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Marshes with and without sills protect estuarine shorelines from erosion better than bulkheads during a Category 1 hurricane

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ABSTRACT

Acting on the perception that they perform better for longer, most property owners in the United States choose hard engineered structures, such as bulkheads or riprap revetments, to protect estuarine shorelines from erosion. Less intrusive alternatives, specifically marsh plantings with and without sills, have the potential to better sustain marsh habitat and support its ecosystem services, yet their shoreline protection capabilities during storms have not been evaluated. In this study, the performances of alternative shoreline protection approaches during Hurricane Irene (Category 1 storm) were compared by 1) classifying resultant damage to shorelines with different types of shoreline protection in three NC coastal regions after Irene; and 2) quantifying shoreline erosion at marshes with and without sills in one NC region by using repeated measurements of marsh surface elevation and marsh vegetation stem density before and after Irene. In the central Outer Banks, NC, where the strongest sustained winds blew across the longest fetch; Irene damaged 76% of bulkheads surveyed, while no damage to other shoreline protection options was detected. Across marsh sites within 25 km of its landfall, Hurricane Irene had no effect on marsh surface elevations behind sills or along marsh shorelines without sills. Although Irene temporarily reduced marsh vegetation density at sites with and without sills, vegetation recovered to pre-hurricane levels within a year. Storm responses suggest that marshes with and without sills are more durable and may protect shorelines from erosion better than the bulkheads in a Category 1 storm. This study is the first to provide data on the shoreline protection capabilities of marshes with and without sills relative to bulkheads during a substantial storm event, and to articulate a research framework to assist in the development of comprehensive policies for climate change adaptation and sustainable management of estuarine shorelines and resources in U.S. and globally.

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1. Introduction

Global climate change, resulting largely from anthropogenic greenhouse gas emissions, is causing the oceans to expand as waters warm and receive additional freshwater from melting glaciers and ice caps, producing rising sea levels. The global rate of sea-level rise is accelerating (Church et al., 2008), and will likely continue to accelerate as the climate continues to warm (Nicholls and Cazenave, 2010). Sea-level rise will require shoreline ecosystems, such as coastal marshes, either to accrete vertically or to transgress landward to higher elevations to persist. Additionally, climate change may result in an increase in the frequency of intense storm events, particularly hurricanes (Grinsted et al., 2013), and cause significant damage to coastal structures and erosion of shorelines (Thieler and Young, 1991). Coastal marshes act as natural buffers to wave energy and inhibit erosion of coastal lands (Barbier et al., 2008; Meyer and Townsend, 1997; Shepard et al., 2011). Nevertheless, these marshes are at great risk from degradation and loss as sea-level rise and increased storminess interact with coastal development and associated shoreline hardening (Grinsted et al., 2013; Nicholls and Cazenave, 2010; Peterson et al., 2008a,b; Rahmstorf, 2010; Titus et al., 2009).

Shoreline hardening, the installation of man-made shoreline protection structures, is intended to protect coastal property from erosion caused by ambient winds, boat wakes, and storm events (Titus, 1998). On the U.S. Atlantic coast, vertical asbestos, treated wood, composite plastic, or steel bulkheads (Fig. 1A), sloping stone, marl, or concrete riprap revetments (Fig. 1B), or a combination of riprap revetment and bulkhead (referred to as hybrid herein) are constructed at or above the observed high-water mark (OHWM),

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Fig. 1. Photographs of shoreline types: A) a bulkhead: a vertical structure typically constructed of vinyl composite, concrete, asbestos, or treated wood placed at or above the observed high water mark; B) a riprap revetment: a sloped structure typically constructed of granite, marl, or concrete placed at or above OHWM; and C) a sill: a structure typically constructed of granite, marl, or oyster shell, seaward of marsh.

which is typically landward of regularly inundated, coastal marshes (United States Army Corps of Engineers [USACE], 2004). Because of their fixed position relative to coastal marshes, bulkheads and riprap revetments have the potential to inhibit upslope transgression of marshes as sea level rises (Peterson et al., 2008b; Titus, 1988). This may ultimately lead to the loss of coastal marsh habitats and their ecosystem services, including nutrient and pollutant filtration, habitat provision for fishes and crustaceans, and erosion prevention (Peterson et al., 2008a). For coastal policies to be comprehensive in providing storm protection for estuarine land owners, while also preventing or minimizing degradation and loss of coastal habitats, the following scientific and engineering information on each shoreline protection approach is needed and is currently lacking or incomplete: (1) relative shoreline protection capabilities; (2) cost effectiveness; (3) ecological effects; and (4) reversibility and adaptability if the approach results in the eventual violation of applicable laws (e.g., Clean Water Act [CWA]) as sea-level rise threatens to drown tidal marshes (Titus, 1998).

Bulkheads and riprap revetments are the dominant method of shoreline protection in North Carolina and many other coastal states (National Research Council [NRC], 2007). Many property owners assume that bulkheads provide superior shoreline protection from erosion and storm damage compared to other methods (Fear and Currin, 2012; Scyphers et al., 2014). However, studies comparing the shoreline protection provided by marshes and marshes with sills to traditional shoreline protection methods are lacking, particularly during storms (see Shepard et al., 2011). A sill is a shoreline protection structure typically constructed of low-rising granite, marl, or oyster shell placed well below OHWM and 1–2 m seaward of regularly inundated marsh macrophytes (Fig. 1C). Incomplete knowledge of the ecosystem effects and adaptability of each alternative shoreline protection approach has resulted in conflicting permitting policies for shoreline protection among the individual districts of the United States Army Corps of Engineers (USACE) and between states. For example, in North Carolina, bulkheads can be exempt from USACE review, via use of Nationwide Permit (NWP) 13, and are often permitted in fewer than two days by the North Carolina Division of Coastal Management (NC DCM). Sills, because of their position relative to OHWM, are not exempt from USACE review. Hence, permitting in North Carolina can take 30–120 days or longer (NC DCM, 2012). However, the Baltimore, Maryland, USACE District does not recognize NWP 13 and the Maryland Department of Natural Resources (MD DENR) requires that marsh planting with or without sills be used in lieu of bulkheads (Titus et al., 2009). To produce estuarine shoreline protection policies within states and nations that maximize benefits and minimizes losses, new studies are needed that address the relative shoreline protection capabilities, costs, ecological effects, and reversibility and adaptability of various shoreline protection approaches.

The hypothesis that bulkheads, riprap revetments, marshes with sills, and marshes without sills, differ in their ability to protect the shoreline from erosion during a storm event was tested during Hurricane Irene. Coastal North Carolina is a relevant location in which to test this hypothesis because the NC coast has been affected by nearly 100 tropical storms or hurricanes since 1851 and as much as 5900 km^2 of the coastal land in North Carolina is expected to be inundated by 2100 under a projected sea level rise of 1.1 m (NC State Climate Office, 2014; Poulter et al., 2009). Our study included: 1) visual classification of the extent of shoreline damage as a function of shoreline protection type over long extents of the back-barrier shorelines of Bogue Banks and the Outer Banks, NC, immediately after passage of Hurricane Irene; and 2) erosion analysis of marshes with and without sills along Bogue Sound, NC, before and after Hurricane Irene. The resulting shoreline-protection evaluation data represent the first empirical progress within a larger framework of information necessary for developing comprehensive and sustainable coastal management policies for estuarine shorelines.

2. Methods

2.1. Description of study sites

Visually apparent damage to bulkheads, riprap revetments, and marshes with sills was recorded within one month of landfall of Hurricane Irene in North Carolina (Fig. 2A). Landfall occurred at Cape Lookout, NC, on August 27, 2011 as a Category 1 Hurricane, with a sustained wind-speed of 38 m/s. The strongest winds were primarily to the east of the eye over Pamlico Sound and the Outer Banks (Avila and Cangialosi, 2011). Approximately 14 km of back-barrier shoreline on the Outer Banks were surveyed within the towns of Rodanthe, Waves, and Salvo on the north end of Hatteras Island (Fig. 2B), as well as approximately 38 km of shoreline within Frisco and Hatteras Village on the southern end of Hatteras Island, NC (Fig. 2C, D). Hatteras Island is a barrier island approximately 320 km in length, bordered by Pamlico Sound to the west and the Atlantic Ocean to the east. Approximately 25 km of back-barrier estuarine shoreline on Bogue Banks (Fig. 2E) were also surveyed. Bogue Banks is a south-facing barrier island approximately 34 km in length, bordered by Bogue Sound to the north and the Atlantic Ocean to the south and the surveyed shoreline on Bogue Banks is situated within 25 km of the Irene landfall.

To determine if marsh with sills or marshes without sills would protect coastal property from erosion during a storm event, three marshes with sills and three unmodified marshes were evaluated in Pine Knoll Shores, NC, bordering Bogue Sound (Fig. 2E). At each sill site, a sill consisting of piled granite boulders (diameter of 20 cm–50 cm) had been constructed between the years of 2002 and 2007. The elevation of the top of each sill was between 0.14 and

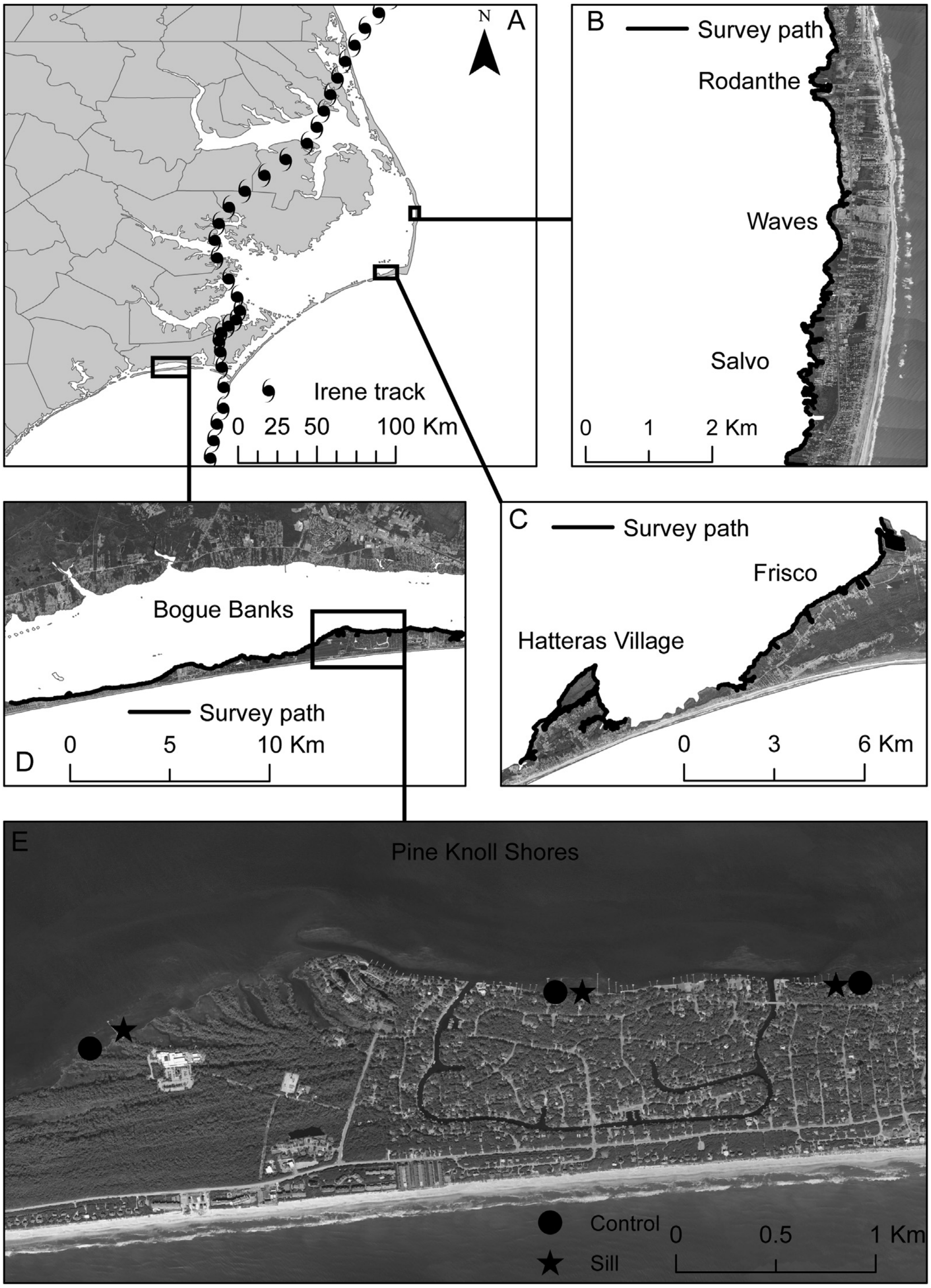

Fig. 2. A map of: A) the study areas relative to the path of Hurricane Irene (made landfall in NC at 34.7°N, 76.6°W; B) survey path for damage classifications on Rodanthe, Waves, and Salvo, NC; C) survey path for damage classifications on Frisco and Hatteras Island, NC; D) survey path for damage classifications on Bogue Banks, NC; and E) zoom-in to the sill sites and unmodified marsh sites that were surveyed along Bogue Banks, NC. The Hurricane Irene track and rate of movement is depicted at 30-min intervals by the location symbol.

0.31 m above mean sea level (MSL). Each sill had an average height ranging from 0.2 m (base to top of the sill) for the oldest to 0.56 m for the youngest sill. Marsh grasses, *Spartina alterniflora* and *S. patens*, had been planted behind each sill along the edge of existing marsh at elevations consistent with the positions of these two grasses on nearby unmodified marshes. A reference marsh site was selected near each sill site (Fig. 2E), based on physical similarity (similar marsh size, shoreline orientation, and elevation) and proximity (within 500 m) to the sill site (sensu Neckles et al., 2002).

2.2. Damage assessment of shoreline protection structures

Using a Trimble GeoExplorer (2008 series), GPS points were recorded at the beginning and end of each continuous stretch of each shoreline protection type. We recorded the presence or absence and category of damage for each shoreline stretch. Damage classifications were modified from Thieler and Young (1991) and were as follows: landward erosion; structural damage; breach; and collapse. Landward erosion was defined as erosion of the shoreline landward of the structure (Fig. 3A). Structural damage was defined as warping or evident damage to the structure without breach or collapse (Fig. 3B). A breach was defined as a gap or hole visible in the structure that allowed landward sediment to escape (Fig. 3C), while a collapse was defined as complete loss of the integrity of the structure so that it was no longer effectively retaining any sediment landward (Fig. 3D). Photographs were taken of each shoreline protection type (e.g., bulkhead, riprap revetment, sill) and each instance of damage to a shoreline protection structure. GPS data were imported into ArcGIS as shapefiles. Shapefiles were overlaid on 2010 aerial orthoimagery (North Carolina One Map, 2013) and digitized shorelines of Bogue Banks and the Outer Banks (NC DCM, 2012). NC DCM classified NC shorelines using 2007 aerial orthoimagery for Dare and Hyde counties and 2010 aerial orthoimagery for Carteret County (where Bogue Banks is located), producing ArcGIS continuous line shapefiles that include the shoreline type (marsh, beach, modified with structure [hardened]) and shoreline structure type (boat ramp, bulkhead, bulkhead and riprap combined, breakwater, groin/jetty, sill, riprap revetment).

A new line shapefile was created based on the NC DCM digitized shorelines and the NC DCM shoreline classifications were verified using GPS points, shoreline photos, and field notes. The NC DCM digitized shoreline associated with each set of GPS points (start and end of each stretch) was classified according to shoreline protection type and damage category recorded during the survey. If our surveyed shoreline classification did not agree with the NC DCM classification (e.g., the survey classified the shoreline as a bulkhead and NC DCM classified the shoreline as a marsh), the known shoreline classification based on survey data was chosen and the NC DCM shoreline classification was corrected. The total linear km of shoreline surveyed by shoreline protection type and the total linear km of shoreline damaged by category and by shoreline protection type for each region were then calculated.

2.3. Erosion analysis of marshes with and without sills

Changes in marsh surface elevation and marsh macrophytic vegetation density during and after Hurricane Irene were determined for marshes with sills and without sills. Pre-Irene surveys were conducted in August 2010 (one year before) and post-Irene surveys in October 2011 (one month after) and October 2012 (13 months after). Surface elevation (±5 mm) was measured along permanent transects at each site using a leveling rod and rotary laser level and referencing the measurements to semi-permanent benchmarks (points established on a stable structure with unchanging elevation, e.g., a piling or tree). Elevations relative to North American Vertical Datum of 1988 (NAVD88) were determined using a Trimble Virtual Reference Station (VRS), Real Time Kinematic (RTK), Global Positioning System (GPS). NAVD88 elevations obtained using these methods are estimated to be accurate to ±6–10 cm (C. Currin 2013, *personal communication*). Five transect locations were selected using restricted random (between 10 m and 20 m apart to maintain independence) sampling (sensu Neckles et al., 2002). Marsh transects began at the water's edge of the marsh and continued to the start of shrub-scrub vegetation or to property owner landscaping. Marsh plots (0.25 m^2) were established at 3 or 5 m intervals along each transect beginning at the lower marsh edge and surface elevation was measured within each plot. The length of each transect (5–20 m) and total number of marsh plots established (9–21) depended on the marsh width from water's edge to upland vegetation at each site. To compare marsh vegetation density between marshes with and without sills and to determine the changes in density over time, plant stem density was measured by species per 0.25-m^2 plot.

Mixed effects models were fit using restricted maximum likelihoods to determine if marsh surface elevation and stem density in marshes with and without sills changed in the short term (<1 month) or long term (13 months) as a result of Hurricane Irene. Treatment (marsh with sill vs. marsh without sill), year (2010, 2011, and 2012), and distance from the lower marsh edge, were fixed effects, while site was a random effect. Tukey's posthoc tests were used to evaluate differences in levels of significant factors. Data were Box–Cox transformed prior to analysis to meet the assumptions of homogeneity of variance (Levene's test, $P > 0.05$). An alpha level of 0.05 was used for all hypothesis testing. Analyses were conducted using JMP 10.0 (SAS, 2012).

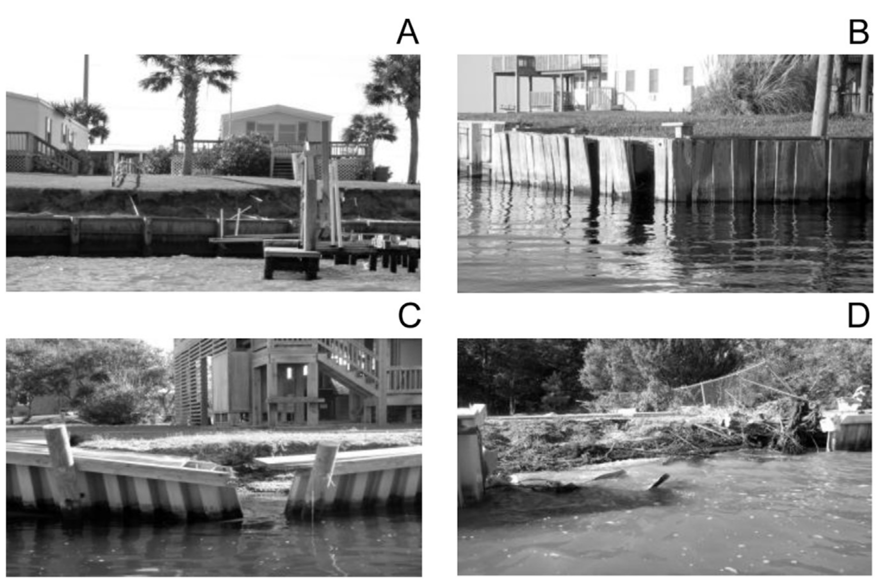

Fig. 3. Bulkhead damage classifications: A) Landward erosion; B) Structural damage; C) Breach; and D) Collapse.

3. Results

3.1. Damage assessment of shoreline protection structures

Of the 76 km of shoreline surveyed along the back-barriers of Hatteras Island and Bogue Banks, 28 km (37%) of the shoreline was protected by bulkheads. Riprap revetments, sills, and hybrid methods were less common than bulkheads, making up only 1.9%, 1.6%, and 2% of the shoreline, respectively, while the remaining shoreline was marsh (53%) or beach (3%) (*see* Fig. 4A for km of shoreline protection types by survey region).

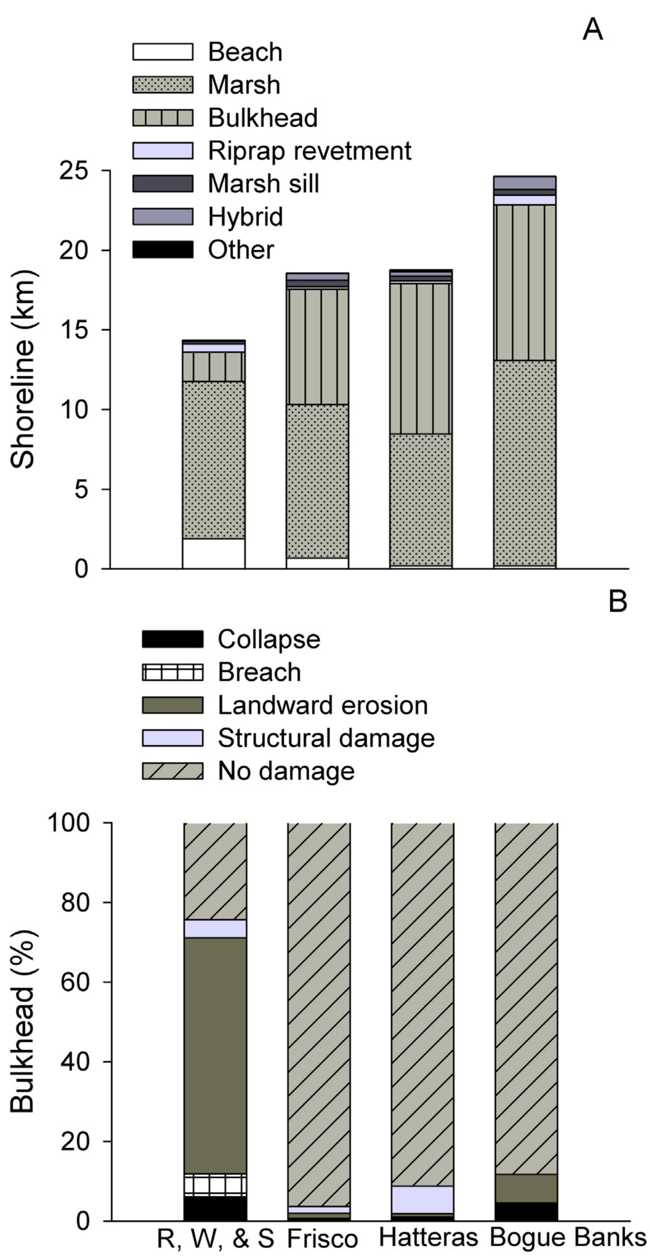

Fig. 4. A) Shoreline classification by type (km) for Rodanthe, Waves, and Salvo; Frisco; Hatteras Village; and Bogue Banks, NC. *See* Fig. 1 for descriptions and photographs of a bulkhead, riprap revetment, and marsh with a sill. Hybrid is a combination of bulkhead and riprap and beach is unvegetated shoreline. B) Bulkhead damage classification by type (%) for Rodanthe, Waves, and Salvo (R, W, & S); Frisco; Hatteras Village; and Bogue Banks, NC. *See* Fig. 3 for photographs of damage classifications.

Of the 1.86 km of bulkheads surveyed in Rodanthe, Waves, and Salvo (Fig. 4A), 76% (1.41 km) was damaged after the Hurricane (Fig. 4B), with damage ranging from landward soil erosion (Fig. 3A) to complete bulkhead collapse (Fig. 3D). In contrast, only 4% (0.26 km) of the 7 km of bulkheads surveyed in Frisco, 9% (0.83 km) of the 9 km of bulkheads in Hatteras Village, and 12% (1.14 km) of the 9.77 km of bulkheads on Bogue Banks (Fig. 4A) was damaged (Fig. 4B). No visible damage (structural failure, landward soil erosion) was detected to sill, riprap revetment, or hybrid shoreline structures surveyed within the study regions.

3.2. Erosion analysis of marshes with and without sills

Mean marsh surface elevations were significantly higher at sites with sills than at marsh sites without sills across all years ($P = 0.001$, Table 1, Fig. 5A). Elevation increased with increasing distance from the lower marsh edge, with the change in elevation being greater from the edge to the upland marsh at sites without sills than at sites with sills ($P < 0.001$). However, a significant change in marsh surface elevation was not detected from August 2010 (before Hurricane Irene) to October 2011 (one month after Hurricane Irene) at marshes with or without sills nor was a significant change detected in marsh surface elevation from October 2011 (immediately after Hurricane Irene) to October 2012 (13 months after Hurricane Irene) ($P = 0.930$, Fig. 5A). There were no significant interactions between treatment and year or treatment, year, and distance from marsh edge ($P > 0.05$).

Vegetation density did not vary between marshes with sills and marshes without sills ($P = 0.078$, Table 1, Fig. 5A), but did increase with increasing distance from the marsh edge ($P = 0.007$). From August 2010 (before Hurricane Irene) to October 2011 (after Hurricane Irene), vegetation density decreased by 167 ± 86 stems m^{-2} within marshes with sills and by 154 ± 73 stems m^{-2} within marshes without sills respectively, ($P < 0.05$, Tukey's post hoc tests, Fig. 5B). Increases of 218 ± 98 macrophyte stems m^{-2} within marshes with sills and 42 ± 59 macrophyte stems within marshes without sills, respectively, occurred from October 2011 (immediately after Hurricane Irene) to October 2012 (13 months after Hurricane Irene) ($P < 0.05$, Tukey's post hoc tests, Fig. 5B). In 2010 and 2012, vegetation density was not significantly different across sites ($P > 0.05$, Tukey's post hoc tests, Fig. 5B). However, while vegetation within marshes with sills in 2012 appeared to have recovered to 2010 levels, within marshes without sills, the marsh did not appear to recover to the same vegetation density over this time period, although this difference in recovery was not statistically significant ($P = 0.289$, Fig. 5B). There were no significant interactions between treatment and year or treatment, year, and distance from marsh edge ($P > 0.05$).

4. Discussion

The purpose of a shoreline protection structure is to prevent erosion of shoreline and damage to coastal property during storm events, such as hurricanes (USACE, 2004). Engineering performance and cost efficiency and are among key deciding factors for coastal property owners when choosing a shoreline protection approach (Scyphers et al., 2014), whereas ecological effects relative to current environmental regulations are important factors for coastal managers charged with permitting shoreline protection structures (Titus, 1998). Hence, data on the shoreline protection capabilities, cost efficiency, effects on ecosystem services, and reversibility and adaptability of alternative shoreline protection approaches are critical to development of economically and ecologically sound coastal management policies.

Table 1
Mixed model results for erosion analysis of marshes with sills and without sills. Significant *p* values ($P < 0.05$) are shown in bold.

Response variable	Fixed factors	DF	*F* ratio	Prob > *F*	REML variance component estimates	Var ratio	Var component	Std error	95% CI lower	95% CI upper	Percent of total
Marsh surface elevation (m)	Shoreline type (sill or no sill)	1	14.60	**0.001**	Site	0.254	0.004	0.002	0.000	0.008	20.25
	Year (2010, 2011, 2012)	2	0.07	0.930	Residual		0.016	0.002	0.013	0.020	79.75
	Plot (distance from marsh edge)	4	59.20	**<0.0001**	Total		0.020	0.002	0.016	0.026	100.00
	Shoreline type*Year	2	0.01	0.992							
	Shoreline type*plot	4	7.20	**0.000**							
	Plot*year	8	0.19	0.990							
	Shoreline type*plot*year	8	0.21	0.988							
Marsh stem density per m^2	Shoreline type (sill or no sill)	1	3.27	0.078	Site	0.536	882	307	280	1484	34.88
	Year (2010, 2011, 2012)	4	4.12	**0.007**	Residual		1647	167	1362	2031	65.12
	Plot (distance from marsh edge)	2	4.62	**0.015**	Total		2529	321	2001	3297	100.00
	Shoreline type*year	2	1.28	0.289							
	Shoreline type*plot	4	0.34	0.846							
	Plot*year	8	0.79	0.611							
	Shoreline type*plot*year	8	0.10	0.999							

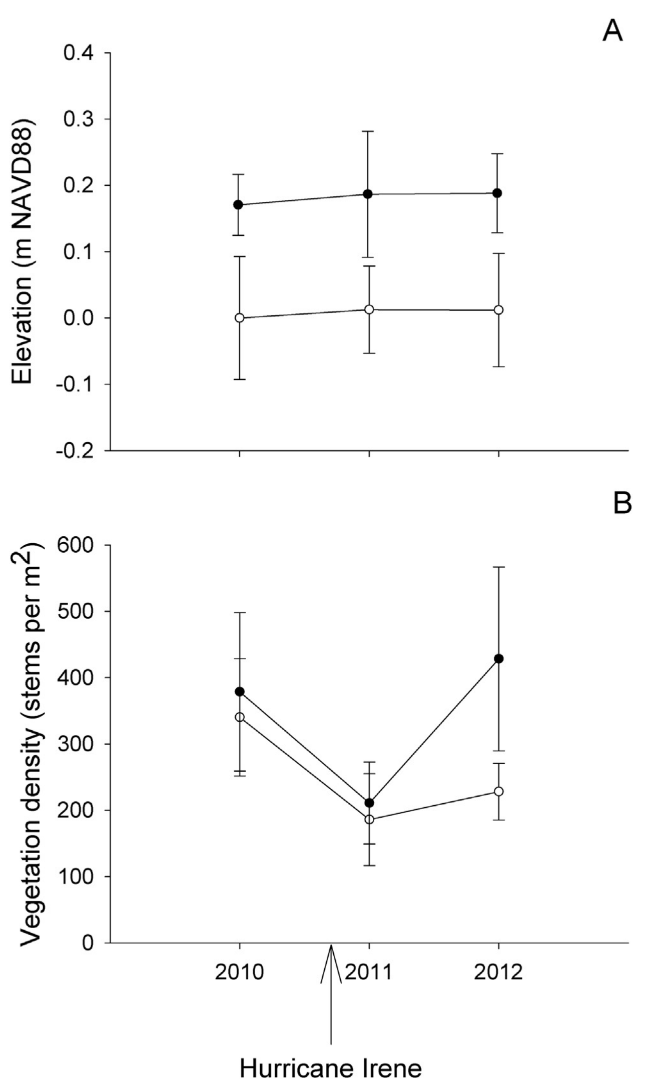

Fig. 5. The effects of Hurricane Irene on: (A) average marsh surface elevation (m, NAVD88); and (B) average vegetation density per m^2 at marsh sites with (closed circles) and without (open circles) sills. Error bars represent ±1SE ($n = 9$ to 21 per site).

4.1. Shoreline protection capabilities

Results of our post-Hurricane Irene damage surveys conducted along shorelines at Rodanthe, Waves, and Salvo, NC, indicated that at least 75% of sampled bulkheads were damaged (Fig. 4B). The percentage of bulkheads damaged within other surveyed regions was far lower, ranging from 4 to 10%. Rodanthe, Waves, and Salvo experienced a greater storm surge (2.16 m) and longer period (30 h) of sustained onshore winds greater than 17 m/s (minimum speed for tropical depression) than our other survey regions (Table 2) (National Oceanographic and Atmospheric Administration [NOAA], 2011). Additionally, the fetch across open water to the shoreline at Rodanthe, Waves, and Salvo was greater (100 km) in the direction of the strongest winds (34 m/s, from the southwest) observed during Irene than the fetch to the other surveyed shorelines (Table 2, Fig. 4A) (NOAA, 2011). Pre-hurricane structural condition of the bulkhead, wave exposure, fetch, and nearshore bathymetry presumably all contributed to observed differences in bulkhead performance among study regions during the hurricane.

Bulkheads were the only type of shoreline protection structure that showed visible damage after the hurricane (Fig. 4A). Thieler and Young (1991) also found greater damage to bulkheads when compared to riprap revetments along barrier island shorelines in South Carolina after Hurricane Hugo. They attributed the high rate of damage to bulkheads (58% of 6.1 km of bulkheading destroyed) and riprap revetments (24% of 7.1 km destroyed) to overtopping by the storm surge (Thieler and Young, 1991). Most of the bulkhead failures observed in our study were probably also a consequence of overtopping of bulkheads by waves and storm surge (Table 2). Bulkheads retain landward sediment at an elevation 1–2 m higher than the natural shoreline. This large difference in elevation, when compared to typically lower-sloped marsh, riprap revetments, or sills, can result in a large and rapid loss of sediment if the stabilizing structure (the bulkhead) collapses or is breached (Fig. 3D). This process was evident from the large amount of sediment lost at all collapsed bulkheads surveyed throughout the NC coast (Fig. 4B). Damage to bulkheads was frequently observed directly adjacent or close to shorelines stabilized with riprap revetments, hybrid structures, and sills that were not damaged (R.K. Gittman, *personal observation*), even along the Rodanthe, Waves, and Salvo shorelines. One of the sill sites surveyed on Bogue Banks was located approximately 100 m from a collapsed bulkhead and experienced no change in overall marsh elevation in 2011 (Figs. 3D and 5A).

Table 2
Meteorological and water level data for surveyed locations during Hurricane Irene and Hurricane Isabel.

Hurricane parameter	Rodanthe, waves, & Salvo[a]	Frisco & Hatteras Island[b]	Bogue Banks[c]	
	Irene	Irene	Irene	Isabel
Duration at or above tropical depression speed	30 h	24 h	29 h	38 h
Average wind speed	17 m/s	12 m/s	22 m/s	17 m/s
Maximum gust	34 m/s	32 m/s	35 m/s	40 m/s
Maximum gust direction	Southwest	East	East northeast	North
Max fetch from max gust direction	100 km	4 km	5 km	5 km
Storm tide	2.32 m	1.25 m	1.91 m	1.61 m
Predicted tide	0.16 m	0.13 m	0.99 m	0.74 m
Storm surge/residual	2.16 m	1.12 m	0.92 m	0.87 m

[a] Data collected from the Oregon Inlet station (ORIN7 8652587), NOAA National Data Buoy Center and the NOAA tide station at the Oregon Inlet Marina, NC (8652587) from August 26, 2011 to August 28, 2011.
[b] Data collected from the Cedar Island station (NCDI), State Climate Office of North Carolina and from the NOAA tide station at the US Coast Guard Station Hatteras, NC, from August 26, 2011 to August 28, 2011. NCDI was the closest wind station available because the Hatteras Island wind station was damaged during the hurricane.
[c] Data collected from the Cape Lookout station (CLKN7) and the NOAA tide station at the NOAA Beaufort Lab, Beaufort, NC, from September 17, 2003 to September 19, 2003 and August 26, 2011 to August 28, 2011.

To evaluate the generality of some of our findings, our post-Irene results can be compared to those presented by Currin et al. (2007), who evaluated shoreline erosion in Bogue Sound after Hurricane Isabel. Specifically, Irene-induced changes in marsh surface elevation at the western-most marsh with sill and marsh without sill sites from before to after Hurricane Irene in PKS, NC (Fig. 2E) can be compared to changes observed by Currin et al. (2007) at the same sites from before (spring 2003) to after (spring 2004) Hurricane Isabel (Category 2 at landfall, 45 km to the northeast of these two sites, Table 2). Marsh surface elevation increased 23.96 ± 2.60 (SE) cm in the marsh with a sill and 11.87 ± 2.53 (SE) cm in the marsh without a sill following Hurricane Isabel, whereas no significant change in surface elevation was observed following Hurricane Irene (Fig. 5A). Currin et al. (2007) also found an increase in marsh elevation after Isabel at two additional marshes with sills and two marshes without sills along shorelines of Bogue and Core Sound, NC. The increases in surface elevation after Isabel, as contrasted to the absence of change in surface elevation after Irene, may have been caused by transport of sediment during the longer period of sustained high winds and the wind direction with maximum gusts coming from the north (perpendicular to the shoreline) during Isabel (Table 2). Storm winds from the north would have increased wave heights at these north-facing study sites, potentially increasing sediment transport and deposition onto the marsh.

The immediate loss of marsh vegetation after Hurricane Irene followed by subsequent recovery of vegetation density within 13 months indicates that the impacts of Hurricane Irene on marsh vegetation at sill and unmodified sites on Bogue Banks were temporary. However, a non-significant difference was also observed in the amount of recovery of the marsh between sill and unmodified sites, with vegetation density at sill sites recovering more completely within the year than at unmodified sites (Fig. 5B). This potential difference in vegetation recovery between sill and unmodified sites could be explained by the ability of sills to protect the marsh by acting as a breakwater, much like an intertidal oyster reef would function, allowing lost or damaged vegetation to regrow in a more sheltered setting, thus potentially enhancing marsh recovery (Meyer and Townsend, 1997). Currin et al. (2007) found an increase in vegetation density at all sites during the year following Hurricane Isabel. Because neither hurricane resulted in surface elevation or permanent vegetation loss, it appears that marshes both with and without sills provided erosion protection during each storm event.

Marshes with and without sills presumably provided erosion protection via wave attenuation and stabilization of sediments (Shepard et al., 2011). Shepard and colleagues conducted a meta-analysis on the protective role of coastal marshes and evaluated the ability of marshes to perform the following functions: wave attenuation, sediment stabilization, and floodwater attenuation. Positive correlations between marsh width and wave attenuation and marsh width and sediment stabilization were found. Additionally, the meta-analysis revealed that marshes less than 10 m in width (which is the width of many fringing marshes found along the NC shorelines surveyed in our study), can reduce wave heights by 80% for waves <0.5 m in height and can reduce wave heights by 50% for waves >0.5 m in height. In terms of sediment stabilization, marshes promoted vertical sediment accretion, reduced sediment loss, and maintained or increased the surface elevation of the shoreline. We acknowledge that wave attenuation abilities of marshes decreases with increasing wave height and because water levels exceeded 0.5 m at our study regions (see Table 2), wave attenuation was likely less than 50% for marsh shorelines in this study. However, given the lack of visible damage and change in surface elevation or vegetation density in comparison to the damage observed to bulkheads within our study regions, we conclude that sills and marsh vegetation stabilized the shoreline despite reduced wave attenuation capabilities of marshes during the storm.

Although marshes with sills sustained little damage as a result of Hurricane Irene, data on the long-term performance of these structures are still necessary to determine their viability as shoreline protection structures. Bulkheads and riprap revetments are estimated to have an average lifespan of 30 years and 50 years, respectively, with appropriate maintenance required, particularly for bulkheads (NC DCM, 2011). However, bulkhead maintenance often includes back filling of landward sediment that has been lost over time to “hold the line” against erosion. The lifespan of marshes with sills is less certain because a majority of the existing sills in NC was constructed within the last 20 years (Fear and Bendell, 2011). However, an assessment by NC DCM in 2011 revealed that all sills constructed in North Carolina remained intact and most of the sills were preventing erosion of the shoreline (Fear and Bendell, 2011). Occasional supplemental planting of the marsh is the only maintenance described by property owners with sills (L. Weaver, *personal communication*). Long-term measurements (decades) of changes in marsh surface elevation and vegetation density at sites with sills, as well as measurements during larger storms, are necessary to truly determine the lifespan of this type of shoreline protection.

4.2. Research framework for informing shoreline protection decisions

This study provides much needed data on the shoreline protection capabilities of different shoreline protection approaches that will help inform coastal management policies. However, data on the performance of shoreline structures during multiple storm events over a wider geographic area, cost efficiency, ecological effects, and the reversibility and adaptability of shoreline protection approaches with climate change are needed for waterfront property owners and coastal mangers to make truly informed decisions about shoreline protection. Here we present a framework for fulfilling the remaining data needs on shoreline protection.

The observed performance of shore protection structures may be limited to the geographic region and to the size and characteristics of the specific storm evaluated in this study. Additional studies evaluating the performance of shore protection in different geographic regions during storms of different magnitudes, durations, and physical characteristics are needed. Data on the age and condition of shore protection structures prior to storm events should also be collected whenever possible. Finally comparisons of shore protection performance within the same geographic region across multiple storm events would also contribute to a more comprehensive understanding of the relative performance of estuarine shore protection structures.

The cost of installing a shoreline protection structure can be a key consideration for a coastal property owner deciding how to protect his or her shoreline. In North Carolina, the average construction cost in 2011 of bulkheads and riprap revetments was estimated to be $450 per linear meter and $400 per linear meter, respectively, with a combination costing approximately $850 (NC DCM, 2011). Marsh planting was estimated to cost $70 per linear meter (assuming a 6 m-wide marsh) and construction of a granite marsh sill (including marsh planting) was estimated at $500 per linear meter (NC DCM, 2011). Although the average construction costs for bulkheads, riprap revetments, and marsh sills are similar, the replacement cost of marsh sills and riprap revetments is likely much lower than the initial construction costs, because the rock structure would likely only need to be rearranged or augmented rather than replaced entirely in the event of structure failures (FitzGerald et al., 1994; Thieler and Young, 1991). Given the documented poor performance of bulkheads relative to riprap revetments and marshes with and without sills in this study, bulkheads are probably the least cost effective method for shoreline protection. However, cost effectiveness needs to be further evaluated to include maintenance and replacement costs as a function of inflating materials and labor costs and the availability of qualified contractors for different shoreline protection approaches.

In addition to considering the engineering capability and cost efficiency of a shoreline protection approach, policymakers should consider the effects of each shoreline protection approach on the ecosystem services provided by marsh and the broader coastal ecosystem. Bulkheads can cause deepening of adjacent shallow subtidal waters via wave refraction and scour, resulting in loss of marsh and seagrass habitat (NRC, 2007). Bulkheads are generally associated with reduced abundances of upland coastal marsh plant species, fish and crustaceans, and benthic infauna (Bilkovic and Roggero, 2008; Bozek and Burdick, 2005; Seitz et al., 2006). Riprap revetments are associated with higher fish and crustacean abundance and diversity than bulkheads, but not natural marshes, probably because riprap provides more structurally complex habitat than a vertical bulkhead wall, but not necessarily more complex than natural marshes (Bilkovic and Roggero, 2008; Seitz et al., 2006). In contrast to bulkheads and riprap revetments, sills create sheltered habitat suitable for coastal marsh and seagrass plants and sills are associated with higher fish and crustaceans abundances equivalent to abundances found in natural marshes (Currin et al., 2007; Gittman et al., in review; Hardaway et al., 2002; Scyphers et al., 2011; Smith et al., 2009). Nevertheless, relevant data are limited, so additional multi-year, multi-site, and before-after-control-impact studies are needed to determine the net ecological effects of each alternative shoreline protection approach (NRC, 2007).

As sea levels continue to rise, bulkheads and riprap revetments will inhibit transgression as the lower edge of the marsh progressively erodes, resulting in net loss and ultimately disappearance of the marsh habitat (Peterson et al., 2008a,b; Titus, 1998). This loss of habitat should result in violation of Section 404 of CWA, implying that the USACE may need to consider how to require mitigation for these losses. Based on the physical characteristics described in Section 4.1 and the costs provided in this section, reversing marsh habitat loss associated with a bulkhead by removing the bulkhead and restoring lost coastal marsh by replanting would be more arduous and costly than supplemental marsh planting or moving or reinforcing a sill. However, research is needed on the feasibility of removing or adaptively managing and modifying alternative shoreline protection structures already in place.

4.3. Conclusions

This study contributes important information on the shoreline protection capabilities of several shoreline protection approaches and is the first study to contrast the performance of bulkheads and riprap revetments to marsh plantings with and without sills during a major storm. Additionally, a framework is provided for future research on the long-term shoreline protection capabilities, cost effectiveness, ecological effects, and reversibility and adaptability of shoreline protection structures. Scientists should focus on filling data gaps, particularly by evaluating the performance of shore protection structures in multiple storm events and by quantifying the ecological effects of alternative shoreline protection approaches. Policymakers should consider data from each component of this decision-framework to develop a synthetic set of policies related to estuarine shoreline protection.

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