Marine Policy 81 (2017) 350–358

Contents lists available at ScienceDirect

Marine Policy

journal homepage: www.elsevier.com/locate/marpol

Hurricane damage along natural and hardened estuarine shorelines: Using homeowner experiences to promote nature-based coastal protection

Carter S. Smith[a,*], Rachel K. Gittman[b], Isabelle P. Neylan[a], Steven B. Scyphers[b], Joseph P. Morton[c], F. Joel Fodrie[a], Jonathan H. Grabowski[b], Charles H. Peterson[a]

[a] Institute of Marine Sciences, University of North Carolina at Chapel Hill, Morehead City, NC 28557, United States
[b] Marine Science Center, Northeastern University, Nahant, MA 01908, United States
[c] Duke Marine Laboratory, Duke University, Beaufort, NC 28516, United States

A R T I C L E I N F O

Keywords:
Bulkhead
Coastal resiliency
Ecosystem service
Shoreline hardening
Storm
Living shoreline

A B S T R A C T

Growing coastal populations, rising sea levels, and likely increases in the frequency of major storm events will intensify coastal vulnerability in coming decades. Decisions regarding how and when to fortify estuarine shorelines against coastal hazards, such as erosion, flooding, and attendant property damages, rest largely in the hands of waterfront-property owners. Traditionally, hard engineered structures (e.g. bulkheads, revetments, seawalls) have been used to protect coastal properties, based on the assumption that these structures are durable and effective at preventing erosion. This study evaluates the validity of these assumptions by merging results from 689 surveys of waterfront-property owners in NC with empirical shoreline damage data collected along estuarine shorelines after Hurricanes Irene (2011) and Arthur (2014). The data show: 1) homeowners perceive bulkheads to be the most durable and effective at preventing erosion, but also the most costly; 2) compared to residents with revetments and natural shorelines, property owners with bulkheads reported double the price to repair hurricane damage to their property and four times the cost for annual shoreline maintenance; 3) 93% of evident post-hurricane shoreline damage was attributable to bulkheads or bulkhead hybrids and a higher proportion of surveyed homeowners with bulkheads reported having property damage from hurricanes; and, 4) shoreline hardening increased by 3.5% from 2011 to 2016 along 39 km of the Outer Banks. These results suggest that bulkheads are not meeting waterfront property-owner expectations despite continued use, and that nature-based coastal protection schemes may be able to more effectively align with homeowner needs.

1. Introduction

By the latter half of this century, over 50% of the world's population will be living within 100 km of a coastline [50]. Concurrently, some models predict a doubling in frequency of Category 4 and 5 hurricanes ([6], but see [25]) and rising sea levels that will increase vulnerability to coastal flooding [48]. Extensive degradation of coastal habitats is already globally documented [13,28]. As aspects of climate change interact with human population growth and land development, continued degradation of natural shoreline habitats and a precipitous reduction in ecological resilience to natural disasters are likely [1]. In recognition of these growing environmental risks with potentially devastating socioeconomic consequences, enhancing coastal resilience has become an issue of fundamental importance [5], and accordingly a priority for governments, industries, and environmental advocates [24,15,34].

In the United States, much of the sheltered coastline is vulnerable to erosion [8]. The prevailing response to this threat has been armoring of shorelines with hard, engineered structures (e.g. bulkheads, revetments, seawalls), under the assumption that "hardened shorelines" are most effective at preventing erosion [16,33,44]. The most commonly used forms of shoreline stabilization along sheltered coasts are bulkheads (fixed, vertical walls typically installed at or above the ordinary high water mark; [56]), revetments (sloping rock structures of marl, granite, or concrete rip rap), and hybrid structures that combine a bulkhead with seaward and/or landward riprap (Fig. 1A, B, C). Bulkheads in particular have been shown to have numerous adverse effects on the habitat landscapes and biological communities around them [9,14,22,46], and revetments are also associated with negative ecological effects [39,4]. Perhaps the greatest environmental concern associated with engineered hard shorelines is the prevention of natural up-slope transgression of salt marsh and other productive shoreline habitats as sea level rises, which is also a process for which we have the least quantitative data. In areas with intense coastal development, this

* Correspondence to: Institute of Marine Sciences, 3431 Arendell St., Morehead City, NC 28557, United States.
E-mail address: scarters@live.unc.edu (C.S. Smith).

http://dx.doi.org/10.1016/j.marpol.2017.04.013
Received 10 February 2017; Received in revised form 10 April 2017; Accepted 12 April 2017

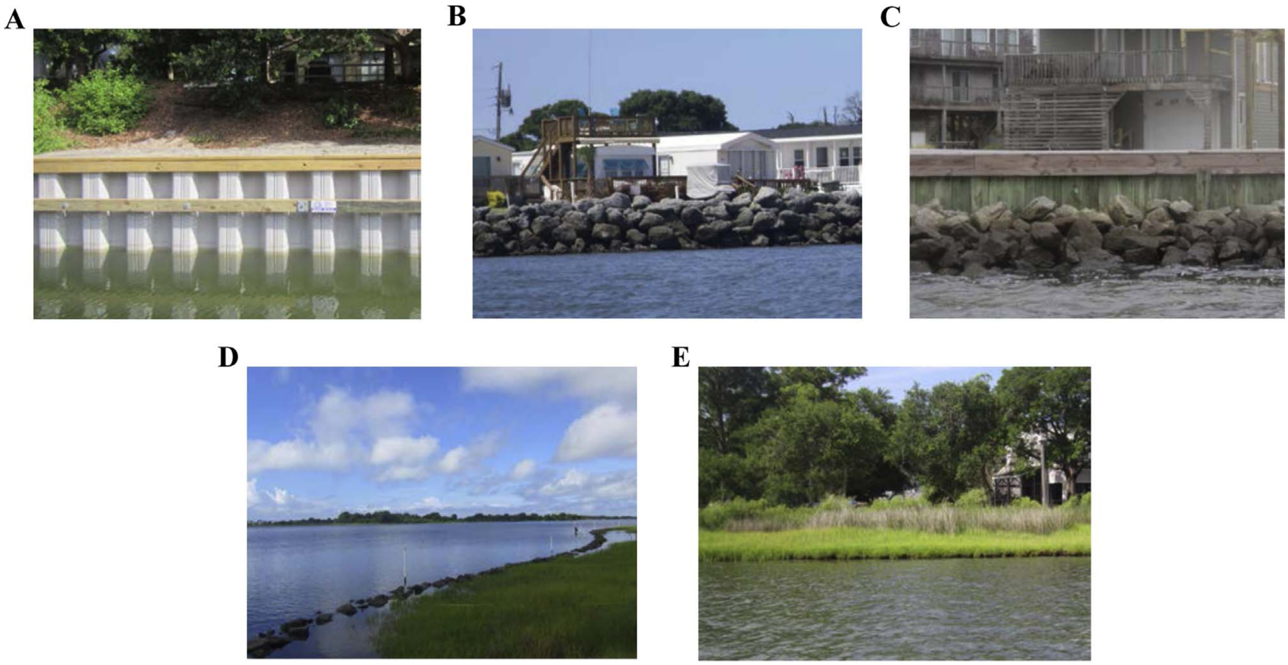

Fig. 1. Example shorelines: (A) bulkhead; (B) riprap revetment; (C) hybrid shoreline, combining a bulkhead with riprap; (D) sill with plantings; and, (E) natural marsh.

"coastal habitat squeeze" threatens the persistence of shoreline habitats and the critical ecosystem services they provide (e.g. reduction of wave energy, pollutant filtration, carbon sequestration, habitat provisioning; [54,41,2]).

Although the negative consequences of shoreline hardening have been well-documented, the percentage of hardened shoreline continues to increase globally, with up to 100% of many urban shorelines and over 14% (22,000 km) of the total US shoreline already hardened [10,21,26]. Lack of awareness of viable alternatives to hardened shorelines may explain the continuing dominance of hardening solutions to erosion hazards. Over the past two decades, restoration practitioners, ecologists, and environmental engineers have advocated use of alternative strategies referred to as "living shorelines", which prioritize both shoreline stabilization and coastal ecosystem protection. Living shorelines often combine an offshore sill (i.e. a low-rising breakwater) with existing, restored, or enhanced marsh plantings. The sill is typically constructed of marl, granite, or oyster shell and placed below the ordinary high water mark ([57]; Fig. 1D). Living shorelines can preserve and even enhance the services of coastal ecosystems [23]; however, most living shoreline projects have been built within the last decade, so there is limited information on the most appropriate protection measures for various shoreline energy regimes [52].

Often the decisions about where and how to harden a shoreline fall to private-property owners, and these individual, small-scale decisions can have cumulative wide-scale impacts [38]. For example, Scyphers et al. [44] showed that one of the most important factors influencing whether a property owner hardened their shoreline was the condition of their neighbor's shoreline, revealing that the social and/or biophysical influence of one homeowner's decision to construct a vertical wall can initiate a reactionary cascade resulting in additional hardening and subsequent habitat degradation. With large portions of shoreline privately owned, the extent and quality of coastal wetlands will hinge in part on understanding and modifying the decision-making process of those property owners [43]. While there is emerging evidence to the contrary [20], many property owners believe that hardened shorelines are the most effective and durable shoreline stabilization options, and continue to preferentially choose engineered structures over natural and ecosystem-compatible alternatives [44]. Therefore, to inform coastal managers and property owners on how to best enhance coastal resilience, a rigorous evaluation of the functions, durability, and socio-economic dimensions of hardened shorelines as compared to nature-based coastal protection is needed.

This study investigates hardened versus natural shorelines by analyzing their performance (effectiveness and durability) during two hurricanes and assessing residential-scale maintenance and hurricane-damage-repair costs. North Carolina is an ideal study system because it has nearly 20,000 km of sheltered coastline [36], it is predicted to be one of the most vulnerable states to sea level rise [51], and it has been impacted by over 100 tropical storms and hurricanes since 1851 [37]. This study synthesizes results from surveys of waterfront-property owners, as well as field surveys of shoreline damage after each of two hurricanes. Specifically, this study assesses which attributes property owners prioritize when choosing a shoreline stabilization method, and then evaluates whether those expectations are being met.

2. Methods

2.1. Waterfront property owner survey design

To assess which attributes waterfront-property owners prioritize when making shoreline-protection decisions, a dual-method (online and mail) survey of waterfront residents was conducted in 16 of 20 coastal counties in North Carolina (Supplemental Fig. 1A). Waterfront properties were selected from county tax assessor websites using a stratified random sampling design. Properties that had been listed as for sale or sold during the previous 12 months were excluded. The number of properties sampled per county was calculated by taking the percentage of the total population, houses, and shoreline length for all the counties, and then averaging these three numbers and using that final percentage to weight the survey distribution across the 16 counties (Supplemental Fig. 1B). Survey participants were recruited using a modified Dillman method [30] involving an initial mailing of postcard invitations to complete an online survey and one follow-up reminder postcard (Supplemental Fig. 2). Survey responses were recorded from May 2014 to February 2015. Printed surveys were mailed to all individuals who requested them. The online survey was hosted and administered using Qualtrics Research Suite.

The survey data presented here were collected as part of a 75-question survey instrument, which was developed and pre-tested by an interdisciplinary team of scientists, coastal managers, and waterfront-property owners. This paper reports on the results of responses to 11 questions from survey sections focused on the economic, ecological, aesthetic, and social considerations involved in shoreline protection decision-making, as well as demographic and environmental descriptors. For instance, property owners were asked a series of questions to identify their perceptions of natural and hardened shorelines for several performance criteria (e.g. durability, cost), and to determine how these different criteria influence their decision-making about shore protection. Property owners were also asked to report actual shoreline damage frequencies and costs to determine if their chosen shoreline protection strategy was meeting expectations.

2.2. Damage assessment field surveys

To assess visually evident shoreline damage caused by each of two recent hurricanes, Irene and Arthur, back-barrier island shoreline damage in NC's Outer Banks was assessed after each storm. Hurricane Irene was a Category 1 hurricane that made landfall at Cape Lookout, NC on August 27, 2011, achieving maximum sustained wind speeds of 39 m/s [3]. On July 3, 2014 Hurricane Arthur followed a similar path, making landfall just West of Cape Lookout, NC as a Category 2 hurricane with sustained wind speeds of 44 m/s ([7]; Fig. 2A). Three temporally discrete surveys were conducted along the same stretches of shoreline in Hatteras, Frisco, and across Rodanthe, Waves, and Salvo (RWS) between 2011 and 2016 (Fig. 2B, C, D). All damage assessment paths were surveyed during each of the following periods: 1) one month after landfall of Hurricane Irene in September 2011; 2) one month after landfall of Hurricane Arthur in July 2014; and, 3) approximately two years after Hurricane Arthur in April 2016.

For the field surveys, damage was evaluated according to the criteria in Gittman et al. [20]. Shoreline type was condensed into 6 categories: 1) bulkhead; 2) hybrid (structures that combined a bulkhead with another engineered structure); 3) riprap revetment; 4) sill with planting (i.e. living shoreline); 5) natural, which encompassed all unmodified shorelines (vegetated and unvegetated); and, 6) other (e.g. jetties, marinas, etc.; Fig. 1). The data were compiled by shoreline type and category of damage.

To determine if damage had occurred or been repaired between sampling dates, separate shapefiles were created that included only damaged shoreline segments from each survey year and the intersect tool in ArcGIS was used to quantify overlap. When there was no overlap, damage was considered independent. When there was overlap in damage but the damage category did not change, the damage was considered unrepaired. When there was a less severe category of damage on a later trip (e.g. a bulkhead was recorded as collapsed in 2011, but only landward erosion was present in 2014), it was assumed that the structure had been repaired and then re-damaged. Lastly, when a more severe category of damage was present on the later trip, additional damage was considered to have been caused between those dates and the initial damage was considered unrepaired. The measure tool in GIS was used to quantify average fetch (the average of 5 evenly spaced measurements taken across open water in an arc from each survey respondent's shoreline) and maximum fetch (the longest distance across open water from each survey respondent's shoreline; Supplementary Fig. 3).

2.3. Statistical analyses

Ordered response variables were converted to Likert scores prior to analysis of the property-owner survey data, and percent responses are also shown for clarity. For the ranking questions focused on perceptions of shoreline characteristics, responses were inversely coded (i.e. Rank 1 = 3, Rank 2 = 2, Rank 3 = 1) and weighted percent responses were calculated. Both univariate and multivariate analyses were used to determine the strongest predictors of shoreline damage/maintenance costs and if property owner-reported costs and maintenance days differed significantly as a function of shoreline type. Survey data analyses were restricted to properties with bulkheads, natural shorelines (vegetated and unvegetated), and riprap revetments; respondents

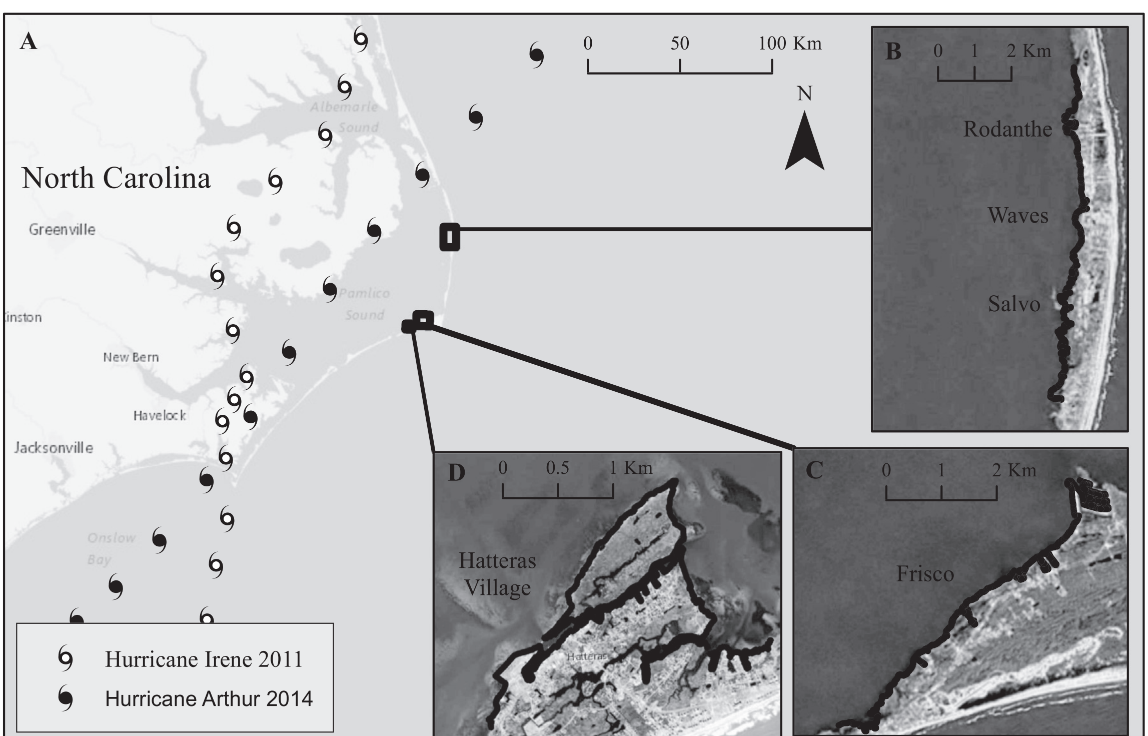

Fig. 2. (A) Map of the study area in NC, showing hurricane tracks for Irene (2011) and Arthur (2014) using location symbols in 1-h increments. Insets show damage assessment survey paths in: (B) Rodanthe, Waves, and Salvo; (C) Frisco; and, (D) Hatteras Village.

with hybrid, sill, and other shorelines were excluded because there were too few responses. The Chi-squared Automatic Interaction Detection (CHAID) tree-based classification model was used to determine which environmental factors were most predictive of shoreline damage/maintenance costs. The CHAID tree growing method isolates the independent variable that has the strongest predictive power at each level, and merges categories that are not significantly different. Trees were separately computed for whether or not a homeowner reported hurricane damage costs, maintenance costs, and maintenance days; fourteen different environmental factors (e.g. maximum fetch, county, shoreline type) were included in the analysis (Supplementary Fig. 4).

Cost data were analyzed in a three-step process, using the delta approach [17,47]. First, Fisher's Exact tests were used to compare the proportions of property owners that reported spending any time or money maintaining or repairing their shoreline versus those who reported spending zero dollars or days. When there was a significant difference, a post-hoc Fisher's Exact test was applied to determine which pairs were significantly different. In the second step, only costs or days greater than zero were included. These data were log transformed to meet the assumptions of normality and then one-way ANOVAs were run to determine if there were significant differences in mean hurricane damage costs, maintenance costs, and maintenance days as a function of shoreline condition. If the ANOVA was significant, pairwise *t*-tests were applied to determine pairwise significance. Third, delta values, or indexes of relative cost/time, were calculated from the product of occurrence and mean cost/time according to the procedures of Serafy et al. [47]. The separate analysis of zero and non-zero data made it possible to address differences in money/time spent among shoreline types, depending on whether or not the property owner needed or was willing to invest money and/or time. Furthermore, for zero-inflated data with large variances, the delta method produces an index that can be more representative of the data than a traditional estimate of the mean [45]. To compare the frequency of damage among shoreline types, steps 1 and 2 were repeated as described above. An alpha level of $p < 0.05$ was used for all statistical analyses. Responses of “do not know” or “do not care” were not included in analyses, and non-responses were only included in the classification trees. As the shoreline boat surveys lacked true replication, these data are presented descriptively. CHAID analyses were performed in SPSS Statistics 23 and all other statistical analyses were performed in R 3.2.3 (R Development Core Team 2015).

3. Results

3.1. Survey results

A total of 689 completed surveys were received from waterfront property owners, for a response rate of 18%. Respondents were largely male (75%), college graduates (72% had a Bachelor's degree or higher), older (mean age = 66), and reported an income of over $100,000 per year (46%). On average, respondents had lived in North Carolina for 34 years and had spent 15 years at their current residence. Forty-one percent (N = 282) of property owners reported having bulkheads (average length = 45 m ± 3 m [mean ± SE]), 40% (N = 275) had natural shorelines (average length = 51 m ± 3 m), 10% (N = 66) had riprap (average length = 77 m ± 14 m), and the remaining 9% had a sill (N = 10), groin (N = 7), or hybrid shoreline (N = 49).

Seventy-nine percent of respondents prioritized effectiveness (defined as erosion prevention) within their top three attributes regarding criteria influencing their decision-making about shoreline protection, followed by cost (65%) and durability (62%). Ecological impact was ranked less frequently (34%), and aesthetics, permitting, water access, and other criteria were rarely prioritized (Fig. 3A). When asked to rank which shoreline type was the most effective, 32% of property owners selected bulkheads, followed by riprap (20%) and planting alone (21%; Fig. 3B). Bulkheads were also considered the most costly option with 46% of respondents ranking them highest, followed by riprap with 22% (Fig. 3C). Bulkheads were perceived as the most durable (32%), but also thought to require the most maintenance (24%) (Fig. 3D, E). Plantings (with and without a sill) were considered more effective and durable than a sill alone (Fig. 3B,D). When asked about shoreline damage, 66% of respondents perceived storms to be the number one cause of property damage (Fig. 4A). This belief was reinforced by the reported damage frequencies, which found storms to be responsible for 78% of reported shoreline damage, with hurricanes/tropical storms responsible for 37% of damage, Nor'easters responsible for 27%, and other storms responsible for 14% (Fig. 4B). A higher proportion of property owners with bulkheads versus natural shorelines reported that their property had been damaged by a hurricane since they had lived there (69% v. 52%, post-hoc Fisher's Exact Test, $p < 0.0001$; Supplemental Table 1A, B), but of those that reported ever having hurricane damage, there was no difference in the number of hurricane damage incidents reported per year among shoreline types (ANOVA, $p = 0.53$; Supplemental Table 1C).

The classification tree analysis revealed that shoreline type was the only significant predictor of whether or not a respondent reported hurricane damage costs, with property owners with bulkhead and riprap shorelines more frequently reporting damage than property owners with natural shorelines (Supplemental Fig. 4A). Only 75% of property owners with natural shorelines reported ever having costs associated with property damage from hurricanes, which was significantly lower than 97% of properties with bulkheads (Fisher's Exact Test, $p < 0.0001$,) and 94% of those with riprap ($p = 0.015$; Fig. 5A). Shoreline type was also the strongest predictor of whether or not maintenance costs were reported, but average fetch was also a factor for respondents with bulkheads, with higher fetches predicting more reports of maintenance costs for bulkheads (Supplemental Fig. 4B). A lower percent of property owners with natural shorelines reported having costs associated with yearly shoreline maintenance versus those with bulkheads (25% v. 61%, $p < 0.0001$), and also a lower percent with riprap than those with bulkheads (40% vs. 61%, $p = 0.0036$, Fig. 5B). Finally, shoreline type was the best predictor of whether or not a respondent reported maintenance days, with bulkhead and riprap shorelines grouping separate from natural shorelines. Maximum fetch was also a factor for bulkhead and riprap shorelines, with higher fetch predicting more reports of maintenance days (Supplemental Fig. 4C). The percent of property owners with natural shorelines that reported spending any time maintaining their shorelines was significantly lower than those with bulkheads (48% v. 67%, $p < 0.0001$), but not significantly different from those with riprap ($p = 0.17$; Fig. 5C, Supplemental Table 1A,B).

For those property owners that did report spending money or time, there was a significant difference between shoreline types in the mean hurricane property damage costs (ANOVA, $F_{2,247} = 3.119$, $p = 0.046$; Fig. 5D) and maintenance costs (ANOVA, $F_{2,216} = 15.106$, $p < 0.0001$; Fig. 5E), but only a marginally significant difference in maintenance days (ANOVA, $F_{2,285} = 2.913$, $p = 0.056$; Fig. 5F; Supplemental Table 1C). Average total property damage costs from hurricanes were nearly twice as high along shorelines with bulkheads than natural shorelines (27.6 ± 7.5 v. 15.4 ± 3.7 $cost m^{-1} yr^{-1}, respectively, Pairwise *t*-test, $p = 0.013$) and maintenance costs were also nearly twice as high along shorelines with bulkheads than natural shorelines (17.7 ± 2.0 v. 10.1 ± 2.3 $cost m^{-1} yr^{-1}, $p < 0.0001$). Maintenance costs were three times higher for bulkhead than riprap shorelines (17.7 ± 2.0 v. 5.9 ± 2.5 $cost m^{-1} yr^{-1}, $p < 0.0001$). There was lower maintenance time reported along shorelines with bulkheads than those with riprap (8.2 ± 0.6 v. 17.5 ± 3.9 d yr^{-1}, $p = 0.018$), whereas there was no significant difference in the number of maintenance days required for bulkheads versus natural shorelines (Supplemental Table 1D).

Mean delta values of total hurricane property damage costs were two times higher for properties with bulkheads than those with natural

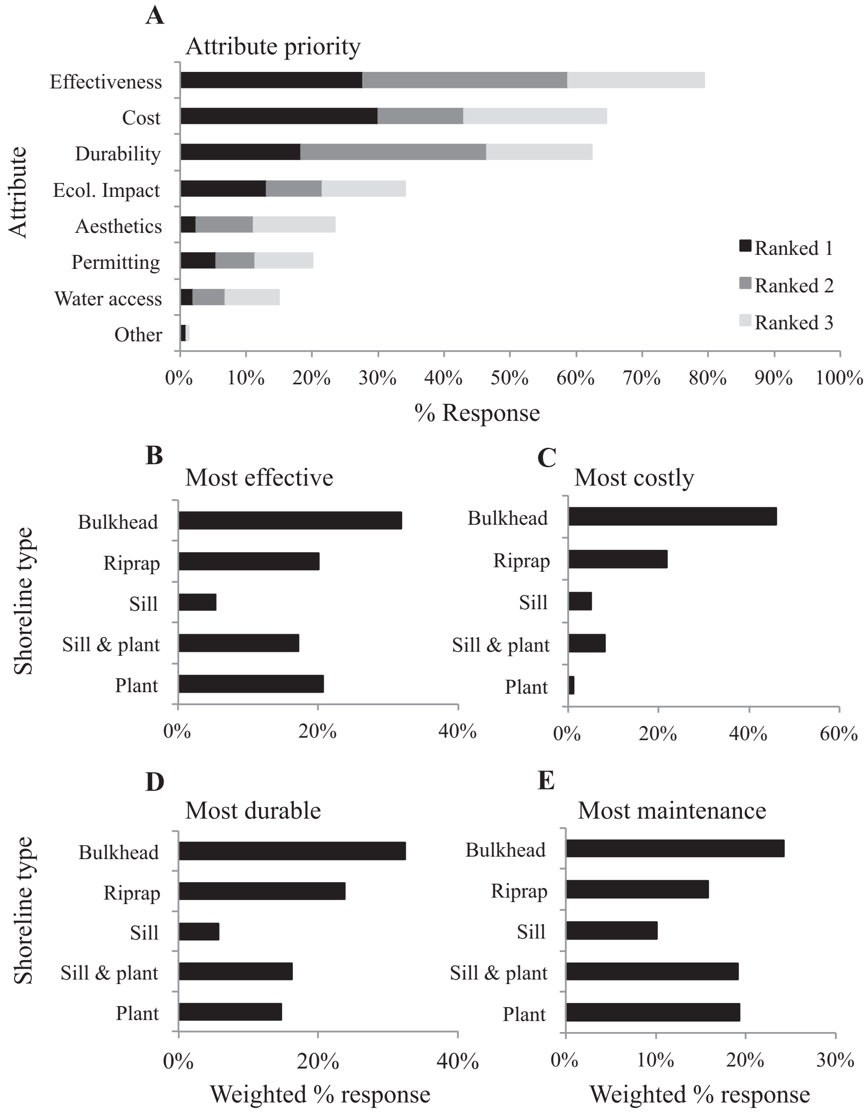

Fig. 3. (A) Priorities for shoreline protection schemes. (B-E) Perceived functions of different shoreline conditions weighted by ranking with weighted percent response shown.

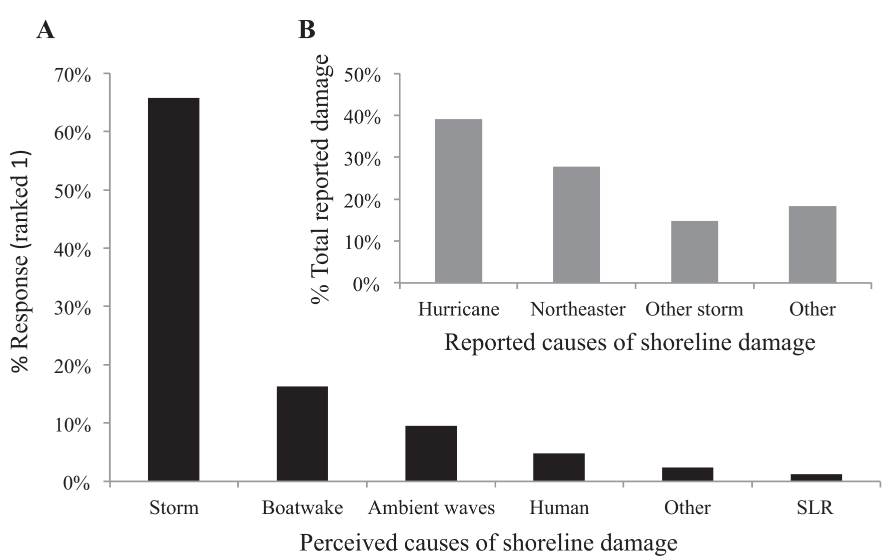

Fig. 4. (A) Perceived causes of shoreline damage shown as a percent of number 1 ranking. (B) Reported causes of shoreline damage shown as a percent of the total damage reported from all causes.

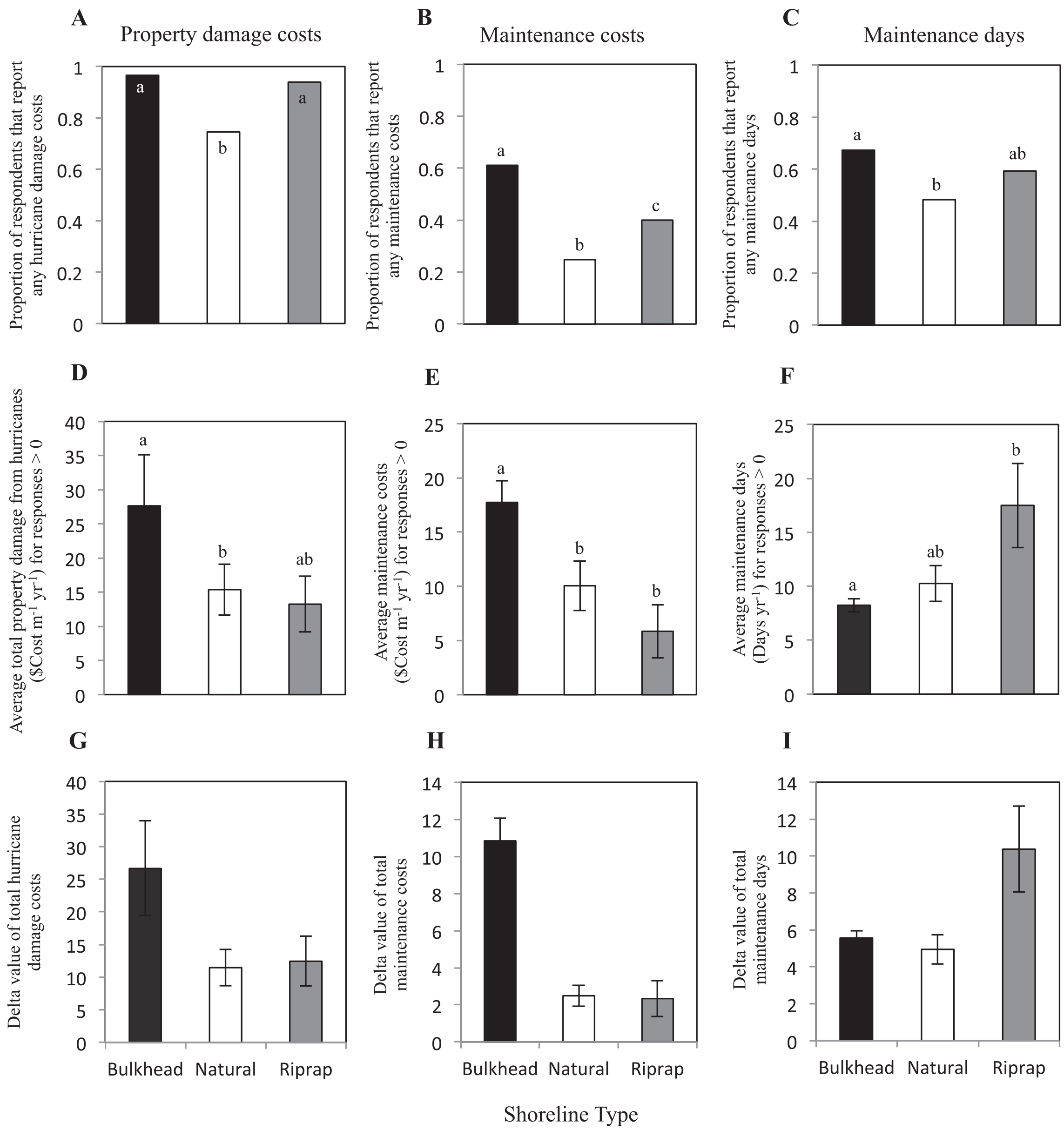

Fig. 5. Reported costs associated with hurricane damage and general shoreline maintenance (cost and time) as a function of shoreline type (bulkhead, natural, and riprap). Other shoreline types were excluded from this analysis because there were too few respondents. (A-C) show the percent of respondents that report any time or money (> 0) invested. (D-F) show the average (mean ± SE) total property damage costs (D), maintenance costs (E), and maintenance days (F) with only responses greater than zero included. (G-I) show delta values, which integrate the percent of respondents that report time/costs with the amount of time/money spent. Different letters above the bars denote significance.

or riprap shorelines (26.7 ± 7.2 v. 11.5 ± 2.8 v. 12.4 ± 3.8, respectively; Fig. 5G). Mean delta values of maintenance costs were more than four times higher for properties with bulkheads than those with natural or riprap shorelines (10.8 ± 1.2 v. 2.5 ± 0.6 v. 2.3 ± 1.0; Fig. 5H). Mean delta values for maintenance days were twice as high for properties with riprap as compared to those with bulkhead or natural shorelines (10.4 ± 2.3 v. 5.5 ± 0.4 v. 5.0 ± 0.8; Fig. 5I).

3.2. Visual damage assessments

The same 39 km of shoreline were surveyed in 2011, 2014, and 2016. Between 2011 and 2016, there was a 3.4% increase in the total length of shoreline that was hardened (bulkhead, hybrid, riprap, and other are considered hardened shorelines, but sills with planting are not), which equated to an additional 0.5 km of hardened shoreline over 5 years. While the length of total bulkhead shoreline decreased by 5%, hybrid shorelines increased by 83%, and many shorelines that were bulkhead alone in 2011 had been reinforced with riprap by 2016 (changing their classification to hybrid). The length of shoreline with sills and plantings increased by 116% between 2011 and 2016 (an additional 0.4 km; Fig. 6A).

After Hurricane Irene in 2011, 100% of visual damage was attributed to bulkheads and 17% of bulkheads surveyed were damaged. After Hurricane Arthur in 2014, 100% of all major damage (collapse and breach) and 90% of total damage was attributed to bulkheads or hybrid structures containing a bulkhead, and in total 23% of bulkhead shoreline was damaged. In 2016, 90% of damage was attributed to structures containing a bulkhead and 11% of the total shoreline remained damaged from 2014 (Fig. 6B). By quantifying damage overlap between 2011 and 2014, we determined that at least 40% of the damage reported after Hurricane Irene was repaired before Hurricane Arthur and at least 60% of the damage from Hurricane Arthur was new damage not present in 2011. By overlapping the damage found in 2014 with the damage from 2016, it was determined that at least 55% of the

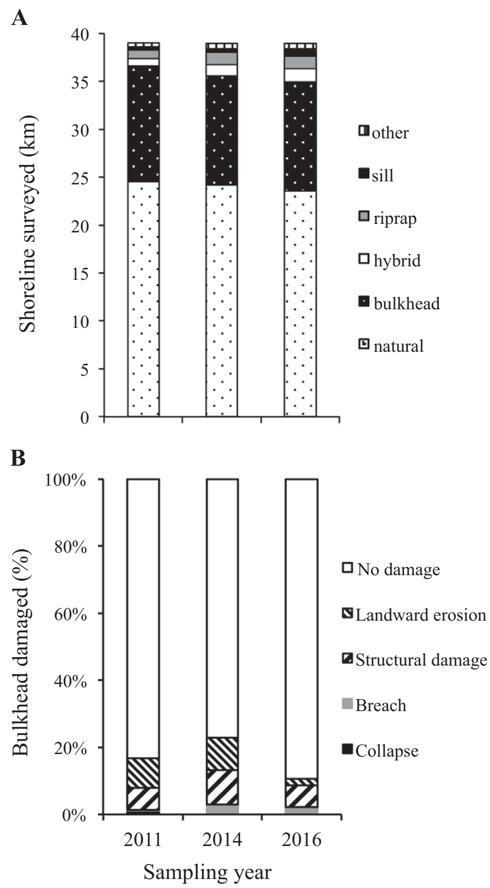

Fig. 6. (A) Total shoreline surveyed, broken down by structure type and (B) percent damage for bulkheads surveyed.

damage from Hurricane Arthur was repaired in the 2 years after the storm and that there was no new damage in 2016. Finally, 52% of the damaged shoreline surveyed in 2016 had been damaged during all three survey periods and was considered unrepaired.

4. Discussion

The designated purpose of a shoreline stabilization structure is to prevent erosion and property damage, particularly during major storm events like hurricanes [56]. This study suggests that bulkheads are not living up to the expectation of superior durability or effectiveness during hurricanes, and are more costly to maintain than natural shorelines or riprap. These data are critical for informing coastal management policies aimed at protecting coastal ecosystems from further damage and creating a framework for the improvement and promotion of nature-based coastal development strategies.

Property owners perceive bulkheads to be the most effective and durable method of shoreline stabilization and erosion control, but also the most costly, suggesting that they believe higher costs are an acceptable trade-off for superior performance. Presumably, property owners would be less willing to incur the higher costs of bulkheads if they were presented with evidence that bulkheads are less effective at preventing erosion, less durable, and require more maintenance than riprap or natural shorelines. Consistent with the findings of Scyphers et al. [44] along the Alabama coastline, North Carolina property owners highly prioritize the attributes of effectiveness, cost, and durability when choosing amongst shoreline stabilization structures. Conversely, Scyphers et al. [44] found that homeowners along the Gulf coast perceived natural shorelines to require more maintenance than bulkheads, whereas NC waterfront property owners perceived bulkheads as requiring the most maintenance. This difference could reflect geomorphological dissimilarities in the two coastlines, differences in the types of bulkheads constructed in each state, more hurricanes and tropical storms making landfall in NC than AL in the last five years, and/or differences in the effectiveness of education and outreach strategies about natural and living shorelines in North Carolina and Alabama. Further research is needed to better understand the local, regional, and national drivers of property owner perceptions about shore protection strategies.

Major storm events are primary agents of shoreline change, particularly along the Eastern and Gulf coasts of the United States [27]. Understanding public risk perception can be an important predictor of hurricane preparedness and hazard adjustment behavior and it is thought to play a key role in shaping hazard policy [49]. Commonly, there exists a disconnect between public and "expert" risk opinions, which can represent a significant impediment to the acceptance of and compliance with new policy [40]; however, in this case, property owners already perceive storm events to be damaging to their shorelines and thus they may be more receptive to new legislation aimed at enhancing resilience.

During the visual damage assessment surveys, over 90% of total damage was attributed to structures containing a bulkhead. Furthermore, every instance of major structural failure (collapse and/or breach) was attributed to bulkheads (Fig. 6). Thieler and Young [55] found similar results in a survey of barrier island shoreline in South Carolina after Hurricane Hugo. They found that 58% of bulkheads and 24% of revetments were completely destroyed in the storm, and they proposed that the overtopping of structures by storm surge was likely the cause. At Hatteras Inlet, Irene and Arthur had maximum storm surges recorded at 1.5 and 0.8 m above mean sea level, respectively [3,7]; however, within long shallow basins like Pamlico sound, water is often forced by the wind and piled up along a shoreline, resulting in prolonged and elevated water levels at either end of the basin axis that often exceed storm surge levels experienced near inlets or along the open coast [29]. Thus, the damage observed in this study was also likely the result of overtopping by waves and storm surge [20]. Bulkheads typically maintain a landward elevation 1–2 m higher than adjacent natural shorelines, often constructed by backfilling to create a lawn. When bulkheads are overtopped or their structural integrity is compromised, there can be rapid loss of landward sediment [20]. Bulkheads are also more prone to total structural failure than riprap revetments or sills because each section is connected to the adjacent section, so if one area of the bulkhead is ripped away it will weaken that entire segment of shoreline. It is also worth noting that for these same reasons, damage to bulkheads is probably easier to detect than damage to other structures (particularly structures that are largely submerged at high tide). For structures like revetments and sills that tend to have more gently sloping grades, the wave activity itself has to be strong enough to physically move the construction material (typically granite or marl stones up to 1 m across) in order to cause structural failure [55].

An issue requiring further consideration is that sediment landward of a bulkhead may be viewed as "sacrificial sand" by some property owners, who are comfortable repeatedly losing that sediment as long as they are allowed to replace it. If the damaged or failed bulkhead is repaired within two years of being damaged (a common practice seen in the visual damage surveys), a property owner in North Carolina (and many other states) is allowed to repair/rebuild the bulkhead and maintain their property line without a new permit [35,56]. In contrast, when sediment is lost from a natural shoreline, it cannot be replaced without a permit because of USACE restrictions on fill below the ordinary high water line [56]. However, USACE has recently changed its permitting rules, allowing for living shorelines (including projects with limited fill) to be constructed and/or repaired using permitting conditions similar to those for bulkheads and riprap [57]. This change may reduce the incentive for property owners to select bulkheads and riprap over living or natural shorelines.

The visual damage assessment surveys indicate that bulkheads are being damaged more often and more severely than other structures. This is consistent with results from the property owner surveys that show that residents with bulkheads are more likely to have experienced property damage from hurricanes and also that monetary costs associated with having and maintaining a bulkhead are significantly higher than having a revetment or natural shoreline. It is also likely that replacement costs are lower for revetments and natural marshes than bulkheads because bulkheads will need to be replaced completely when destroyed, whereas property owners may only have to reorient rather than replace boulders associated with sills and revetments [20,55]. This study shows that homeowners with revetments spent approximately twice as many days repairing their shoreline than those with bulkheads or natural shorelines, which supports the notion that homeowners themselves are repairing damage to revetments without having to hire an outside contractor.

There are multiple potential explanations for why bulkheads may be damaged more frequently and/or severely than other shore types, including the possibility that bulkheads may simply be located in areas that are more vulnerable to storm damage than other shore types. However, damaged bulkhead shorelines observed during the visual damage assessments and the properties where owners reported damage to their bulkheads were consistently interspersed with other shoreline types that were not visibly damaged or reported as damaged. Furthermore, the tree-based classification models found shoreline type to be the best predictor of costs, suggesting that environmental setting (e.g. fetch) is not the primary driver of damage frequency and associated costs. It is possible that environmental factors not included in the classification trees (e.g. nearshore bathymetry, currents) could influence rates of shoreline damage and erosion, and thus further research is needed.

Between 1980 and 2014, tropical cyclones caused $545 billion dollars in damage in the U.S., making them the most damaging natural disaster category from an economic standpoint [32]. Coastal property damage has greatly increased over recent decades, probably in response to increased development in vulnerable areas [60]. Presumably, sea-level rise will intensify damage to fixed structures, like bulkheads and revetments, and increase the number of vulnerable structures, which will cause escalating individual and community costs to maintain coastal infrastructure. In addition to revealing that bulkheads are more frequently being damaged and repaired than other shore types, the shoreline damage surveys also reveal that shoreline hardening increased by 3.4% from 2011 to 2016. While the length of hybrid shoreline nearly doubled, the proportion of coastline with bulkheads decreased slightly. This finding could be attributed, in part, to dissatisfaction with bulkhead performance after Hurricane Irene in 2011, which may have driven property owners to reinforce or rebuild existing bulkheads with riprap, resulting in more robust, hybrid structures. On average, bulkhead installation costs about $450 per linear meter, revetments cost about $400 per meter, and living shorelines range from $72 to $500 per meter depending on how they are constructed [16]. If homeowners are spending more money to build bigger and “better” bulkheads, then their overall costs are doubling and dwarfing the costs of even the most expensive nature-based shoreline stabilization options. This suggests that property owners might be amenable to alternate forms of shoreline stabilization (like living shorelines) if it can be demonstrated that they outperform bulkheads and meet the desired priorities at lower cost. In fact, Temmerman et al. [53] and Van Slobbe et al. [58] found that ecosystem-based defenses that created or restored natural habitats in urban environments (salt marsh and beach, respectively) could provide a more sustainable and cost-effective option to flood protection than traditional hard engineered structures. Furthermore, bulkhead remediation (e.g. removing a bulkhead and returning the shoreline to a more natural profile) is difficult and seldom undertaken (but *see* [12]), which underscores the importance of acting expediently to inform property owners about more cost-effective and ecosystem friendly approaches to shoreline protection.

Beyond their relative shoreline protection capabilities and costs, it is also important to understand the ecological effects of different shoreline stabilization structures. The property-owner surveys revealed that property owners were concerned about ecological impacts; however, the short-term desire to prevent erosion and protect private property seemingly is being prioritized over the long-term loss of public trust coastal habitats, like salt marshes. Paradoxically, given the intent of many property owners, some of the most notable services of coastal salt marshes are their ability to protect against erosion, stabilize sediment, and ameliorate wave energy, even under storm surge conditions [19,2,31]. By prioritizing immediate needs over long-term goals and endangering the future of coastal salt marshes via shoreline hardening, coastal residents may be further increasing the vulnerability of these areas to future storm events and floods [18].

Surveyed property owners ranked sills and plantings higher than sills alone for effectiveness and durability, which indicates an understanding of the wave amelioration properties of natural vegetation. Scyphers et al. [44] similarly found that homeowners in Alabama recognized the inherent aesthetic and ecological values of habitats in their natural state, and were receptive to more ecosystem friendly alternatives if they were more cost effective and feasible. Sutton-Grier et al. [52] also suggested that management and legislation in favor of streamlining the permitting process for living shoreline alternatives to shoreline hardening could sway homeowner choices. Added to the fact that they may require less maintenance and repair after storms, there is a potential for living shorelines to adapt to rising sea levels on their own, without the investment of further resources. Salt marshes and oyster reefs, which can be incorporated into living shoreline designs, accrete vertically at rates that can keep pace with predicted rates of sea level rise [11,42]. Even under more extreme sea-level rise scenarios that may outpace vertical accretion potential [59], living shorelines promote the persistence of salt marshes by enabling them to transgress landward. It is now important to not only conserve coastal habitats but also to adopt management schemes that enhance ecological system adaptability by incorporating living habitats into shoreline defense schemes; however, more research into the relative storm protection capabilities of different living shoreline designs as compared to hardened shorelines is sorely needed. Without continued research, effective policy changes, and communication about the advantages of nature-based strategies for coastal protection, further degradation of coastal shorelines and the potential for escalating costs associated with residential shoreline management are likely.

Acknowledgements

This research was funded by a University of North Carolina at Chapel Hill Royster Society Fellowship and NC Sea Grant Coastal Policy Fellowship to C. Smith, and NC Coastal Recreational Fishing License Grants to C. Peterson, C. Smith, J. Fodrie, R. Gittman, J. Grabowski, and S. Scyphers. S Scyphers was supported by a National Science Foundation SEES Fellowship (OCE-1215825).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.marpol.2017.04.013.

References

[1] K.K. Arkema, G. Guannel, G. Verutes, S.A. Wood, A. Guerry, M. Ruckelshaus, P. Kareiva, M. Lacayo, J.M. Silver, Coastal habitats shield people and property from sea-level rise and storms, Nat. Clim. Change 3 (10) (2013) 913–918.

[2] L.N. Augustin, J.L. Irish, P. Lynett, Laboratory and numerical studies of wave damping by emergent and near-emergent wetland vegetation, Coast. Eng. 56 (3) (2009) 332–340.

[3] L.A. Avila, J. Cangialosi, Tropical Cyclone Report: Hurricane Irene (AL092011).

National Hurricane Center Tropical Cyclone Report. August 2011:45, 2012.
[4] R.G. Balouskus, T.E. Targett, Fish and blue crab density along a riprap-sill-hardened shoreline: comparisons with Spartina marsh and riprap, Trans. Am. Fish. Soc. 145 (4) (2016) 766–773.
[5] E.B. Barbier, A global strategy for protecting vulnerable coastal populations, Science 345 (6202) (2014) 1250–1251.
[6] M.A. Bender, T.R. Knutson, R.E. Tuleya, J.J. Sirutis, G.A. Vecchi, S.T. Garner, I.M. Held, Modeled impact of anthropogenic warming on the frequency of intense Atlantic hurricanes, Science 327 (5964) (2010) 454–458.
[7] R. Berg, Tropical cyclone report: hurricane arthur (AL012014) National Hurricane Center Tropical Cyclone Report, October 2015, pp. 22–28.
[8] B.J. Boruff, C. Emrich, S.L. Cutter, Erosion hazard vulnerability of US coastal counties, J. Coast. Res. 21 (5) (2005) 932–942.
[9] C.M. Bozek, D.M. Burdick, Impacts of seawalls on saltmarsh plant communities in the Great Bay Estuary, New Hampshire USA, Wetl. Ecol. Manag. 13 (5) (2005) 553–568.
[10] M.G. Chapman, F. Bulleri, Intertidal seawalls—new features of landscape in intertidal environments, Landsc. Urban Plan. 62 (3) (2003) 159–172.
[11] C.A. Currin, P.C. Delano, L.M. Valdes-Weaver, Utilization of a citizen monitoring protocol to assess the structure and function of natural and stabilized fringing salt marshes in North Carolina, Wetl. Ecol. Manag. 16 (2) (2008) 97–118.
[12] J.L. Davis, R.L. Takacs, R. Schnabel, R. Evaluating ecological impacts of living shorelines and shoreline habitat elements: an example from the upper western Chesapeake Bay. Management, Policy, Science, and Engineering of Nonstructural Erosion Control in the Chesapeake Bay, 2006, p. 55.
[13] R.J. Diaz, R. Rosenberg, Spreading dead zones and consequences for marine ecosystems, Science 321 (5891) (2008) 926–929.
[14] J.E. Dugan, D.M. Hubbard, I.F. Rodil, D.L. Revell, S. Schroeter, Ecological effects of coastal armoring on sandy beaches, Mar. Ecol. 29 (s1) (2008) 160–170.
[15] Executive Office of the President, The President's Climate Action Plan, The White House, Washington, DC, 2013.
[16] J. Fear, C. Currin, Sustainable Estuarine Shoreline Stabilization: Research, Education and Public Policy in North Carolina. NOAA/UNH Cooperative Institute for Coastal and Estuarine Environmental Technology, Final Report (October 31, 2008), 2012. p. 2.
[17] D. Fletcher, D. MacKenzie, E. Villouta, Modeling skewed data with many zeros: a simple approach combining ordinary and logistic regression, Environ. Ecol. Stat. 12 (1) (2005) 45–54.
[18] J.A. Foley, R. DeFries, G.P. Asner, C. Barford, G. Bonan, S.R. Carpenter, F.S. Chapin, M.T. Coe, G.C. Daily, H.K. Gibbs, J.H. Helkowski, Global consequences of land use, Science 309 (5734) (2005) 570–574.
[19] P.W. French, Coastal Defenses: Processes, Problems and Solutions, Psychology Press, 2001.
[20] R.K. Gittman, A.M. Popowich, J.F. Bruno, C.H. Peterson, Marshes with and without sills protect estuarine shorelines from erosion better than bulkheads during a category 1 hurricane, Ocean Coast. Manag. 102 (2014) 94–102.
[21] R.K. Gittman, F.J. Fodrie, A.M. Popowich, D.A. Keller, J.F. Bruno, C.A. Currin, C.H. Peterson, M.F. Piehler, Engineering away our natural defenses: an analysis of shoreline hardening in the US, Front. Ecol. Environ. 13 (6) (2015) 301–307.
[22] R.K. Gittman, S.B. Scyphers, C.S. Smith, I.P. Neylan, J.H. Grabowski, The ecological consequences of shoreline hardening: a meta-analysis, Bioscience 66 (2016) 763–773.
[23] R.K. Gittman, C.H. Peterson, C.A. Currin, F. Joel Fodrie, M.F. Piehler, J.F. Bruno, Living shorelines can enhance the nursery role of threatened estuarine habitats, Ecol. Appl. 26 (1) (2016) 249–263.
[24] IPCC Working Group II, Climate Change 2014: Impacts, Adaptation, and Vulnerability. Intergovernmental Panel on Climate Change, 2014.
[25] T.R. Knutson, J.J. Sirutis, S.T. Garner, G.A. Vecchi, I.M. Held, Simulated reduction in Atlantic hurricane frequency under twenty-first-century warming conditions, Nat. Geosci. 1 (6) (2008) 359–364.
[26] N.W. Lam, R. Huang, B.K. Chan, Variations in intertidal assemblages and zonation patterns between vertical artificial seawalls and natural rocky shores: a case study from Victoria harbour, Hong Kong, Zool. Stud. 48 (2) (2009) 184–195.
[27] S.P. Leatherman, Barrier Island Handbook, University of Maryland, (1982), p. 109.
[28] H.K. Lotze, H.S. Lenihan, B.J. Bourque, R.H. Bradbury, R.G. Cooke, M.C. Kay, S.M. Kidwell, M.X. Kirby, C.H. Peterson, J.B. Jackson, Depletion, degradation, and recovery potential of estuaries and coastal seas, Science 312 (5781) (2006) 1806–1809.
[29] G. Mariotti, S. Fagherazzi, P.L. Wiberg, K.J. McGlathery, L. Carniello, A. Defina, Influence of storm surges and sea level on shallow tidal basin erosive processes, J. Geophys. Res.: Oceans 115 (C11) (2010).
[30] M.M. Millar, D.A. Dillman, Improving response to web and mixed-mode surveys, Public Opin. Q. 75 (2) (2011) 249–269.
[31] I. Möller, M. Kudella, F. Rupprecht, T. Spencer, M. Paul, B.K. van Wesenbeeck, G. Wolters, K. Jensen, T.J. Bouma, M. Miranda-Lange, S. Schimmels, Wave attenuation over coastal salt marshes under storm surge conditions, Nat. Geosci. 7 (10) (2014) 727–731.
[32] National Climatic Data Center (NCDC), Billion-Dollar U.S. Weather/Climate Disasters 1980–2014. National Oceanic and Atmospheric Administration. 〈http://www.ncdc.noaa.gov/billions/summary-stats〉, 2016.
[33] National Research Council, Mitigating Shore Erosion along Sheltered Coasts, The National Academies Press, Washington, DC, 2007.
[34] National Research Council, Reducing Coastal Risks on the East and Gulf Coasts, The National Academies Press, 2014.
[35] North Carolina Department of Environmental Quality, General permit for construction of bulkheads and riprap revetments for shoreline protection in estuarine and public trust waters and ocean hazard areas, 〈http://deq.nc.gov/about/divisions/coastal-management/coastal-management-rules/coastal-development-rules〉, 2009.
[36] North Carolina Division of Coastal Management, Estuarine shoreline mapping project, 〈http:dcm2.enr.state.nc.us/estuarineshoreline/mapping.html〉, 2012.
[37] North Carolina State Climate Office, Hurricane Statistics, 〈http://climate.ncsu.edu/climate/hurricanes/statistics.php〉, 2016.
[38] W.E. Odum, Environmental degradation and the tyranny of small decisions, BioScience 32 (9) (1982) 728–729.
[39] C.J. Patrick, D.E. Weller, X. Li, M. Ryder, Effects of shoreline alteration and other stressors on submerged aquatic vegetation in subestuaries of Chesapeake Bay and the Mid-Atlantic Coastal Bays, Estuar. Coasts 37 (6) (2014) 1516–1531.
[40] W.G. Peacock, S.D. Brody, W. Highfield, Hurricane risk perceptions among Florida's single family homeowners, Landsc. Urban Plan. 73 (2) (2005) 120–135.
[41] C.H. Peterson, R.T. Barber, K.L. Cottingham, H.K. Lotze, C.A. Simenstad, R.R. Christian, M.F. Piehler, J. Wilson, National estuaries. Preliminary review of adaptation options for climate-sensitive ecosystems and resources: A report by the US Climate Change Science Program and the Subcommittee on Global Change Research, US Environmental Protection Agency, Washington, DC, 2008.
[42] A.B. Rodriguez, F.J. Fodrie, J.T. Ridge, N.L. Lindquist, E.J. Theuerkauf, S.E. Coleman, J.H. Grabowski, M.C. Brodeur, R.K. Gittman, D.A. Keller, M.D. Kenworthy, Oyster reefs can outpace sea-level rise, Nat. Clim. Change 4 (6) (2014) 493–497.
[43] P. Schultz, Conservation means behavior, Conserv. Biol. 25 (2011) 1080–1083.
[44] S.B. Scyphers, J.S. Picou, S.P. Powers, Participatory conservation of coastal habitats: the importance of understanding homeowner decision making to mitigate cascading shoreline degradation, Conserv. Lett. 8 (1) (2015) 41–49.
[45] G.A.F. Seber, The estimation of animal abundance, 1982.
[46] R.D. Seitz, R.N. Lipcius, N.H. Olmstead, M.S. Seebo, D.M. Lambert, Influence of shallow-water habitats and shoreline development on abundance, biomass, and diversity of benthic prey and predators in Chesapeake Bay, Mar. Ecol. Progress. Ser. 326 (2006) 11–27.
[47] J.E. Serafy, M. Valle, C.H. Faunce, J. Luo, Species-specific patterns of fish abundance and size along a subtropical mangrove shoreline: an application of the delta approach, Bull. Mar. Sci. 80 (3) (2007) 609–624.
[48] C.C. Shepard, V.N. Agostini, B. Gilmer, T. Allen, J. Stone, W. Brooks, M.W. Beck, Assessing future risk: quantifying the effects of sea level rise on storm surge risk for the southern shores of Long Island, New York, Nat. Hazards 60 (2) (2012) 727–745.
[49] P.E. Slovic, The Perception of Risk, Earthscan publications, 2000.
[50] C. Small, R.J. Nicholls, A global analysis of human settlement in coastal zones, J. Coast. Res. 19 (3) (2003) 584–599.
[51] B. Strauss, C. Tebaldi, S. Kulp, S. Cutter, C. Emrich, D. Rizza, D. Yawitz, North Carolina and the Surging Sea: A vulnerability assessment with projections for sea level rise and coastal flood risk. Climate Central Research Report, 2014, pp. 1–29.
[52] A.E. Sutton-Grier, K. Wowk, H. Bamford, Future of our coasts: the potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems, Environ. Sci. Policy 51 (2015) 137–148.
[53] S. Temmerman, P. Meire, T.J. Bouma, P.M. Herman, T. Ysebaert, H.J. De Vriend, Ecosystem-based coastal defence in the face of global change, Nature 504 (7478) (2013) 79–83.
[54] J.G. Titus, Rising seas, coastal erosion, and the takings clause: how to save wetlands and beaches without hurting property owners, Md. Law Rev. 57 (1998) 1279.
[55] E.R. Thieler, R.S. Young, Quantitative evaluation of coastal geomorphological changes in South Carolina after Hurricane Hugo, J. Coast. Res. (1991) 187–200.
[56] United States Army Corps of Engineers, Nationwide permit 13. Bank Stabilization, 2016a.
[57] United States Army Corps of Engineers, Nationwide permit 54. Living Shorelines, 2016b.
[58] E. Van Slobbe, H.J. De Vriend, S. Aarninkhof, K. Lulofs, M. De Vries, P. Dircke, Building with nature: in search of resilient storm surge protection strategies, Nat. Hazards 66 (3) (2013) 1461–1480.
[59] C.M. Voss, R.R. Christian, J.T. Morris, Marsh macrophyte responses to inundation anticipate impacts of sea-level rise and indicate ongoing drowning of North Carolina marshes, Mar. Biol. 160 (1) (2013) 181–194.
[60] K. Zhang, B.C. Douglas, S.P. Leatherman, Twentieth-century storm activity along the US east coast, J. Clim. 13 (10) (2000) 1748–1761.