mean fetch and erosion reduction at living shorelines projects or control segments. In the northern region, maximum fetch averaged

36.03 km (range of 4.7 to 72.9 km) and in the southern region maximum fetch averaged 2.65 km (range of 0.5 to 6.9 km). Like mean fetch, no trend was observed. The lack of trend in fetch is likely due to the lack of normality within the sample size, a larger sample size with more variability may reveal trends. It, however, does not appear that fetch is a primary factor in the success of a project in reducing erosion; this is also an indicator that the structural portions of these projects were designed to withstand the effects of fetch. Furthermore, no trends were observed along southern sites between maximum fetch orientation and erosion reduction abilities. However, at northern sites (JRP 2, DRP, SPR), all living shoreline projects that experienced an increase in erosion have a maximum fetch orientation that is 270°; only JRP 1 experienced a reduction in erosion at this orientation. There is not a large enough sample size to discern whether this is a significant trend.

Conclusion

The disparity between hard structures and living shoreline implementation can be attributed to complex interaction of public policy impediments, lack of public knowledge on living shorelines, and the desire for more research affirming the benefits of living shorelines. This study posited that sites that had living shorelines with sills would experience less erosion than shoreline segments without living shorelines. This study finds that shoreline segments with living shoreline with sills experience significantly less erosion than shoreline segments without living shorelines. Living shorelines with sills can reduce erosion and promote accretion in areas that are eroding. The positive effects of living shorelines can transcend site characteristics such as geomorphology, surrounding land use practices, level of anthropogenic activity, wake and wave action, hydrodynamic processes, length of the living shoreline, structural materials used, or tidal regime. Sites with projects in this study experienced a positive effect after installation of a sill living shoreline. This study shows that accretion can occur whether a project is in a wind-driven tidal cycle or semidiurnal tidal regime or on a barrier island or on the mainland. A reduction in erosion can be seen in as little as a year after installation. Results show that living shorelines with sills are an effective means of mitigating erosion and can lead to accretion at sites that have historically seen erosion.

Further study of all types of living shorelines, particularly how their performance compares to other shoreline stabilization methods and exploring trends in design characteristics, is a necessary aspect to guide future coastal management strategy. Some of the results in this study reflect its limitations; one of these includes the limited number of living shoreline project sites with consistent characteristics, such as year of installation and structural components. Another limitation was access to

baseline aerial imagery. Access to aerial imagery of the exact baseline year for each project site would aid increasing accuracy of each era. Continued research should expand this study to include hard structures as well as different types living shoreline sites. Future research should consider project design attributes, such as materials used, in addition to project age, as well as other site characteristics in more detail. Expanding the study to include more sites would allow for increased accuracy.

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