COASTAL RECREATIONAL FISHING LICENSE

FINAL REPORT

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Recipient: University of North Carolina at Chapel Hill, Office of Sponsored Research, 104 Airport Drive, Suite 2200 CB#1350, Chapel Hill, NC 27599-1350

Dr. F. Joel Fodrie (PI), Associate Professor, Institute of Marine Sciences & Department of Marine Sciences, University of North Carolina at Chapel Hill, 3431 Arendell Street, Morehead City, NC 28557, Phone: 252-726-6841 (ext 149), Email: jfodrie@unc.edu

Grant Collaborators: Dr. Rachel Gittman, Postdoctoral Research Associate, Northeastern University, Dr. Steven Scyphers, Assistant Professor, Northeastern University, and Dr. Jonathan Grabowski, Associate Professor, Northeastern University

Note: The content of manuscripts listed in Appendix A, which have been published, are in review or are in preparation for publication in peer-reviewed journals are reflected in this report. The final, peer-reviewed versions of these manuscripts will supersede the information presented in this report and will be delivered upon publication.

Abstract/Executive Summary

Enhancing public education on the value, function, and major threats to coastal fish habitats is a key management goal for the Coastal Recreational Fishing License (CRFL) Grant Program. Effective educational tools, however, cannot be developed without a clear understanding of the public's current knowledge and perceptions of coastal fish habitats. The unifying goal of our project was to provide managers and researchers with the information needed to understand how waterfront resident, recreational fishermen and the broader NC society are interlinked with the health of coastal habitats in a framework for outreach and education initiatives. We utilized stakeholder and public surveys to generate essential data describing the: i) perceived value and status of coastal habitats; ii) perceived threats facing those habitats and the coastal zone; iii) ecological, economic, aesthetic and social considerations of coastal property owners related to coastal habitat protection and shoreline development; and iv) support for various habitat and coastal management strategies.

The survey was comprised of five general sections and developed in an online survey platform, Qualtrics Research Suite. The first section of each survey collects demographic information (i.e., age, education, income, etc.) to allow thorough comparison of the various stakeholder groups. The second section focused on recreational fishing activities. The third section focused on the perceived current condition and value of the habitats and on identifying and prioritizing potential threats facing NC coastal habitats as perceived by stakeholders. The fourth section of the survey instrument measured support for a variety of coastal management initiatives. The fifth section focused on the ecological, economic, aesthetic and social considerations of coastal property owners related to habitat protection and shoreline development (delivered to waterfront residents only).

For the NC waterfront resident surveys, we distributed postcard invitations to complete an on-line survey to waterfront property owners in the northern, central and southern regions of the state (each postcard had a link to the survey). 854 waterfront residents responded in 2014 across 17 coastal counties. Forty-one percent (N=282) of property owners reported having bulkheads (average length= 45m ± 3m [mean ± SE]), 40% (N=275) had natural shorelines (average length= 51m ± 3m), 10% (N= 66) had riprap (average length= 77m ±14m), and the remaining 9% had a sill (N= 10), groin (N= 7), or hybrid shoreline (N= 49). A majority of respondents were residents of Carteret, New Hanover, Onslow, Dare, and Craven counties and the most common types of shorelines in these counties were natural or bulkhead shorelines. Bulkheads with riprap revetments were the most costly to install: \$877 ± 210 m^{-1} (N=23), followed by bulkheads alone \$727 ± 88 m^{-1} (N=82), and followed by riprap \$282 ±58 m^{-1} (N=23). The cost of installing a living shoreline was reported as \$343 ± 95 m^{-1} (N=5). When asked what stabilization approach they would select to stabilize their eroding shorelines, hardened shoreline owners overwhelmingly selected hard approaches, while natural/living shoreline owners selected living shorelines. Hardened shoreline owners indicated that the condition of their neighbors' shorelines influenced their own stabilization decisions.

We developed and distributed the NC resident survey via e-mail through a contract with Qualtrics, a survey distribution company. The results of the NC resident survey were received in October 2013. We had 1,000 respondents from ages 18 to 92 from all NC counties. Of the NC residents surveyed (1) identify industrial pollution, residential development and more intense or frequent storms as the top three environmental problems facing NC; (2) a majority believe that the climate is warming; (3) are most concerned about rising temperatures and more intense of frequent storms associated with climate change and (4) support the construction of wind turbines off the coast of NC (62% in favor).

A majority of fishermen respondents from the waterfront survey, the NC resident survey, and the tournament surveys reported fishing in NC inland waters, as opposed to NC Ocean or Federal waters. Flounder was the most targeted species by all fishermen in NC, regardless of

license type, with red drum, speckled trout and striped bass also frequently targeted. When targeting flounder, red drum, and speckled trout, fishermen preferred to fish along hard bottom, oyster reefs/oyster spawning sanctuaries, and beaches, while fishermen targeting striped bass also preferred to fish in submerged aquatic vegetation.

This information has been be used to improve coastal sustainability by integrating direct input from coastal stakeholders into environmental science through the development of education and outreach products, including: (1) a more interactive and updated version of the shoreline stabilization website developed by the NC Coastal Reserve / National Estuarine Research Reserve (NERR) for waterfront residents based on our survey results; (2) Shorelines, a webpage (http://www.northeastern.edu/scyphers/shorelines/) with pictures, videos, and facts about coastal habitats, habitat restoration, ecosystem services, etc.; (3) in-person trainings with NC NERR and DCM for real estate developers, coastal engineers, and marine contractors and 'do it yourself' homeowners in 2016 on how to use marsh plantings to stabilize their shoreline and how to maintain their shoreline; (4) presentations at multiple local, national, and international conferences, workshops, webinars, and public meetings; and (5) recent and future publications in peer-reviewed journals.

Introduction

Coastal communities are directly affected by the health and management of fisheries and coastal habitats. Simultaneously, coastal ecosystems are often strongly influenced by the actions of coastal residents. Acknowledging this reciprocal relationship, the NC Coastal Habitat Protection Plan (CHPP) states that socioeconomic concerns and reasoning should be integrated into fisheries and habitat management processes (Deaton 2010). This need is also recognized at the national level, as inclusion of socioeconomic considerations is mandated by the reauthorization of the Magnuson-Stevens Fishery Conservation and Management Act (2007). As management techniques evolve towards ecosystem-based approaches, they must strive to incorporate the various manners in which humans interact with, impact, and rely on natural ecosystems to improve resource conservation. In particular, evolving towards an ecosystem-based approach will require that managers engage stakeholders to examine how these natural and social systems are coupled. In most coastal regions, including NC, waterfront residents and property owners are an important and growing group of stakeholders. Residential development often results in the conversion of ecologically important coastal habitats like saltmarsh into hardened shorelines consisting primarily of vertical bulkheads and unvegetated bottom. Understanding the social, economic and political factors that influence the actions of waterfront residents (and what they value in choosing to live near the water) will be essential for developing education and outreach initiatives to improve the sustainability of coastal habitats. In NC, very little is known about how key stakeholders (e.g., waterfront residents, recreational fishermen) or the general public perceive the coastal environments upon and from which they depend and benefit. Our study involved four themes strategically designed to collect essential data to develop stakeholder education and outreach initiatives.

Theme 1: NC Waterfront Property Owners

Coastal and waterfront residents have a complicated and multidirectional relationship with nearshore marine habitats. Tidal salt marshes, seagrass beds, and oyster reefs act as natural buffers to wave energy and, as a result, protect waterfront homes and prevent erosion of coastal lands (Crooks and Turner 1999). Coastal habitats also act as nutrient filters and pollutant traps for terrestrial runoff (Peterson et al. 2008), thereby improving water quality in the estuaries and sounds along the coast of the United States. In NC, the human population in the 20 coastal counties increased by more than 150,000 from 2000 to 2010 (U.S. Census Bureau 2010). Human population growth and economic development have altered coastal land use and are primary drivers of coastal habitat loss and degradation (MEA 2005). At the same time, global climate

change is expected to have a steadily increasing impact on these coastal ecosystems, with the impacts from the previous 100 years already considered to be significant (MEA 2005). In particularly vulnerable regions, sea level rise and the potential for increases in the frequency and intensity of major storm events may drown and erode coastal habitats, resulting in unprecedented coastal habitat losses (Rahmstorf 2010, Nicholls and Marinova 2011, Mendelsohn et al. 2012).

In the United States, much of the sheltered coastline is vulnerable to erosion (Boruff et al. 2005). 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 (National Research Council 2007, Fear and Currin 2012, Scyphers et al. 2015, Gittman et al. 2015). 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; USACE 2016a), revetments (sloping rock structures of marl, granite, or concrete rip rap), and hybrid structures that combine a bulkhead with seaward and/or landward riprap (Gittman et al. 2015, Figure 1A, B, C). Bulkheads in particular have been shown to have numerous adverse effects on the habitat landscapes and biological communities around them (Bozek and Burdick 2005, Seitz et al. 2006, Dugan et al. 2008, Gittman et al. 2016a), and revetments are also associated with negative ecological effects (Patrick et al. 2014, Balouskus and Targett 2016). 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 "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; Titus 1998, Peterson et al. 2008, Augustin et al. 2009). 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 (Chapman and Bulleri 2003, Lam et al. 2009, Gittman et al. 2015). 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 (USACE 2016b; Figure 1D). Living shorelines can preserve and even enhance the services of coastal ecosystems (Gittman et al. 2016b); 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 (Sutton-Grier et al. 2015). 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 (Odum 1982). For example, Scyphers et al. (2015) 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 (Schultz 2011). While there is emerging evidence to the contrary (Gittman et al. 2014), 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 (Scyphers et al. 2015).

Recent syntheses have revealed that efforts to protect or rebuild ecosystems are only successful when the views of key stakeholders and broader society are considered and guide conservation efforts (Duarte et al. 2008, Mora et al. 2009, Worm et al. 2009). Stakeholders, however, are usually not as engaged in the management process as they can or should be (2012 Mid-Atlantic Fishery Management Council Stakeholder Input Report). Thus, socioeconomic surveys will help develop a more holistic understanding of the major drivers behind anthropogenic change to estuarine shorelines. The waterfront resident component of these surveys will help to rank important factors (i.e. cost, durability, aesthetics, ecological impact, habitat value for marine organisms, water quality) that influence individual's benefits and attitudes to coastal habitat restoration projects and shoreline armoring. Our study will benefit coastal regulators by providing managers with shoreline residents' perceptions of these coastal activities, which will inform them how future policies regarding these activities would be received and where outreach activities on coastal fish habitat would be most useful. Nearshore ecosystems, especially shoreline habitats, provide an interesting and necessary setting to investigate the dynamics of a coupled social-ecological system in the face of natural and anthropogenic stressors. The only previous studies of NC waterfront residents were conducted by the NC NERR (J. Fear PI) in 2009 and NC NERR and DCM in 2010.

Seventy-five waterfront residents were surveyed in the 2009 effort, and approximately 30 residents with a specific type of shoreline stabilization (i.e., marsh sills) and their neighbors were surveyed in 2010. The NC NERR and DCM studies only focused on the impacts/services of altered shoreline types (e.g., bulkheads, sills, planted vegetation, breakwaters), whereas our study will examine natural (e.g., sand, beach, woody, marsh) and altered shorelines, as well as adjacent nearshore coastal habitats (e.g., submerged aquatic vegetation, oyster reefs). The NC NERR and DCM studies determined that environmental considerations (i.e., water quality, ecosystem function) are important to residents when considering shoreline protection alternatives, but examining the linkages to nearshore fish habitats or healthy fisheries was not within their scope. A recent study of 1,000 waterfront homes in Mobile Bay, AL investigated perceived changes in the shorelines, marine life and water quality of the bay (Scyphers et al. 2015). In Mobile Bay, shoreline armoring has been steading increasing with population growth for over half of a century and has had physical and ecological consequences on the system (Douglass and Pickel 1999). The responses to the socioeconomic survey revealed that many coastal residents are very interested in conserving the ecosystem services and processes supported by natural shoreline, but nearly two thirds of respondents stated their shoreline was protected by a bulkhead or seawall and a majority would choose this method again if forced to stabilize or protect their shoreline today. These findings highlight the need for coastal stakeholder knowledge and perspectives to be included in coastal zone and fish habitat management discussions because their individual choices collectively influence the health of the habitats that coastal societies rely upon. The intent of our study was to help isolate the factors that most influence the coastal residents and stakeholders whom directly or indirectly affect and are affected by the health of coastal systems.

Theme 2: Broader NC Population

The issue of sustainable coastal development and the value of coastal habitats extends far beyond the coastal zone. Estuarine habitats comprise only 0.7 % of global biomes, yet they contribute $7.9 trillion dollars per year, or approximately 24% of total global ecosystem services (Costanza et al. 1997). These benefits include disturbance resistance, nutrient cycling, food production, and recreation. Furthermore, estuaries provide distinct and unique ways of life for societies all around the world (Ditton and Stoll 2003). Unfortunately, marine habitats that closely border coastal and estuarine shorelines are among the most degraded and threatened habitats in the world because of their sensitivity to coastal development, non-point source pollution, climate change and major storms (Beck et al. 2011). Maintaining sustainable harvests or attempting to rebuild coastal species and habitats back to historical levels are extremely challenging tasks

(Hobbs and Harris 2001, Grabowski and Peterson 2007), and these activities will not succeed without stakeholder and broader societal support (Duarte et al. 2008, Mora et al. 2009, Worm et al. 2009). Thus, our study contributes to ongoing and future efforts to restore and conserve these critically impaired habitats by: (1) informing managers regarding the attitudes, perceptions and knowledge gaps of residents from throughout NC about coastal habitat; and (2) employing a variety of outreach efforts aimed at training and educating NC residents regarding the benefits and costs of habitat restoration and shoreline armoring activities (see Theme 4).

Theme 3: Recreational Fishermen (CRFL Licensees)

Our surveys included questions that identify CRFL licensees so that we can compare their responses to those of the general NC population (among both coastal residents and non-residents). Collectively, NC anglers spend thousands of days on the water each year, and many of these individuals take great pride in understanding marine ecosystems processes, coastal environmental threats, and the rationale behind resource management actions. Therefore, managers and scientists would also benefit greatly from cataloging the corporate knowledge of these stakeholders to improve our understanding of the coastal ocean. For example, extracting non-traditional data from fishermen might elucidate how the distribution of fishing effort has changed over time (among species or habitats/sites), as well as why these shifts have occurred. Furthermore, querying anglers would illustrate which environmental issues require aggressive education campaigns to fully inform this stakeholder group (i.e., where managers and scientists are currently failing to conduct effective outreach). Otherwise, managers and scientists cannot fully appreciate how well these users understand the coastal threats cited in the CHPP. Since conservation initiatives ultimately depend on public support and "buy-in", these data are critical for guiding public education campaigns (Duarte et al. 2008, Mora et al. 2009). Recently, fisheries scientists have used approaches that integrate traditional fishermen knowledge with fishery-independent data. These studies have demonstrated that anglers can be remarkably in touch with the status of fisheries (Boudreau and Worm 2010, Powers et al. 2015), although their perceptions toward different management approaches and their effectiveness can be strongly affected by demographic and socioeconomic factors such as age. Our study assessed whether current perceptions among coastal anglers and coastal managers are aligned, and identified where aggressive outreach activities are needed to educate this influential stakeholder group.

Theme 4: Improving Education and Outreach Initiatives

Communicating the value of coastal ecosystems along with ways to improve their sustainability is a fundamental tenet of ecosystem management and the CRFL program. Traditionally, legitimate and perceived boundaries have limited the exchange of knowledge and ideas between scientists, managers and the general public, but the last decade has brought a new generation of scientists and innovative technologies that help conquer traditional obstacles. To best serve the 300,000-500,000 "customers" who purchase annual salt-water fishing licenses (and ultimately all North Carolinians), we contend that the NC Wildlife Resources and Marine Fisheries Commissions require data to account for the backgrounds, concerns and biases of key users such as recreational fishers and waterfront property owners. The importance of reaching the public and stakeholders regarding the health and current issues facing coastal ecosystems has measurable value for management and conservation initiatives. Therefore, the final component of this project was to integrate the data we collect into a coastal sustainability outreach program to reach stakeholders and the NC public through presentations and interactive websites. In summary, we proposed a study that will address many unresolved questions regarding how North Carolinians, including coastal residents and anglers, affect and perceive the health of NC fisheries, fish habitats, and related coastal management issues (Figure 2).

Methods

We outline our methods under each theme of the project below.

Theme 1: NC Waterfront Property Owners

Survey distribution

To assess which attributes waterfront-property owners prioritize when making shoreline-protection decisions, a dual-method (online and mail) survey (Appendix B) of waterfront residents was conducted in 16 of 20 coastal counties in North Carolina. 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 (Table 1, Figure 3). Survey participants were recruited using a modified Dillman method (Millar and Dillman 2011) involving an initial mailing of postcard invitations to complete an online survey and one follow-up reminder postcard (Figure 4). 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.

Survey content

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 (Appendix B). 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. For example, respondents were asked to report the following information: (1) length of their shoreline; (2) condition of their shoreline, including what (if any) shore stabilization structures were present; (3) how many years their shoreline had been in its current state; and (4) how much the shore stabilization structure or approach cost (in U.S. dollars) to install if the respondent was the property owner when the structure/approach was installed or implemented. Property owners were also asked to report actual shoreline damage frequencies and costs to determine if their chosen shoreline protection strategy was meeting expectations.

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. Only installation costs reported from 1984 to 2014 were included because 1984 was the first year that costs were reported for both bulkheads and riprap (or the combination of both) in all three states. Installation costs were converted to 2014 U.S. dollars by first subtracting the years the shoreline has been in its current state from the survey response year (2014), and then adjusting for changes in national inflation from the year the shore structure was installed to 2014. We again converted installation costs to 2014 costs using the implicit price deflator (IPD) for residential gross private domestic investments for the years 1929– 2014 from the Bureau of Economic Analysis (BEA 2017). For example, the cost of a structure installed in 1965 expressed in 2014 dollars is the cost multiplied by the ratio of the 2014 IPD to 1965 IPD (2014 cost = 1965 cost * [112.795/13.033], Pielke et al. 2008). Installation costs were expressed as costs per meter of shoreline reported. Data for shorelines reported as less than 10 meters long were excluded.

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. 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. 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).

Converted 2014 installation cost data were log transformed to meet the assumptions of normality and homogeneity of variance, and then one-way analyses of variance (ANOVAs) were run to determine if there were significant differences in mean installation costs per meter as function of shoreline condition (bulkhead, riprap revetment, and bulkhead & riprap revetment combined). If installation costs were significantly different across shore types, then Tukey's posthoc tests were applied to determine differences between shore types. When the assumptions of normality and homogeneity of variances was not met, Kruskall-Wallis tests were used to compare installation costs across shore types and Dunn's test were used for post hoc comparisons.

Damage and maintenance cost data were analyzed in a three-step process, using the delta approach (Fletcher et al. 2005, Serafy et al. 2007). 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. (2007). 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 (Seber 1982). 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).

Theme 2: Broader NC Population

Survey distribution

We distributed a 42-question survey (Appendix C) to 1,000 North Carolina residents via e-mail through a panel contracted with Qualtrics, a survey distribution company, in October 2013. The survey was distributed until 1,000 responses were received and the respondents were representative of the general population of adults (18 years or older) in North Carolina. Collection

of 1,000 responses took approximately two weeks.

Survey Content

The statewide survey contained the same questions as the NC Waterfront Survey with the exception of the last selection about shoreline condition, which was only relevant for waterfront residents.

Theme 3: Recreational Fishermen (CRFL Licensees)

Survey distribution

In addition to surveying NC waterfront and NC residents as described under Themes 1 and 2, we also conducted targeted surveys of participants in two recreational fishing tournaments held in North Carolina. A subset of six questions (Appendix D) was selected for an in-person survey of participants in the Barta Boys and Girls Club Billfish and Inshore Fishing Tournament (http://www.bartabillfish.com/) in July 2014 and the Reeling to Heal Inshore Slam in Jacksonville, NC, in August 2014. Tournament participants were approached at the weigh-in for each tournament and only participants 18 years or older were surveyed.

Survey content

The survey questions focused on 1) fishing habits and preferences (e.g., targeted fish species, habitats fished for target species); 2) catch data for targeted fish species (e.g., length and weight of largest targeted fish caught and the year caught); 3) coastal habitat values and threats (*see* Appendix D). For the NC resident and NC Waterfront surveys, participants indicated whether he or she fishes by answering the survey question "What kind of North Carolina saltwater fishing license do you currently hold?" All participants that selected a response other than "I don't fish" were included in the results presented under Theme 3.

Theme 4: Improving Education and Outreach Initiatives

We worked with the North Carolina National Estuarine Research Reserve (NC NERR) staff to ensure that the results of this research were integrated into education and outreach activities. In December 2014, we worked with Emily Woodward, Communications and Project Management Specialist, NC NERR, to update the DCM estuarine shoreline stabilization webpage as part of our education and outreach component of the grant. We provided photos and peer-reviewed papers related to estuarine shoreline stabilization for the web page. In May and June 2015, Rachel Gittman presented some of the research findings from this project and previous CRFL-funded projects as part of "Living Shorelines for Erosion Control on Estuarine Shorelines" and "Promoting Living Shorelines for Stabilization – A Workshop for Real Estate Professionals", a series of workshops for for marine contractors, engineers, landscape architects, land use planners, and other technical professionals hosted by NC NERR. In 2016, Dr. Gittman and Ms. Carter Smith presented the research to NC DCM staff, the Governor's South Atlantic Alliance, and to participants in Restore America's Estuaries Living Shorelines Workshop. Dr. Gittman is also a current expert reviewer for reports and other gray literature being included in the Living Shorelines Academy repository, where the results of this project will also be included. Dr. Gittman has also contributed to several media communications about this project. Finally, manuscripts are also being prepared and are in the process or will be published in peer-reviewed journals in the coming year (*see* Appendices A and E).

Results

We outline our results under each theme of the project below.

Theme 1: NC Waterfront Property Owners

Waterfront Respondent Demographics

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.

Waterfront Respondent Shoreline Condition

Forty-one percent (N=282) of property owners reported having bulkheads (average length= 45m ± 3m [mean ± SE]), 40% (N=275) had natural shorelines (average length= 51m ± 3m), 10% (N= 66) had riprap (average length= 77m ±14m), and the remaining 9% had a sill (N= 10), groin (N= 7), or hybrid shoreline (N= 49). A majority of respondents were residents of Carteret, New Hanover, Onslow, Dare, and Craven counties and the most common types of shorelines in these counties were natural or bulkhead shorelines (Figure 5).

Waterfront Respondent Installation Costs for Shore Protection Structures

Bulkheads with riprap revetments were the most costly to install: $877 ± 210 m^{-1} (N=23), followed by bulkheads alone $727 ± 88 m^{-1} (N=82), followed by riprap $282 ±58 m^{-1} (N=23). The cost of installing a living shoreline was reported as $343 ± 95 m^{-1} (N=5).

Perceptions of Shore Protection Approaches

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 (Figure 6A). 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%; Figure 6B). Bulkheads were also considered the most costly option with 46% of respondents ranking them highest, followed by riprap with 22% (Figure 6C). Bulkheads were perceived as the most durable (32%), but also thought to require the most maintenance (24%) (Figure 6D, E). Plantings (with and without a sill) were considered more effective and durable than a sill alone (Figure 6B,D). When asked about shoreline damage, 66% of respondents perceived storms to be the number one cause of property damage (Figure 7A).

Reported Shoreline Damage

The belief that storms were the primary cause of shoreline damage 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% (Figure 7B). 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, $p < 0.0001$; Tables 3 & 4), 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, $p= 0.53$; Table 5). 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 (Figure 8A). 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 ($p = 0.015$; Figure 9A).

Reported Shoreline Maintenance

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 (Figure 8B). 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%, $p = 0.0036$, Figure 9B). 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 (Figure 8C). 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 ($p = 0.17$; Figure 9C, Tables 3 & 4).

Reported Shoreline Damage and Maintenance Costs

For those property owners that did report spending money and/or time, there was a significant difference between shoreline types in the mean hurricane property damage costs (ANOVA, $F_{2, 247} = 3.119$, $p = 0.046$; Figure 9D) and maintenance costs (ANOVA, $F_{2, 216} = 15.106$, $p < 0.0001$; Figure 9E), but only a marginally significant difference in maintenance days (ANOVA, $F_{2, 285} = 2.913$, $p = 0.056$; Figure 9F; Table 6). 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 (Table 7). Mean delta values of total hurricane property damage costs were two times higher for properties with bulkheads than those with natural or riprap shorelines (26.7 ± 7.2 v. 11.5 ± 2.8 v. 12.4 ± 3.8, respectively; Figure 9G). 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; Figure 9H). 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; Figure 9I).

Perceptions of Neighbor's Shoreline Condition

When asked about the effects of his or her shore protection approach on his or her property, respondents with traditional hard shoreline approaches overwhelmingly felt that his or her chosen approach was beneficial for his or her property (88% of bulkhead owners, 67% of groin owners, and 53% of riprap revetment owners, Figure 10). Trends were similar for how respondents viewed the effects of their shore protection approach on his or her neighbor's shoreline, with 62% of bulkhead owners, 86% of groin owners, and 53% of riprap owners believing that his or her shore protection approach was beneficial for his or her neighbor's

shoreline (Figure 11). In contrast, a majority of property owners with living (55%) or natural shorelines (77%) felt that his or her shoreline protection approach was neither beneficial nor harmful for his or her own shoreline or for his or her neighbor's shoreline (Figures 10 & 11). When asked how his or her neighbor's shoreline affects the respondent's shoreline, 57% of respondents with a bulkhead or riprap revetment felt that a neighbor's bulkhead or riprap shoreline was beneficial for his or her shoreline, respectively (Figures 12 & 13). Nearly 25% of bulkhead owners felt that a neighbor's natural shorelines were harmful to his or her shoreline, while a smaller percentage of bulkhead owners felt that bulkheads (9%) or riprap revetments (8%) were harmful to his or her shoreline (Figure 12). A larger percentage of riprap revetment owners felt that neighbors' living shorelines (33%) were harmful to his or her shoreline than neighbors' bulkheads (22%), natural shorelines (22%) or riprap revetments (7%, Figure 13). Thirteen percent of respondents with living shorelines felt that bulkheads were harmful for his or her shoreline and all living shoreline respondents felt that other neighbor shore types were either beneficial or had no effect on his or her shoreline (Figure 14). More than 20% of respondents with natural shorelines felt that bulkheads and riprap had negative effects on his or her property, while 98% viewed natural and living shorelines as having positive or no effect on his or her property (Figure 15).

Influences on Decisions to Stabilize Waterfront Property

When asked what stabilization approach they would select to stabilize their eroding shorelines, hardened shoreline owners overwhelmingly selected hard approaches, while natural/living shoreline owners selected living shorelines (Figure 16). Hardened shoreline owners indicated that the condition of their neighbors' shorelines influenced their own stabilization decisions (Figure 17). In contrast, natural/living shoreline owners generally were not influenced by neighbors and did not believe that their shorelines affected their neighbors' shorelines, or vice versa (Figure 17). Respondents with natural shorelines reported the highest annual erosion rates (0.27 m per year), followed by riprap (0.18 m per year) and bulkhead (0.16 m per year) owners (Figure 18). Living shoreline and groin owners reported lower annual erosion rates at 0.06 and 0.03 m per year, respectively (Figure 18).

Nearshore Habitat Change and Recovery

Respondents perceived wetlands and submerged aquatic vegetation as the most important for fisheries and water quality, followed closely by oyster reefs. Beaches were perceived to be the most important for tourism and storm protection. Waterfront residents generally perceived increases in adjacent subtidal habitat (oyster, mudflat, SAV) coverage (Figure 19). Only respondents with living shorelines perceived significant increases (>10%) in adjacent intertidal vegetated habitat (marsh and forest) and respondents with hard shorelines reported losses in beach habitat adjacent to their shorelines (Figure 19). When asked what the best action would be to promote habitat recovery, 46% of respondents said allow for natural recovery, 20% said restore the habitat to its previous condition, 18% suggested designating no wake zones, 15% suggested building a sill or breakwater to reduce wave energy, and only 2% suggested removing neighboring stabilization structures.

Additional results of waterfront surveys related to shoreline stabilization will be presented in peer-reviewed manuscripts currently in preparation.

Theme 2: NC Residents

North Carolina residents ranked industrial pollution as the greatest threat to NC coasts, regardless of whether he or she lived in an inland country, coastal county, or on waterfront

property and regardless of age (Figure 20). A majority of NC respondents believe that the climate is warming, but fewer respondents that live on the waterfront believe the climate is warming than respondents that live inland or along the coast, but not on the waterfront (Figure 21). Waterfront respondents were most concerned about sea-level rise, while non-waterfront coastal respondents and inland respondents were most concerned about storms and rising temperatures (Figure 22). Despite being the most concerned about sea-level rise, waterfront respondents reported lower anticipated rises in sea level than non-waterfront coastal or inland respondents (Figure 23). Waterfront respondents age 35 or older were generally supportive of the expansion of shellfish aquaculture in North Carolina, while younger waterfront respondents and non-waterfront coastal and inland respondents were mostly unsure about whether they would support expanding shellfish aquaculture (Figure 24). A majority of respondents supported the construction of wind turbines within North Carolina coastal waters, regardless of age or geographic location (Figure 25). Additional results comparing inland, non-waterfront coastal, and waterfront perceptions of coastal habitat value, use, and threats will be presented in peer-reviewed manuscripts currently in preparation.

Theme 3: NC Fishermen

Of the NC inland, coastal, and waterfront residents surveyed, 681 held coastal recreational fishing licenses, 89 held commercial fishing licenses, and 360 fished from a pier or a licensed boat. Fishermen with both CRFL and commercial license have been fishing for the longest, at an average of 36 years, while CRFL-only license holders have been fishing for 27 years, followed by commercial-only at 20 years, and then pier or licensed boat fishermen at 15 years (Figure 26). A majority of fishermen respondents fish in NC inland waters, as opposed to NC Ocean or Federal waters (Figure 27). Flounder was the most targeted species by all fishermen in NC, regardless of license type (Figures 28-31). Fishermen also frequently targeted red drum, striped bass and speckled trout (along with whatever bites the hook); however, shrimp were the second most targeted species for commercial fishermen after flounder (Figure 29). There was no relationship between fish size (length) and the year caught for the biggest flounder, red drum, speckled trout, and striped bass reported by fishermen (Figure 32). When targeting flounder, red drum, and speckled trout, fishermen preferred to fish along hard bottom, oyster reefs/oyster spawning sanctuaries, and beaches, while fishermen targeting striped bass also preferred to fish in submerged aquatic vegetation (Figure 33). A majority of fishermen fish from a boat, as compared to the shore or a pier, except those fishermen that only fish from a pier or licensed-boat (Figure 34). Additional results comparing inland, non-waterfront coastal, and waterfront fishermen perceptions of coastal habitat value, use, and threats will be presented in peer-reviewed manuscripts currently in preparation.

Theme 4: Education and Outreach

See Appendix E for a list of presentations and outreach materials developed as part of this project.

Discussion

Shoreline Stabilization

The designated purpose of a shoreline stabilization structure is to prevent erosion and property damage, particularly during major storm events like hurricanes (USACE 2016a). 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. (2015) 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. (2015) 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 (Leatherman 1982). 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 (Slovic 2000). 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 (Peacock et al. 2005); 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. 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 (Theiler and Young 1991, Gittman et al. 2014). 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, the tree-based classification models found shoreline type to be the best predictor of costs, suggesting that environmental setting 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 (National Climatic Data Center 2016). Coastal property damage has greatly increased over recent decades, probably in response to increased development in vulnerable areas (Zhang et al. 2000). 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. Meanwhile, the proportion of coastline with bulkheads decreased slightly, while the proportion of hybrid shoreline nearly doubled. 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 (Fear and Currin 2012). 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. Furthermore, bulkhead remediation (e.g. removing a bulkhead and returning the shoreline to a more natural profile) is difficult and seldom undertaken (but *see* Davis et al. 2006), 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 (French 2001, Augustin et al. 2009). 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 (Foley et al. 2005).

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. (2015) 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. Based on the survey results, living shorelines appear to be cheaper to install than bulkheads; however, additional data are needed given the variability in design, construct materials, and scale of projects that meet broader definitions, such as NOAA, of living shorelines (e.g., Gittman et al. 2016a,b). There are also cross-scale issues to consider when comparing the cost of shoreline management structures. For sandy beach coastlines, shoreline management decisions are typically outside the locus of control of individual residents. Instead, the cost of large-scale beach nourishment are typically funded or subsidized by taxpayers. Within sheltered coasts, these external forces include the biophysical consequence of nearby hardened shoreline structures, coastal storms, channel dredging, shipping and boating (Gittman et al. 2014, Scyphers et al. 2015). Sutton-Grier et al. (2015) 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 (Currin et al. 2008, Rodriguez et al. 2014). Even under more extreme sea-level rise scenarios

that may outpace vertical accretion potential (Voss et al. 2013), 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.

Perceptions of Coastal Habitat Value and Environmental Threats

Interpretations of NC resident perceptions of coastal habitats and threats as a function of geographic location and fishing activity will be presented in peer-reviewed manuscripts to be delivered as products in the future.

Data limitations

Final analyses and interpretation of the results of this project will be presented in peer-reviewed publications to be completed in the near future. Once published, the results and interpretation of results presented in those publications should be used for management decisions in lieu of the results and interpretations presented in this report if those results and interpretations differ.

Adherence to proposed project objectives

This project adhered to the primary objective provided in the proposal: "The unifying goal of our project was to provide managers and researchers with the information needed to understand how waterfront resident, recreational fishermen and the broader NC society are interlinked with the health of coastal habitats in a framework for outreach and education initiatives." (Fodrie 2012). However, we revised the components necessary for achievement of this objective based on the decision to use improved survey methods for achieving the proposed objective and the opportunity to expand our project to include collaboration with other ongoing research also supported by the CRFL program. We deviated from the proposed approach (*from* Fodrie 2012) as follows:

(1) We opted to use e-mail distribution for NC resident surveys in lieu of telephone surveys. This decision was based on the preference to use the same survey method for NC residents and NC waterfront residents to allow direct comparison of results, the cost of survey distribution ($7,000 as opposed to $10,000), and the ability to reach a more representative sample of NC residents using e-mail instead of random-digit telephone surveys.

(2) We also decided to distribute the NC resident survey before distributing the NC waterfront resident survey because the NC resident survey is shorter and provided a baseline for determining the ease of obtaining sufficient survey response. We opted to mail postcards to NC waterfront addressed selected from publically accessible NC county GIS websites in lieu of hand-delivering surveys. This decision was based on the ability to distribute the survey to a larger number of waterfront residents and to be able to easily link responses to geographic locations of respondents.

(3) In December 2014, we worked with Emily Woodward, Communications and Project

Management Specialist, NC Coastal Reserve and National Estuarine Research Reserve, NC Division of Coastal Management, to update the DCM estuarine shoreline stabilization webpage as part of our education and outreach component of the grant. We provided photos and peer-reviewed papers related to estuarine shoreline stabilization for the web page. We will continue to work with NC NERR to ensure the results of the surveys conducted for this project are made accessible on the webpage.

Applicability of study results to CRFL Strategic Plan and priorities

This CRFL Project is directly applicable to the "Habitat" Management Goal. This research directly addressed Strategy H.1.1.4 (Enhance education of fishermen and the public concerning fish habitats, how they function, and what people can do to protect them). In particular, the results of our study will help scientists and DENR managers understand how NC residents value and rank fish habitats to help guide future protection efforts.

Recommendations

We recommend that the results of this CRFL project be considered when making new priorities for habitat protection, research needs, and education and outreach goals within the CRFL Strategic Plan and future revisions to the Coastal Habitat Protection Plan. We also recommend that NC DCM continue to work with the United Stated Army Corps of Engineers to develop and approve a Regional General Permit for Living Shorelines. Additional recommendations will be made in peer-reviewed manuscripts currently in preparation, which will be delivered as products in the future.

Budget expenditures

Category	Expenditures
Personnel	$28,811
Fringe	$3,271
Travel	$7,270
Equipment	$0
Supplies	$2,587
Construction	$0
Contractual	$0
Communication	$2,694
Printing	$1,065
Other	$9,173
Total Direct	$54,871
Indirect	$8,230
TOTAL	
	$63,101

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Tables

Table 1. 2010 population density, shoreline length, housing units, total number of survey respondents by county, and number of survey respondents with each shoreline type by county.

County name	2010 Population estimate[1]	2010 Housing units[1]	Length of shoreline (km)[2]	# Of survey respondents	Shoreline breakdown (bulkhead/ natural/ riprap/ other)
Beaufort	47759	24688	1289	46	25/9/8/4
Bertie	21282	9822	487	4	1/1/0/2
Brunswick	107431	77482	1434	70	19/42/6/3
Camden	9980	4104	362	7	7/0/0/0
Carteret	66469	48179	2679	95	28/52/6/9
Craven	103505	45002	869	76	17/24/21/14
Currituck	23547	14453	1418	30	22/0/4/4
Dare	33920	33492	1569	79	53/12/3/11
New Hanover	202667	101436	1016	92	25/60/4/3
Onslow	177772	68226	1652	87	26/45/6/10
Pamlico	13144	7534	1032	18	7/4/5/2
Pasquotank	40661	16833	317	20	15/3/0/2
Pender	52217	26724	1397	24	4/17/2/1
Perquimans	13453	6986	363	21	16/4/0/1
Tyrrell	4407	2068	436	3	2/0/1/0
Washington	13228	6491	140	12	12/0/0/0
Unknown				5	3/2/0
TOTAL	**1010485**	**484961**	**16460**	**689**	**282/275/66/66**

[1] https://www.census.gov/prod/cen2010/cph-2-35.pdf
[2] North Carolina Estuarine Shoreline Mapping Project (NC DCM)

Table 2. Average ± standard error installation costs, age, and expected longevity of shore protection approaches, as reported by NC waterfront respondents.

		Living Shoreline	Bulkhead	Riprap Revetment
Installation Cost (2014 $, per m)	***Avg. ± SE***	$556 ± $167	$900 ± $110	$394 ± $93
	N	5	114	30
Structure Age (years)	***Avg. ± SE***	43 ± 6	24 ± 1	21 ± 2
	N	26	295	67
Expected Longevity (years)	***Avg. ± SE***	42 ± 7	34 ± 2	38 ± 4
	N	13	134	38

Table 4. A comparison of the number of property owners reporting spending time or money maintaining or repairing their shoreline versus those who report spending zero dollars or days based on the type of shoreline structure on their property (bulkhead, natural marsh, or riprap revetment).

Hurricane damage costs	**No**	**Yes**
Bulkhead	5	141
Natural	28	82
Riprap	2	31
Fisher's Exact Test $p < \mathbf{0.0001}$		
Maintenance costs		
	No	**Yes**
Bulkhead	91	143
Natural	176	58
Riprap	36	24
Fisher's Exact Test $p < \mathbf{0.0001}$		
Maintenance days		
	No	**Yes**
Bulkhead	71	146
Natural	118	110
Riprap	22	32
Fisher's Exact Test $p = \mathbf{0.0002}$		
Hurricane damage frequency	**No**	**Yes**
Bulkhead	74	168
Natural	118	128
Riprap	21	39
Fisher's Exact Test $p = \mathbf{0.0003}$		

Table 5. Post-hoc Fisher's Exact Test examining the differences in number of properties reporting spending money or time repairing or maintaining their shoreline as the result of a hurricane or for general maintenance depending on the shoreline structure type present on their property (bulkhead, natural marsh, or riprap revetment).

	Structure	Structure	P-value
Hurricane damage cost			
	Bulkhead	Natural	**<0.0001**
		Riprap	0.6144
	Natural	Riprap	**0.01508**
Maintenance cost			
	Bulkhead	Natural	**<0.0001**
		Riprap	**0.0036**
	Natural	Riprap	**0.0239**
Maintenance days			
	Bulkhead	Natural	**<0.0001**
		Riprap	0.2675
	Natural	Riprap	0.1735
Hurricane damage frequency			
	Bulkhead	Natural	**<0.0001**
		Riprap	0.5361
	Natural	Riprap	0.0829

Table 6. One-way ANOVA comparisons of cost (monetary and effort time) and damage frequency for bulkheads, natural marshes, and riprap revetments due to either hurricane damage or general maintenance.

	Degrees of freedom	F statistic	P-value	Bulkhead mean ± SE (n)	Natural mean ± SE (n)	Riprap mean ± SE (n)
Hurricane damage cost ($cost yr^{-1} m^{-1})	2:247	3.119	**0.0459**	27.64 ± 7.51 (139)	15.37 ± 3.72 (81)	13.24 ± 4.07 (30)
Maintenance cost ($cost yr^{-1} m^{-1})	2:216	15.106	**<0.0001**	17.74 ± 2.00 (141)	10.05 ± 2.28 (56)	5.85 ± 2.45 (22)
Maintenance days (days m^{-1})	2:285	2.913	0.0559	8.24 ± 0.61 (146)	10.26 ± 1.66 (110)	17.50 ± 3.91 (32)
Hurricane damage frequency (storm yr^{-1})	2:332	0.6296	0.5334	0.24 ± 0.02 (168)	0.26 ± 0.02 (128)	0.35 ± 0.10 (39)

Table 7. Post-hoc pairwise comparisons (Pairwise T-tests) examining differences in cost and effort time between bulkheads, natural marshes, and riprap revetments in response to hurricane damage or general maintenance needs.

	Structure (I)	Structure (II)	P-value
Hurricane damage cost ($cost yr^{-1} m^{-1})			
	Bulkhead	Natural	**0.013**
		Riprap	0.510
	Natural	Riprap	0.312
Maintenance cost ($cost yr^{-1} m^{-1})			
	Bulkhead	Natural	**<0.0001**
		Riprap	**<0.0001**
	Natural	Riprap	0.19
Maintenance days (days m^{-1})			
	Bulkhead	Natural	0.275
		Riprap	**0.018**
	Natural	Riprap	0.107

Figures

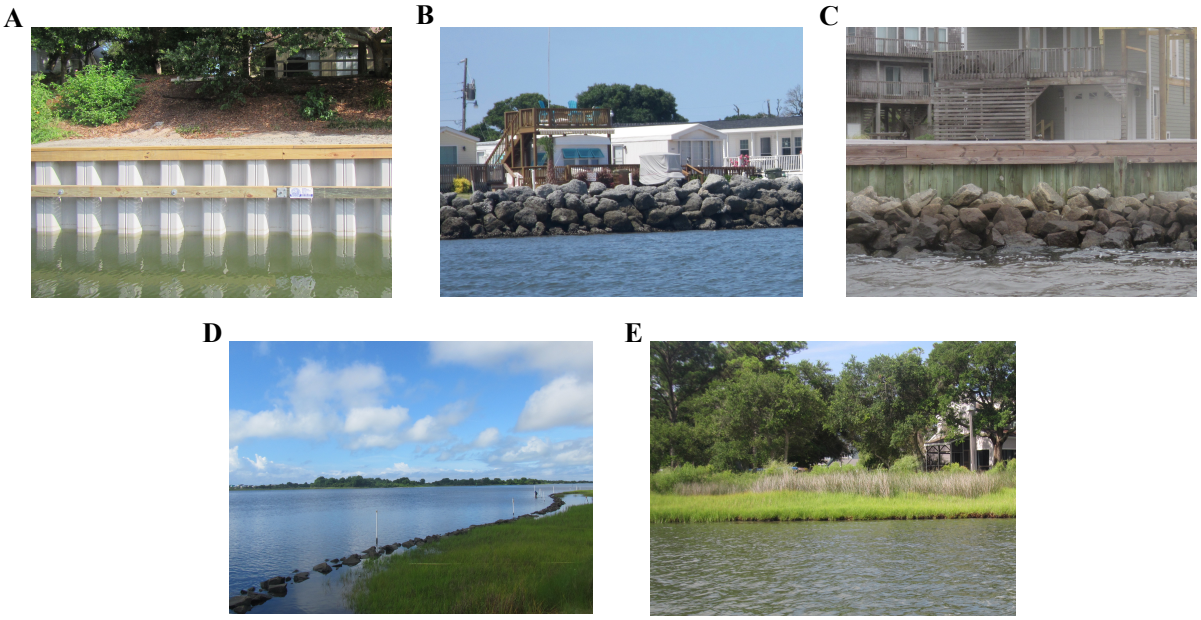

Figure 1 (from Smith et al. in review). Example shorelines: (A) bulkhead; (B) riprap revetment; (C) hybrid shoreline, combining a bulkhead with riprap; (D) sill with plantings; and, (E) natural marsh.

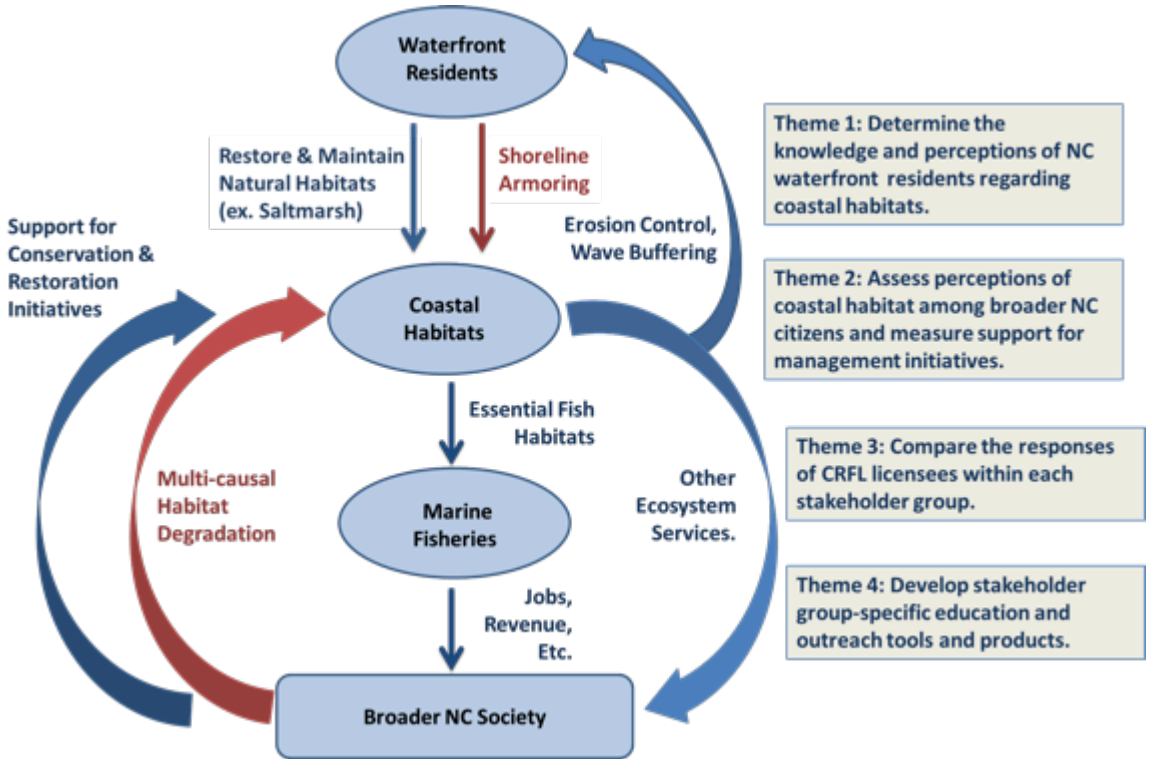

Figure 2. Illustration of study goal to collect data on the perceptions of coastal habitats to improve education and outreach programs. In human-natural coupled systems, interactions can be negative (red arrows), but also positive (blue arrows) if stakeholder knowledge and input are included in ecosystem-based management plans.

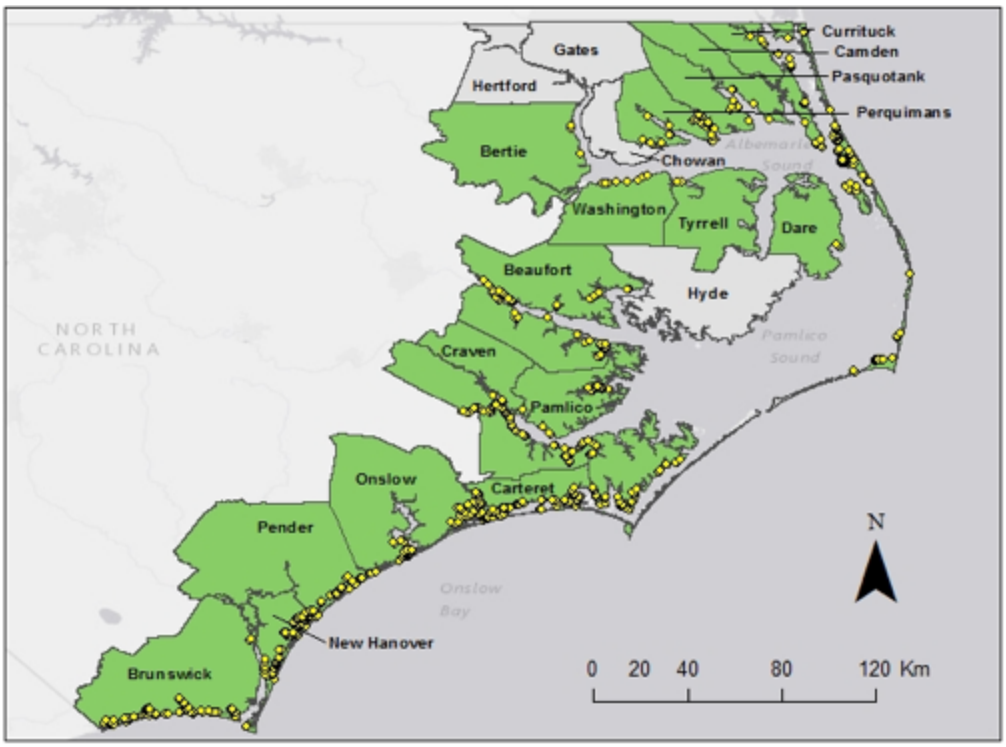

Figure 3. NC counties included in the waterfront-property owner surveys are shown in green, with excluded counties in gray. Yellow dots represent individual survey respondents.

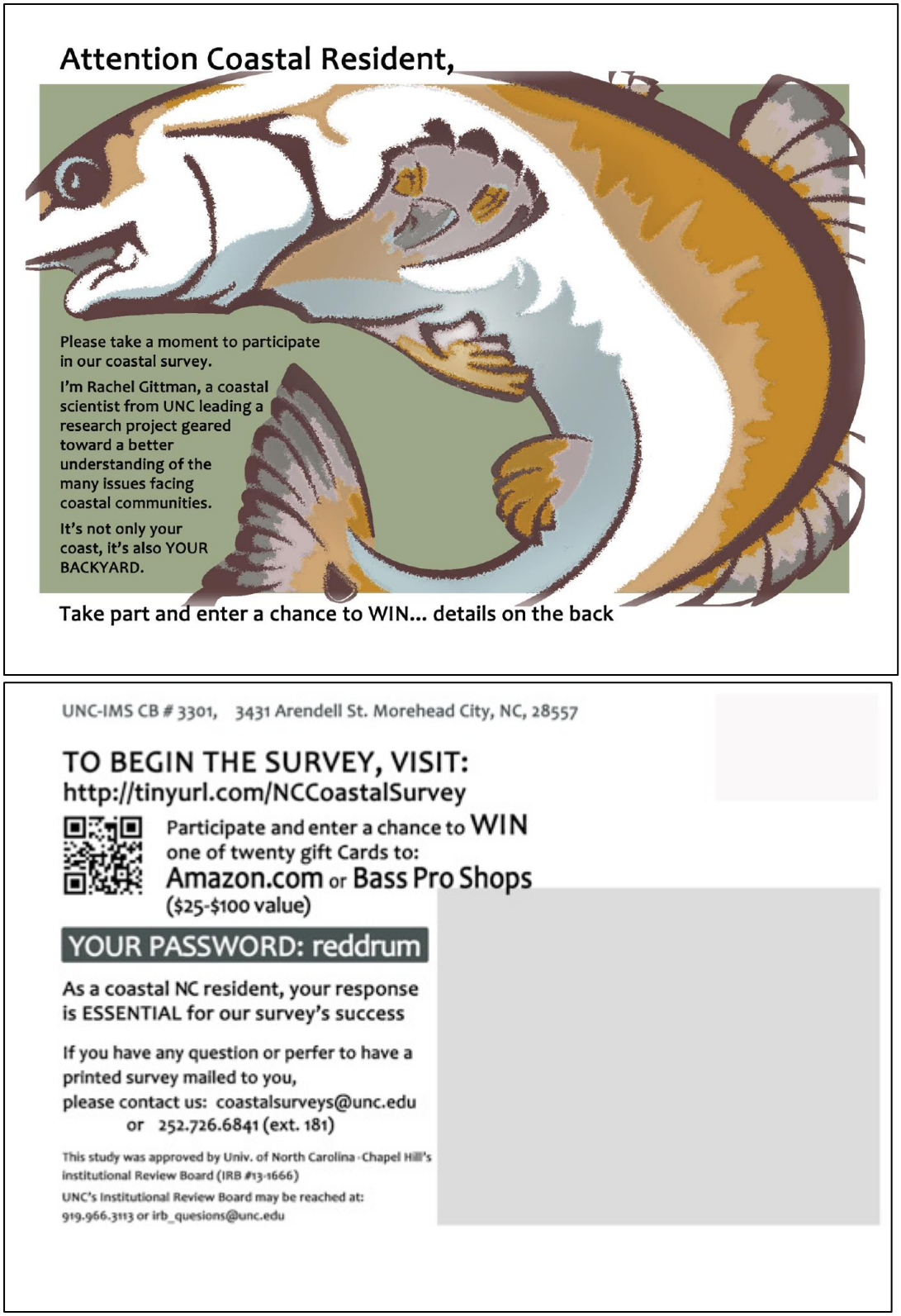

Figure 4. Survey postcard mailed to NC waterfront residents

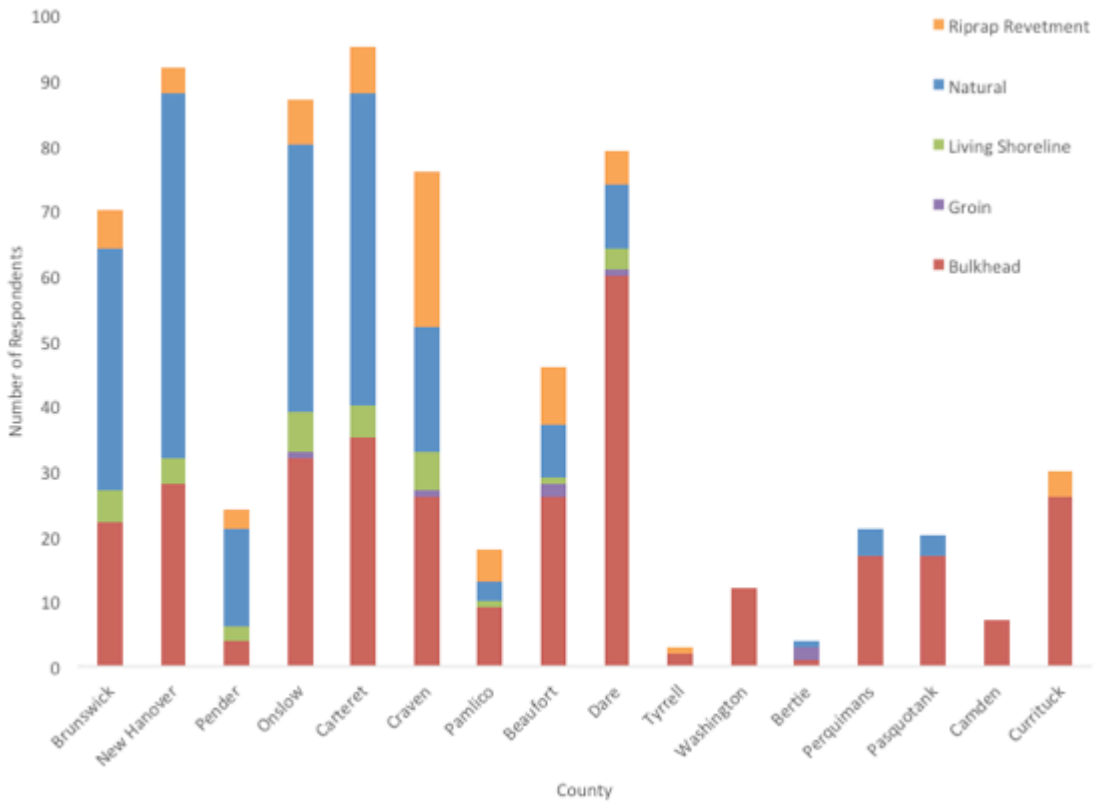

Figure 5. NC waterfront shoreline conditions by survey respondent by county. Some respondents reported multiple shoreline types and these counts are shown separately by county.

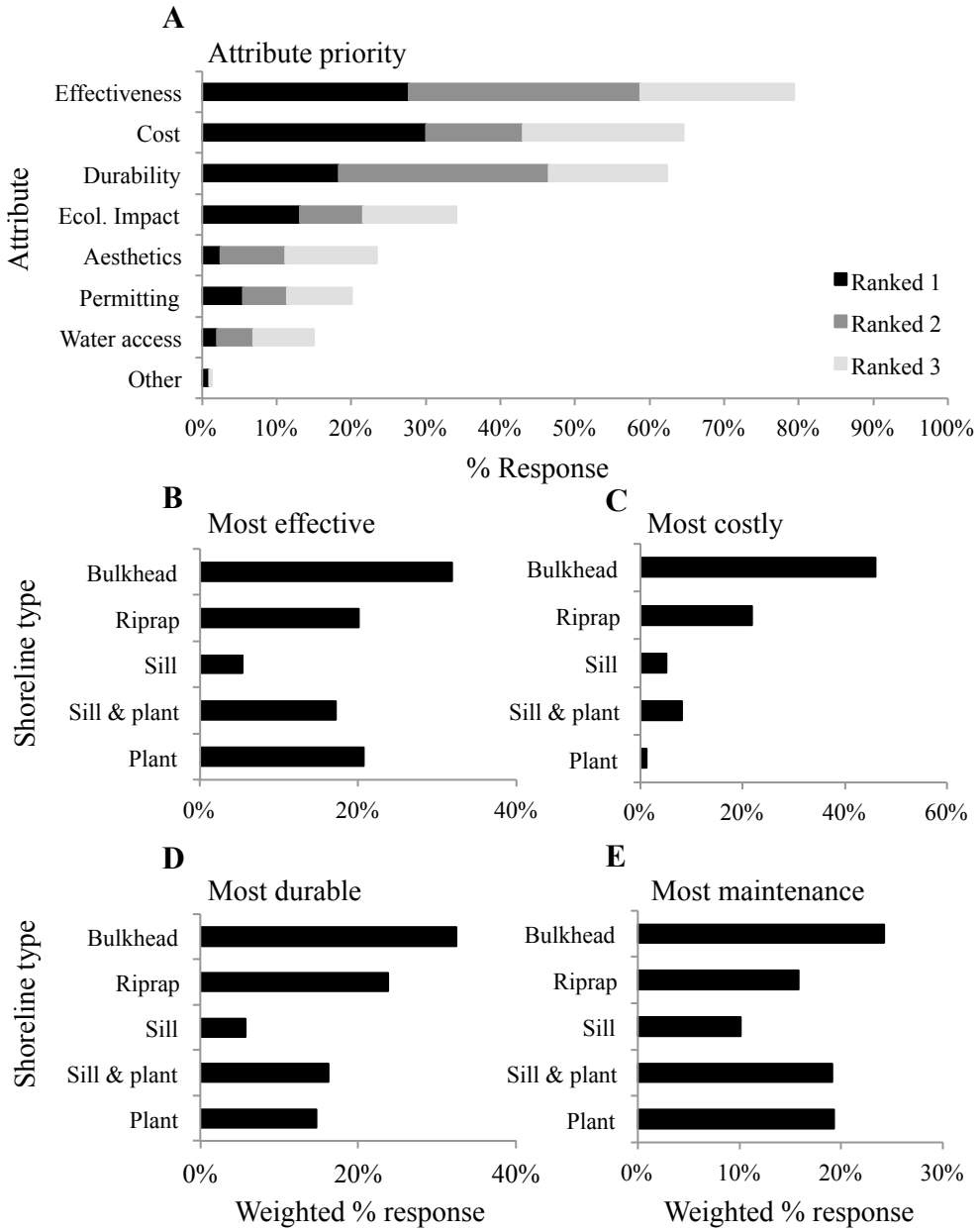

Figure 6. (A) Priorities for shoreline protection schemes. (B-E) Perceived functions of different shoreline conditions weighted by ranking with weighted percent response shown.

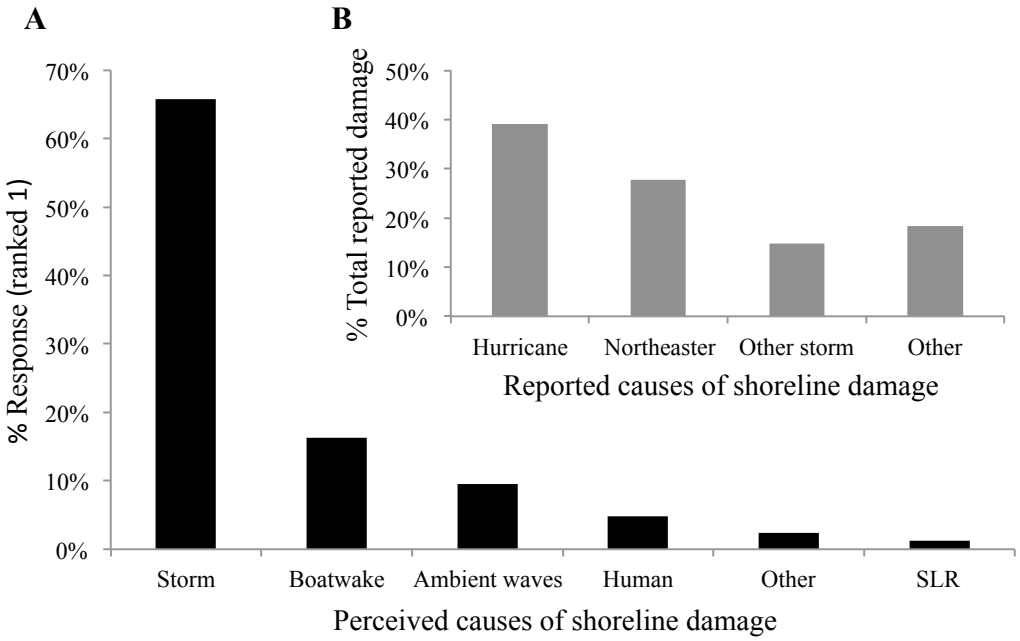

Figure 7. (A) Perceived causes of shoreline damage shown as a percent of number 1 ranking. (B) Reported causes of shoreline damage shown as a percent of the total damage reported from all causes.

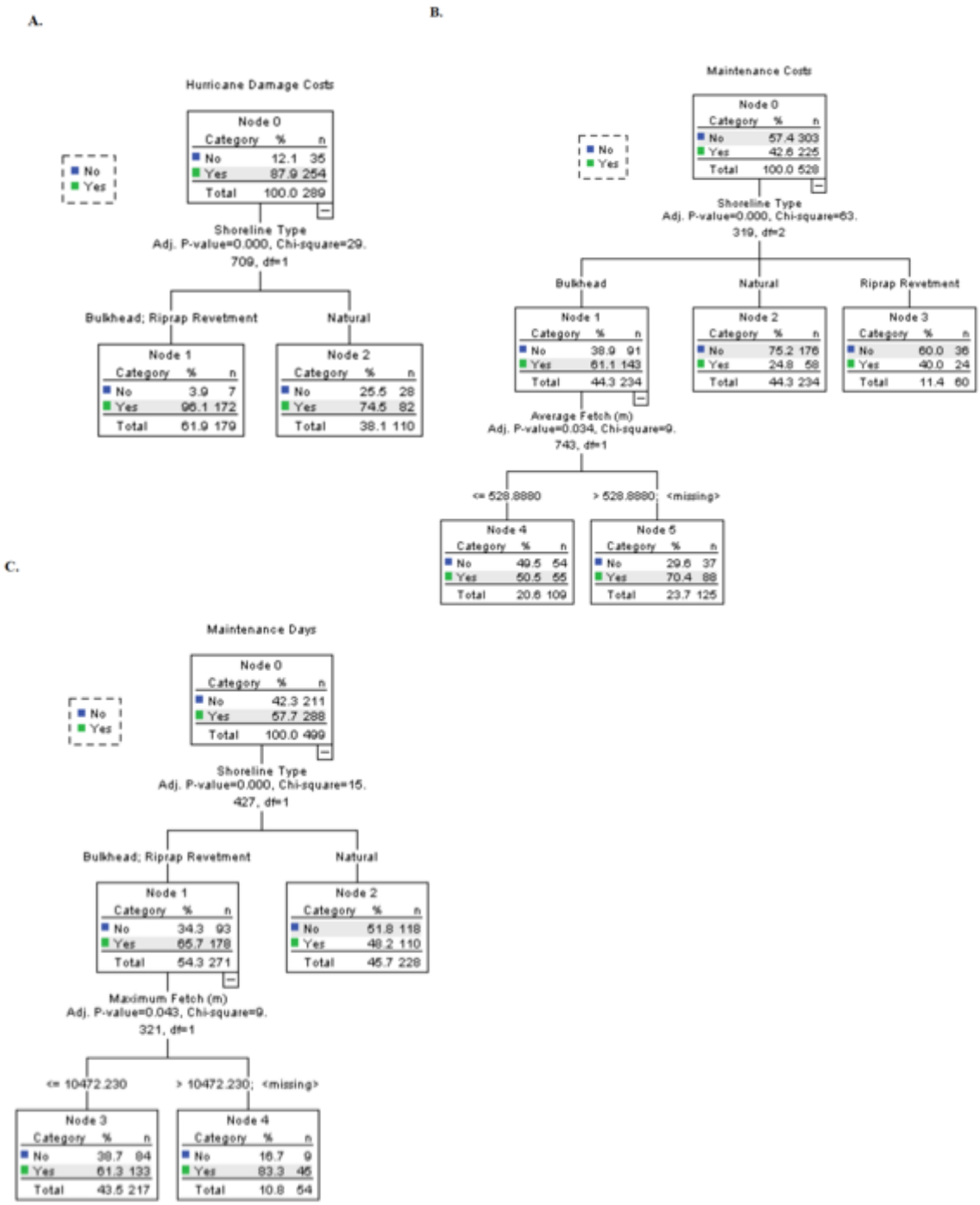

Figure 8. CHAID classification tree analysis showing the strongest predictors of whether a respondent did or did not report (A) hurricane damage costs (B) maintenance costs and (C) maintenance days. For each model the following factors were included: maximum fetch, average fetch, predominant wind direction, shore type (e.g. bay, channel, creek, sound, river), mean tide range, property size, property value, land value, building value, year built, zip code, county, county location (Northern, Central, Southern), and shoreline type (bulkhead, riprap revetment, and natural). Different branches indicate significant differences ($p < 0.05$).

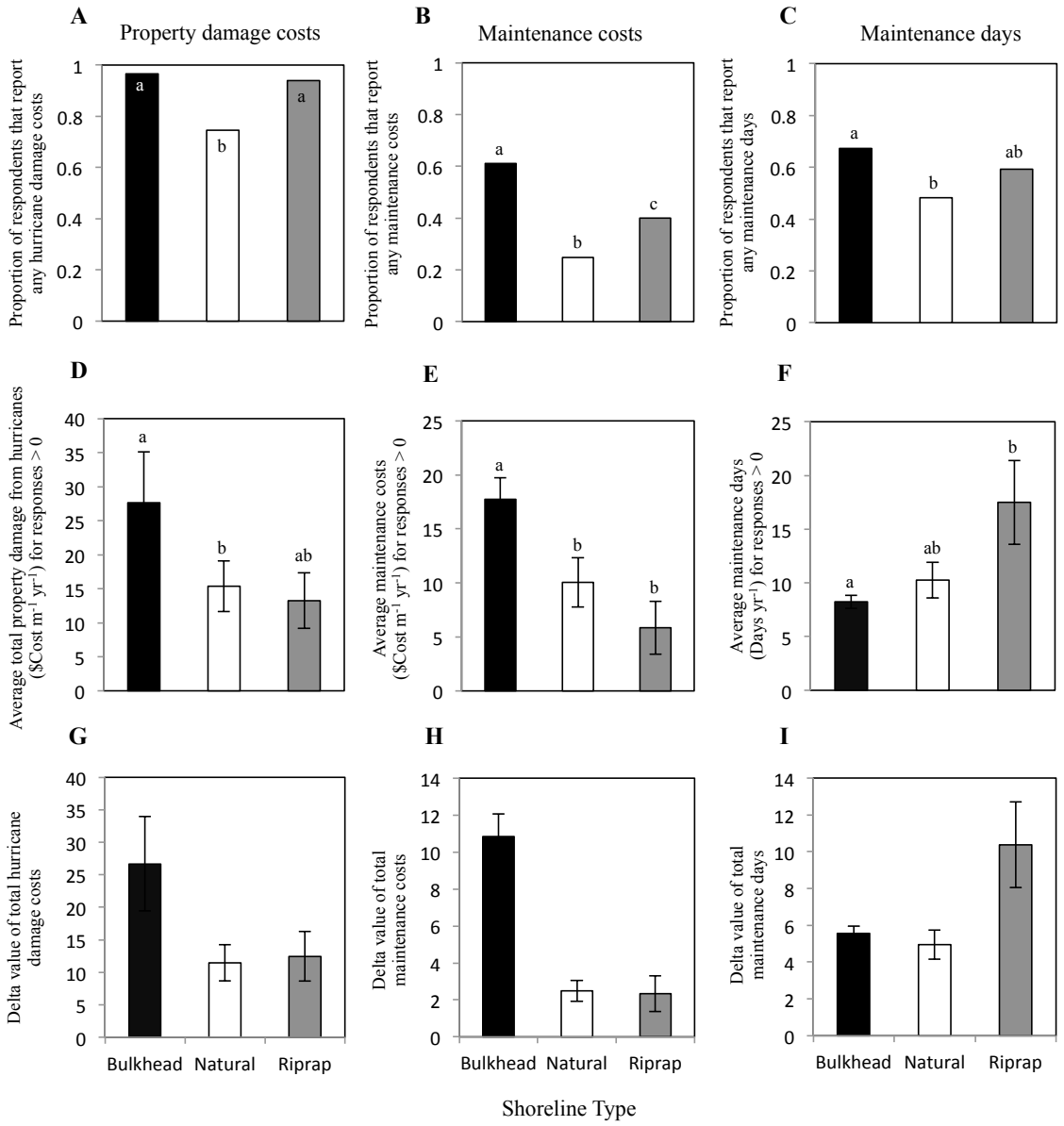

Figure 9. Reported costs associated with hurricane damage and general shoreline maintenance (cost and time) as a function of shoreline type (bulkhead, natural, and riprap). Other shoreline types were excluded from this analysis because there were too few respondents. (A-C) show the percent of respondents 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.

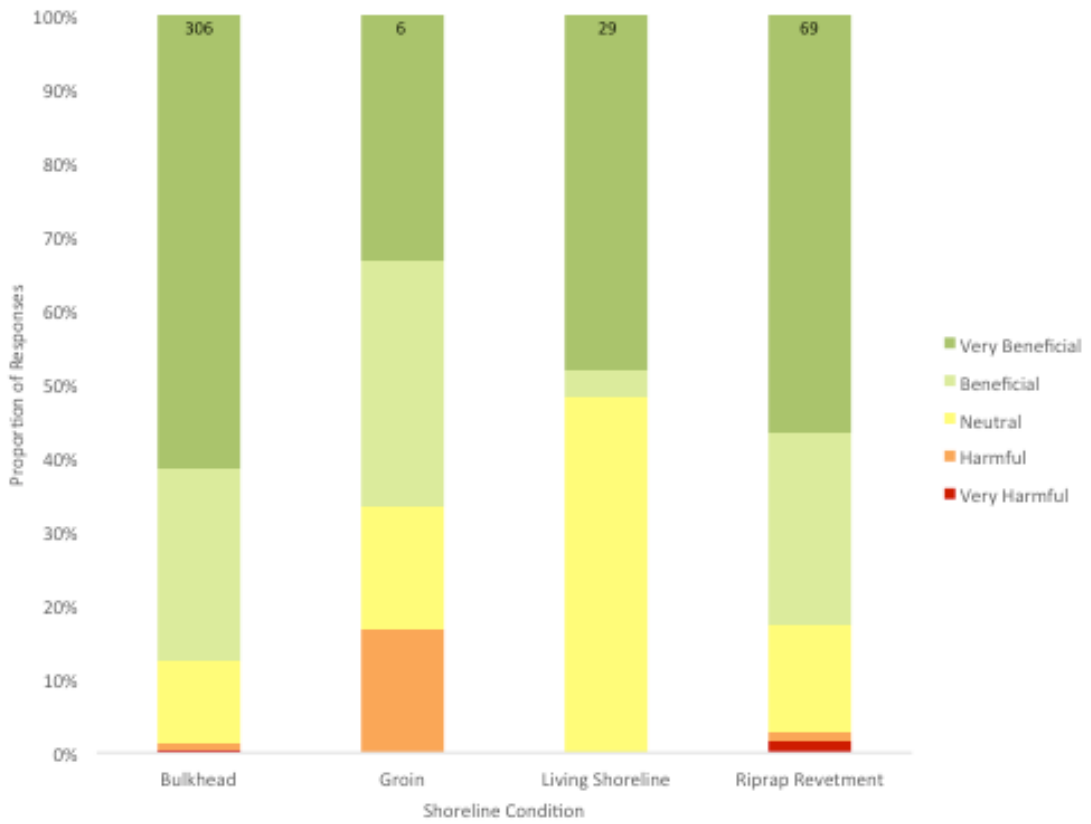

Figure 10. Waterfront respondent's perception of the effects of his or her shoreline protection approach on his or her property.

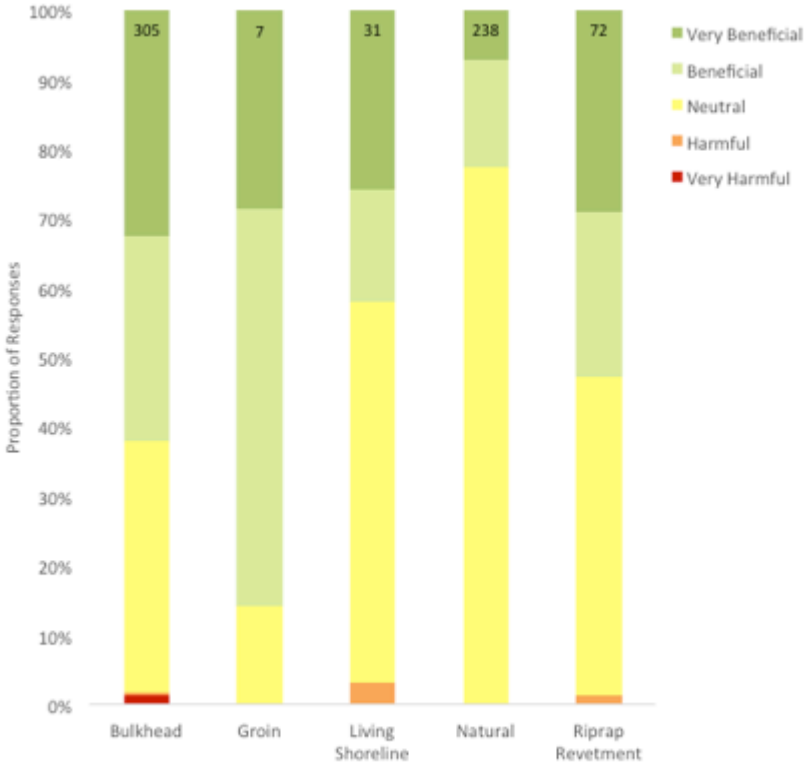

Figure 11. Waterfront respondent's perception of the effects of his or her shoreline protection approach on his or her neighbor's property.

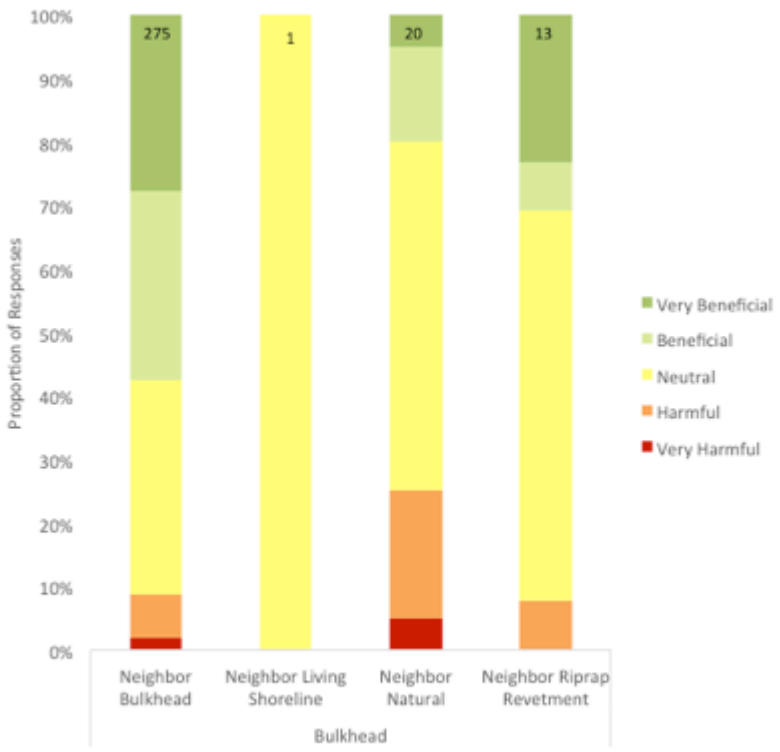

Figure 12. Bulkhead owner perceptions of the effects of his or her neighbor's shoreline protection approach on his or her property.

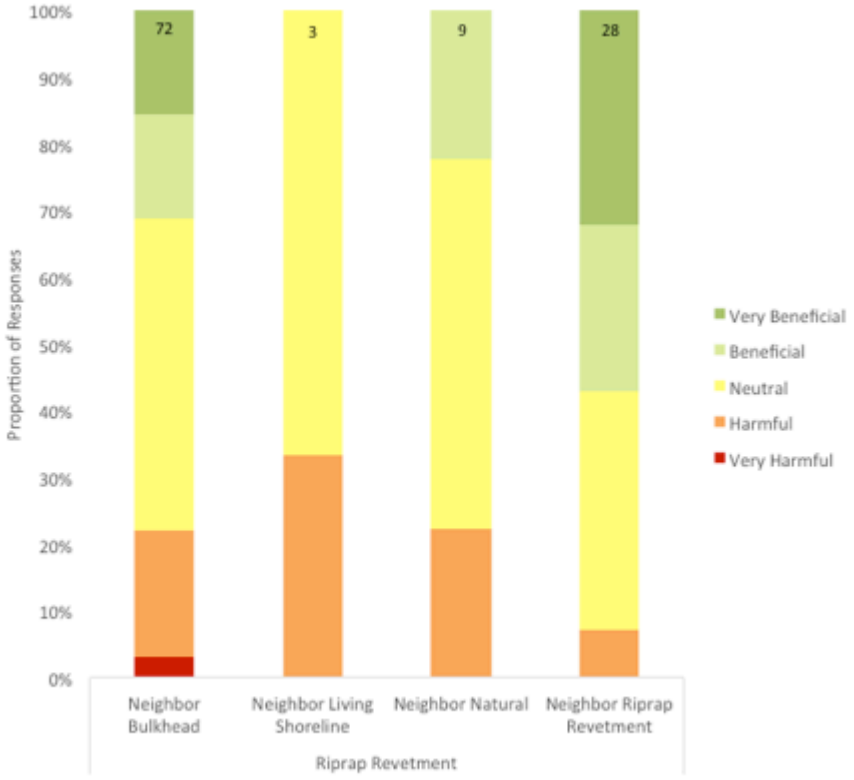

Figure 13. Riprap revetment owner perceptions of the effects of his or her neighbor's shoreline protection approach on his or her property.

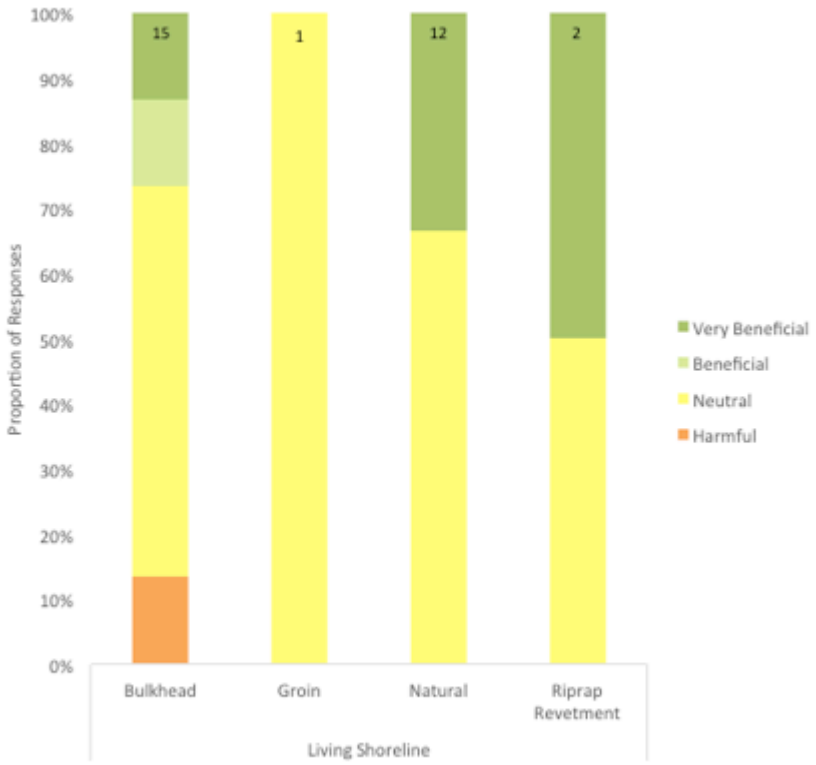

Figure 14. Living shoreline owner perceptions of the effects of his or her neighbor's shoreline protection approach on his or her property.

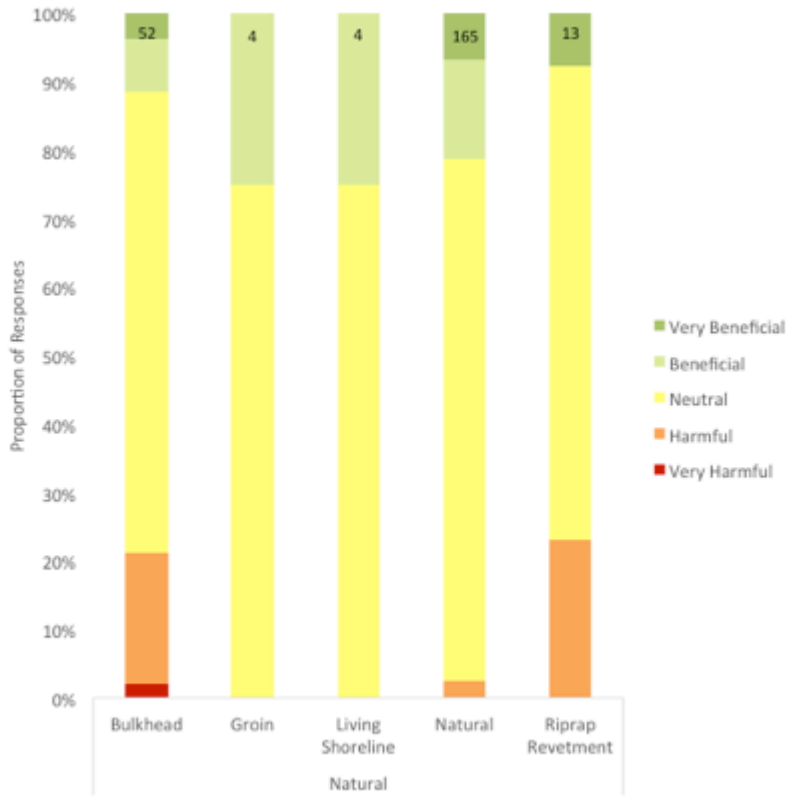

Figure 15. Natural shoreline owner perceptions of the effects of his or her neighbor's shoreline protection approach on his or her property.

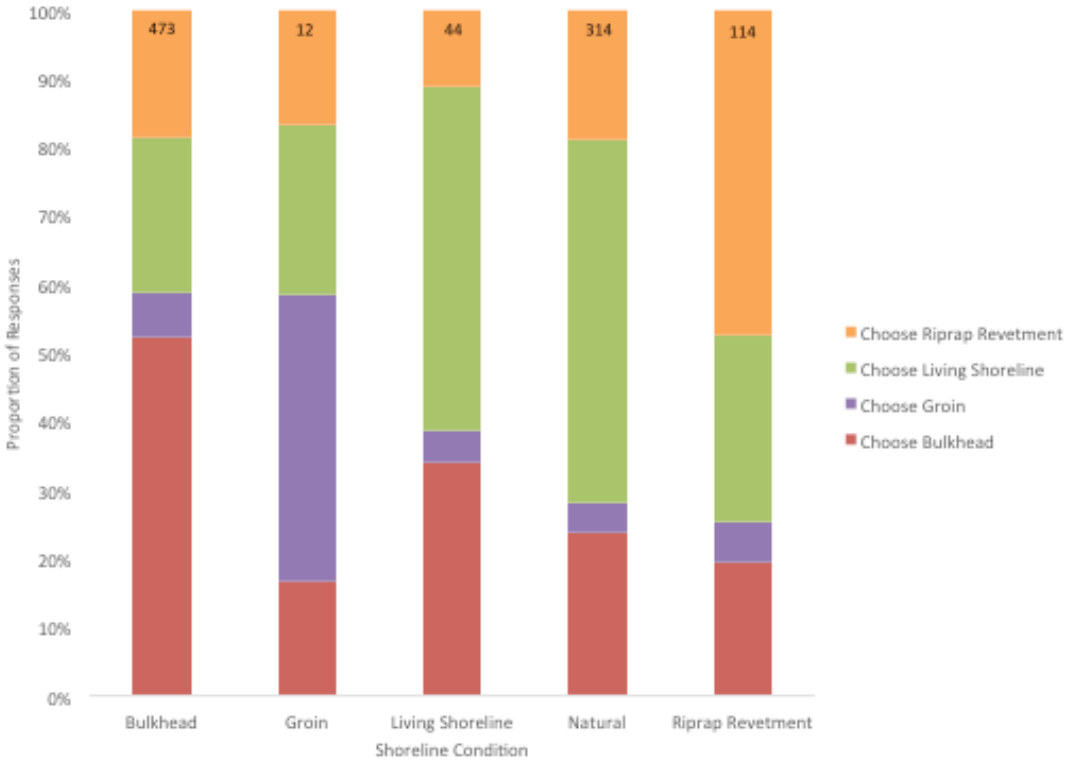

Figure 16. Proportion of respondents that would select a shoreline stabilization approach to stabilize his or her eroding shoreline, grouped by the type of shoreline the respondent currently has.

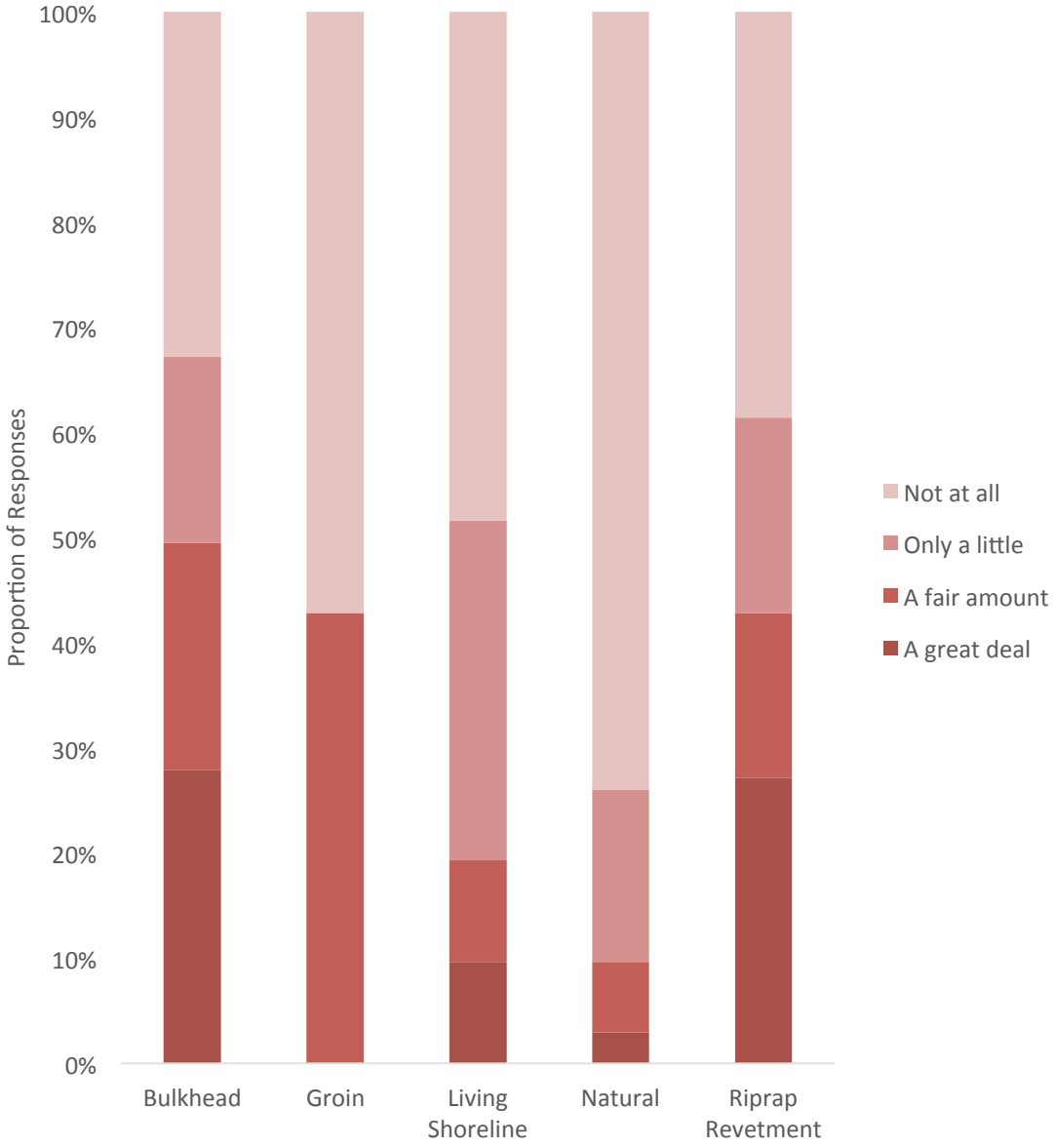

Figure 17. Reported influence of neighbor's shoreline condition on a respondent's decision to stabilize his or her shoreline, grouped by respondent's shore condition.

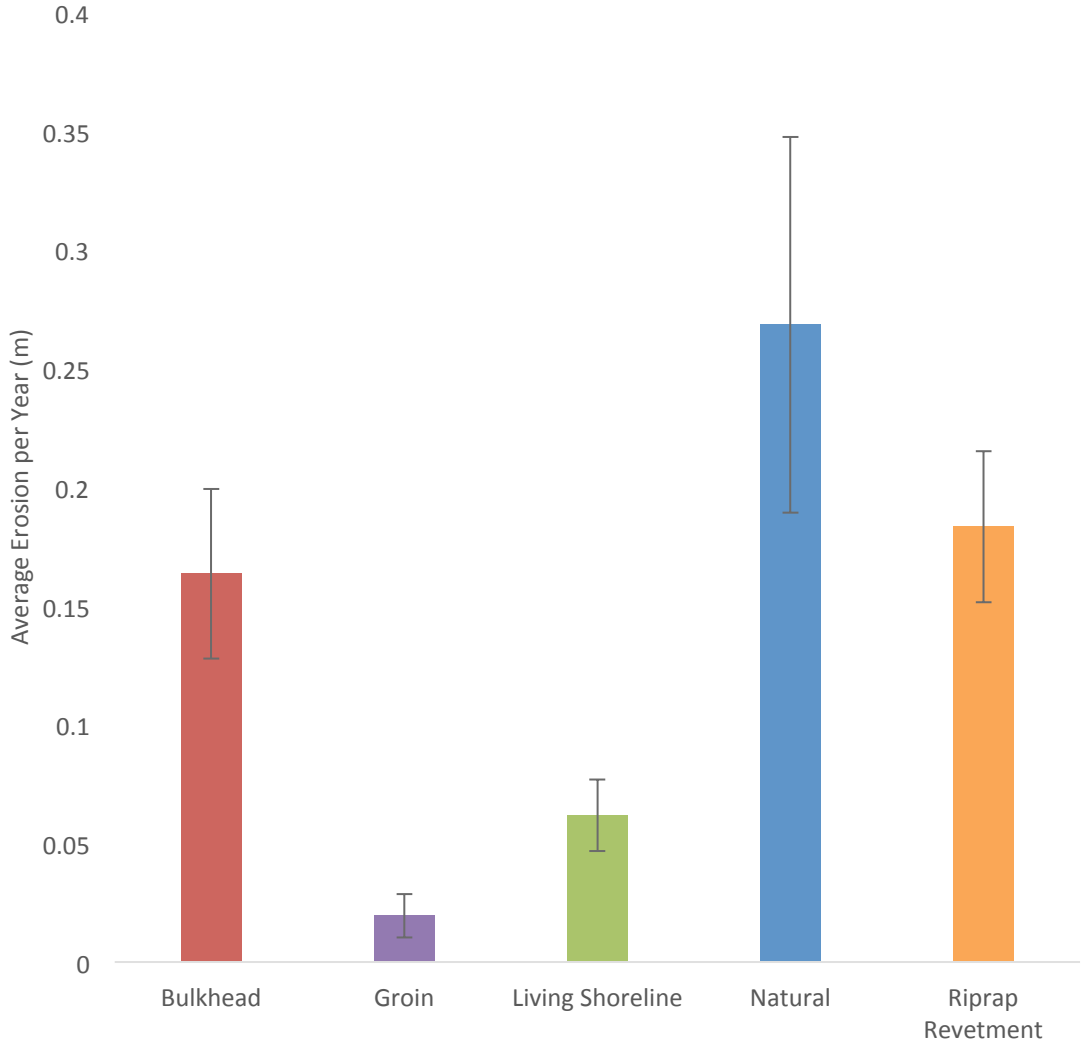

Figure 18. Annual erosion rates reported by respondents as a function of shore type. Error bars are ± standard error.

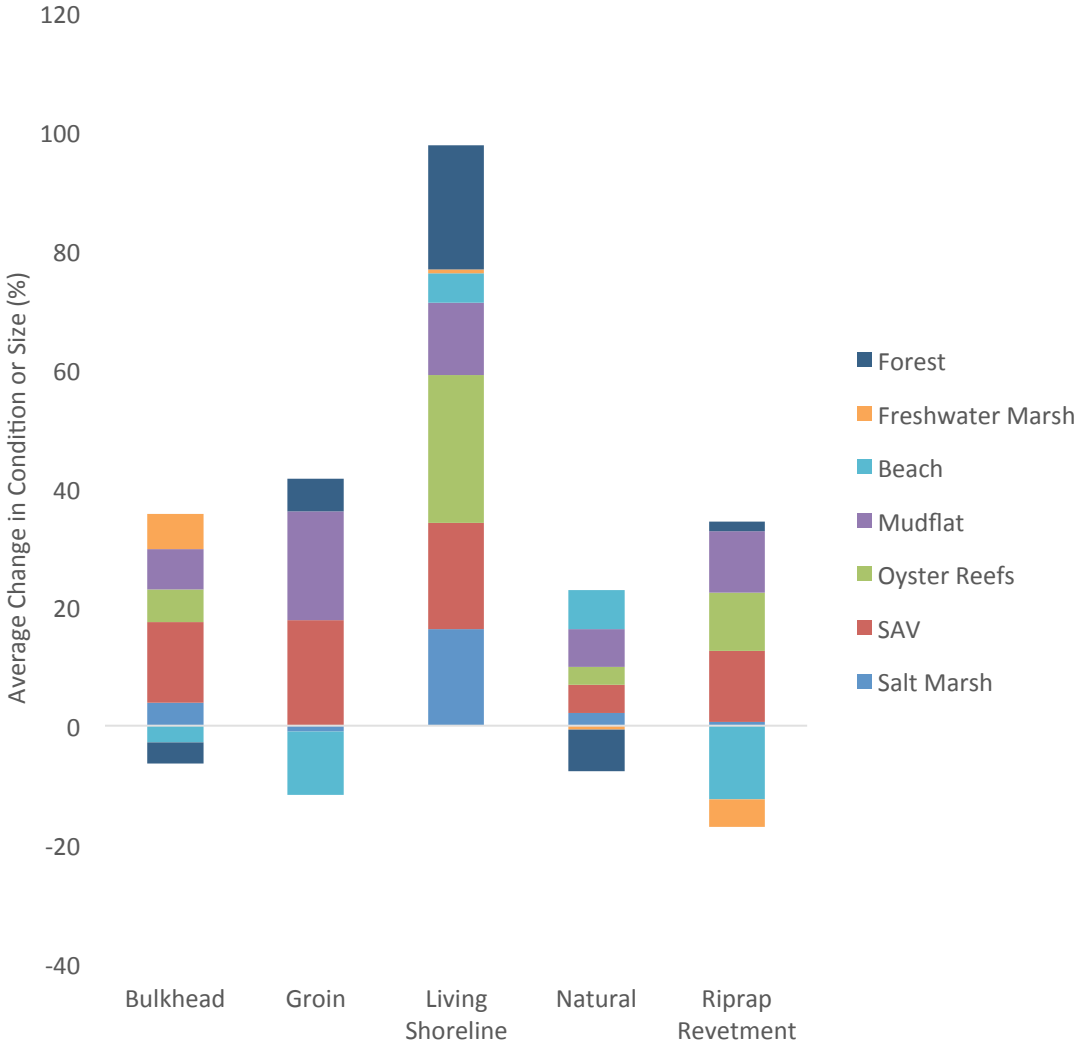

Figure 19. Perceived changes in adjacent habitats by shore type.

Figure 20. Greatest environmental problems facing NC coasts as reported by for inland, coastal, and waterfront respondents.

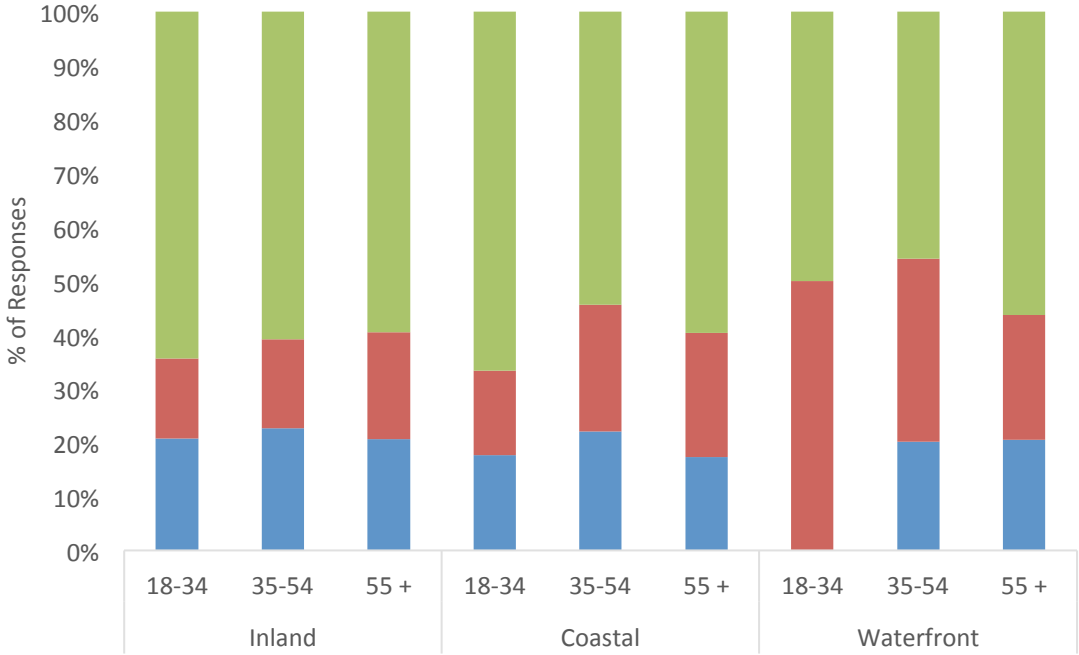

Figure 21. Belief in global warming for inland, coastal, and waterfront respondents. Responses: yes (green), no (red), or blue (don't know/not sure).

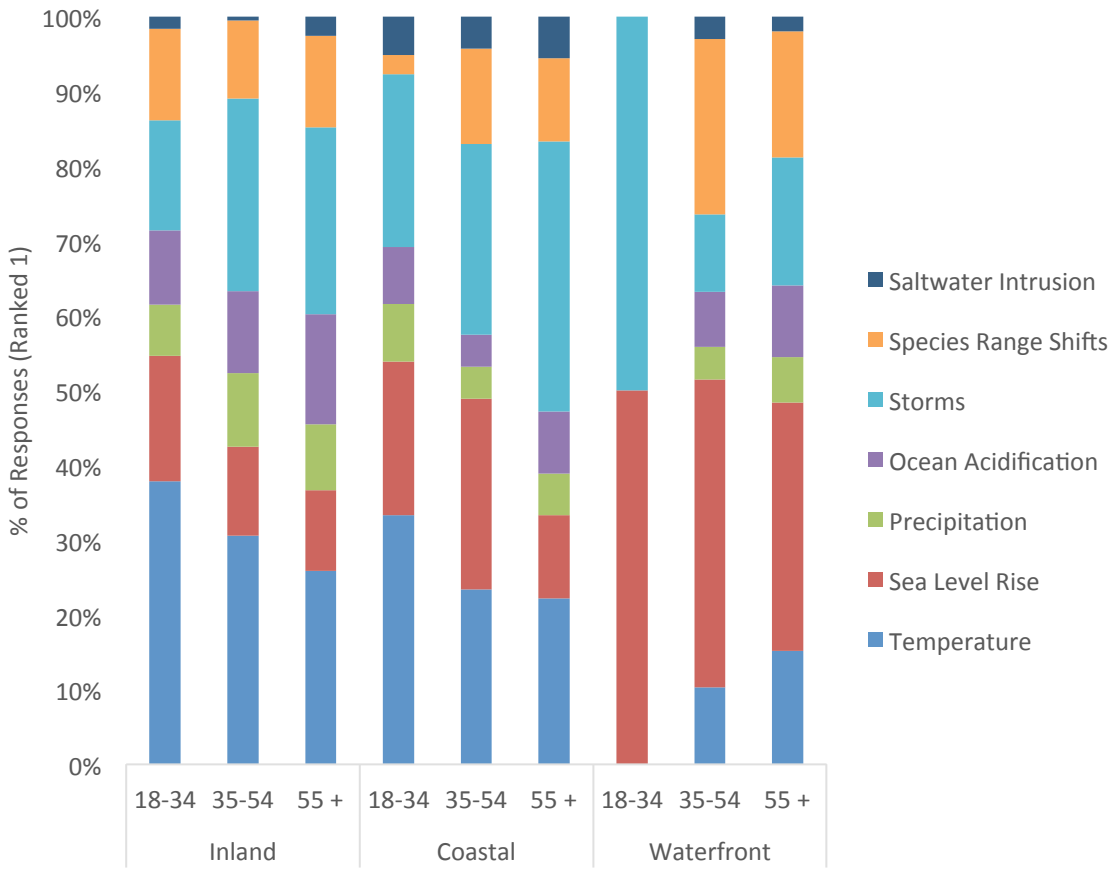

Figure 22. Greatest concern regarding climate change for inland, coastal, and waterfront residents.

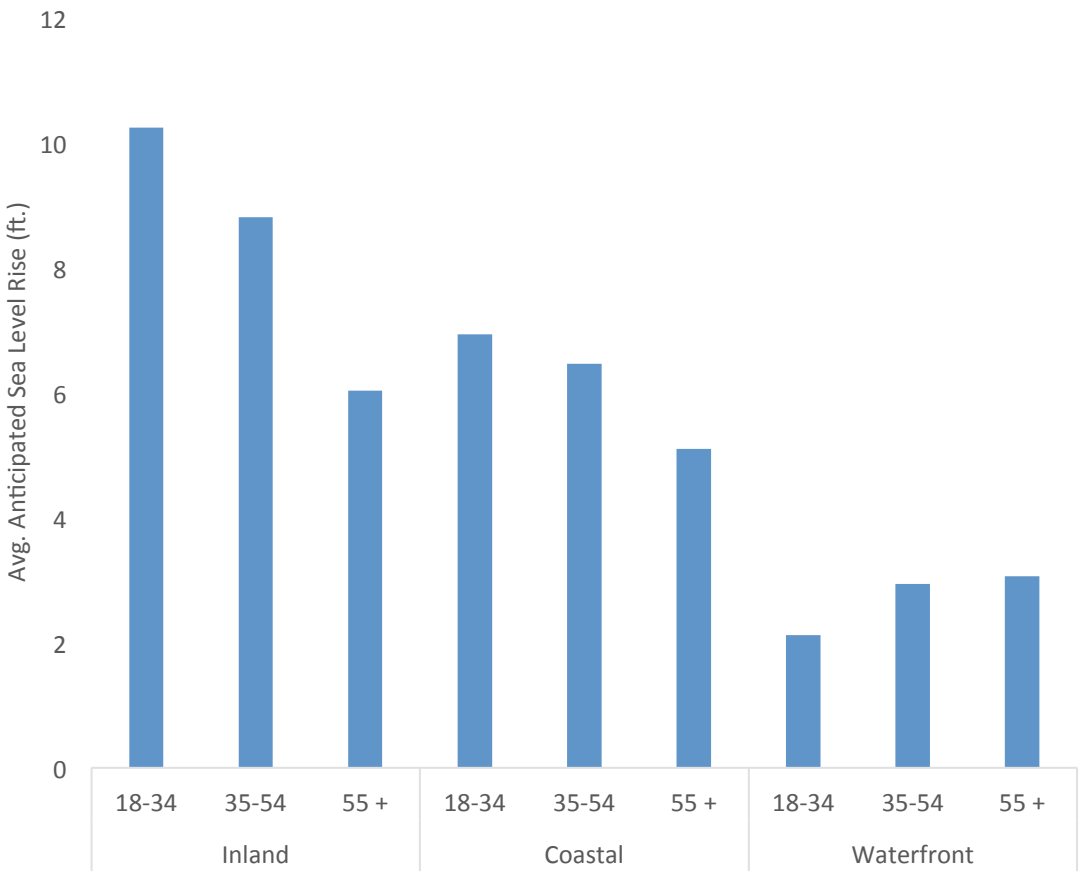

Figure 23. Average anticipated sea level rise by inland, coastal, and waterfront residents.

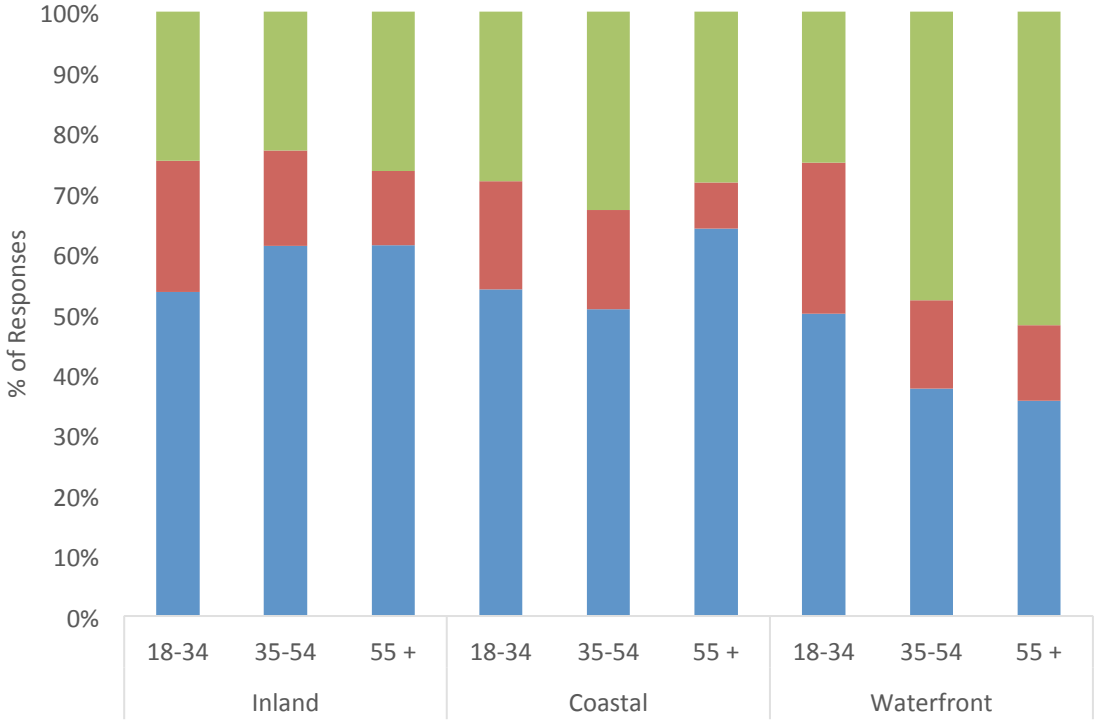

Figure 24. Percentage of inland, coastal, and waterfront respondents support the practice and expansion of leasing of water bottom for shellfish aquaculture in North Carolina. Responses: yes (green), no (red), or blue (Don't know/not sure).

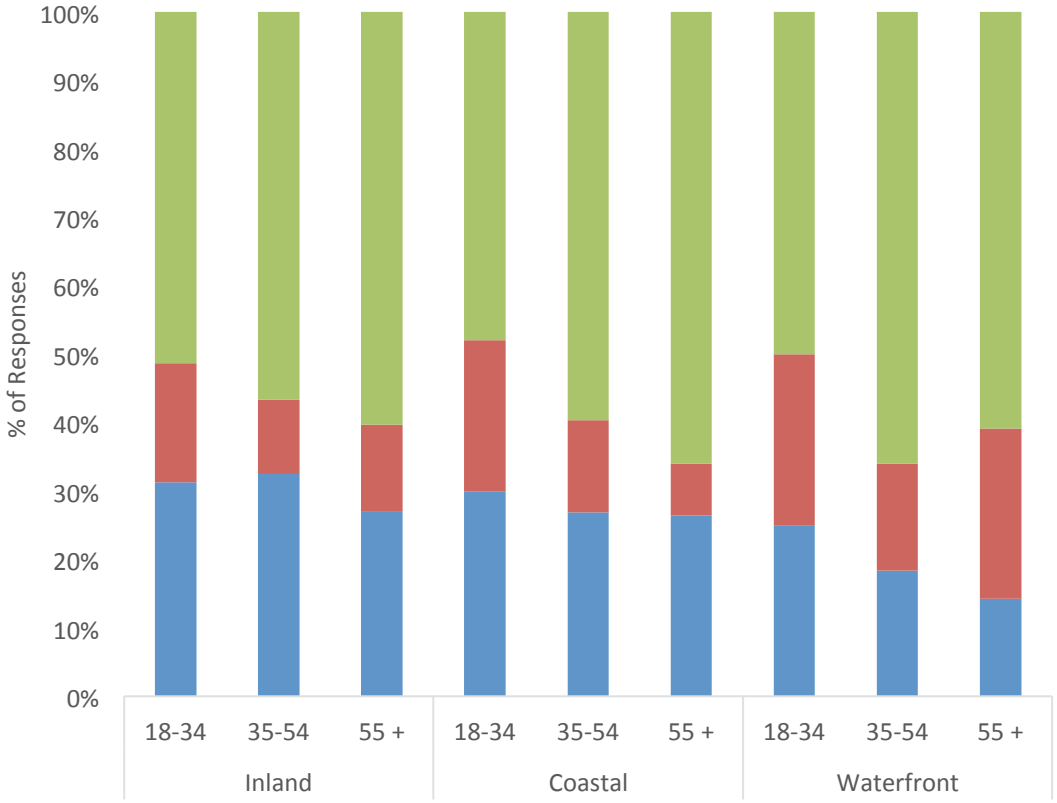

Figure 25. Percentage of inland, coastal, and waterfront respondents support the construction of wind turbines in North Carolina. Responses: yes (green), no (red), or blue (Don't know/not sure).

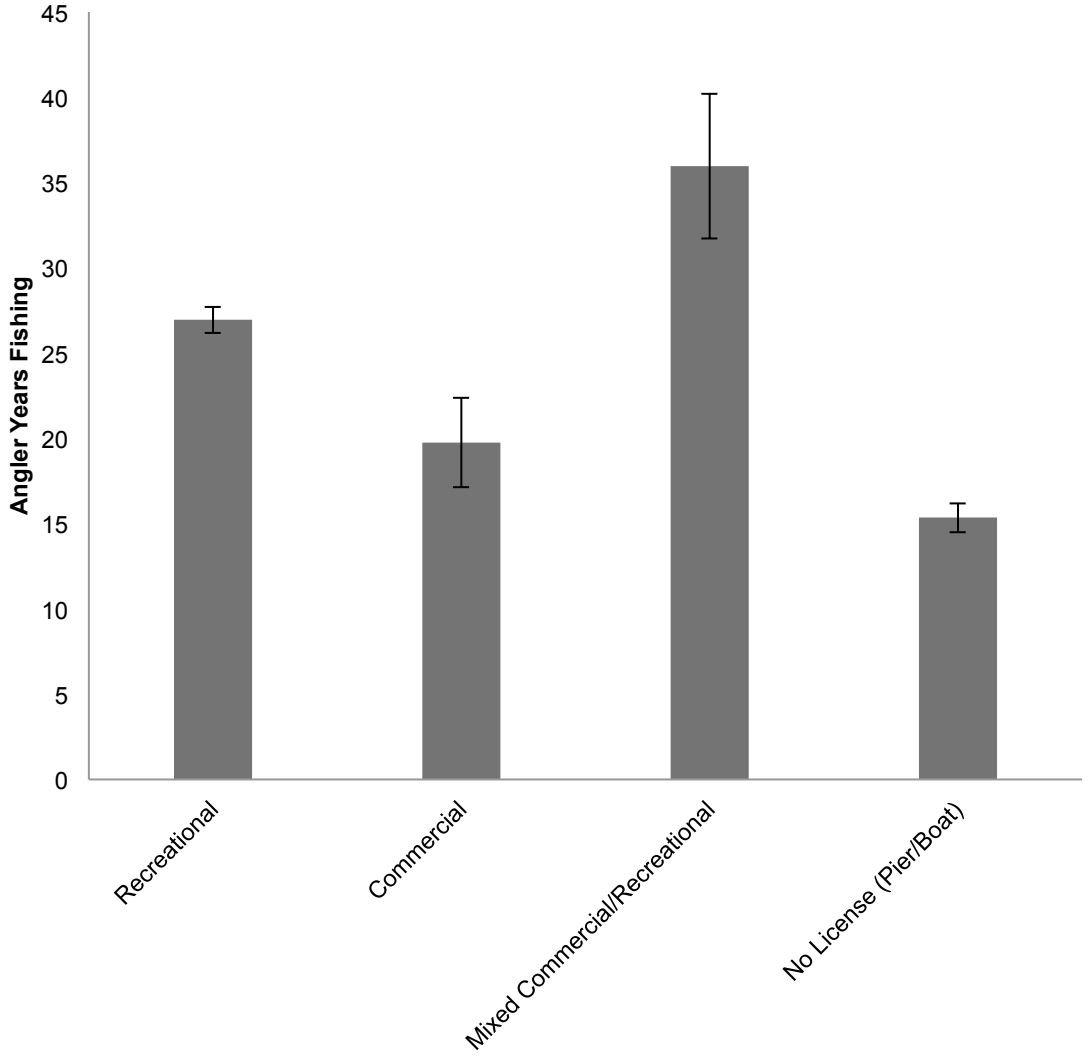

Figure 26. Average number of years spent fishing by license type. Error bars are ± standard error.

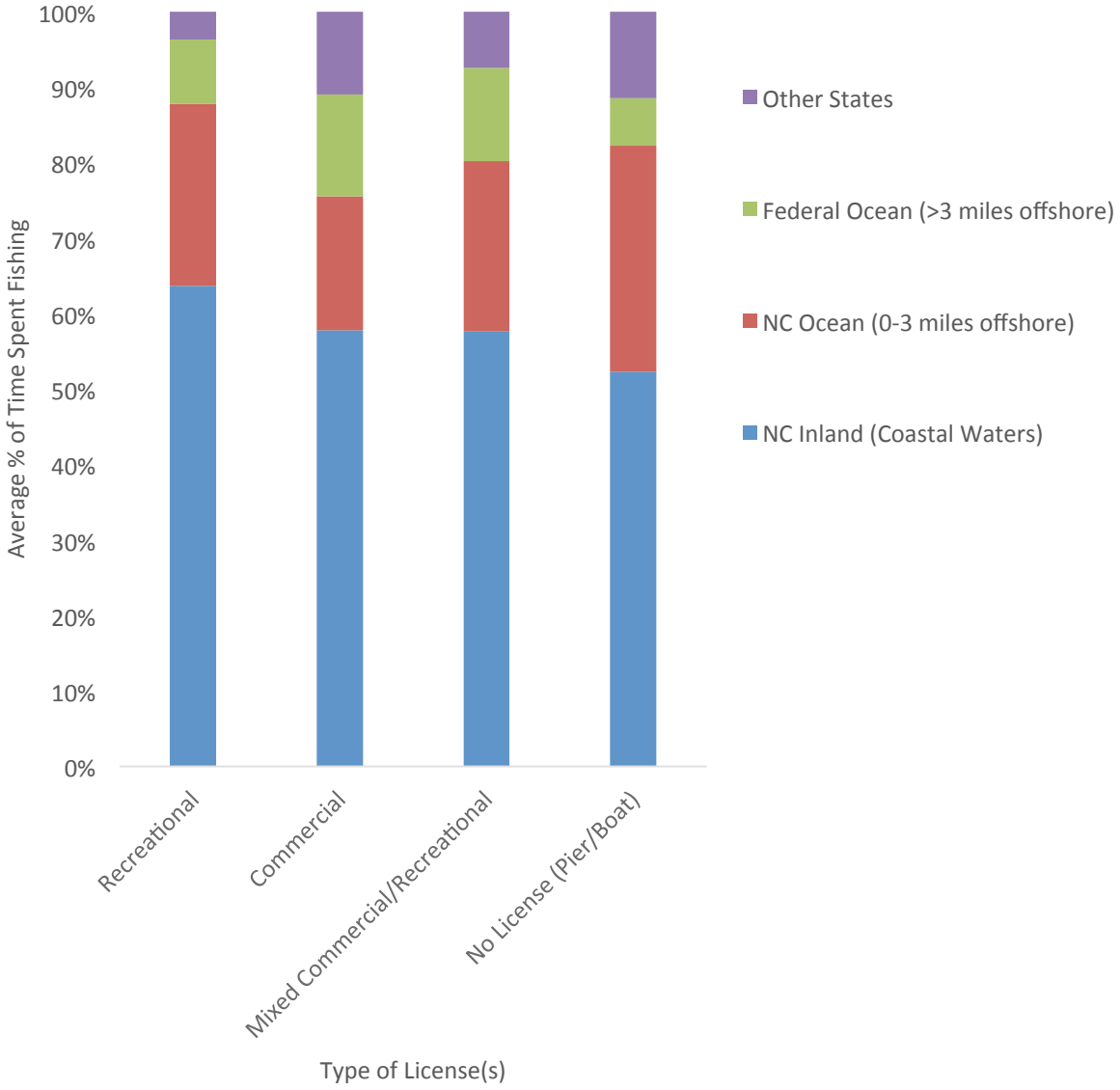

Figure 27. Percent of time spent fishing in Federal, NC Ocean, or NC Inland waters by fishing license type.

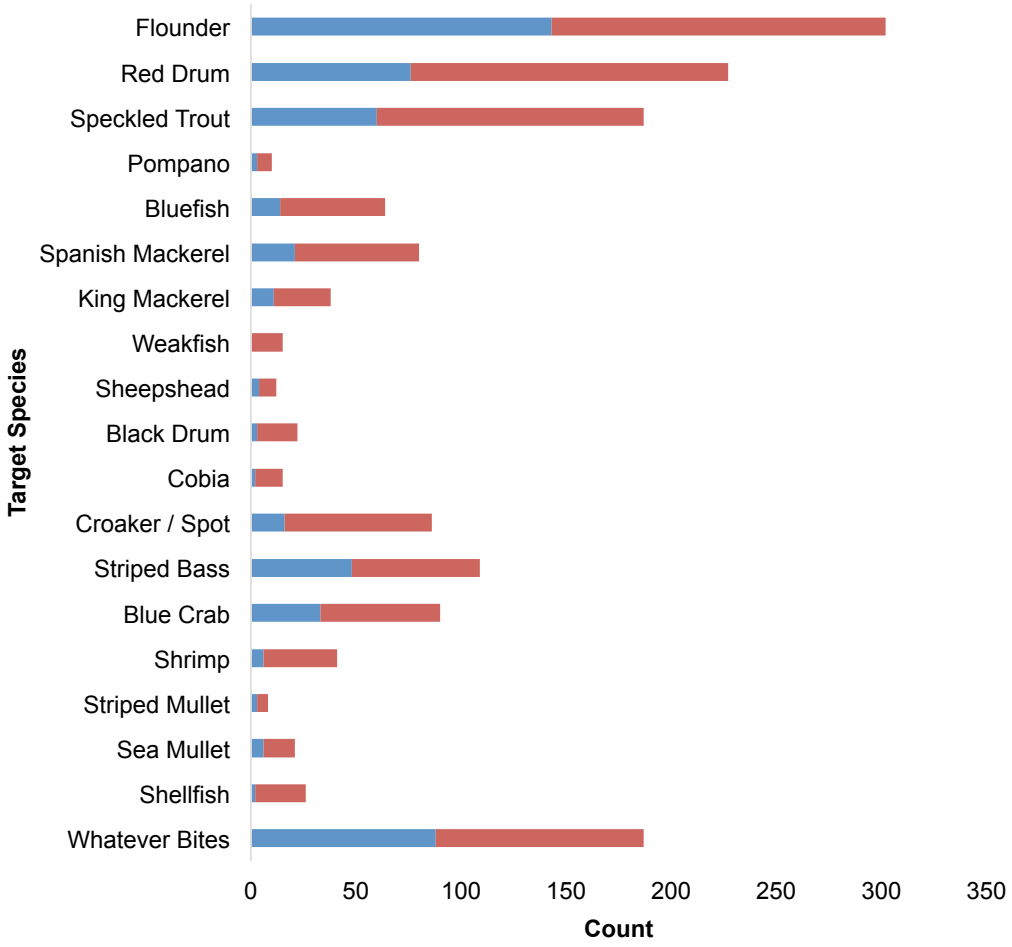

Figure 28. Most frequently targeted species by fishermen with recreational licenses. Species ranked number 1 in blue and species ranked 2 and 3 in red.

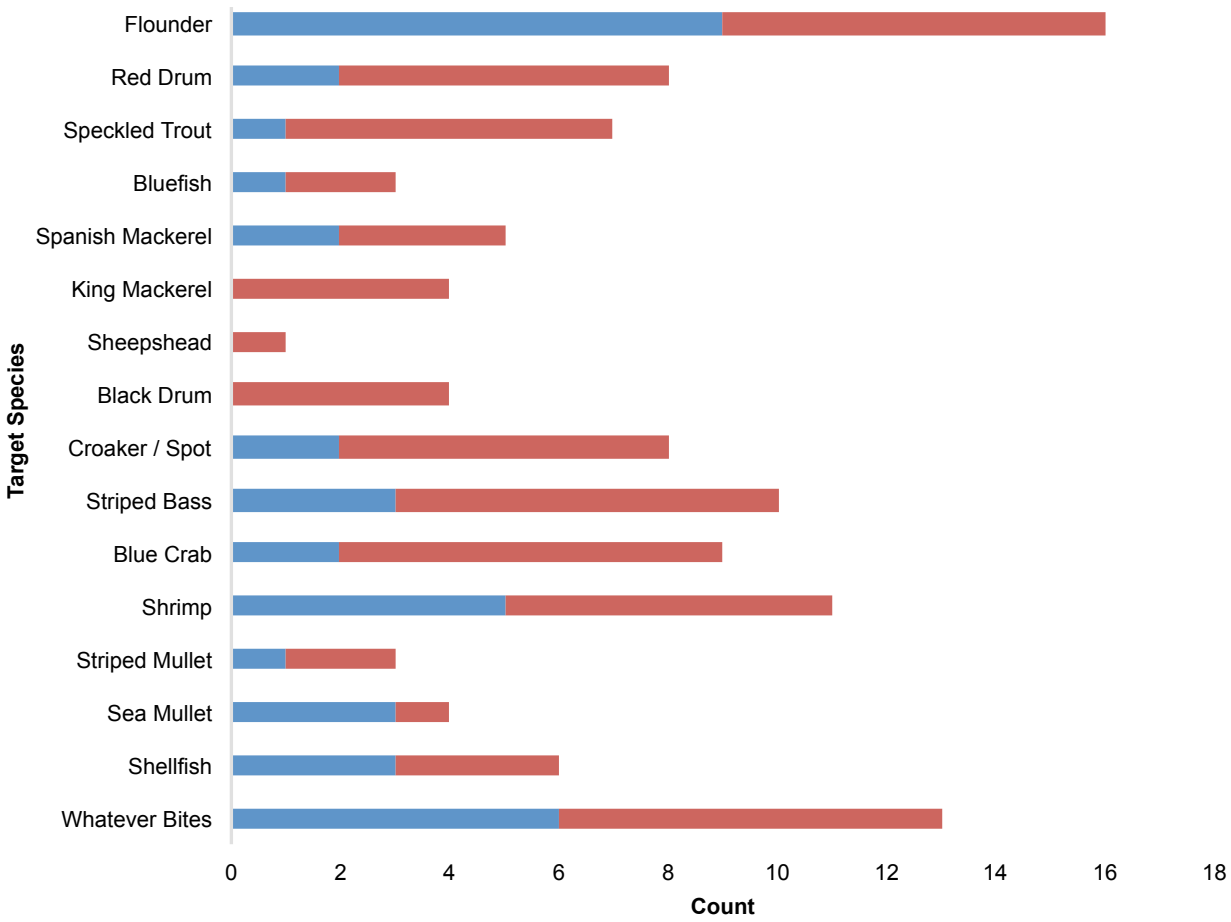

Figure 29. Most frequently targeted species by fishermen with commercial licenses. Species ranked number 1 in blue and species ranked 2 and 3 in red.

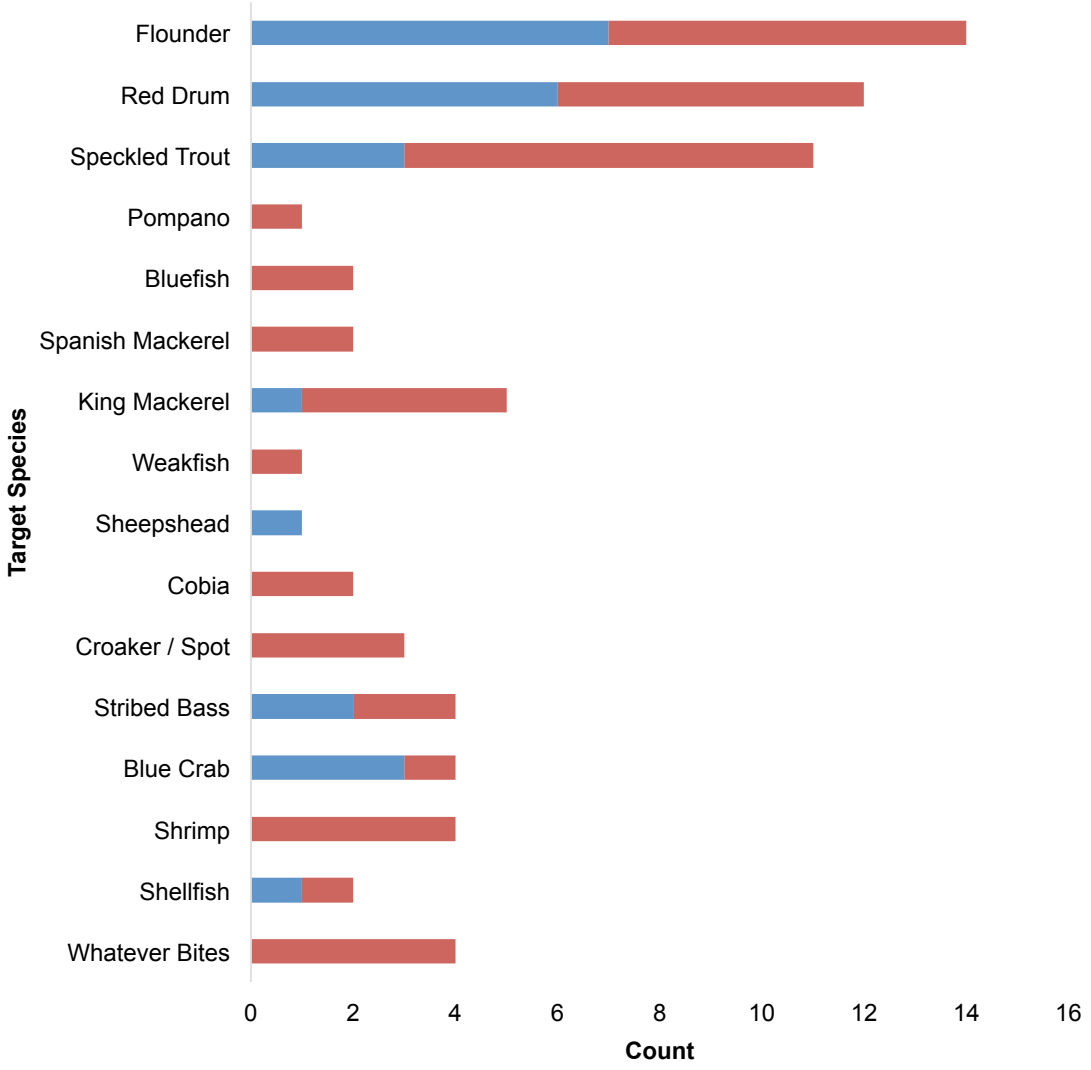

Figure 30. Most frequently targeted species by fishermen that hold both commercial and recreational licenses. Species ranked number 1 in blue and species ranked 2 and 3 in red.

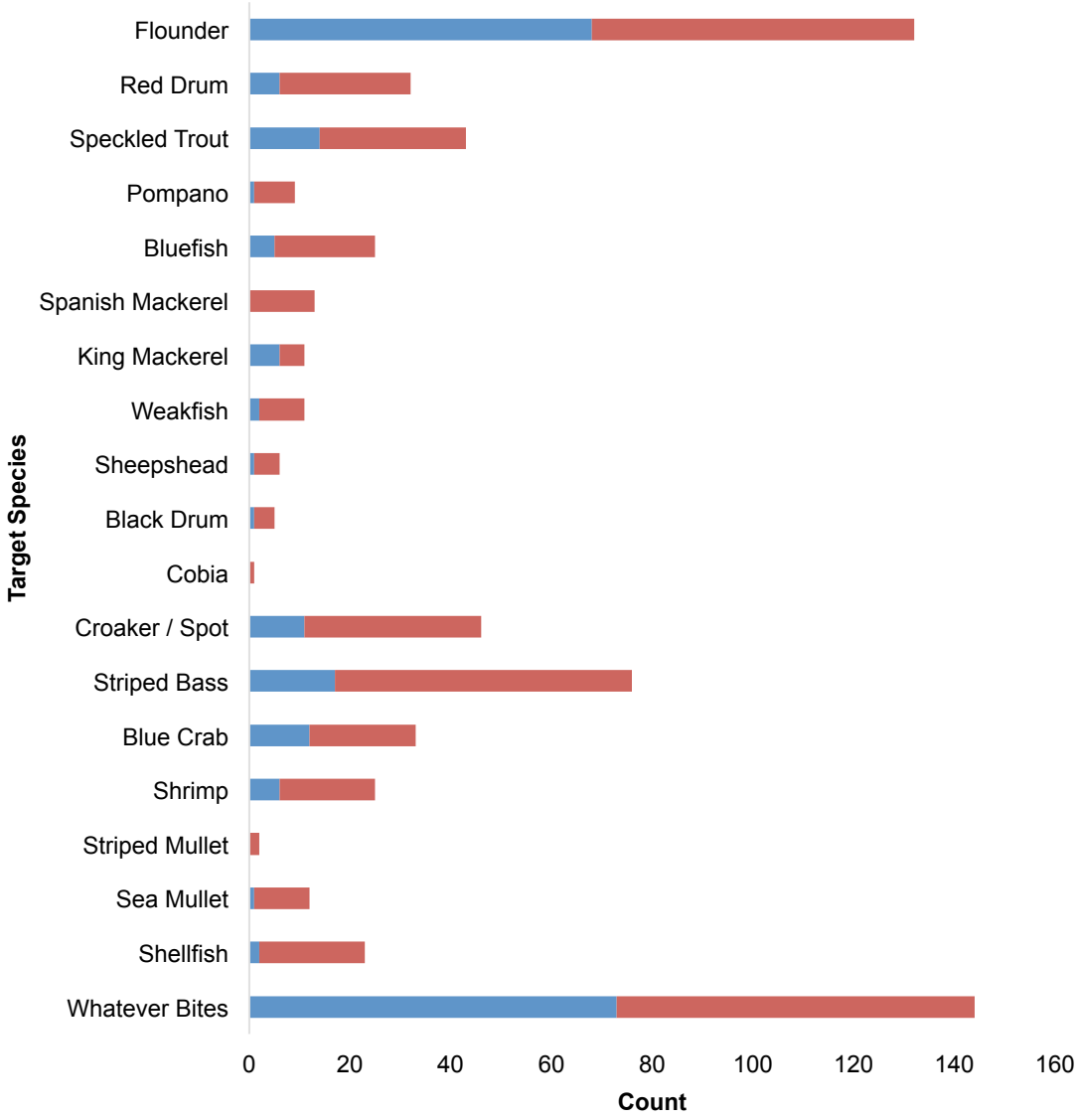

Figure 31. Most frequently targeted species by fishermen with no license (pier or charter boat fishing). Species ranked number 1 in blue and species ranked 2 and 3 in red.

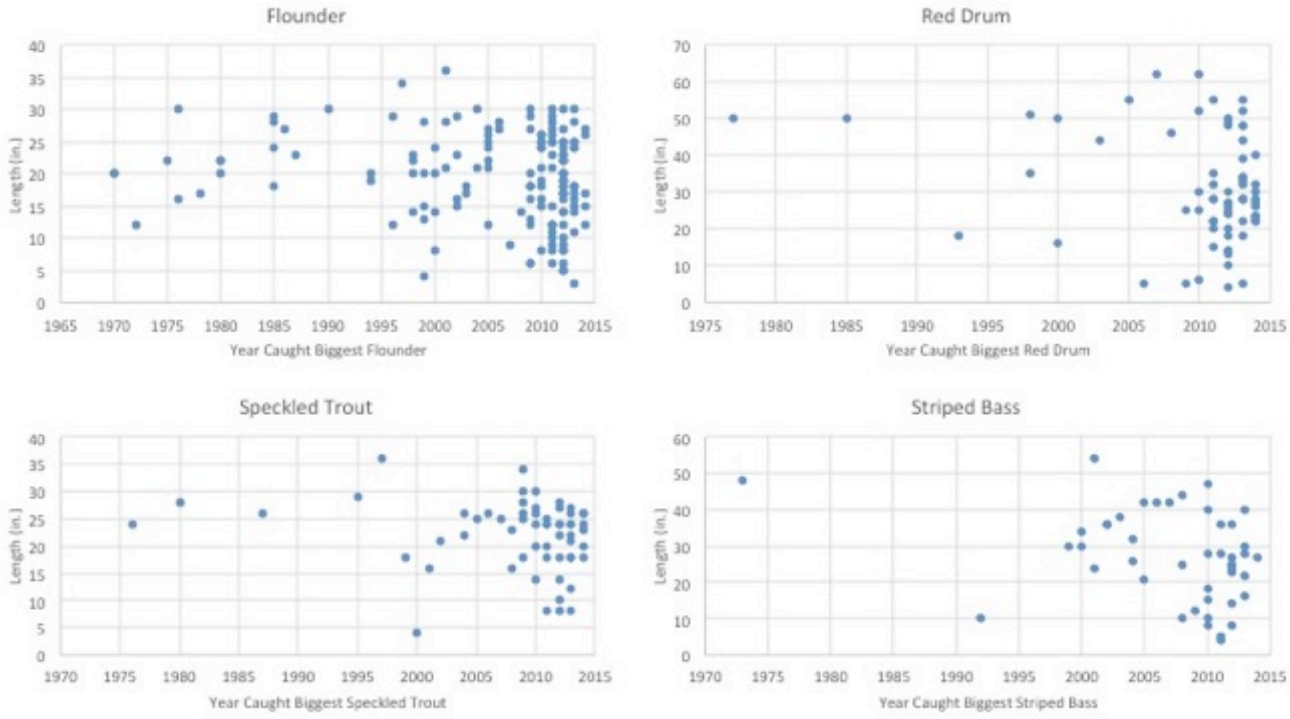

Figure 32. Size (length in inches) of most frequently targeted species by fishermen by year caught.

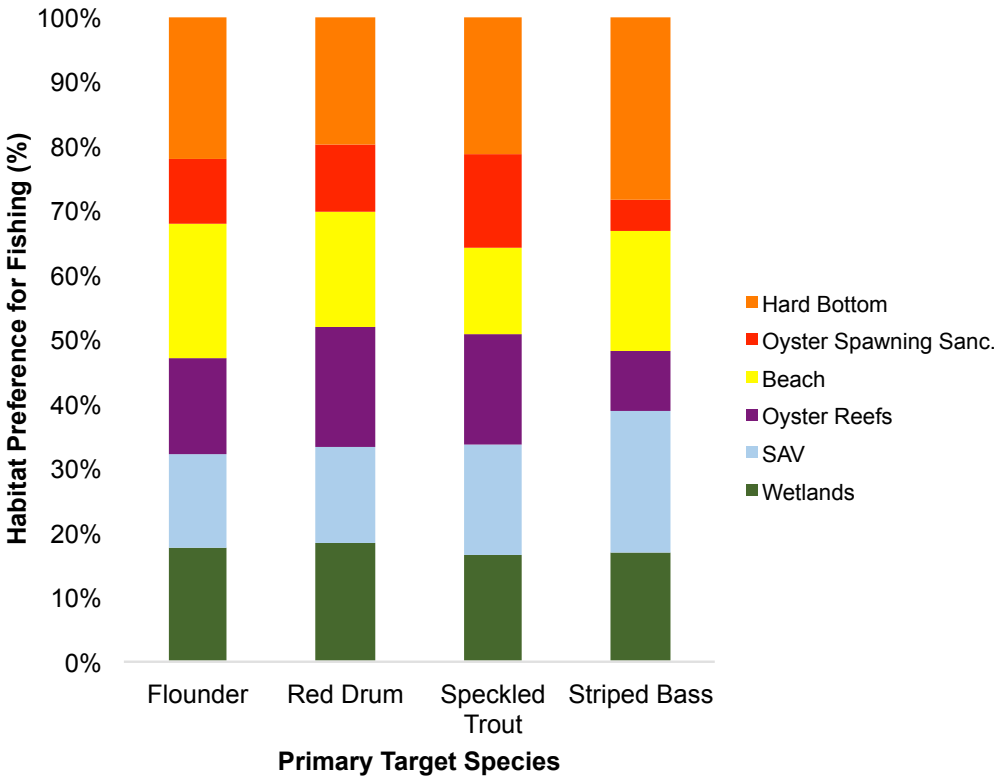

Figure 33. Habitat preference by primary species targeted.

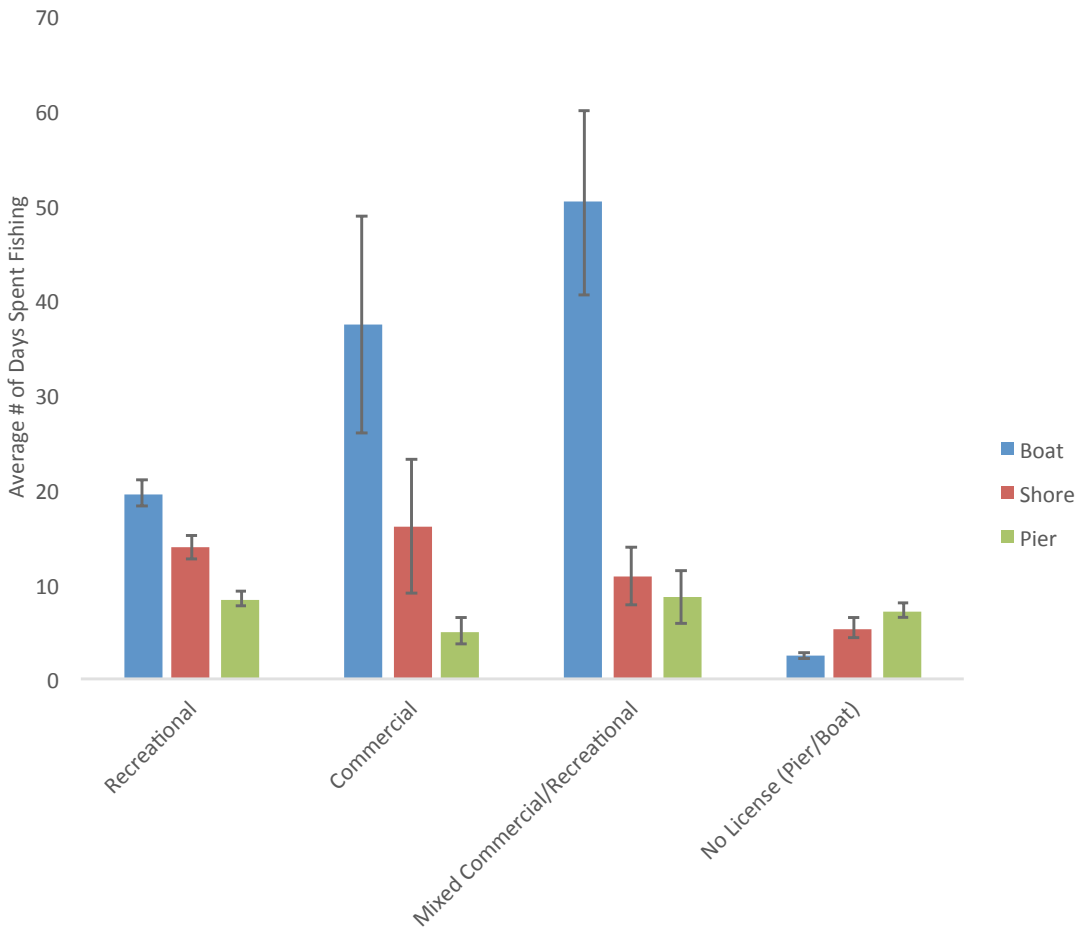

Figure 34. Average number of days per year spent fishing on a boat, on shore, or on a pier by license type. Error bars are ± standard error.

Appendix A. Related publications and manuscripts in review

The published papers and manuscripts in review listed below were partially funded by this CRFL grant and also funded by CRFL grant A10-1485-003 , "Fisheries Habitat Impacts of Marsh Sills (Living Shorelines) as a Shoreline Stabilization/Restoration Alternative to Bulkheads" and CRFL grant

Gittman R.K., Popowich A.M., Bruno J.F., and Peterson C.H. 2014. Marshes with and without sills protect estuarine shorelines from erosion better than bulkheads during a Category 1 hurricane. Ocean and Coastal Management 102: 94-102

Gittman R.K., Fodrie F.J., Popowich A.M., Keller D.A., Bruno J.F., Currin C.A., Peterson C.H., and Piehler M.F. 2015. Engineering away our natural defenses: an analysis of shoreline hardening in the United States. Frontiers in Ecology and the Environment 13(6): 301-307.

Gittman R.K., Peterson C.H., Currin C.A., Fodrie F.J., Piehler M.F., and Bruno J.F. 2016. Living shorelines can enhance the nursery role of threatened coastal habitats. Ecological Applications 26(1): 249-263.

Smith C.S., Gittman R.K., Neylan I.P., Scyphers S.B., Morton, J. P., Fodrie F.J., Grabowski J.H., and Peterson, C.H. 2017. Hurricane damage along natural and hardened estuarine shorelines: Using homeowner experiences to promote nature-based coastal protection. Marine Policy 81: 350-358.

Gittman R.K., and Scyphers, S.B. *In review.* The cost of coastal protection: A comparison of hardened and living shorelines. Shore & Beach: Dedicated Issue Advances in Living Shorelines

Appendix B

Dear North Carolina Waterfront Resident,

Please enter the password listed on the back of the postcard:

_____

Thank you for responding to our survey! Before we go any further, we need to inform you of a few details of our survey as required by our University. Your home was randomly selected from all coastal waterfront homes in North Carolina. Your part in this study will be handled in a confidential manner, as our analyses of survey responses will not be linked to individual properties. There are no direct benefits for your participation; however, you may choose to participate in a participant raffle drawing for a chance at winning small prizes. The survey should be completed by the person of the household over 18 years old that is responsible for most financial and residential decisions. If there is more than one person that fits this description, the person with the most recent birthday should complete the survey. You do not have to be a property-owner or fishermen to take the survey. You can refuse to answer any question, and you can quit the survey at any time. Completion of the survey should take no more than 20 minutes.

If you have any questions about your rights in this research, you may contact the UNC Office of Human Subjects Research Ethics at 919-966-3113. You may call anonymously or collect.

Please feel free to contact the Project Lead, Rachel Gittman at coastalsurveys@unc.edu.

Is it OK if I start the survey?

☐ Yes
☐ No

If No Is Selected, Then Do Not Complete the Survey.

Please note: The survey questions are found on the front and back of each page.

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MARINE SCIENCES

Q1 In which state do you currently reside?

- ☐ North Carolina
- ☐ Alabama
- ☐ Alaska
- ☐ Arizona
- ☐ Arkansas
- ☐ California
- ☐ Colorado
- ☐ Connecticut
- ☐ Delaware
- ☐ District of Columbia
- ☐ Florida
- ☐ Georgia
- ☐ Hawaii
- ☐ Idaho
- ☐ Illinois
- ☐ Indiana
- ☐ Iowa
- ☐ Kansas
- ☐ Kentucky
- ☐ Louisiana
- ☐ Maine
- ☐ Maryland
- ☐ Massachusetts
- ☐ Michigan
- ☐ Minnesota
- ☐ Mississippi
- ☐ Missouri
- ☐ Montana
- ☐ Nebraska
- ☐ Nevada
- ☐ New Hampshire
- ☐ New Jersey
- ☐ New Mexico
- ☐ New York
- ☐ North Dakota
- ☐ Ohio
- ☐ Oklahoma
- ☐ Oregon
- ☐ Pennsylvania
- ☐ Puerto Rico
- ☐ Rhode Island
- ☐ South Carolina
- ☐ South Dakota
- ☐ Tennessee
- ☐ Texas
- ☐ Utah
- ☐ Vermont
- ☐ Virginia
- ☐ Washington
- ☐ West Virginia
- ☐ Wisconsin
- ☐ Wyoming
- ☐ I do not reside in the United States

If Any State Other than North Carolina Is Selected, Then Do Not Complete the Survey.

Q2 How many total years have you lived in North Carolina?

_____ Years

Q3 What is your gender?

- ☐ Male
- ☐ Female

Q4 What year were you born?

_____

Q5 What is the postal ZIP code of your waterfront property?

_____

Q6 How many people lived in your household in 2013 (including dependents)?

_____

Q7 What is your highest level of education? (Please select one)

- ☐ Less than high school
- ☐ High school diploma or GED
- ☐ Some college or 2 year degree
- ☐ Bachelor's degree
- ☐ Master's degree
- ☐ Law or MD
- ☐ Doctorate (PhD)
- ☐ Other (Please list) _____

Q8 What was your total household income in 2013?

- ☐ Less than $25k
- ☐ $25k to $35k
- ☐ $35k to $50k
- ☐ $50k to $75k
- ☐ $75k to $100k
- ☐ $100k to $150k
- ☐ $150k or more

Q9 What is your occupation? If you are retired, please indicate so and list your previous occupation.

_____

Q10 Some people who work in industries such as seafood, tourism, and real estate, feel that their jobs depend on maintaining good environmental conditions in the local waterways, bays, and beaches. How much (%), if any, does your job depend on environmental conditions in the local waterways, bays, and beaches?

_____ Percentage (%)

Q11 What kind of North Carolina saltwater fishing license do you currently hold? (select all that apply)

- ❑ CRFL 10-day license
- ❑ CRFL annual license
- ❑ CRFL lifetime license
- ❑ I don't have a license, but I fish from piers or charter boats
- ❑ Commercial shellfish license
- ❑ Commercial general license
- ❑ I don't fish

If You Do Not Fish, Skip to Question 23.

Q12 How many years have you fished along the North Carolina coast?

_____ Years

Q13 On average, from 2011-2013 how many days per year did you fish along the North Carolina coast from...

_____ a boat/kayak
_____ shore
_____ a pier

Q14 What type of boat do you use to fish? (check all that apply)

- ❑ Personally-owned motor-operated boat
- ❑ Chartered boat
- ❑ Kayak/Canoe
- ❑ Other _____

Q15 What percentage of your fishing is within the following?

_____ NC inland coastal waters (%)
_____ NC ocean waters (0-3 miles from shore)
_____ Federal ocean waters off of NC (3 or more miles from shore)
_____ Waters in other states

Q16 Which species do you most frequently target? (Place a 1 next your most targeted, a 2 next to 2nd most targeted and 3 next to your 3rd most targeted.)

_____ Flounder

_____ Red Drum (Redfish, Puppy Drum)

_____ Spotted Seatrout (Speckled Trout)

_____ Florida Pompano

_____ Bluefish

_____ Spanish Mackerel

_____ King Mackerel

_____ Weakfish (Gray Trout)

_____ Sheepshead

_____ Black Drum

_____ Cobia

_____ Spot / Croaker

_____ Striped Bass

_____ Blue Crabs

_____ Shrimp

_____ Striped Mullet

_____ Sea Mullet (Kingfish, Ground Mullet, Virginia Mullet, Whiting)

_____ Shellfish (clams, oysters)

_____ Whatever bites the hook

Q17 If known, what length was the largest fish that you have ever caught of the species your most frequently target (from Q16)?

Species: _____ Length: _____ inches

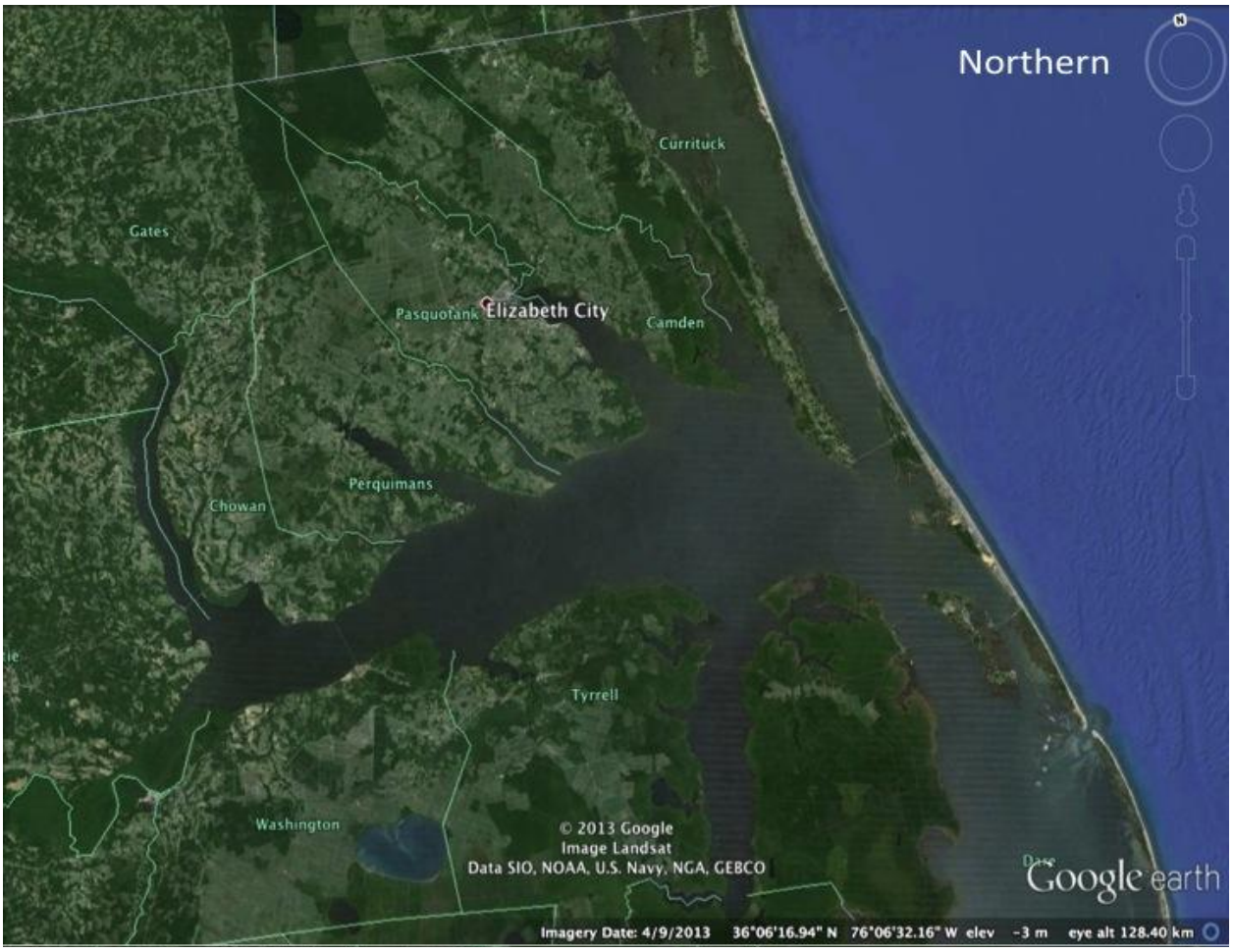
Q18 If known, what weight was the largest fish of this species that you have ever caught?

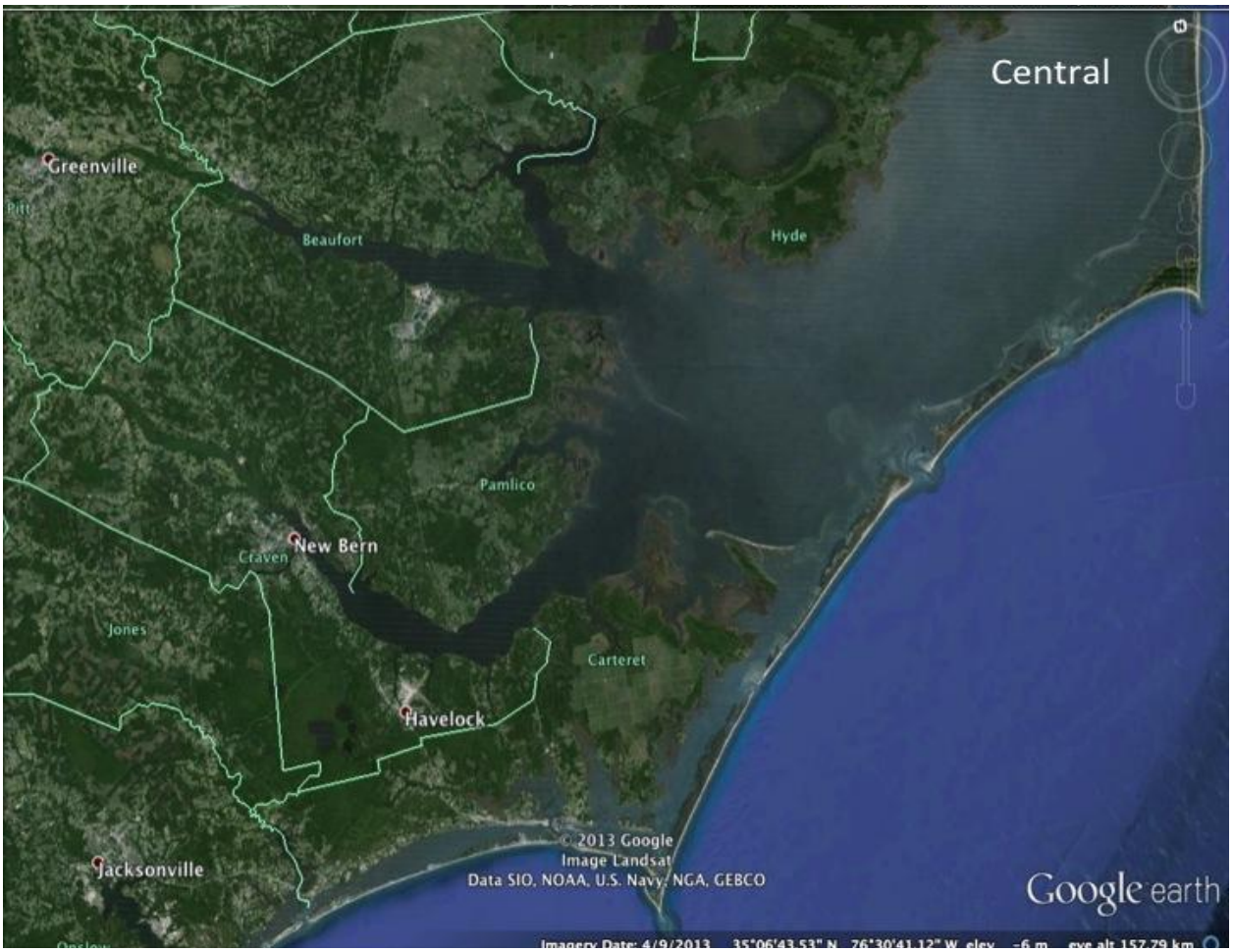
Species: _____ Weight: _____ lbs

Q19 What year did you catch the largest fish of this species?

Species: _____ Year: _____

Q20 Please draw an "X" on the locations in North Carolina where you most frequently fish. (Select up to 5 locations on the three regions of NC below).

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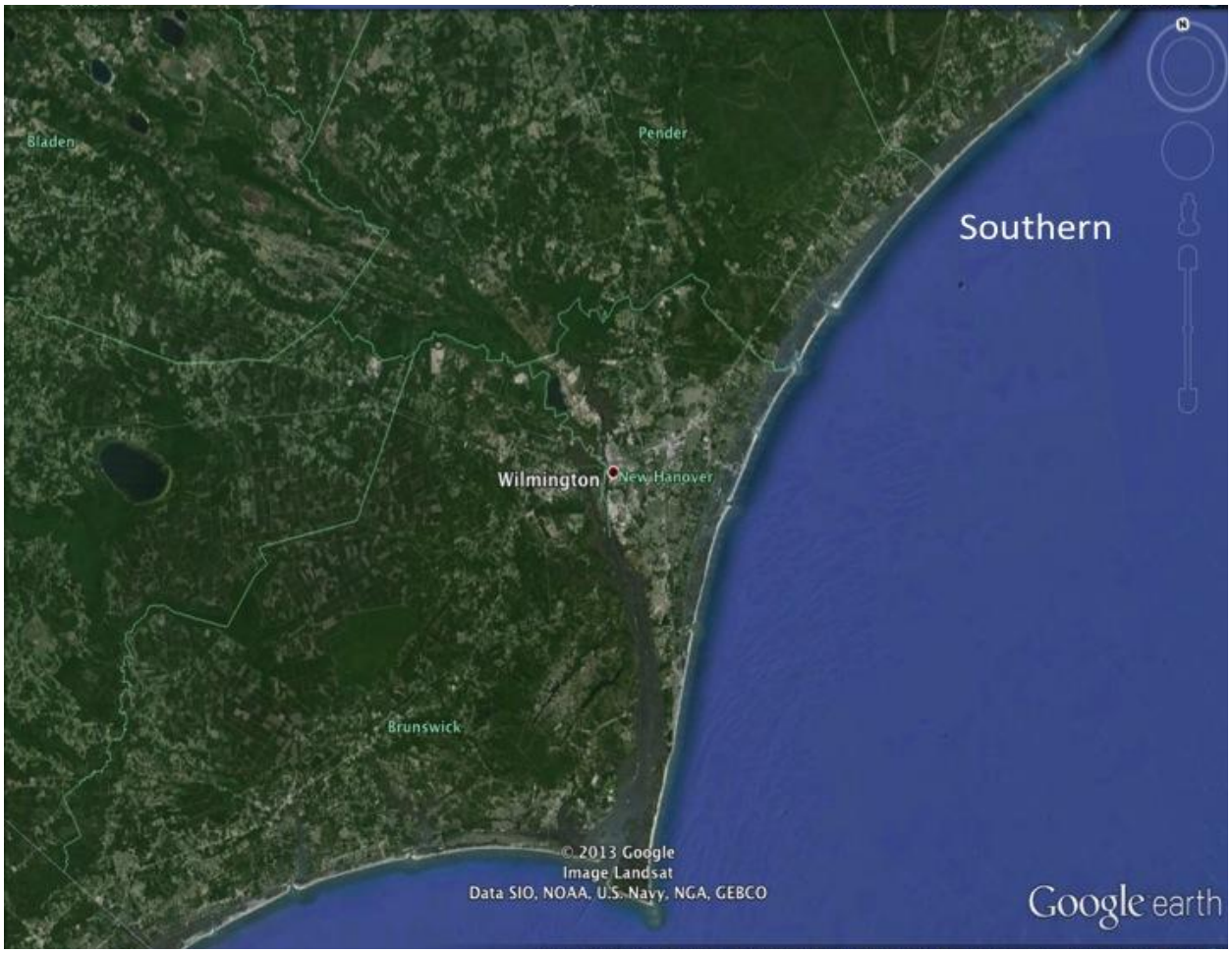


Q21 For the species you target most (based on your selection above), in which of the following habitats are you most likely to fish? Check all that apply.

- ☐ Wetlands
- ☐ Submerged aquatic vegetation
- ☐ Oyster reefs
- ☐ Beach
- ☐ Oyster spawning sanctuaries
- ☐ Hard bottom
- ☐ Other

Q22 In your lifetime, when were fisheries in the North Carolina coastal regions in the best condition?

_____ Year

Q23 On a scale from 1 to 10, with 10 being very important and 1 being not important, please indicate how important each estuarine habitat is to FISHERIES in North Carolina?

_____ Wetlands (e.g., salt marsh, freshwater marsh, cypress)
_____ Submerged aquatic vegetation (e.g., seagrass)
_____ Oyster Reefs
_____ Beach
_____ Hard Bottom (e.g., natural submerged rock)

Q24 On a scale from 1 to 10, with 10 being very important and 1 being not important, please indicate how important each estuarine habitat is to TOURISM in North Carolina?

_____ Wetlands (e.g., salt marsh, freshwater marsh, cypress)
_____ Submerged aquatic vegetation (e.g., seagrass)
_____ Oyster Reefs
_____ Beach
_____ Hard Bottom (e.g., natural submerged rock)

Q25 On a scale from 1 to 10, with 10 being very important and 1 being not important, please indicate how important each estuarine habitat is to WATER QUALITY in North Carolina?

_____ Wetlands (e.g., salt marsh, freshwater marsh, cypress)
_____ Submerged aquatic vegetation (e.g., seagrass)
_____ Oyster Reefs
_____ Beach
_____ Hard Bottom (e.g., natural submerged rock)

Q26 On a scale from 1 to 10, with 10 being very important and 1 being not important, please indicate how important each estuarine habitat is to STORM PROTECTION in North Carolina?

_____ Wetlands (e.g., salt marsh, freshwater marsh, cypress)
_____ Submerged aquatic vegetation (e.g., seagrass)
_____ Oyster Reefs
_____ Beach
_____ Hard Bottom (e.g., natural submerged rock)

Q27 What do you see as the top THREE ENVIRONMENTAL problems facing coastal North Carolina?

_____ Recreational Fishing
_____ Commercial Fishing
_____ Residential Development
_____ Industrial Pollution
_____ Agriculture
_____ Tourism
_____ Beach Renourishment
_____ Sea Level Rise
_____ Stronger or More Frequent Storms
_____ Warmer Temperature
_____ Poor Water Quality
_____ Dredging
_____ Other

Q28 Do you think that the global climate is warming?

☐ Yes
☐ No
☐ Don't know/ Not sure

If You Answered "No" to Q28, Skip to Q31.

Q29 What do you think is causing the earth to warm (check all that apply)?

❑ Natural (non-human) processes
❑ Carbon dioxide and other greenhouse gas emissions from human activities (e.g., burning fossil fuels)
❑ Other (please specify) _____

Q30 What aspects of climate change are you most concerned about in your lifetime?

_____ Warmer temperatures
_____ Sea level rise
_____ Changes in precipitation
_____ Ocean acidification
_____ Increased storminess
_____ Changes in marine organisms populations and distributions (e.g., shifts in range, migration patterns, etc.)
_____ Saltwater intrusion
_____ Other (please specify)

Q31 How much do you think sea level will rise in the next century?

_____ Feet

Q32 Do you support the practice and expansion of leasing of water bottom for shellfish aquaculture in North Carolina?

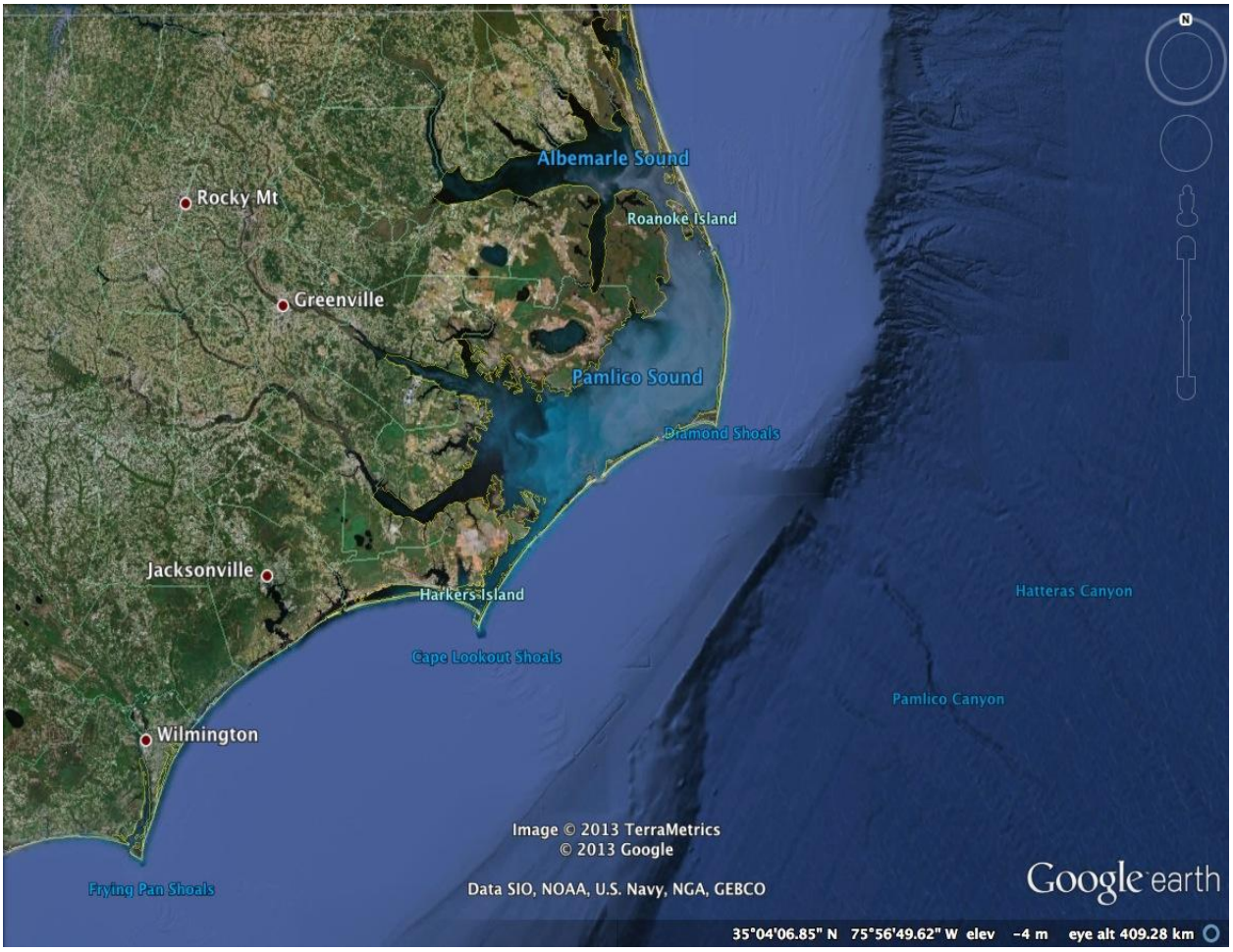
- ☐ Yes
- ☐ No
- ☐ Don't know/ Not sure

Q33 Do you support the construction of wind turbines off the coast of North Carolina?

- ☐ Yes
- ☐ No
- ☐ Don't know/ Not sure

If You Answered “No” to Q33, Skip to Q35.

Q34 Please draw and “X” on the location you think is best suited (in your opinion) to the construction of wind turbines (select up to 3 locations).



Q35 What is your primary concern with wind turbine construction off the coast of North Carolina?

- ☐ Economic feasibility (cost)
- ☐ Aesthetics (ability to see them offshore)
- ☐ Could harm migratory birds or marine mammals
- ☐ Could affect fishing
- ☐ Could affect shipping routes
- ☐ Other _____

Q36 How long have you lived at your current location?

_____ Years

Q37 Is this your primary residence?

☐ Yes
☐ No

Q38 Do you Own, Lease, or Rent this property?

☐ Own
☐ Rent/Lease
☐ Other _____

If Own Is Not Selected, Then Skip To End of Survey

Q39 What is the approximate length of your shoreline? (Feet)

_____

Q40 Please indicate the number of times your shoreline has been damaged by the following since you have lived on your property:

_____ Hurricane/Tropical Storm
_____ Northeaster
_____ Other storm
_____ Human activities
_____ Other: please describe the event or activity that damaged your shoreline:

_____

Q41 How much has each type of event or activity cost ($) you in terms of cumulative (total) damage to your property since you have owned it?

_____ Hurricane/Tropical Storm
_____ Northeaster
_____ Other storm
_____ Human activities
_____ Other

Q42 Is your shoreline currently eroding?

☐ Yes
☐ No
☐ Don't know/ Not sure

Q43 To your knowledge, has your shoreline eroded in the past (during the time you have owned the property)?

☐ Yes
☐ No
☐ Don't know/ Not sure

If You Answered “No” to both Q42 and Q43, Then Skip to Q47.

Q44 In your opinion, what are primary causes of current or past erosion of your shoreline?

_____ Major storms (e.g., hurricanes, northeasters)
_____ Boat wakes
_____ Daily, natural wave energy
_____ Human activities (please specify)
_____ Other (please specify)

Q45 What caused the erosion of your shoreline to stop?

☐ Installation of a shoreline stabilization structure (e.g., bulkhead. riprap revetment, breakwater)
☐ Planting of marsh vegetation
☐ The erosion stopped naturally
☐ Other (please specify) _____

Q46 How many feet has your shoreline eroded since you have lived at this property?

_____ Feet

Q47 What is the current state of your shoreline? (Check all that apply)

- ❑ Bulkhead or seawall (vertical wall placed at or above the high tide line)
- ❑ Rip-rap revetment (sloped rock structure placed parallel to shore at or above the high tide line)
- ❑ Groin (rock or concrete structure placed perpendicular to shore)
- ❑ Breakwater or sill (shore-parallel structure composed of rock, concrete, oyster or other material located below the high tide line, seaward of wetland vegetation)
- ❑ Natural wetlands (specify what kind, e.g., salt marsh, freshwater marsh) _____
- ❑ Planted vegetation (specify what kind, e.g., salt marsh, freshwater marsh) _____
- ❑ Beach
- ❑ Wooded (specify what kind, e.g., cypress, maritime, pine) _____
- ❑ Marina
- ❑ Dock
- ❑ Other _____

Q48 How long would you say the shoreline has been in its current state?

_____ Years

If You Have a Natural Shoreline with No Stabilization Structures (Specified in Q47), Skip to Q54.

Q49 Were you the property-owner when this stabilization method was installed?

- ☐ Yes
- ☐ No

If You Answered “No” to Q49, Skip to Q51.

Q50 How much did the initial installation of this stabilization method cost?

$_____

Q51 How long do you expect the current shoreline protection scheme that you have to be functional or able to be maintained?

_____ Years

Q52 On average, how much would you say you spend per year to maintain your shoreline?

_____ Dollars
_____ Days of your time

Q53 How would you say this shoreline stabilization approach has been for your property?

- ☐ Very Beneficial
- ☐ Beneficial
- ☐ Neutral
- ☐ Harmful
- ☐ Very Harmful

Q54 What is the state of your neighbors' shorelines? (Check all that apply)

- ❑ Bulkhead or seawall (vertical wall placed at or above the high tide line)
- ❑ Rip-rap revetment (sloped rock structure placed parallel to shore at or above the high tide line)
- ❑ Groin (rock or concrete structure placed perpendicular to shore)
- ❑ Breakwater or sill (shore-parallel structure composed of rock, concrete, oyster or other material located below the high tide line, seaward of wetland vegetation)
- ❑ Natural wetlands (specify what kind, e.g., salt marsh, freshwater marsh) _____
- ❑ Planted vegetation (specify what kind, e.g., salt marsh, freshwater marsh) _____
- ❑ Beach
- ❑ Wooded (specify what kind, e.g., cypress, maritime, pine) _____
- ❑ Marina
- ❑ Dock
- ❑ Other _____

Q55 How would you say that the state of your neighbors' shorelines has affected your property?

- ☐ Very Beneficial
- ☐ Beneficial
- ☐ Neutral
- ☐ Harmful
- ☐ Very Harmful

Q56 How would you say that the state of your shoreline has affected your neighbor's property?

- ☐ Very Beneficial
- ☐ Beneficial
- ☐ Neutral
- ☐ Harmful
- ☐ Very Harmful

Q57 What influence did the condition of your neighbors' shoreline have on your shoreline protection decisions?

- ☐ A great deal
- ☐ A fair amount
- ☐ Only a little
- ☐ Not at all

Q58 Please rank the top 3 types of shoreline stabilization in terms of preventing erosion.

_____ Bulkhead
_____ Riprap revetment
_____ Groin
_____ Sill or breakwater
_____ Sill or breakwater with planted vegetation
_____ Planted vegetation

Q59 Please rank the 3 most durable methods of shoreline stabilization.

_____ Bulkhead
_____ Riprap revetment
_____ Groin
_____ Sill or breakwater
_____ Sill or breakwater with planted vegetation
_____ Planted vegetation

Q60 Please rank the 3 most expensive methods of shoreline stabilization.

_____ Bulkhead
_____ Riprap revetment
_____ Groin
_____ Sill or breakwater
_____ Sill or breakwater with planted vegetation
_____ Planted vegetation

Q61 Please rank the 3 methods of shoreline stabilization that require the most maintenance.

_____ Bulkhead
_____ Riprap revetment
_____ Groin
_____ Sill or breakwater
_____ Sill or breakwater with planted vegetation
_____ Planted vegetation

Q62 Please rank the 3 most environmentally preferable methods of shoreline stabilization.

_____ Bulkhead
_____ Riprap revetment
_____ Groin
_____ Sill or breakwater
_____ Sill or breakwater with planted vegetation
_____ Planted vegetation

Q63 Please rank the 3 most visually appealing methods of shoreline stabilization.

_____ Bulkhead
_____ Riprap revetment
_____ Groin
_____ Sill or breakwater
_____ Sill or breakwater with planted vegetation
_____ Planted vegetation

Q64 Please rank the three most important factors that influence (or will influence) your chosen method to protect or stabilize your shoreline.

_____ Cost
_____ Durability
_____ Effectiveness
_____ Aesthetics
_____ Ecological Impact
_____ Accessibility to Water
_____ Permitting Approval Process
_____ Other

Q65 If you were forced to protect your unaltered but eroding shoreline today, which method would you choose? (Check all that apply)

_____ Bulkhead
_____ Riprap revetment
_____ Groin
_____ Sill or breakwater
_____ Sill or breakwater with planted vegetation
_____ Planted vegetation

Q66 Which of the following habitats are found in the water below (within 50 feet) or on your property? (Select all that apply)

- ❑ Salt-marsh
- ❑ Seagrass or Submerged aquatic vegetation
- ❑ Oysters or Oyster reef
- ❑ Mudflat
- ❑ Sandy Beach
- ❑ Cypress trees/maritime forest
- ❑ Swamp/freshwater marsh
- ❑ Other _____

Q67 Based on your observations and experience, how much have each of the habitats adjacent to your property decreased (negative values) or increased (positive values) in size or condition (%) in recent years?

Salt-marsh : _____ (%)
Seagrass or Submerged aquatic vegetation : _____ (%)
Oysters or Oyster reef : _____ (%)
Mudflat : _____ (%)
Sandy Beach : _____ (%)
Cypress trees/maritime forest : _____ (%)
Swamp/freshwater marsh : _____ (%)
Other _____: _____ (%)

Q68 From your experience and observations, what has caused the decline or increase in habitat condition and when did it occur?

Q69 For improving the condition of the habitats, which approach would be most beneficial for recovery?

- ☐ Nothing or allow natural recovery
- ☐ Restore the habitat to previous condition
- ☐ Build sill or breakwater to reduce wave energy
- ☐ Remove neighboring stabilization structures
- ☐ Designate no wake zones
- ☐ Other _____

Q70 How do you think sea level rise will affect your coastal property?

Q71 How do you plan to adapt to sea level rise? (check all that apply)

- ❑ Sell your coastal property and move inland
- ❑ Harden your shoreline
- ❑ Raise your house above its current elevation
- ❑ Move your house inland
- ❑ I don't plan on making any changes to my property
- ❑ Other _____

Q72 At what annual rate increase (%) in homeowners insurance (including flood and all other insurances) from your current rate would you consider moving to a non-waterfront property?

_____ Insurance rate increase (%)

Q73 Coastal property owners in NC may choose to harden their shoreline with bulkheads (vertical walls) or riprap (rock) revetments to protect their property, gain access to the water, and for aesthetics (State general permit cost = $400). Approximately 5-10% of NC shorelines are currently hardened.
However, bulkheads/riprap may cause erosion of salt marshes located seaward of hardened shorelines. Two potential options to prevent or mitigate salt marsh losses related to shoreline hardening are presented as Options A and B. You may disagree with either/both options, and prefer that no changes occur regarding shoreline permitting (The No Action Option). Please select your preferred option.

☐ **No Action Option**: **No changes are made.**
Resulting Ecological Condition
If neither option is chosen, shoreline hardening will continue along the NC coast at its current rate. Salt marshes may continue to be lost as a result of shoreline hardening.
Total cost to your household would be $0 in new 2014 state taxes.

☐ **Option A: Reduction in Shoreline Hardening**
Coastal property owners are required to pay a higher permit fee (50% increase in the current fee) for installation of a hard shoreline structure (bulkhead, riprap, etc.). The permit fee is reduced by 25% for property owners using marsh planting, oyster shell placement, or other natural methods for erosion protection.
Resulting Ecological Condition
Rates of shoreline hardening are reduced. Rates of salt marsh loss are reduced. Restoration of salt marsh habitat increases.
Total cost to your household would be $0 in new 2014 state taxes because the increased fees for shoreline hardening would cover the cost of waiving permit fees for marsh planting or other natural methods.

☐ **Option B: Prohibition of Shoreline Hardening**
The use of bulkheads and riprap revetments is prohibited along shorelines bordering salt marsh. Shoreline hardening is permitted at the current fee along shorelines without salt marsh. Along shorelines without salt marsh, the permit fee is waived completely for property owners using natural shoreline stabilization methods such as marsh planting and oyster reef construction.
Resulting Ecological Condition
Loss of existing salt marsh to new shoreline hardening is prevented. Restoration of salt marsh habitat increases.
Total cost to your household would be $5 in new 2014 state taxes to cover the cost of waiving permit fees for marsh planting or other natural methods.

Q73 Coastal property owners in NC may choose to harden their shoreline with bulkheads (vertical walls) or riprap (rock) revetments to protect their property, gain access to the water, and for aesthetics (State general permit cost = $400). Approximately 5-10% of NC shorelines are currently hardened.
However, bulkheads/riprap may cause erosion of salt marshes located seaward of hardened shorelines. Two potential options to prevent or mitigate salt marsh losses related to shoreline hardening are presented as Options A and B. You may disagree with either/both options, and prefer that no changes occur regarding shoreline permitting (The No Action Option). Please select your preferred option.

☐ **No Action Option: No changes are made.**
Resulting Ecological Condition
If neither option is chosen, shoreline hardening will continue along the NC coast at its current rate. Salt marshes may continue to be lost as a result of shoreline hardening.
Total cost to your household would be $0 in new 2014 state taxes.

☐ **Option A: Reduction in Shoreline Hardening**
Coastal property owners are required to pay a higher permit fee (25% increase in the current fee) for installation of a hard shoreline structure (bulkhead, riprap, etc.). The permit fee is reduced by 50% for property owners using marsh planting, oyster shell placement, or other natural methods for erosion protection.
Resulting Ecological Condition
Rates of shoreline hardening are reduced. Rates of salt marsh loss are reduced. Restoration of salt marsh habitat increases.
Total cost to your household would be $5 in new 2014 state taxes because the increased fees for shoreline hardening would only partially cover the cost of waiving permit fees for marsh planting or other natural methods.

☐ **Option B: Prohibition of Shoreline Hardening**
The use of bulkheads and riprap revetments is prohibited along shorelines bordering salt marsh. Shoreline hardening is permitted at the current fee along shorelines without salt marsh. Along shorelines without salt marsh, the permit fee is waived completely for property owners using natural shoreline stabilization methods such as marsh planting and oyster reef construction.
Resulting Ecological Condition
Loss of existing salt marsh to new shoreline hardening is prevented. Restoration of salt marsh habitat increases.
Total cost to your household would be $5 in new 2014 state taxes to cover the cost of waiving permit fees for marsh planting or other natural methods.

Q73 Coastal property owners in NC may choose to harden their shoreline with bulkheads (vertical walls) or riprap (rock) revetments to protect their property, gain access to the water, and for aesthetics (State general permit cost = $400). Approximately 5-10% of NC shorelines are currently hardened.
However, bulkheads/riprap may cause erosion of salt marshes located seaward of hardened shorelines. Two potential options to prevent or mitigate salt marsh losses related to shoreline hardening are presented as Options A and B. You may disagree with either/both options, and prefer that no changes occur regarding shoreline permitting (The No Action Option). Please select your preferred option.

☐ **No Action Option** No changes are made.
Resulting Ecological Condition
If neither option is chosen, shoreline hardening will continue along the NC coast at its current rate. Salt marshes may continue to be lost as a result of shoreline hardening.
Total cost to your household would be $0 in new 2014 state taxes.

☐ **Option A: Reduction in Shoreline Hardening**
Coastal property owners are required to pay a higher permit fee (25% increase in the current fee) for installation of a hard shoreline structure (bulkhead, riprap, etc.). The permit fee is reduced by 75% for property owners using marsh planting, oyster shell placement, or other natural methods for erosion protection.
Resulting Ecological Condition
Rates of shoreline hardening are reduced Rates of salt marsh loss are reduced. Restoration of salt marsh habitat increases.
Total cost to your household would be $7 in new 2014 state taxes because the increased fees for shoreline hardening would only partially cover the cost of waiving permit fees for marsh planting or other natural methods.

☐ **Option B: Prohibition of Shoreline Hardening**
The use of bulkheads and riprap revetments is prohibited along shorelines bordering salt marsh. Shoreline hardening is permitted at the current fee along shorelines without salt marsh. Along shorelines without salt marsh, the permit fee is waived completely for property owners using natural shoreline stabilization methods such as marsh planting and oyster reef construction.
Resulting Ecological Condition
Loss of existing salt marsh to new shoreline hardening is prevented. Restoration of salt marsh habitat increases.
Total cost to your household would be $5 in new 2014 state taxes to cover the cost of waiving permit fees for marsh planting or other natural methods.

Q74 Oyster harvest supports many coastal fishing communities. Oyster reefs also deliver valuable services such as fish habitat provision, water filtration and shoreline stabilization. Because of destructive harvest and degraded water quality, 60-85% of NC's oyster reefs have been lost. Two options have been put forth to compensate for these losses as Options A and B. However, you may disagree with either/both, and not be willing to pay for oyster reef conservation (the No Action Option). Please select your preferred option.

☐ **No Action Option No changes will be made.**
Resulting Ecological Condition If neither option is chosen, there will likely be a net long-term decline in oyster biomass and acreage.
Total costs to your household in new 2014 state taxes to support oyster reef protection/restoration is: $0

☐ **Option A: Oyster Preservation**
50% of NC oyster reefs will be designated as "no-take" sanctuaries for oysters. Harvest of finfish, crabs and shrimp will remain open in all oyster bottom.
Resulting Ecological Condition
Approximately 2,000 acres of existing oyster reef habitat will be preserved for decades. The cost of locally harvested oysters will increase. Catches of finfish, crabs and shrimp may increase in response to bottom habitat condition and improved water quality. Enforcement costs supported by public funds will be required to maintain closures.
Total costs to your household in new 2014 state taxes to support oyster reef protection is: $5.

☐ **Option B: Oyster Restoration**
NC will adopt a 1-to-1 policy so that every 1 bushel of harvested oysters will be matched by 1 bushel of planted oyster shell to restore oyster reefs. Harvest of finfish, crabs and shrimp will remain open in all oyster bottom.
Resulting Ecological Condition
Oyster acreage will remain at current levels over the next several decades as harvest and restoration activities balance one another. The cost of locally harvested oysters will not change. Catches of finfish, crabs and shrimp will not change. Restoration costs (purchase of shell, transport of shell, monitoring) supported by public funds will be required to maintain or expand reef coverage.
Total costs to your household in new 2014 state taxes to support oyster reef restoration is: $5.

Q74 Oyster harvest supports many coastal fishing communities. Oyster reefs also deliver valuable services such as fish habitat provision, water filtration and shoreline stabilization. Because of destructive harvest and degraded water quality, 60-85% of NC's oyster reefs have been lost. Two options have been put forth to compensate for these losses as Options A and B. However, you may disagree with either/both, and not be willing to pay for oyster reef conservation (the No Action Option). Please select your preferred option.

☐ **No Action Option No changes will be made.**
Resulting Ecological Condition
If neither option is chosen, there will likely be a net long-term decline in oyster biomass and acreage.
Total costs to your household in new 2014 state taxes to support oyster reef protection/restoration is: $0

☐ **Option A: Oyster Preservation**
75% of NC oyster reefs will be designated as "no-take" sanctuaries for oysters. Harvest of finfish, crabs and shrimp will remain open in all oyster bottom.
Resulting Ecological Condition
Approximately 3,000 acres of existing oyster reef habitat will be preserved for decades. The cost of locally harvested oysters will increase. Catches of finfish, crabs and shrimp may increase in response to bottom habitat condition and improved water quality. Enforcement costs supported by public funds will be required to maintain closures.
Total costs to your household in new 2014 state taxes to support oyster reef protection is: $7.

☐ **Option B: Oyster Restoration**
NC will adopt a 1-to-1 policy so that every 1 bushel of harvested oysters will be matched by 1 bushel of planted oyster shell to restore oyster reefs. Harvest of finfish, crabs and shrimp will remain open in all oyster bottom.
Resulting Ecological Condition
Oyster acreage will remain at current levels over the next several decades as harvest and restoration activities balance one another. The cost of locally harvested oysters will not change. Catches of finfish, crabs and shrimp will not change. Restoration costs (purchase of shell, transport of shell, monitoring) supported by public funds will be required to maintain or expand reef coverage.
Total costs to your household in new 2014 state taxes to support oyster reef restoration is: $5.

Q74 Oyster harvest supports many coastal fishing communities. Oyster reefs also deliver valuable services such as fish habitat provision, water filtration and shoreline stabilization. Because of destructive harvest and degraded water quality, 60-85% of NC's oyster reefs have been lost. Two options have been put forth to compensate for these losses as Options A and B. However, you may disagree with either/both, and not be willing to pay for oyster reef conservation (the No Action Option).

Please select your preferred option.

☐ **No Action Option**
No changes will be made.
Resulting Ecological Condition
If neither option is chosen, there will likely be a net long-term decline in oyster biomass and acreage.
Total costs to your household in new 2014 state taxes to support oyster reef protection/restoration is: $0

☐ **Option A: Oyster Preservation**
25% of NC oyster reefs will be designated as "no-take" sanctuaries for oysters. Harvest of finfish, crabs and shrimp will remain open in all oyster bottom.
Resulting Ecological Condition
Approximately 1,000 acres of existing oyster reef habitat will be preserved for decades. The cost of locally harvested oysters will increase. Catches of finfish, crabs and shrimp may increase in response to bottom habitat condition and improved water quality. Enforcement costs supported by public funds will be required to maintain closures.
Total costs to your household in new 2014 state taxes to support oyster reef protection is: $3.

☐ **Option B: Oyster Restoration**
NC will adopt a 1-to-1 policy so that every 1 bushel of harvested oysters will be matched by 1 bushel of planted oyster shell to restore oyster reefs. Harvest of finfish, crabs and shrimp will remain open in all oyster bottom.
Resulting Ecological Condition
Oyster acreage will remain at current levels over the next several decades as harvest and restoration activities balance one another. The cost of locally harvested oysters will not change. Catches of finfish, crabs and shrimp will not change. Restoration costs (purchase of shell, transport of shell, monitoring) supported by public funds will be required to maintain or expand reef coverage.
Total costs to your household in new 2014 state taxes to support oyster reef restoration is: $5.

Q75 Thank you very much for taking our survey. If you are interested in seeing the results and publications that come from this study, please feel free to email us at coastalsurveys@unc.edu. If you are willing to answer follow-up questions and would like to be entered in a raffle to win a gift card from Amazon.com or Bass Pro Shops ($25- $100 value), please provide your e-mail address below. Your email address will not be shared with any outside individuals or groups. Thanks again!

E-mail: _____

Appendix C
NC State-wide Survey

Please note that survey logic is not displayed in this document version of the survey. Several survey questions were only asked of respondents when he or she gave a specific response to a previous question. These questions have a "" next to the question. Also, response options or restrictions (e.g., numeric response only) are not shown for all questions.*

Demographics

Q1 In which state do you currently reside?

Q2 How many total years have you lived in North Carolina?

Q3 What is your gender?
- ❍ Male (1)
- ❍ Female (2)

Q4 What year were you born?

Q5 What is your postal ZIP code?

Q6 How many people live in your household in 2012 (including dependents)?

Q7 What is your highest level of education? (Please select one)
- ❍ Less than high school (1)
- ❍ High school diploma or GED (2)
- ❍ Some college or 2 year degree (3)
- ❍ Bachelor's degree (4)
- ❍ Master's degree (5)
- ❍ Law or MD (6)
- ❍ Doctorate (PhD) (7)
- ❍ Other (Please list) (8) _____

Q8 What was your total household income in 2012?
- ❍ Less than $25k (1)
- ❍ $25k to $35k (2)
- ❍ $35k to $50k (3)
- ❍ $50k to $75k (4)
- ❍ $75k to $100k (5)
- ❍ $100k to $150k (6)
- ❍ $150k or more (7)

Q9 What is your occupation? If you are retired, please indicate so and list your previous occupation.

Q10 Some people who work in industries such as seafood, tourism, and real estate, feel that their jobs depend on maintaining good environmental conditions in the local waterways, bays, and beaches. How much (%), if any, does your job depend on environmental conditions in the local waterways, bays, and beaches?
_____ Percentage (%) (1)

Q11 What kind of saltwater fishing license do you currently hold? (select all that apply)
- ❑ CRFL 10-day license (1)
- ❑ CRFL annual license (2)
- ❑ CRFL lifetime license (3)
- ❑ I don't have a license, but I fish from piers or charter boats (4)
- ❑ Commercial shellfish license (5)
- ❑ Commercial general license (6)
- ❑ I don't fish (7)

Fishing Questions
(*asked to all respondents that did NOT select "I don't fish" for Q11*)

*Q12 How many years have you fished along the North Carolina coast?

*Q13 On average from 2010-2012, how many days per year did you fish along the North Carolina coast from...
_____ a boat/kayak (1)
_____ shore (2)
_____ a pier (3)

*Q14 What type of boat do you use to fish? (check all that apply)

- ❑ Personally-owned motor-operated boat (1)
- ❑ Chartered boat (2)
- ❑ Kayak/Canoe (3)
- ❑ Other (4) _____

*Q15 What percentage of your fishing is within the following?

_____ NC inland coastal waters (%) (1)
_____ NC ocean waters (0-3 miles from shore) (2)
_____ Federal ocean waters off of NC (3 or more miles from shore) (3)
_____ Waters in other states (4)

*Q16 Which species do you most frequently target? (Drag and drop your targeted species into each category. Please only place one species in each category.)

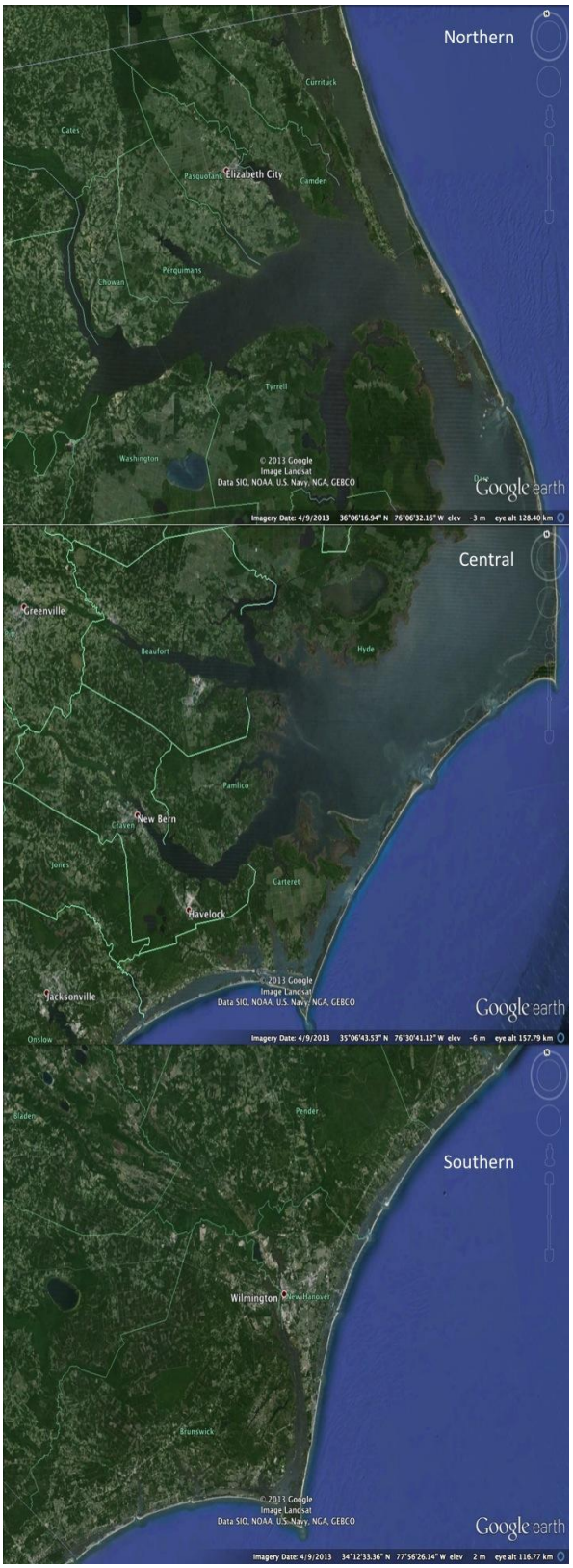
Most Targeted	Second Most Targeted	Third Most Targeted
_____ Flounder (1)	_____ Flounder (1)	_____ Flounder (1)
_____ Red Drum (Redfish, Puppy Drum) (2)	_____ Red Drum (Redfish, Puppy Drum) (2)	_____ Red Drum (Redfish, Puppy Drum) (2)
_____ Spotted Seatrout (Speckled Trout) (3)	_____ Spotted Seatrout (Speckled Trout) (3)	_____ Spotted Seatrout (Speckled Trout) (3)
_____ Florida Pompano (4)	_____ Florida Pompano (4)	_____ Florida Pompano (4)
_____ Bluefish (5)	_____ Bluefish (5)	_____ Bluefish (5)
_____ Spanish Mackerel (6)	_____ Spanish Mackerel (6)	_____ Spanish Mackerel (6)
_____ King Mackerel (7)	_____ King Mackerel (7)	_____ King Mackerel (7)
_____ Weakfish (Gray Trout) (8)	_____ Weakfish (Gray Trout) (8)	_____ Weakfish (Gray Trout) (8)
_____ Sheepshead (9)	_____ Sheepshead (9)	_____ Sheepshead (9)
_____ Black Drum (10)	_____ Black Drum (10)	_____ Black Drum (10)
_____ Cobia (11)	_____ Cobia (11)	_____ Cobia (11)
_____ Spot / Croaker (12)	_____ Spot / Croaker (12)	_____ Spot / Croaker (12)
_____ Striped Bass (13)	_____ Striped Bass (13)	_____ Striped Bass (13)
_____ Blue Crabs (14)	_____ Blue Crabs (14)	_____ Blue Crabs (14)
_____ Shrimp (15)	_____ Shrimp (15)	_____ Shrimp (15)
_____ Striped Mullet (16)	_____ Striped Mullet (16)	_____ Striped Mullet (16)
_____ Sea Mullet (Kingfish, Ground Mullet, Virginia Mullet, Whiting) (17)	_____ Sea Mullet (Kingfish, Ground Mullet, Virginia Mullet, Whiting) (17)	_____ Sea Mullet (Kingfish, Ground Mullet, Virginia Mullet, Whiting) (17)
_____ Shellfish (clams, oysters) (18)	_____ Shellfish (clams, oysters) (18)	_____ Shellfish (clams, oysters) (18)
_____ Whatever bites the hook (19)	_____ Whatever bites the hook (19)	_____ Whatever bites the hook (19)

*Q17 If known, what length (inches) was the largest fish of this species that you have ever caught?

*Q18 If known, what weight (lbs) was the largest fish of this species that you have ever caught?

*Q19 What year did you catch the largest fish of this species?

*Q20 Please select the locations in North Carolina where you most frequently fish. (Click up to 5 locations on the three regions of NC below).



*Q21 For the species you target most (based on your selection above), in which of the following habitats are you most likely to fish?
_____ Wetlands (1)
_____ Submerged aquatic vegetation (2)
_____ Oyster reefs (3)
_____ Beach (4)
_____ Oyster spawning sanctuaries (5)
_____ Hard bottom (6)
_____ Other (7)

*Q22 In your lifetime, when were fisheries in the North Carolina coastal regions in the best condition?
_____ Year (1)

Habitat Condition
(asked of all respondents)

Q23 On a scale from 1 to 10, with 10 being very important and 1 being not important, please indicate how important each estuarine habitat is to FISHERIES in North Carolina?
_____ Wetlands (e.g., salt marsh, freshwater marsh, cypress) (1)
_____ Submerged aquatic vegetation (e.g., seagrass) (2)
_____ Oyster Reefs (3)
_____ Beach (4)
_____ Hard Bottom (e.g., natural submerged rock) (5)

Q24 On a scale from 1 to 10, with 10 being very important and 1 being not important, please indicate how important each estuarine habitat is to TOURISM in North Carolina?
_____ Wetlands (e.g., salt marsh, freshwater marsh, cypress) (1)
_____ Submerged aquatic vegetation (e.g., seagrass) (2)
_____ Oyster Reefs (3)
_____ Beach (4)
_____ Hard Bottom (e.g., natural submerged rock) (5)

Q25 On a scale from 1 to 10, with 10 being very important and 1 being not important, please indicate how important each estuarine habitat is to WATER QUALITY in North Carolina?

_____ Wetlands (e.g., salt marsh, freshwater marsh, cypress) (1)
_____ Submerged aquatic vegetation (e.g., seagrass) (2)
_____ Oyster Reefs (3)
_____ Beach (4)
_____ Hard Bottom (e.g., natural submerged rock) (5)

Q26 On a scale from 1 to 10, with 10 being very important and 1 being not important, please indicate how important each estuarine habitat is to STORM PROTECTION in North Carolina?

_____ Please select Answer choice "4" (1)
_____ Wetlands (e.g., salt marsh, freshwater marsh, cypress) (2)
_____ Submerged aquatic vegetation (e.g., seagrass) (3)
_____ Oyster Reefs (4)
_____ Beach (5)
_____ Hard Bottom (e.g., natural submerged rock) (6)

Q27 What do you see as the top THREE ENVIRONMENTAL problems facing coastal North Carolina? (1=Worst Problem, 2=Next, etc)

_____ Recreational Fishing (1)
_____ Commercial Fishing (2)
_____ Residential Development (3)
_____ Industrial Pollution (4)
_____ Agriculture (5)
_____ Tourism (6)
_____ Beach Renourishment (7)
_____ Sea Level Rise (8)
_____ Stronger or More Frequent Storms (9)
_____ Warmer Temperature (10)
_____ Poor Water Quality (11)
_____ Dredging (13)
_____ Other (14)

Q28 Do you think that the global climate is warming?

- ❍ Yes (1)
- ❍ No (2)
- ❍ Don't know/ Not sure (3)

*Q29 What do you think is causing the earth to warm (check all that apply)?

- ❑ Natural (non-human) processes (1)
- ❑ Carbon dioxide and other greenhouse gas emissions from human activities (e.g., burning fossil fuels) (2)
- ❑ Other (please specify) (3) _____

*Q30 What aspects of climate change are you most concerned about in your lifetime? Please rank your top 3 concerns, with 1 being the most concerning and 3 being the least concerning.

_____ Warmer temperatures (1)
_____ Sea level rise (2)
_____ Changes in precipitation (3)
_____ Ocean acidification (4)
_____ Increased storminess (5)
_____ Changes in marine organisms populations and distributions (e.g., shifts in range, migration patterns, etc.) (6)
_____ Saltwater intrusion (7)
_____ Other (please specify) (8)

Q31 How much do you think sea level will rise in the next century (Feet)?

Coastal Management Options
(asked of all respondents)

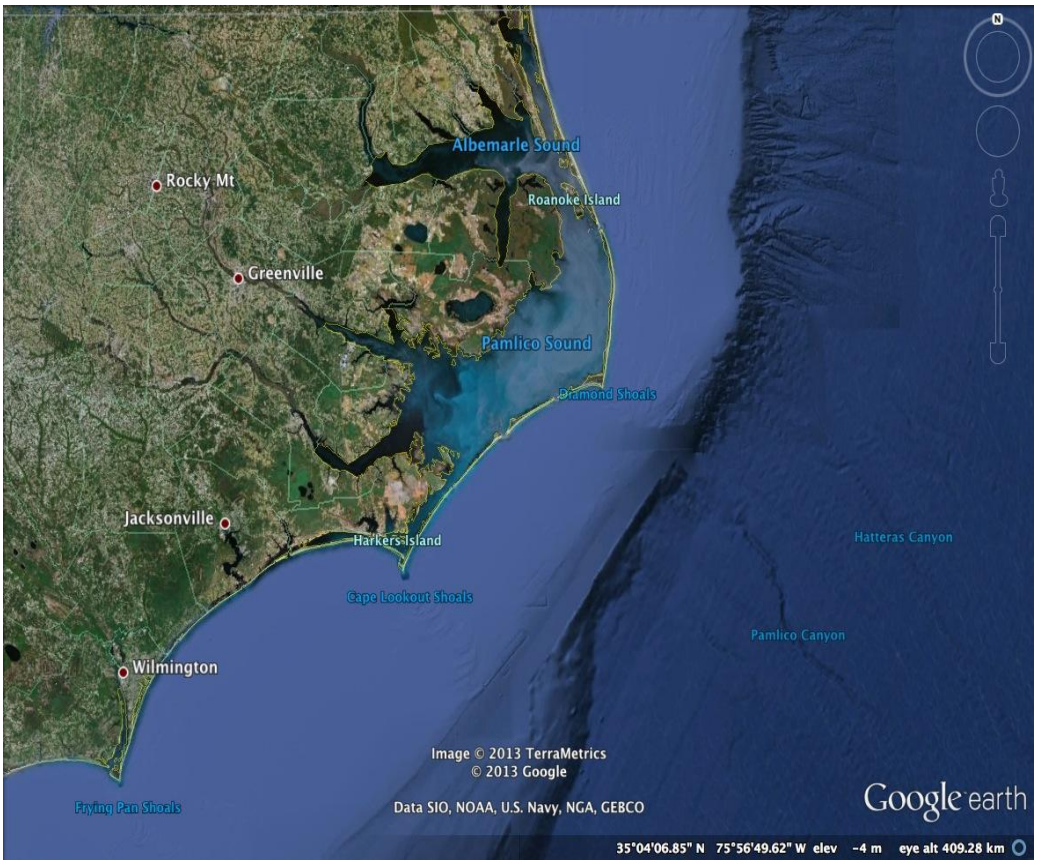
Q32 Do you support the practice and expansion of leasing of water bottom for shellfish aquaculture in North Carolina?

- ❍ Yes (1)
- ❍ No (2)
- ❍ Don't know/ Not sure (3)

Q33 Do you support the construction of wind turbines off the coast of North Carolina?

- ❍ Yes (1)
- ❍ No (2)
- ❍ Don't know/ Not sure (3)

*Q34 Please select the location you think is best suited (in your opinion) to the construction of wind turbines (click up to 3 locations).



*Q35 What is your primary concern with wind turbine construction off the coast of North Carolina?

- ❍ Not economically feasible (too expensive) (1)
- ❍ Aesthetically displeasing (don't want to see them offshore) (2)
- ❍ Could harm migratory birds or marine mammals (3)
- ❍ Could affect fishing (4)
- ❍ Could affect shipping routes (5)
- ❍ Other (6) _____

Contingency Questions
(only 1 randomly selected version of one of the next two questions was asked of a each respondent)

Q36 Coastal property owners in NC may choose to harden their shoreline with bulkheads (vertical walls) or riprap (rock) revetments to protect their property, gain access to the water, and for aesthetics (State general permit cost = $400). Approximately 5-10% of NC shorelines are currently hardened. However, bulkheads/riprap may cause erosion of salt marshes located seaward of hardened shorelines. Two potential options to prevent or mitigate salt marsh losses related to shoreline hardening are presented as Options A and B. However, you may disagree with either/both options, and prefer that no changes occur regarding shoreline permitting (The No Action Option). Please select your preferred option.

- **No Action Option**
  No changes are made. Resulting Ecological Condition If neither option is chosen, shoreline hardening will continue along the NC coast at its current rate. Salt marshes may continue to be lost as a result of shoreline hardening. Total cost to your household would be $0 in new 2014 state taxes. (1)

- **Option A: Reduction in Shoreline Hardening**
  Coastal property owners are required to pay a higher permit fee (50% increase in the current fee) for installation of a hard shoreline structure (bulkhead, riprap, etc.). The permit fee is reduced by 25% for property owners using marsh planting, oyster shell placement, or other natural methods for erosion protection. Resulting Ecological Condition Rates of shoreline hardening are reduced. Rates of salt marsh loss are reduced. Restoration of salt marsh habitat increases. Total cost to your household would be $0 in new 2014 state taxes because the increased fees for shoreline hardening would cover the cost of waiving permit fees for marsh planting or other natural methods. (2)

- **Option B: Prohibition of Shoreline Hardening**
  The use of bulkheads and riprap revetments is prohibited along shorelines bordering salt marsh. Shoreline hardening is permitted at the current fee along shorelines without salt marsh. Along shorelines without salt marsh, the permit fee is waived completely for property owners using natural shoreline stabilization methods such as marsh planting and oyster reef construction. Resulting Ecological Condition Loss of existing salt marsh to new shoreline hardening is prevented. Restoration of salt marsh habitat increases. Total cost to your household would be $5 in new 2014 state

taxes to cover the cost of waiving permit fees for marsh planting or other natural methods. (3)

Q37 Coastal property owners in NC may choose to harden their shoreline with bulkheads (vertical walls) or riprap (rock) revetments to protect their property, gain access to the water, and for aesthetics (State general permit cost = $400). Approximately 5-10% of NC shorelines are currently hardened. However, bulkheads/riprap may cause erosion of salt marshes located seaward of hardened shorelines. Two potential options to prevent or mitigate salt marsh losses related to shoreline hardening are presented as Options A and B. However, you may disagree with either/both options, and prefer that no changes occur regarding shoreline permitting (The No Action Option). Please select your preferred option.

- **No Action Option**
  No changes are made. Resulting Ecological Condition If neither option is chosen, shoreline hardening will continue along the NC coast at its current rate. Salt marshes may continue to be lost as a result of shoreline hardening. Total cost to your household would be $0 in new 2014 state taxes. (1)

- **Option A: Reduction in Shoreline Hardening**
  Coastal property owners are required to pay a higher permit fee (25% increase in the current fee) for installation of a hard shoreline structure (bulkhead, riprap, etc.). The permit fee is reduced by 50% for property owners using marsh planting, oyster shell placement, or other natural methods for erosion protection. Resulting Ecological Condition Rates of shoreline hardening are reduced. Rates of salt marsh loss are reduced. Restoration of salt marsh habitat increases. Total cost to your household would be $5 in new 2014 state taxes because the increased fees for shoreline hardening would only partially cover the cost of waiving permit fees for marsh planting or other natural methods. (2)

- **Option B: Prohibition of Shoreline Hardening**
  The use of bulkheads and riprap revetments is prohibited along shorelines bordering salt marsh. Shoreline hardening is permitted at the current fee along shorelines without salt marsh. Along shorelines without salt marsh, the permit fee is waived completely for property owners using natural shoreline stabilization methods such as marsh planting and oyster reef construction. Resulting Ecological Condition Loss of existing salt marsh to new shoreline hardening is prevented. Restoration of salt marsh habitat increases. Total cost to your household would be $5 in new 2014 state taxes to cover the cost of waiving permit fees for marsh planting or other natural methods. (3)

Q38 Coastal property owners in NC may choose to harden their shoreline with bulkheads (vertical walls) or riprap (rock) revetments to protect their property, gain access to the water, and for aesthetics (State general permit cost = $400). Approximately 5-10% of NC shorelines are currently hardened. However, bulkheads/riprap may cause erosion of salt marshes located seaward of hardened shorelines. Two potential options to prevent or mitigate salt marsh losses related to shoreline hardening are presented as Options A and B. However, you may disagree with either/both options, and prefer that no changes occur regarding shoreline permitting (The No Action Option). Please select your preferred option.

- **No Action Option**
  No changes are made. Resulting Ecological Condition If neither option is chosen, shoreline hardening will continue along the NC coast at its current rate. Salt marshes may continue to be lost as a result of shoreline hardening. Total cost to your household would be $0 in new 2014 state taxes. (1)

- **Option A: Reduction in Shoreline Hardening**
  Coastal property owners are required to pay a higher permit fee (25% increase in the current fee) for installation of a hard shoreline structure (bulkhead, riprap, etc.). The permit fee is reduced by 75% for property owners using marsh planting, oyster shell placement, or other natural methods for erosion protection. Resulting Ecological Condition Rates of shoreline hardening are reduced Rates of salt marsh loss are reduced. Restoration of salt marsh habitat increases. Total cost to your household would be $7 in new 2014 state taxes because the increased fees for shoreline hardening would only partially cover the cost of waiving permit fees for marsh planting or other natural methods. (2)

- **Option B: Prohibition of Shoreline Hardening**
  The use of bulkheads and riprap revetments is prohibited along shorelines bordering salt marsh. Shoreline hardening is permitted at the current fee along shorelines without salt marsh. Along shorelines without salt marsh, the permit fee is waived completely for property owners using natural shoreline stabilization methods such as marsh planting and oyster reef construction. Resulting Ecological Condition Loss of existing salt marsh to new shoreline hardening is prevented. Restoration of salt marsh habitat increases. Total cost to your household would be $5 in new 2014 state taxes to cover the cost of waiving permit fees for marsh planting or other natural methods. (3)

Q39 Oyster harvest supports many coastal fishing communities. Oyster reefs also deliver valuable services such as fish habitat provision, water filtration and shoreline stabilization. Because of destructive harvest and degraded water quality, 60-85% of NC's oyster reefs have been lost. Two options have been put forth to compensate for these losses as Options A and B. However, you may disagree with either/both, and not be willing to pay for oyster reef conservation (the No Action Option). Please select your preferred option.

- **No Action Option**
  No changes will be made. Resulting Ecological Condition If neither option is chosen, there will likely be a net long-term decline in oyster biomass and acreage. Total costs to your household in new 2014 state taxes to support oyster reef protection/restoration is: $0 (1)

- **Option A: Oyster Preservation**
  50% of NC oyster reefs will be designated as "no-take" sanctuaries for oysters. Harvest of finfish, crabs and shrimp will remain open in all oyster bottom. Resulting Ecological Condition Approximately 2,000 acres of existing oyster reef habitat will be preserved for decades. The cost of locally harvested oysters will increase. Catches of finfish, crabs and shrimp may increase in response to bottom habitat condition and improved water quality. Enforcement costs supported by public funds will be required to maintain closures. Total costs to your household in new 2014 state taxes to support oyster reef protection is: $5. (2)

- **Option B: Oyster Restoration**
  NC will adopt a 1-to-1 policy so that every 1 bushel of harvested oysters will be matched by 1 bushel of planted oyster shell to restore oyster reefs. Harvest of finfish, crabs and shrimp will remain open in all oyster bottom. Resulting Ecological Condition Oyster acreage will remain at current levels over the next several decades as harvest and restoration activities balance one another. The cost of locally harvested oysters will not change. Catches of finfish, crabs and shrimp will not change. Restoration costs (purchase of shell, transport of shell, monitoring) supported by public funds will be required to maintain or expand reef coverage. Total costs to your household in new 2014 state taxes to support oyster reef restoration is: $5. (3)

Q40 Oyster harvest supports many coastal fishing communities. Oyster reefs also deliver valuable services such as fish habitat provision, water filtration and shoreline stabilization. Because of destructive harvest and degraded water quality, 60-85% of NC's oyster reefs have been lost. Two options have been put forth to compensate for

these losses as Options A and B. However, you may disagree with either/both, and not be willing to pay for oyster reef conservation (the No Action Option). Please select your preferred option.

- **No Action Option**
  No changes will be made. Resulting Ecological Condition If neither option is chosen, there will likely be a net long-term decline in oyster biomass and acreage. Total costs to your household in new 2014 state taxes to support oyster reef protection/restoration is: $0 (1)

- **Option A: Oyster Preservation**
  75% of NC oyster reefs will be designated as "no-take" sanctuaries for oysters. Harvest of finfish, crabs and shrimp will remain open in all oyster bottom. Resulting Ecological Condition Approximately 3,000 acres of existing oyster reef habitat will be preserved for decades. The cost of locally harvested oysters will increase. Catches of finfish, crabs and shrimp may increase in response to bottom habitat condition and improved water quality. Enforcement costs supported by public funds will be required to maintain closures. Total costs to your household in new 2014 state taxes to support oyster reef protection is: $7. (2)

- **Option B: Oyster Restoration**
  NC will adopt a 1-to-1 policy so that every 1 bushel of harvested oysters will be matched by 1 bushel of planted oyster shell to restore oyster reefs. Harvest of finfish, crabs and shrimp will remain open in all oyster bottom. Resulting Ecological Condition Oyster acreage will remain at current levels over the next several decades as harvest and restoration activities balance one another. The cost of locally harvested oysters will not change. Catches of finfish, crabs and shrimp will not change. Restoration costs (purchase of shell, transport of shell, monitoring) supported by public funds will be required to maintain or expand reef coverage. Total costs to your household in new 2014 state taxes to support oyster reef restoration is: $5. (3) _____

Q41 Oyster harvest supports many coastal fishing communities. Oyster reefs also deliver valuable services such as fish habitat provision, water filtration and shoreline stabilization. Because of destructive harvest and degraded water quality, 60-85% of NC's oyster reefs have been lost. Two options have been put forth to compensate for these losses as Options A and B. However, you may disagree with either/both, and not be willing to pay for oyster reef conservation (the No Action Option). Please select your preferred option.

- **No Action Option**
  No changes will be made. Resulting Ecological Condition If neither option is chosen, there will likely be a net long-term decline in oyster biomass and acreage. Total costs to your household in new 2014 state taxes to support oyster reef protection/restoration is: $0 (1)

- **Option A: Oyster Preservation**
  25% of NC oyster reefs will be designated as "no-take" sanctuaries for oysters. Harvest of finfish, crabs and shrimp will remain open in all oyster bottom. Resulting Ecological Condition Approximately 1,000 acres of existing oyster reef habitat will be preserved for decades. The cost of locally harvested oysters will increase. Catches of finfish, crabs and shrimp may increase in response to bottom habitat condition and improved water quality. Enforcement costs supported by public funds will be required to maintain closures. Total costs to your household in new 2014 state taxes to support oyster reef protection is: $3. (2)

- **Option B: Oyster Restoration**
  NC will adopt a 1-to-1 policy so that every 1 bushel of harvested oysters will be matched by 1 bushel of planted oyster shell to restore oyster reefs. Harvest of finfish, crabs and shrimp will remain open in all oyster bottom. Resulting Ecological Condition Oyster acreage will remain at current levels over the next several decades as harvest and restoration activities balance one another. The cost of locally harvested oysters will not change. Catches of finfish, crabs and shrimp will not change. Restoration costs (purchase of shell, transport of shell, monitoring) supported by public funds will be required to maintain or expand reef coverage. Total costs to your household in new 2014 state taxes to support oyster reef restoration is: $5. (3)

Q42 Thank you very much for taking our survey. If you are interested in seeing the results and publications that come this study, please feel free to email us at coastalsurveys@unc.eduIf you are willing to answer follow-up questions, please provide your e-mail address below. Your email address will not be shared with any outside individuals or groups. Thanks again!

Appendix D. NC Tournament Survey

Dear North Carolina Tournament Participant,

Before we go any further, we need to inform you of a few details of our survey as required by our University. Your part in this study will be handled in a confidential manner, as our analyses of survey responses will not be linked to individuals. There are no direct benefits for your participation; however, you may choose to participate in a participant raffle drawing for a chance at winning small prizes. The survey should be completed bya person over 18 years old. You can refuse to answer any question, and you can quit the survey at any time. Completion of the survey should take no more than 5 minutes.

If you have any questions about your rights in this research, you may contact the UNC Office of Human Subjects Research Ethics at 919-966-3113. You may call anonymously or collect.

Please feel free to contact the Project Lead, Rachel Gittman at coastalsurveys@unc.edu.

Is it OK if I start the survey?

☐ Yes
☐ No

Q1 What year were you born?

_____

Q2 Which inshore species do you most frequently target? (within 3 nautical miles or within state waters if they ask what inshore means)

_____ Flounder

_____ Red Drum (Redfish, Puppy Drum)

_____ Spotted Seatrout (Speckled Trout)

_____ Florida Pompano

_____ Bluefish

_____ Spanish Mackerel

_____ King Mackerel

_____ Weakfish (Gray Trout)

_____ Sheepshead

_____ Black Drum

_____ Cobia

_____ Spot / Croaker

_____ Striped Bass

_____ Blue Crabs

_____ Shrimp

_____ Striped Mullet

_____ Sea Mullet (Kingfish, Ground Mullet, Virginia Mullet, Whiting)

_____ Shellfish (clams, oysters)

_____ Whatever bites the hook

Q3 If known, what length was the largest fish that you have ever caught of the species your most frequently target? (or just the largest fish they have caught if they say whatever bites the hook)

Species: _____ Length: _____ inches

Q4 If known, what weight was the largest fish of this species that you have ever caught? (or just the largest fish they have caught if they say whatever bites the hook)

Species: _____ Weight: _____ lbs

Q5 What year did you catch the largest fish of this species?

Species: _____ Year: ___

Q6 In your lifetime, when were fisheries in the North Carolina coastal regions in the best condition?

_____ Year

Appendix E. Education and Outreach Activities

Invited Presentations to Managers, Practitioners, and the Public (only presenter listed)

Gittman, R.K. Living shorelines: Are we designing functional, sustainable, and resilient coasts?" Restore America's Estuaries, Living Shorelines Workshop, New Orleans, LA. December 2016.

Gittman, R.K. Ecological effects of shoreline hardening and living shorelines & homeowners' perceptions of shoreline protection options" North Carolina Division of Coastal Management Staff Training, Beaufort, NC. June 2016.

Gittman, R.K. "Living shorelines" Biscayne Bay Regional Restoration and Coordination Team, Webinar. 2016

Gittman, R.K. "Living shorelines: Are we designing functional, sustainable, and resilient coasts?" Joint Public Advisory Committee of the Commission for Environmental Cooperation of North America, Workshop on Emerging Scientific Research Relating to Ecosystem-based Adaptation, Webinar. 2016

Gittman, R.K. "Living shorelines technical briefing webinar" Pew Charitable Trusts, Washington, DC. 2016

Gittman, R.K. "Advancing nature-based solutions to coastal erosion." Congressional Coastal Community Caucus, Washington, DC. 2016

Gittman, R.K. "Living shorelines: Are we designing functional, sustainable, and resilient coasts?" Next in Science Seminar Series, The Radcliffe Institute for Advanced Study, Harvard University, Cambridge, MA. 2016

Gittman, R.K. "Wetland value and functions." NC Coastal Training Program. Beaufort, NC. 2016

Gittman, R.K. "The living shoreline approach as an alternative to shoreline hardening: Using science to inform coastal management policy." New Hampshire Coastal Climate Summit, Greenland, NH. 2016

Gittman, R.K. "The living shoreline approach as an alternative to shoreline hardening: Using science to inform coastal management policies." GSAA Living Shoreline Summit, Jacksonville, FL. 2016

Gittman, R.K. "Living shorelines: an overview." Pew Charitable Trusts, Webinar. 2016

Gittman, R.K. "Ecological effects of shoreline hardening: A meta-analysis." Pew Charitable Trusts, Webinar. 2016

Gittman, R.K. "The ecology and ecosystem services of living shorelines." Restore America's Estuaries Living Shoreline Summit, Hartford, CT. 2015

Gittman, R.K. "Living shorelines: benefits & limitations." NC Promoting living shorelines for stabilization: a workshop for real estate professionals. Beaufort & Wilmington NC. 2015

Gittman, R.K. "Effects of Hurricane Irene on alternative shoreline stabilization structures and marsh habitat use by fishes in North Carolina." Southeast Regional Partnership for Planning and Sustainability (SERPPAS) Meeting, Camp Lejeune, NC. 2013

Gittman, R.K. "Effects of Hurricane Irene on alternative shoreline stabilization structures and marsh habitat use by fishes in North Carolina." Living Shorelines Workshop, Smithsonian Environmental Research Center, Edgewater, MD. 2013

Smith, C.S. Shore protection structure performance over multiple storms: A socioeconomic analysis. NC Department of Coastal Management Staff Living Shorelines Training, Beaufort, NC, December 2016.

Smith, C.S. Addressing misperceptions about the effectiveness, durability, and cost of hardened versus living shorelines. Restore America's Estuaries Summit, Living Shorelines Workshop, New Orleans, December 2016.

Invited Presentations to an Academic Audience (only presenter listed)

Gittman, R.K. Living shorelines: Are we designing functional, sustainable, and resilient coasts? University of Virginia, Charlottesville, VA. February 2017

Gittman, R.K. Living shorelines: Are we designing functional, sustainable, and resilient coasts? East Carolina University, Greenville, NC. December 2016.

Gittman, R.K. Living shorelines: Are we designing functional, sustainable, and resilient coasts? University of Florida, Gainesville, FL. December 2016.

Gittman, R.K. Living shorelines: Are we designing functional, sustainable, and resilient coasts? University of Massachusetts Boston, Boston, MA. September 2016.

Gittman, R.K. Sustaining ecosystem services of estuarine shoreline habitats by use of "living shorelines". Mote Marine Lab, Sarasota, FL. April 2016.

Gittman, R.K. The function and resilience of engineered versus natural shore defenses. University of Florida, Gainesville, FL. April 2016

Presentations at International Academic Conferences (only presenter listed)

Gittman, R.K. The living shoreline approach as an alternative to shoreline hardening: implications for the ecology and service delivery of salt marshes. Ecological Society of America Organized Session: Natural Infrastructure: Societal Benefits of Healthy Coastal Ecosystems Baltimore, MD. August 2015.

Gittman, R.K. "Engineering away our natural defenses: an analysis of shoreline hardening in the United States." Benthic Ecology Meeting. Quebec City, Quebec, CA. 2015

Gittman, R.K. "Living shorelines can enhance the nursery role of threatened coastal habitats." Restore America's Estuaries, National Harbor, MD. 2014

Gittman, R.K. "Prevalence and impending ecological consequences of shoreline hardening along US coasts." Ecological Society of America, Sacramento, CA. 2014

Gittman, R.K. "Effects of Hurricane Irene on alternative shoreline stabilization structures and marsh habitat use by fishes in North Carolina." Coastal Estuarine Research Federation Meeting, San Diego, CA. 2013

Smith, C.S. Hurricane damage along natural and engineered shorelines in NC. Benthic Ecology Conference, Portland, March 2016.

Smith, C.S. Hurricane damage along natural and engineered shorelines in NC. Atlantic Estuarine Research Society Spring Meeting, Virginia Beach, March 2016.

Smith, C.S. Addressing homeowner misperceptions about the effectiveness, durability, and cost of hardened shorelines: An analysis of hurricane damage in North Carolina. Restore America's Estuaries Summit, New Orleans, December 2016.

Media Communications

2016 Gittman, R.K. Interview, "Ecological effects of shoreline hardening", National Audubon Society

2016 Gittman, R.K. Podcast, "Shoreline Hardening", Bioscience Talks, American Institute of Biological Sciences

2016 Gittman, R.K. Article, "Meta-analysis shows engineered hard shorelines are a threat to ecosystems", AIBS

2016 Gittman, R.K. Interview, "Living shorelines provide better habitat and erosion protection than bulkheads, A Q&A with marine ecologist Rachel Gittman", The Pew Charitable Trusts

2016 Gittman, R.K. Article, "Living shorelines will get fast track to combat sea level rise", ClimateWire & The Scientific American

2016 Gittman, R.K. Article, "Nature as storm defender: Seawalls not only fail often but can promote environmental damage, researcher says", Harvard Gazette

2016 Gittman, R.K. Article, "As sea level rises, how to protect our coasts?", Yale Climate Connections

2016 Gittman, R.K. Article, “NOAA encourages living shorelines”, The Pew Charitable Trusts.
2016 Gittman, R.K. Article, “Living shorelines: a key line of defense”, The Pew Charitable Trusts
2016 Gittman, R.K. Article, “Marshes and wetlands beat seawalls when it comes to protecting people and wildlife”, Take Part
2016 Gittman, R.K. Article, “Evidence mounts of shorelines’ success”, The Coastal Review
2016 Gittman, R.K. Article, “Living shorelines: better than bulkheads”, The Coastal Review
2015 Gittman, R.K. Article, “Over 14,000 miles of America's coastline is covered in concrete”, The Smithsonian
2015 Gittman, R.K. Article, “Climate change evidence all around”, The Coastal Review
2015 Gittman, R.K. Article, “Rise of 'shoreline hardening' threatens coastal ecosystems”, Conservation Magazine
2015 Gittman, R.K. Article, “Armored in concrete, hardened shorelines lose the soft protections of coastal wetlands”, Ecological Society of America
2015 Gittman, R.K. Article, “Shore hardening study: An opportunity?”, Paint Square News
2015 Gittman, R.K. Radio Interview, Shoreline Hardening in the US, Michael Iantorno, Acessible Media, Inc.
2014 Gittman, R.K. Radio Interview, Living Shorelines, Jared Brumbaugh, Public Radio East, NPR

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

Rachel K. Gittman [a, *], Alyssa M. Popowich [a, 1], John F. Bruno [b], Charles H. Peterson [a, b]

[a] Institute of Marine Sciences, University of North Carolina at Chapel Hill, Morehead City, NC 28557, USA
[b] Department of Biology, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599, USA

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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),

* Corresponding author.
E-mail address: gittman@email.unc.edu (R.K. Gittman).
[1] Present address: United States Coast Guard, Portsmouth, VA 23703, USA.

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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

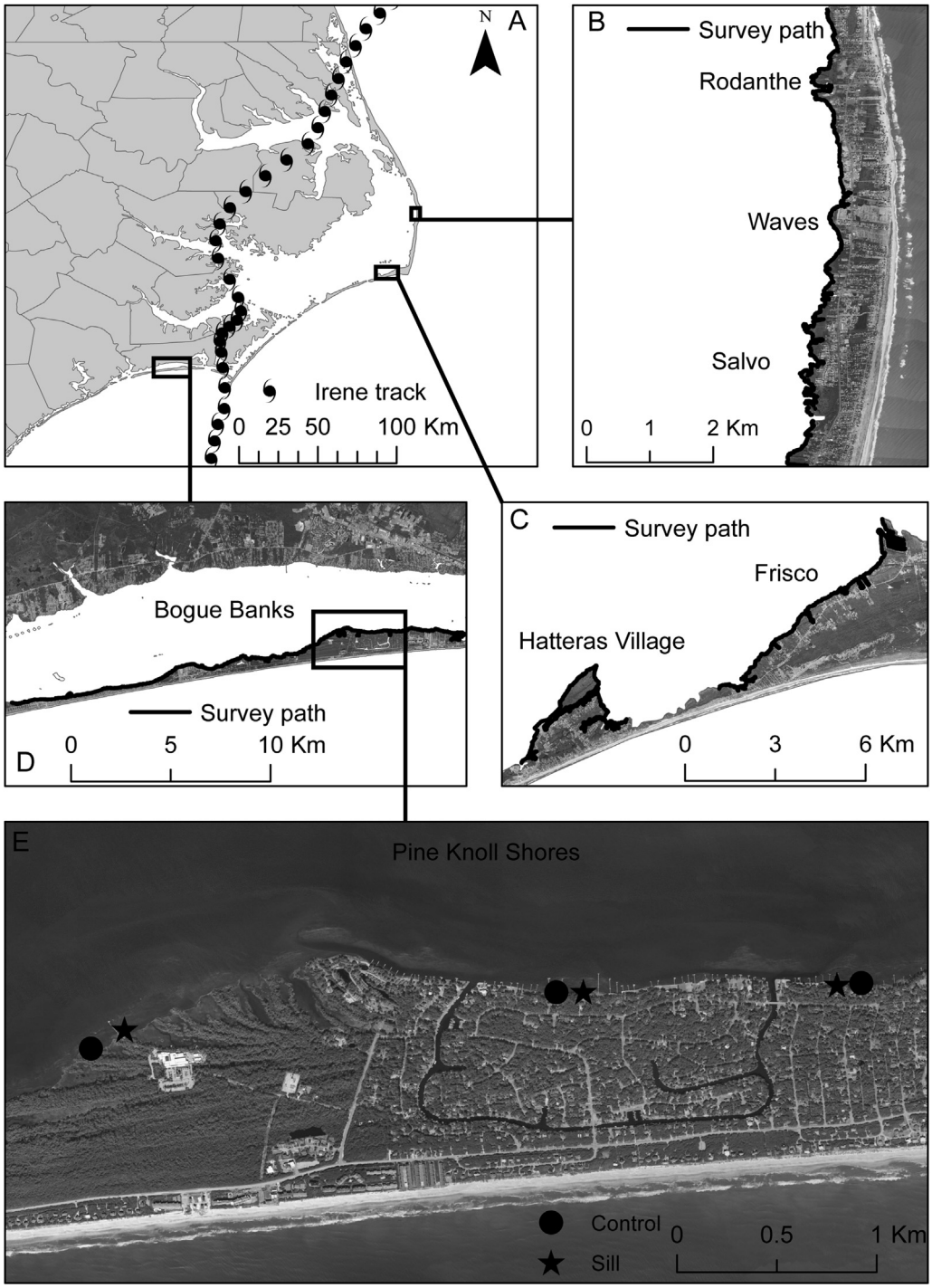

Fig. 2. A map of: A) the study areas relative to the path of Hurricane Irene (made landfall in NC at 34.7°N, 76.6°W; B) survey path for damage classifications on Rodanthe, Waves, and Salvo, NC; C) survey path for damage classifications on Frisco and Hatteras Island, NC; D) survey path for damage classifications 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).

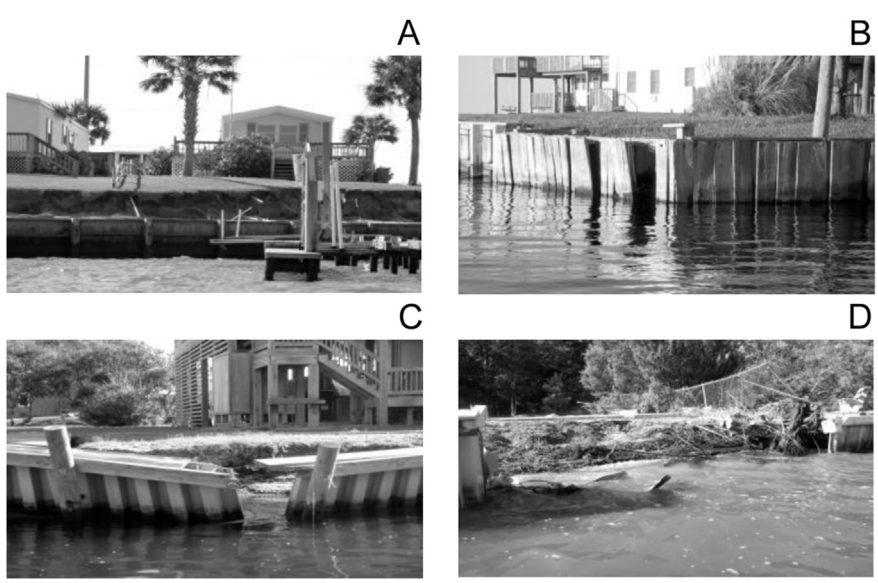

Fig. 3. Bulkhead damage classifications: A) Landward erosion; B) Structural damage; C) Breach; and D) Collapse.

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).

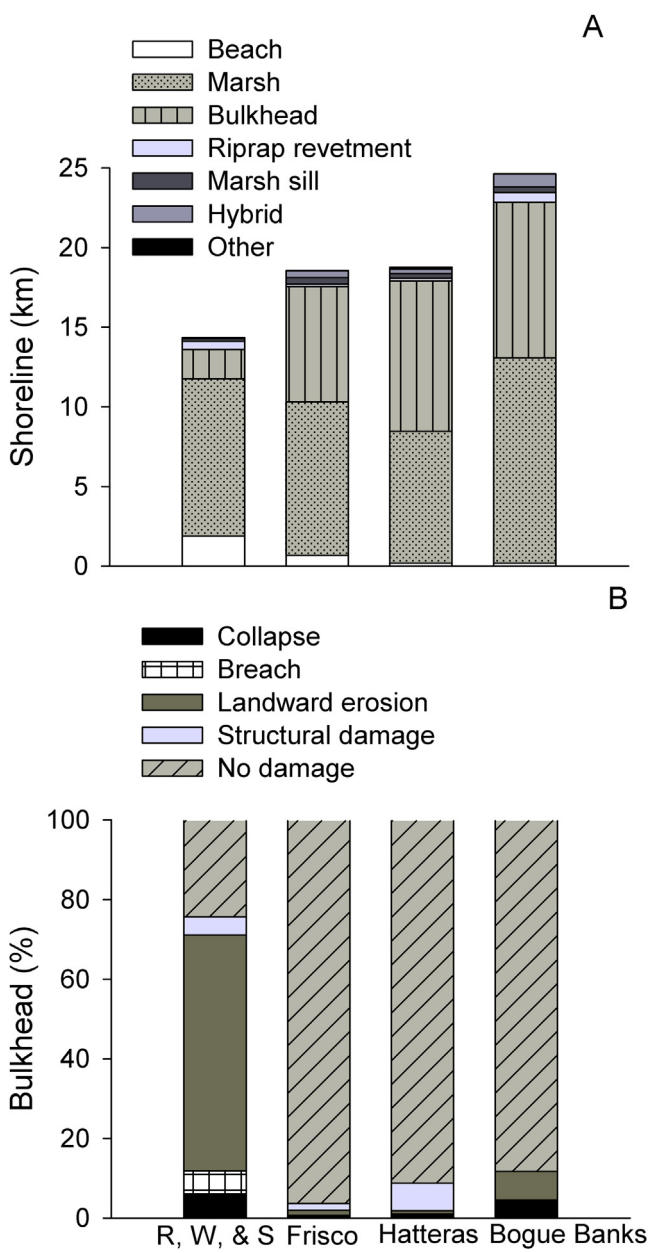

Fig. 4. A) Shoreline classification by type (km) for Rodanthe, Waves, and Salvo; Frisco; Hatteras Village; and Bogue Banks, NC. *See* Fig. 1 for descriptions and photographs of a bulkhead, riprap revetment, and marsh with a sill. Hybrid is a combination of bulkhead and riprap and beach is unvegetated 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							

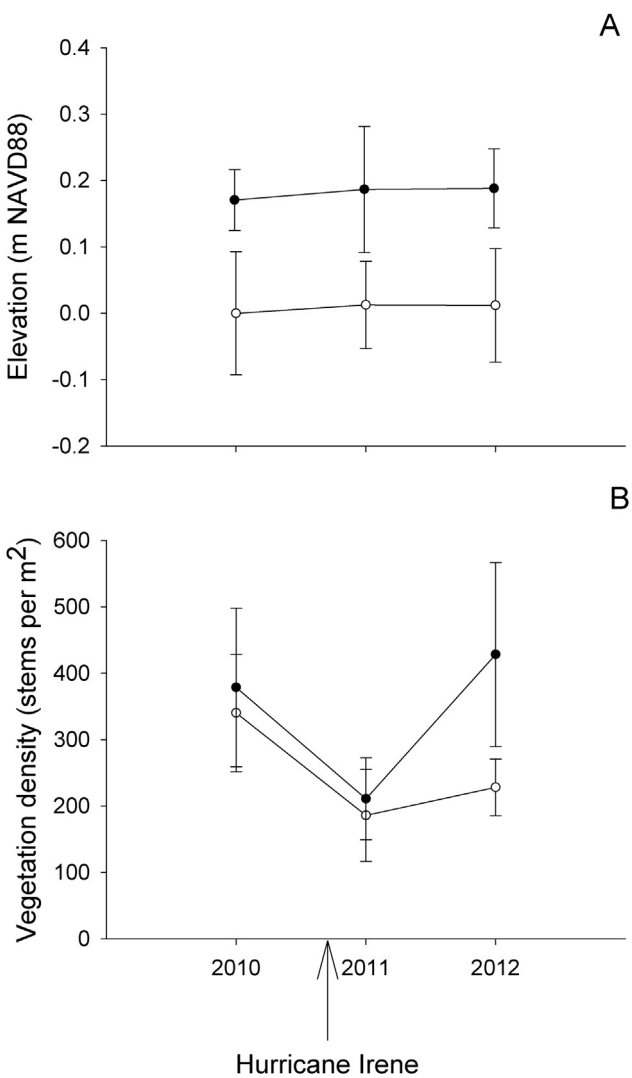

Fig. 5. The effects of Hurricane Irene on: (A) average marsh surface elevation (m, NAVD88); and (B) average vegetation density per m^2 at marsh sites with (closed circles) and without (open circles) sills. Error bars represent ±1SE ($n = 9$ to 21 per site).

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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Engineering away our natural defenses: an analysis of shoreline hardening in the US

Rachel K Gittman[1*†], F Joel Fodrie[1], Alyssa M Popowich[2], Danielle A Keller[1], John F Bruno[3], Carolyn A Currin[4], Charles H Peterson[1], and Michael F Piehler[1]

Rapid population growth and coastal development are primary drivers of marine habitat degradation. Although shoreline hardening or armoring (the addition of concrete structures such as seawalls, jetties, and groins), a byproduct of development, can accelerate erosion and loss of beaches and tidal wetlands, it is a common practice globally. Here, we provide the first estimate of shoreline hardening along US Pacific, Atlantic, and Gulf of Mexico coasts and predict where future armoring may result in tidal wetland loss if coastal management practices remain unchanged. Our analysis indicates that 22 842 km of continental US shoreline – approximately 14% of the total US coastline – has been armored. We also consider how socioeconomic and physical factors relate to the pervasiveness of shoreline armoring and show that housing density, gross domestic product, storms, and wave height are positively correlated with hardening. Over 50% of South Atlantic and Gulf of Mexico coasts are fringed with tidal wetlands that could be threatened by future hardening, based on projected population growth, storm frequency, and an absence of coastal development restrictions.

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Although coastal regions constitute less than 4% of the Earth's land area, coastal habitats (eg beaches and tidal wetlands; Figure 1) rank among the most valuable natural resources globally (MA 2005). Over one-third of the human population lives within 100 km of a coastline and development is increasing rapidly in most coastal regions of the world (MA 2005). Coastal development is vulnerable to damage and loss from erosion, including ambient waves, flooding, storms, and sea-level rise (SLR) (Peterson *et al.* 2008).

Historically, shoreline hardening has been a common response to coastal erosion, storm risks, and SLR, particularly in industrialized countries with large coastal populations, such as the US, the Netherlands, and Japan (Dugan *et al.* 2011). Shoreline hardening or armoring is defined as the construction or placement of vertical seawalls or bulkheads, sloped riprap (eg rocks) revetments, groins, jetties, or breakwaters along a shoreline (Figure 1). Although humans have been armoring coastlines for centuries, the extent and rate at which this occurs has increased markedly since 1900, and the effects of armoring on coastal ecosystem functions and services have only recently begun to be evaluated (NRC 2007).

Hardening of shorelines by means of seawalls or bulkheads can steepen and shorten shallow intertidal habitat over time (Dugan *et al.* 2008). The structures themselves also provide less physically complex habitat as compared with natural shorelines, so that hardened shorelines generally support fewer species (Figure 1; Seitz *et al.* 2006; Gittman *et al.* in press). When constructed landward of tidal wetlands, hard structures may also increase seaward scour during storm events and can prevent upslope migration of tidal wetlands as sea level rises, leading to their eventual loss (termed "coastal squeeze"; Doody 2004).

Despite its adverse ecological effects, efforts to understand the underlying causes and rates of shoreline armoring have been limited (Dugan *et al.* 2011). Filling these data gaps could help determine where and how much shoreline is at risk. More specifically, identifying shorelines with tidal wetlands that are threatened with hardening will help coastal managers to adopt more stringent regulations for shoreline armoring that could prevent future wetland losses. The purpose of this study was to: (1) catalog tidal shoreline hardening in all continental US coastal counties; (2) determine which physical and socioeconomic features of a coastal region may be more commonly associated with armoring; (3) identify regions of the US likely to experience continued hardening and subsequent coastal habitat loss; and (4) identify alternative management strategies for coastal protection.

Methods

We selected the US for our analysis because of its extensive coastline, high coastal population density (39% of the population lives in coastal counties), and data availability, as well as its vulnerability to shoreline erosion, flooding, and property damage (MA 2005; NOAA 2013). Furthermore, in the US, there is growing interest in developing a national coastal protection and adaptation

[1]*Institute of Marine Sciences, University of North Carolina at Chapel Hill, Morehead City, NC;* [†]*current address: Marine Science Center, Northeastern University, Nahant, MA* [*]*(r.gittman@neu.edu);* [2]*US Coast Guard, Portsmouth, VA;* [3]*Department of Biology, University of North Carolina at Chapel Hill, Chapel Hill, NC;* [4]*Center for Coastal Fisheries and Habitat Research, National Oceanographic and Atmospheric Administration, Beaufort, NC*

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(a–h) R Gittman

Figure 1. *Types of natural and artificially hardened shorelines found in the US: (a) rocky shore; (b) beach; (c) tidal marsh; (d) mangrove; (e) seawall; (f) riprap revetment; (g) bulkhead; and (h) breakwater. For images of other shoreline types found in the US, refer to the NOAA ESI shoreline types image gallery (http://response.restoration.noaa.gov/esi-shoreline-types).*

framework in response to changing climatic conditions (Peterson *et al.* 2008; Arkema *et al.* 2013).

Estimation of shoreline hardening along the US coast

We used the National Oceanic and Atmospheric Administration (NOAA) Office of Response and Restoration's Environmental Sensitivity Index (ESI) geodatabases to calculate the linear kilometers of total shoreline and kilometers of hardened shoreline for each coastal county within the continental US (NOAA 2005). The ESI identifies 15 shoreline types (eg Type 1: exposed rocky shore or seawall) that are further subdivided into more specific shoreline types (eg Type 1A: exposed rocky shores; Type 1B: exposed, solid, man-made structures [seawalls]; Figure 1; WebTable 1). We grouped all man-made structures (seawalls, bulkheads, riprap structures [revetments, breakwaters, groins/jetties], and hybrid seawall/bulkheads with riprap) to calculate the cumulative lengths of hardened shoreline (Figure 1; WebTable 1). We divided each state's ESI shoreline by coastal county and, for the Pacific and Atlantic coasts, by whether the shoreline was "open" (ie directly exposed to the ocean) or "sheltered" (ie located in a bay, sound, lagoon, or tidally influenced river). We did not divide the Gulf of Mexico coast into "open" or "sheltered" categories because much of the Gulf coastline (eg the Louisiana coastline, the Big Bend region of Florida) consists of reticulated wetlands that cannot be easily classified in this way. We then calculated the length (in kilometers) of tidal shoreline (total and armored), as well as the percentage of hardened shore for each county. Additionally, we calculated the length of tidal wetland shoreline (total and armored).

Regression tree analyses

To evaluate the relationship between potential drivers and the percentage of hardened shoreline in each US coastal county, we considered the following factors: 2010 housing density (units per square kilometer), 2010 gross domestic product (GDP, expressed in US dollars), coastal slope (%), accretion/erosion rates (meters per year [m yr^{-1}]), geomorphology, mean tidal range (m), mean wave height (m), relative SLR (millimeters per year [mm yr^{-1}]), storm frequency between the years 1970–2010, relative county shoreline position (north to south or west to east along the coast), and years since a ban on shoreline hardening was passed (sources included: the US Census Bureau, the National Ocean Economics Program, the US Geological Survey Coastal Vulnerability Index [USGS CVI] [for a description of the variables, see Hammer-Klose and Thiehler 2001], the Federal Emergency Management Agency's US Presidential Major Disaster and/or Emergency Declarations [FEMA 2014], and federal and state legislation and permitting procedures).

We ran separate regression trees for the Atlantic open and sheltered coasts, the Pacific open and sheltered coasts, and the Gulf of Mexico coast, to describe differences among county-level shoreline hardening patterns, vis-à-vis repeated partitioning of county armoring percentages into increasingly homogeneous groups based on serial, bimodal splits among potential drivers of hardening (De'ath and Fabricius 2000). Because USGS CVI data were not available for the Pacific sheltered coastal coun-

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ties, the regression tree for the Pacific sheltered coast does not include these factors. We developed regression trees using the analysis of variance (ANOVA) method of recursive partitioning and we pruned over-fitted trees using *k*-fold cross-validation. We ran all regression tree analyses using R version 3.1.0 and rpart (Therneau *et al.* 2014).

Results

The continental US was estimated to have 160 168 km of tidal shoreline, of which 22 842 km (14%) was hardened (WebTable 2). Brackish and salt marsh were the dominant types of tidal wetland found along US coasts, making up 48% of the total US shoreline (WebTable 3). Approximately 1% (886 km) of existing tidal marsh shoreline has been armored (eg a hard structure has been built along and typically landward of the marsh) (WebTable 3), although this does not account for marsh already lost on the seaward side of man-made structures.

Shoreline hardening along US open coasts

Along the open coasts of the Atlantic and Pacific, 846 km (9%) of the shoreline has been hardened (Figures 2a and 3a). Atlantic coastal counties that experienced 17 or more storm events between 1970 and 2010 (in Massachusetts, Maine, and New Hampshire) had a higher percentage of hardened shoreline (μ = 30.7 ± 9.6%) than counties that experienced fewer than 17 storms (μ = 8.3 ± 1.4%, R^2 = 0.25; Figure 2a). The percentage of armoring along the Pacific open coast was higher (μ = 24.1 ± 2.8%) in counties where the mean wave height was <1.3 m (ie counties in southern California) (Figure 3a). Counties with mean wave heights ≥1.3 m and located south of San Francisco County, California, had more hardening (μ = 11.0 ± 2.7%) than counties north of San Mateo County, California (μ = 2.4 ± 0.9%). Mean wave height accounted for 70% of the variance in hardened shoreline along the open Pacific coast (R^2 = 0.80, full tree).

Shoreline hardening along US sheltered coasts

Despite a considerable amount of hardening along open coast-

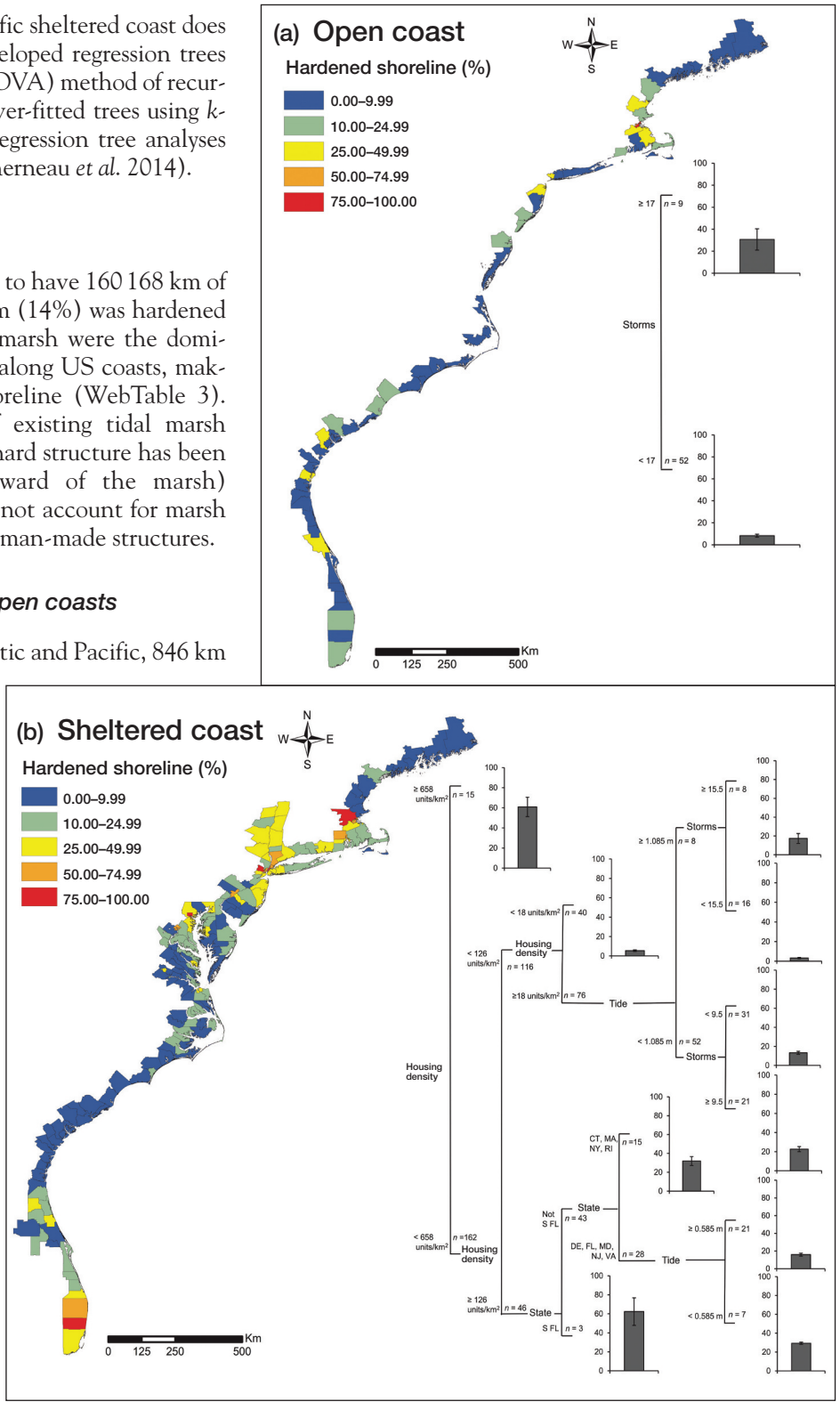

Figure 2. *The percentage of total tidal shoreline hardened by county and the regression tree results for (a) the Atlantic open coast and (b) the Atlantic sheltered coast. "Housing density" is the number of individual housing units per square kilometer (as defined by the US Census Bureau), "Storms" are the total number of storms that resulted in a US Presidential Major Disaster and/or Emergency Declaration from 1970 to 2010 (FEMA 2014), "Tide" is the mean tide range (m), "State" is the state in which the shoreline is found, and "n" is the number of counties split into each node and used to calculate the percentage of hardened shoreline. Error bars represent one standard error.*

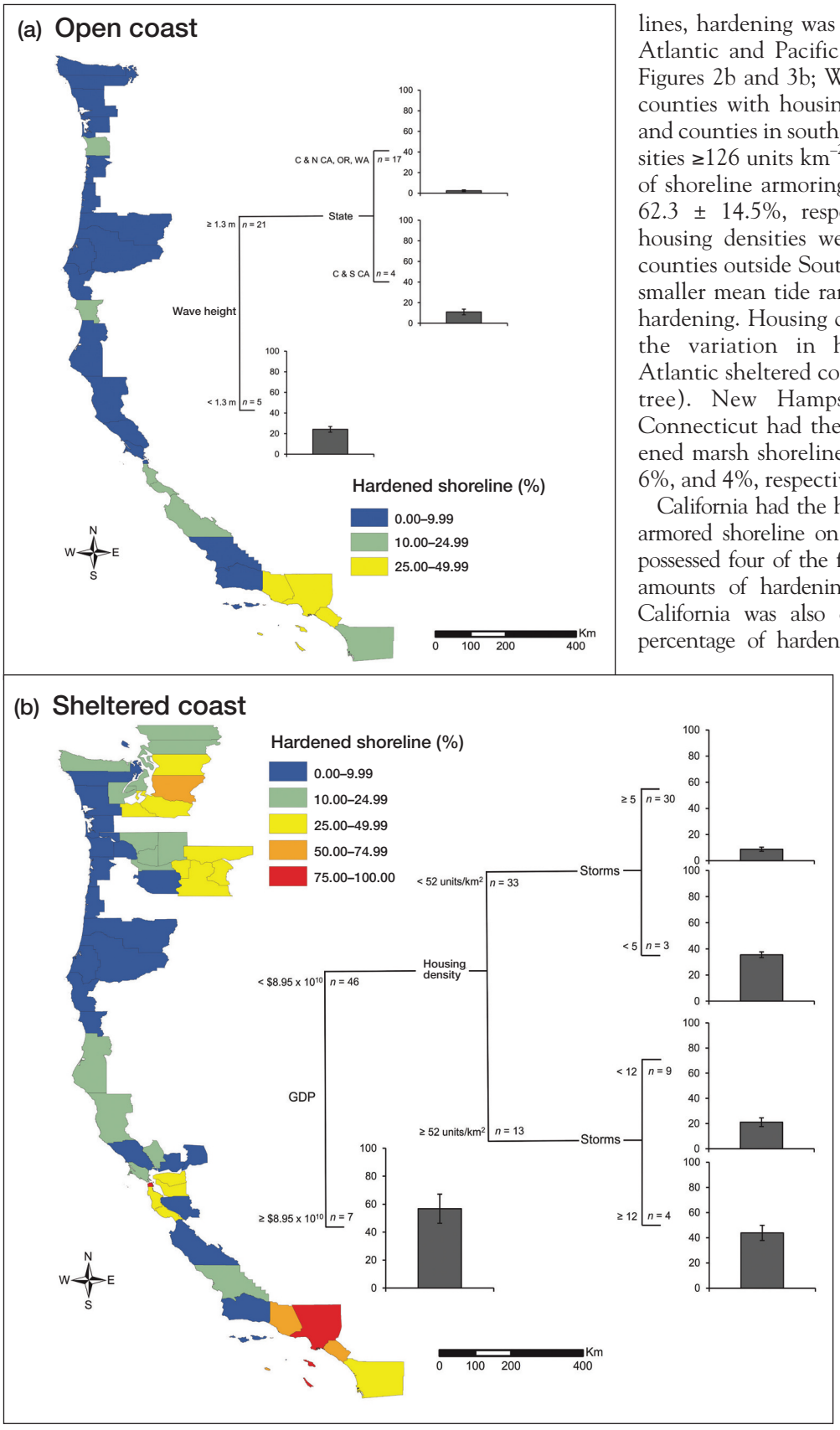

Figure 3. *The percentage of total tidal shoreline hardened by county and the regression tree results for (a) the Pacific open coast and (b) the Pacific sheltered coast. "Wave height" is the mean wave height (m); "GDP" is the 2010 US gross domestic product (US$, as defined by the US Bureau of Economic Analysis); and "Housing density", "Storms", "State", "n", and error bars are defined as in Figure 2.*

lines, hardening was more prevalent on sheltered Atlantic and Pacific coasts (14% or 14 607 km; Figures 2b and 3b; WebTable 2). Atlantic coastal counties with housing densities ≥ 658 units km^{-2} and counties in southern Florida with housing densities ≥126 units km^{-2} had the highest percentages of shoreline armoring (μ = 60.9 ± 4.8% and μ = 62.3 ± 14.5%, respectively; Figure 2b). When housing densities were <126 units km^{-2} and in counties outside South Florida, fewer storms and a smaller mean tide range were associated with less hardening. Housing density accounted for 41% of the variation in hardened shoreline among Atlantic sheltered coastal counties (R^2 = 0.72, full tree). New Hampshire, Rhode Island, and Connecticut had the highest percentage of hardened marsh shoreline on the Atlantic coast (7%, 6%, and 4%, respectively; WebTable 3).

California had the highest percentage of sheltered armored shoreline on the Pacific coast (28%) and possessed four of the five counties with the greatest amounts of hardening (Figure 3b; WebTable 3). California was also characterized by the highest percentage of hardened marsh shoreline (2%) on the Pacific Coast; in San Francisco County, for instance, 71% of marsh shoreline had been armored (WebTable 3). Counties with the highest GDP (≥ $8.95 × 10^{10}) along the Pacific sheltered coast also had the highest percentages of hardened sheltered shorelines (μ = 56.7 ± 10.4%; Figure 3b). When GDP was < $8.95 × 10^{10}, and housing density was ≥ 52 units km^{-2}, counties with more frequent storms also had higher percentages of armoring (μ = 43.9 ± 6.0%) than counties with the same housing densities but with fewer than 12 storms (Figure 3b). GDP and housing density accounted for 53% of the variance in hardened shoreline percentages along the sheltered Pacific coast (R^2 = 0.69, full tree).

Shoreline hardening along the US Gulf of Mexico coast

The Gulf of Mexico coast had the same percentage of

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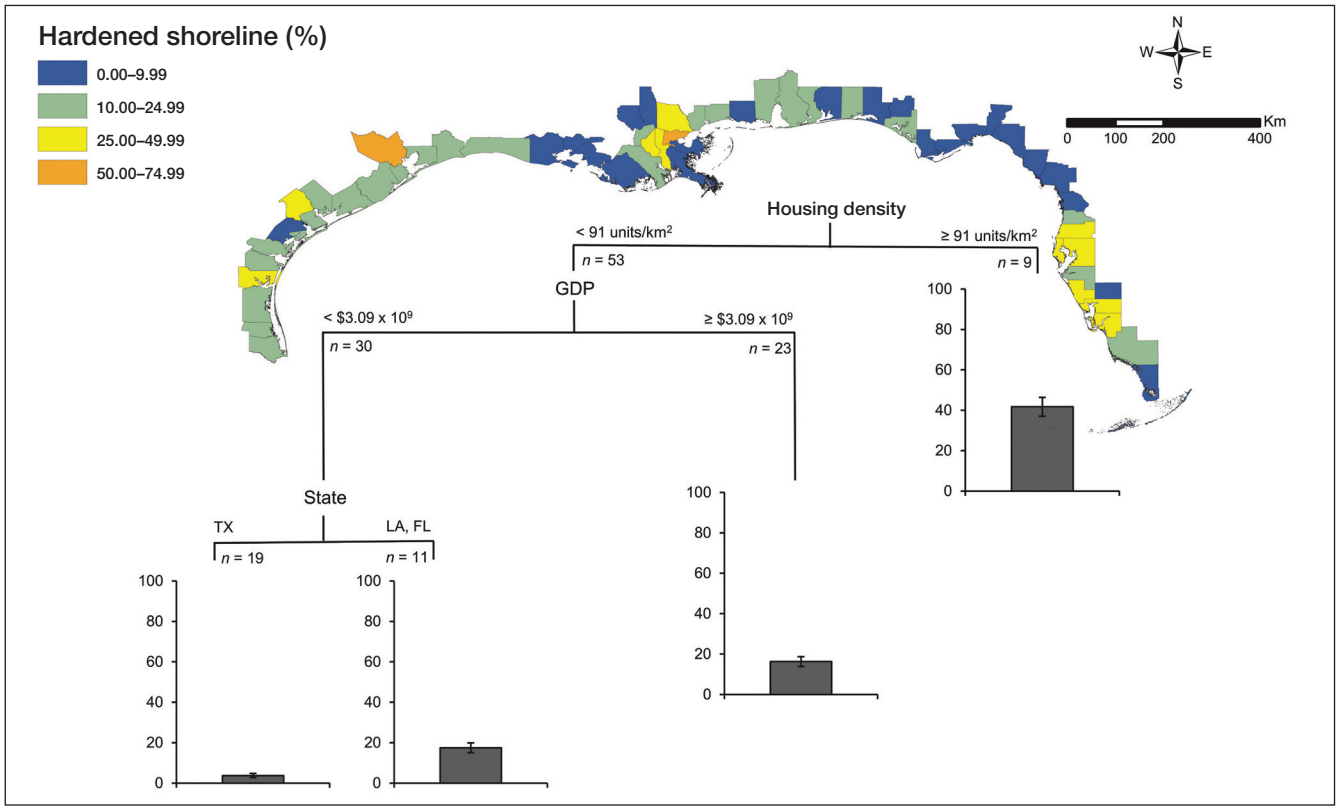

Figure 4. *The percentage of total tidal shoreline hardened by county and the regression tree results for the Gulf of Mexico coast. "Housing density", "GDP", "State", "n", and error bars are defined as in Figures 2 and 3.*

hardened shoreline (16%) as the entire Pacific coast (this percentage drops to 9% when all of the highly reticulated marsh shoreline of Louisiana is included) (WebTable 2; Figure 4). Counties with higher housing densities (≥91 units km^{-2}, eg Orleans Parish, Louisiana; Harris County, Texas) had higher percentages of armoring (μ = 41.7 ± 4.7%) than counties with lower housing densities (Figure 4). When GDP was < $\$3.09 \times 10^9$, Gulf counties in Texas had more hardening (μ = 16.3 ± 2.5%) than Gulf counties outside of Texas (μ = 3.7 ± 1.1%; Figure 4). Housing density alone partitioned 46% of the variation in the percentage of hardened shoreline along the Gulf coast (R^2 = 0.56, full tree). Texas had more than five times as much armored marsh shoreline (6%) than other Gulf states (0.4–1.4%) (WebTable 3).

Discussion

Our analysis indicates that 14% of the contiguous US shoreline is hardened and that 64% of armoring has occurred along Atlantic and Pacific sheltered shorelines, such as estuaries, lagoons, and tidally influenced rivers (WebTable 2; Figures 2b and 3b). Thus, shoreline hardening is likely a substantial yet largely understudied means by which humans modify and degrade coastal ecosystems in the US.

Potential drivers of shoreline hardening

Understanding the potential drivers of shoreline hardening could help identify where and how much shoreline and associated habitats are at risk of being lost to this process in the near future. Our analyses revealed that housing density and GDP, respectively, were the best predictors of armoring on US Atlantic and Pacific sheltered coasts, as well as along the Gulf of Mexico coast (Figures 2–4). Globally, man-made shoreline structures are associated with densely populated coastlines (eg around the Mediterranean), and have been used to protect both commercial and residential development and infrastructure for generations (Dugan *et al.* 2011). Most major US coastal metropolitan areas are located on sheltered coasts and tend to be heavily armored (eg New York, Los Angeles, New Orleans), regardless of other physical shoreline characteristics or processes.

Coastal metropolitan areas also support development in neighboring coastal counties (eg for the purposes of industry and tourism); this likely contributes to the spread of shoreline hardening, despite relatively low housing densities in these adjacent areas (Figures 2b, 3b, and 4; NOAA 2013). Specifically, these regions have a history of coastal modification that includes dredging of canals, to support shipping traffic from major ports (eg New York, Corpus Christi, Miami) and for flood control (eg South Florida canal systems), that probably contributed to hardening (US Census Bureau 2010).

Outside of metropolitan areas, the addition of man-made structures is more closely related to the vulnerability of coastal developments to damage from physical processes (eg storms, erosion). Along the Pacific open coast, the rocky shorelines of northern California, Oregon, and

Washington are associated with wave heights greater than 1.3 m, and are therefore not suitable for most types of development; this may be the reason for the lesser degree of armoring in these regions (Figure 3a). The regression tree selected a single variable that reduced the most variance in shoreline hardening; however, wave height was also strongly positively correlated with both county location (R^2 = 0.82) and the number of years since a ban on shoreline hardening was implemented (R^2 = 0.67).

Greater storm frequency was the most important predictor of armoring on the Atlantic open coast (Figure 2a). Hard structures are often built along coastlines in response to damage and erosion from major storm events (eg seawall construction in Galveston, Texas, following a major hurricane; Hansen 2007); areas prone to major storms would therefore be expected to have more hardened shoreline. However, there is evidence that natural beach dune and marsh shorelines experience less erosion and damage than hardened shorelines during single storm events (Thieler and Young 1991; Gittman *et al.* 2014). Given the uncertainty associated with the performance of bulkheads and seawalls during these storm events, the use of hard structures in response to storms should be evaluated further.

Given the strong relationships between both housing density and GDP and shoreline hardening, other socioeconomic factors we did not include – such as commercial and recreational shoreline uses, coastal land ownership (public versus private), and coastal property values – may provide additional insights into the patterns of observed shoreline hardening in the US. Further refinement of the relationship between socioeconomic factors and armoring will allow policy makers and coastal-resource managers to develop targeted strategies (eg tax breaks for waterfront property owners that choose not to build a bulkhead or seawall) for reducing shoreline hardening in areas with vulnerable coastal habitats. These approaches may become increasingly fine-tuned as we learn more about how construction/repair costs or the cascading effects of neighboring shoreline hardening (Scyphers *et al.* 2015) drive decisions regarding shoreline maintenance.

Predictions for future hardening and habitat loss

Although European countries have been adding man-made structures to their shorelines for centuries, in the US, most of this construction likely occurred after 1900 (Dugan *et al.* 2011), making the rate of shoreline hardening in the US about 200 km yr^{-1}. If this rate remains constant and coastal populations continue to increase according to NOAA projections (NOAA 2013), the percentage of hardened shoreline will double by 2100, resulting in nearly one-third of the contiguous US coastline being armored. This projected rate is probably conservative but assumes that no additional restrictions are placed on shoreline hardening (only eight states have implemented total or partial bans on construction of hard structures along the shore).

Some of the largest increases in population density are predicted to occur along the South Atlantic and Gulf coasts, where most of the US's remaining tidal salt marshes (>50%) and mangrove forests (100%) are currently found (WebTable 3; Kennish 2001). As much as 50% of US salt marsh has been lost over the past century, largely as a result of human activities (Kennish 2001). Although only a small percentage (1%) of existing tidal wetlands is currently hardened, this percentage does not account for the wetlands likely lost in the past to hardening (WebTable 3). On the Atlantic coast, 60% of the land between 0–1 m above current sea level is expected to be developed and hardened, thereby resulting in a large-scale coastal squeeze on tidal wetlands (Titus *et al.* 2009). Given the prevalence and ecological consequences of shoreline hardening, steps should be taken to reduce the rate of armoring and to implement alternative stabilization strategies (eg submerged sills, marsh planting; see Gittman *et al.* in press).

Conclusions

Our assessment demonstrates that much of the US shoreline is vulnerable to future habitat loss if actions are not taken to revise current coastal management strategies. Our estimate – that 14% of US tidal shoreline is hardened – is conservative, as all types of tidal shoreline were included in our analysis. When shorelines that are not likely to be armored (eg naturally rocky shores) are excluded, the majority of the natural shoreline most vulnerable to future hardening (eg beaches, wetlands) is found along the Gulf of Mexico and South Atlantic coasts. Given the projected increases in population for these two regions, these coasts will likely experience the highest rates of future hardening and the associated loss of marsh and other vegetated intertidal habitat to coastal squeeze (Doody 2004). This, in turn, will result in the loss of critical coastal ecosystem services such as provision of nursery habitat for commercially and recreationally valuable fish and crustaceans, filtration of nutrients and pollutants from terrestrial runoff, carbon burial, and erosion protection (Peterson *et al.* 2008).

Further analyses of the socioeconomic drivers of shoreline hardening are needed to determine how to prevent or reduce further destruction of sensitive habitats such as tidal wetlands. Although our analysis provides baseline estimates of armoring, continued updates will be required to calculate region-specific rates. Coastal managers could use these rates to assess the cumulative impacts on coastal habitats and to assess the risk of future habitat loss. Policy makers should also use these assessments to develop informed legislation and regulations, including a revision of the US Army Corps of Engineers' policy on nationwide permits to account for the future loss of habitat as a result of coastal squeeze, which will likely extend well beyond the construction footprint of a hard structure. Finally, we recommend that new management guidelines be devel-

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oped to incorporate green infrastructure and planning for shoreline migration (eg rolling easements, bulkhead removal) with SLR. Without substantial changes to coastal management policies and development practices, the US coastlines will likely lose their natural defenses.

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Living shorelines can enhance the nursery role of threatened estuarine habitats

Rachel K. Gittman,[1,4] Charles H. Peterson,[1] Carolyn A. Currin,[2] F. Joel Fodrie,[1] Michael F. Piehler,[1] and John F. Bruno[3]

[1]*Institute of Marine Sciences, University of North Carolina at Chapel Hill, Morehead City, North Carolina 28557 USA*
[2]*Center for Coastal Fisheries and Habitat Research, National Oceanographic and Atmospheric Administration, Beaufort, North Carolina 28516 USA*
[3]*Department of Biology, University of North Carolina at Chapel Hill, North Carolina 27599 USA*

Abstract. Coastal ecosystems provide numerous services, such as nutrient cycling, climate change amelioration, and habitat provision for commercially valuable organisms. Ecosystem functions and processes are modified by human activities locally and globally, with degradation of coastal ecosystems by development and climate change occurring at unprecedented rates. The demand for coastal defense strategies against storms and sea-level rise has increased with human population growth and development along coastlines worldwide, even while that population growth has reduced natural buffering of shorelines. Shoreline hardening, a common coastal defense strategy that includes the use of seawalls and bulkheads (vertical walls constructed of concrete, wood, vinyl, or steel), is resulting in a "coastal squeeze" on estuarine habitats. In contrast to hardening, living shorelines, which range from vegetation plantings to a combination of hard structures and plantings, can be deployed to restore or enhance multiple ecosystem services normally delivered by naturally vegetated shores. Although hundreds of living shoreline projects have been implemented in the United States alone, few studies have evaluated their effectiveness in sustaining or enhancing ecosystem services relative to naturally vegetated shorelines and hardened shorelines. We quantified the effectiveness of (1) sills with landward marsh (a type of living shoreline that combines marsh plantings with an offshore low-profile breakwater), (2) natural salt marsh shorelines (control marshes), and (3) unvegetated bulkheaded shores in providing habitat for fish and crustaceans (nekton). Sills supported higher abundances and species diversity of fishes than unvegetated habitat adjacent to bulkheads, and even control marshes. Sills also supported higher cover of filter-feeding bivalves (a food resource and refuge habitat for nekton) than bulkheads or control marshes. These ecosystem-service enhancements were detected on shores with sills three or more years after construction, but not before. Sills provide added structure and may provide better refuges from predation and greater opportunity to use available food resources for nekton than unvegetated bulkheaded shores or control marshes. Our study shows that unlike shoreline hardening, living shorelines can enhance some ecosystem services provided by marshes, such as provision of nursery habitat.

Key words: bulkhead; coast; ecosystem service; erosion; fish; nekton; salt marsh; seagrass; sea-level rise; shoreline stabilization; sill; subtidal breakwater

Introduction

Ecosystem services are the direct and indirect benefits that humans derive from ecosystems, and in coastal environments include nutrient cycling, climate regulation, habitat provision for organisms of value, and recreational uses (Carpenter et al. 2009). Many human activities are degrading coastal ecosystems and the services they provide (Vitousek et al. 1997, Millennium Ecosystem Assessment [MEA] 2005, Dahl and Stedman 2013). Coastal development and global climate change, particularly sea-level rise and increased storm frequency and intensity, are threatening coastal ecosystems and have already resulted in significant losses of these ecosystems (MEA 2005, Hoegh-Guldberg

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[4]Present address: Marine Science Center, Northeastern University, Nahant, Massachusetts 01908 USA. E-mail: r.gittman@neu.edu

and Bruno 2010). With nearly 40% of the world's population living within 100 km of a coastline (MEA 2005), there is considerable need for development strategies that sustain, restore, or enhance delivery of these globally important ecosystem services (Carpenter et al. 2009).

One of the most pressing concerns over continued coastal development is protection against erosion and subsequent property loss resulting from the joint impacts of storm events and sea-level rise (Törnqvist and Meffert 2008, Temmerman et al. 2013). Traditional shoreline protection methods, such as seawalls or bulkheads, are designed to protect the shore from erosion and public or private infrastructure from flood and structural damage, but can fail during major storm events and even exacerbate impacts (Thieler and Young 1991, Gittman et al. 2014). In contrast to the putative erosion and damage protection for upland property, these structures can also induce erosion of habitats located seaward of or adjacent to the structure, resulting in the loss of valuable intertidal and/or shallow vegetated (e.g., salt/brackish/fresh marsh, seagrass, mangrove), beach, or mudflat habitat (Hall and Pilkey 1991, Doody 2004, Bozek and Burdick 2005, Dugan et al. 2008, Pontee 2013). Further, as sea levels rises, a "coastal squeeze" can occur where coastal habitat is lost from the high intertidal zone being held at a constant position by a structure and the low intertidal zone migrating landward (Titus 1998, Pontee 2013). Additionally, bulkhead and seawall shorelines support a lower abundance and diversity of benthic infauna, fish, and mobile crustaceans than natural shorelines dominated by salt marsh (Seitz et al. 2006, Bilkovic and Roggero 2008, Dugan et al. 2008, Lucrezi et al. 2010). Heightened awareness of the adverse ecological effects of "hard" shoreline protection methods and the billions of dollars in damage done to coastal properties and infrastructure by major storm events (e.g., Hurricane Katrina in 2005 and Superstorm Sandy in 2012 in the United States) have increased demand for alternative methods that incorporate natural components for coastal protection (Arkema et al. 2013, Cheong et al. 2013, Gittman et al. 2015).

Some alternative methods of coastal protection, broadly termed "living shorelines," include restoration of habitats that provide natural protection from erosion, such as salt marshes and intertidal oyster reefs (Crooks and Turner 1999, Piazza et al. 2005). Living shorelines also include hybrid techniques that consist of pairing an offshore sill composed of granite boulders, concrete, marl, or oyster shell with marsh plantings (referred to as sill hereafter, see Fig. 1 for examples of sills; National Research Council [NRC] 2007, Currin et al. 2009). Over 200 projects identified as living shorelines have been permitted and constructed in the United States, with sills comprising more than half of them (Fear and Bendell 2011, Chesapeake Bay Trust 2014, Coasts, Oceans, Ports and Rivers Institute [COPRI] 2014). The goals of these projects are to go beyond providing erosion protection to include sustaining additional ecosystem services, such as provision of habitat for various marine organisms and filtration of nutrients or pollutants (Coasts, Oceans, Ports, and Rivers Institute (COPRI) 2014). However, few studies have assessed the success of living shoreline approaches in sustaining or enhancing ecosystem services (but see Currin et al. 2007, Scyphers et al. 2011, La Peyre et al. 2014). Furthermore, existing studies have only evaluated the short-term ecological functions of living shorelines (<3 years post-construction) and have not included comparisons to the ecological functions of bulkheaded shores.

We hypothesized that hybrid living shorelines, sills with landward marsh, would support higher abundances, biomass, and diversity of mobile fishes and crustaceans (nekton), particularly juveniles and estuarine residents, than fringing salt marshes alone or than unvegetated bulkheads. Our hypothesis is based on the expectation that sills would enhance preexisting uses of habitat through one or both of the following mechanisms: (1) increasing the structural complexity of the habitat and providing spatial refuge from predation and environmental stress (i.e., wave exposure); and (2) increasing resource (food) availability via providing additional substrata for epibiota (prey) and organic matter deposition. Nekton abundance and production are positively related to structural habitat complexity, such as submerged aquatic vegetation (Orth et al. 1984, Bell and Westoby 1986), oyster reefs (Grabowski and Peterson 2007, Grabowski et al. 2008, Stunz et al. 2010), and salt marshes (Peterson and Turner 1994, Minello et al. 2003) relative to mudflat or sandy bottom habitats, which lack emergent structure. The addition of sills may increase the availability of structured habitat by providing novel substrate for the settlement of foundation species such as oysters and mussels, and may increase the deposition of other organic materials as food resources (Peterson et al. 2003). To test our hypothesis, we compared nekton catch rates and diversity along sills of varying ages (0–8 years) to shorelines with natural, fringing salt marshes, and to bulkheaded shorelines without marsh.

Methods

Study design

To ensure our study would provide a comprehensive assessment of nekton use of habitats associated with different shore stabilization approaches, we made four independent comparisons of nekton catch rates along different types of shorelines. We first compared nekton catch rates and diversity in intertidal marsh (Appendix S1: Fig. S1A) and shallow subtidal habitat (Appendix S1: Fig. S1B) between sites with sills (three or more years after sill construction) and sites without sills (control marsh sites), referred to as the control–impact

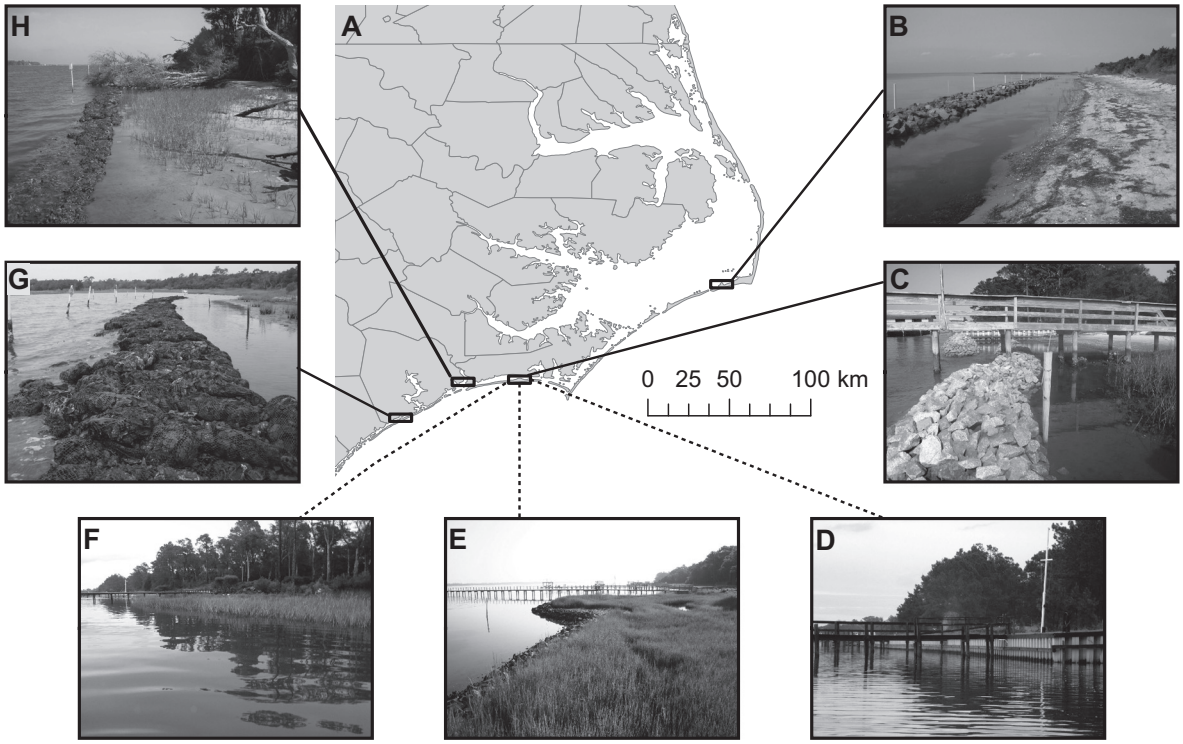

FIG. 1. (A) Map of locations of the (B) before–after-control–impact (BACI) sill site and control marsh site (not pictured) on Hatteras Island, Outer Banks, North Carolina, USA; (C) BACI sill, (D) bulkhead (one of three), (E) control–impact (CI) sill (one of three), and (F) control marsh sites (one of three) in Pine Knoll Shores (PKS), North Carolina; (G) the BACI oyster bag sill site and control marsh site (not pictured) at Morris Landing, Holly Ridge, North Carolina; and (H) the BACI oyster bag sill site and control marsh site (not pictured) on Jones Island, Swansboro, North Carolina. Solid lines to photographs indicate BACI sites and dotted lines to photographs indicate CI sites. As shown in the photographs, the BACI and CI sills have varied designs in terms of structure material (granite vs. oyster shell) and different distances between breaks in the sill. Photo credit: R. K. Gittman.

(CI) study. We also compared nekton catch rates and diversity in intertidal marsh and shallow subtidal habitat before and after sill construction to nekton catch rates and diversity at control sites, referred to as the before–after-control–impact (BACI) study. We then determined if nekton catch rates and diversity in habitat adjacent to sills differed between a newly constructed sill and sills that had been in place for three or more years (the period of time estimated to be necessary for nekton to respond to new habitat; La Peyre et al. 2014). To make this determination, we compared nekton catch rates and diversity at a BACI sill less than 1 yr after construction and at three CI sill sites (one sill 3 yr and two sills 8 yr after construction) within the same geographic region. Finally, we compared nekton catch rates and diversity in unvegetated intertidal habitat adjacent to sills, adjacent to bulkheads with no marsh, and adjacent to control marsh sites (Appendix S1: Fig. S1S3), referred to as the bulkhead comparison (BC) study. To identify factors (e.g., increased structural complexity) potentially associated with differences in nekton catch rates and diversity among different shoreline types, we also measured habitat characteristics at each shoreline type.

Description of study sites

The CI study consisted of surveying three existing granite sills and three control marsh sites located in Pine Knoll Shores (PKS), North Carolina, USA (Fig. 1A; 34°42′11″ N, 76°48′21″ W). At each sill site, a sill consisting of piled granite boulders (20–50 cm diameter) was constructed between 2002 and 2007 (Fig. 1E). The elevation of the base of each sill was between 0.14 and 0.31 m below mean sea level (MSL). Each sill had a mean height ranging from 0.2 m (base to top of the sill) for the oldest sill to 0.56 m for the youngest sill. Each sill also had either a drop-down (area of lower elevation interrupting the sill crest; Appendix S1: Fig. S2S1) or an overlapping gap (a break in two sill sections; Appendix S1: Fig. S2S2) to allow water to flow behind the sill at intervals of every ~20 m for the entire length of the sill (range: 40–100 m long). Marsh grasses, *Spartina alterniflora* and *S. patens*, were planted behind each sill along the lower

edge of existing marsh at elevations consistent with the positions of these two grasses in nearby unmodified marshes (Currin et al. 2007; J. Shallcross and J. Best, *personal communication*). To minimize site-specific differences that may affect nekton catch rates, we paired each sill site with a control site with similar physical characteristics (e.g., marsh width, wave exposure) and close proximity (<200 m) along the same shoreline (Fig. 1F).

BACI sites were located in PKS, Hatteras (35°13′18″ N, 75°41′35″ W), Swansboro (34°41′49″ N, 77° 6′24″ W), and Holly Ridge, North Carolina (34°28′12″ N, 77°30′28″ W; Fig. 1A). At each site, a low sill, consisting of granite boulders (Hatteras and PKS, Fig. 1B, C) or oyster shell bags (Holly Ridge and Swansboro, Fig. 1G, H), was constructed to a height just above MSL. Each sill had a mean height ranging from 0.3 m (oysterbag sills) to 0.7 m (stone sills). As with our CI sites, *S. alterniflora* (low marsh) and *S. patens* (high marsh) were planted behind the sill at elevations consistent with nearby marshes. The Swansboro, Hatteras, Holly Ridge, and PKS sills were constructed in September 2010, March 2011, November 2011, and April 2012, respectively. The Swansboro and Hatteras sill sites were planted in May 2011 and the Holly Ridge sill site was planted in May 2012. The PKS sill site was not planted during the study period. A marsh control site was selected as described for CI sites. The PKS sill site from this BACI study was also compared to the CI study sill sites to test for the effects of sill age on ecosystem service delivery (nekton use).

For the BC study, we selected three bulkheaded sites with no seaward marsh in PKS along the same shoreline as the CI sills and control marshes (Fig. 1D–F). Each bulkhead consisted of a vertical vinyl wall constructed at the observed high water mark (OHWM) or ~0.59 m above MSL (tide data *available online*).[5]

Nekton sampling

We conducted all nekton sampling monthly from June to October, with CI, BACI, and BC sampling occurring in 2010, from 2010 to 2012, and in 2011, respectively. We sampled nekton utilizing the marsh (defined here to include the marsh interior, marsh edge, and unvegetated mudflat within 3 m of the marsh edge) at paired sill and control marsh sites (CI study) by simultaneously setting two fyke nets at each site during a night spring high tide and recovering gear during the subsequent low tide (~6-h sets; Appendix S1: Fig. S1S1). Fyke nets were placed at the sill drop-downs or gaps at the sill sites (Appendix S1: Fig. S13) and haphazardly along the edge of control marsh sites. Fyke net openings were set at approximately the same distance from the marsh edge (3–5 m, depending on sill location relative to the marsh edge) at each paired site (Rozas and Minello 1997, Currin et al. 2007). The fyke nets consisted of a 0.9 × 0.9 × 5.1 m compartmentalized, 3.175-mm-mesh bag with 0.9 × 5.1 m wings that stretched out from the bag (set for a total mouth width of 8 m). To determine nekton catch rates and diversity of subtidal habitats adjacent to sills and at control sites (CI study), we seined two times parallel to the shoreline for 20 m (~5 m from the sill or marsh edge) at each site during afternoon spring low tides (Appendix S1: Fig. S1S2). Seines were 7.3 m wide by 1.8 m tall, made from 3.175-mm mesh, and included a 1.8 × 1.8 × 1.2 m bag. Nekton use of unvegetated subtidal habitat within 1 m of sills (between the sills and landward marsh edges), and seaward of bulkheads and control marshes was assessed by setting replicate (n = 10) minnow traps (3.175-mm-galvanized mesh) at the edge of each shoreline type 2 h before high tide and collecting the traps 2 h after high tide (Appendix S1: Fig. S1S3). We opted for a maximum minnow trap soak time possible for our study sites, as the unvegetated edge of the marsh and mudflat adjacent to the bulkheads samples becomes exposed 3 h after high tide. Our results are nonetheless conservative measures of abundance, and observed differences between sills, control marshes, and bulkheads are likely greater than what was observed in our study. This interpretation of soak time bias is consistent with Teo and Able (2003), who also found large differences between sites with a soak time of greater than 60 min and assumed that these differences were conservative.

Nekton was identified to species, when possible, counted, and weighed wet, before the first 20 of each species were measured for standard length (fish and shrimp) or carapace length (crabs) either in the field or in the lab (after being held or transported using buckets and air bubblers), with subsequent release. All species were classified as resident or transient and the mean length and biomass data were used to determine if a majority of individuals were juveniles or adults for each species, as per Hettler (1989) and Peterson and Turner (1994). We pooled across nets or traps at each site and abundance data are reported as catch per unit effort (CPUE) for nekton caught by all nets or traps per site per sampling effort (individuals or grams per set). Sampling effort was standardized as two fyke nets soaking for 6 h, two 20-m seine pulls, and 10 traps soaking for 4 h.

Habitat characteristics

We measured several habitat characteristics (e.g., marsh surface elevation, marsh macrophyte density, sediment organic matter [SOM] content) to better assess the relationship between shoreline type and nekton use of available habitats. To characterize the intertidal habitat structure available to nekton, we quantified total stem density of marsh macrophytes at each CI and BACI site. Five intertidal transect locations were

[5]http://tidesandcurrents.noaa.gov/waterlevels.html?id=8656483

selected using restricted random (between 10 and 20 m apart to maintain independence) sampling (Neckles et al. 2002). Transects began at the seaward edge of the marsh and continued to the start of shrub-scrub vegetation or to property-owner landscaping. Marsh plots were established at 3- or 5-m intervals along each transect beginning at the lower marsh edge. The length of each transect (5–20 m) and total number of marsh plots established (9–21) depended on the marsh width from seaward edge to upland vegetation at each site. Stem density was measured by marsh plant species per 0.25-m^2 plot (Daoust and Childers 1998). Total stem density of marsh plants was calculated by summing the stem densities of all species present within a plot. We surveyed subtidal areas up to 20 m seaward of the marsh edge to determine the type of subtidal habitat available to nekton at all CI and BACI sites (e.g., sand/mud flat, seagrass, or both). Sampling plots began at the lower marsh edge and seagrass shoot density was estimated every 5 m along each transect by counting the total number of shoots per species inside 0.25-m^2 quadrats (Hauxwell et al. 2001).

Surface elevation was measured within 1 m landward of the sill using a leveling rod and rotary laser level and referencing the measurements to semipermanent benchmarks (points established on a stable structure with unchanging elevation, e.g., a piling or tree) with elevations determined using a Trimble Virtual Reference Station (VRS; Trimble, Sunnyvale, California, USA), Real Time Kinematic (RTK), Global Positioning System (GPS). North American Vertical Datum of 1988 (NAVD88) elevations obtained using these methods are estimated to be accurate to ± 6 cm (P. Hensel, *personal communication*). To determine the availability of organic material available to benthic or filter-feeding nekton, we took sediment organic matter (SOM) samples by coring the top 3–5 cm of sediment at every plot on all site transects. Cores were transported to the lab and frozen for later analysis. For SOM analysis, a homogenized subsample of ~30 g (wet mass) was dried overnight at 100°C, weighed, and then ashed at 450°C for 6–8 h and reweighed to obtain ash-free dry mass by subtraction (Currin et al. 2007). To determine availability of epibiota (macroalgae and invertebrates) at sill, control marsh, and bulkhead sites, we sampled the sills (granite), control marsh edges (unconsolidated sediment), and bulkheads (vinyl) in September 2011. We determined the proportion and composition of epibiotic organisms attached to the substrate by determining the presence/absence of each species at each of 16 intercepts in situ using the point-intercept method within a 0.25-m^2 quadrat with a monofilament grid (Drummond and Connell 2005).

Statistical analyses

Because of natural environmental variability among our sites (e.g., proximity to channels, shoreline orientation, sample date), we paired our CI sill and control marsh sites for all analyses. We compared catch rates and Shannon-Wiener diversity indices (H') of nekton between paired CI sill sites and control marsh sites using grouped (by site), matched-pairs two-tailed t tests. Catch rates of nekton were analyzed separately for each habitat (marsh samples using fyke nets or subtidal samples using seines). We applied a sequential Bonferroni correction (Holm 1979), correcting from an initial alpha level of 0.05, separately to the following families of matched-pair t tests: (1) individuals, biomass (g), and diversity of fishes per fyke net set sampled in marsh habitat; (2) individuals and biomass (g) of crustaceans per fyke net set sampled in marsh habitat; (3) individuals, biomass (g), and diversity of fishes per seine net set sampled in seagrass habitat; and (4) individuals and biomass (g) of crustaceans per seine net set sampled in seagrass habitat. We grouped our analyses into families based on the habitat sampled (marsh or subtidal habitat) and the organism group sampled (e.g., fishes or crustaceans; Appendix S2: Table S2).

We also compared the mean total stem density (per m^2) of marsh plants, sediment surface elevation 1-m landward of the sill, and SOM (%) within the marsh using matched pairs two-tailed t tests. To determine if seagrass habitat varied between sill and control sites as a function of distance from the marsh edge (1, 5, 10, 15, and 20 m), we compared mean total shoot density (per m^2) of all seagrasses at sill and control sites using a generalized linear model (GLM). An alpha level of 0.05 was used for the individual site characteristic tests.

To compare the catch rates of nekton between BACI sill sites and control marsh sites before and after the sills were constructed, we performed separate BACI analyses (two-way ANOVAs) for each site, with treatment (sill vs. control marsh), time (before vs. after), and treatment × time as fixed factors. Sequential Bonferroni corrections were applied as described for CI analyses of nekton catch rates (Appendix S2: Table S1).

We compared the mean differences in nekton catch rates between the three CI sills and control marsh sites in PKS to the mean difference between the BACI sill (<1 yr post-construction) and control marsh in PKS site using a one-sample t test (transforming all sill-minus-control data so that BACI differences would equal 0). We also compared the mean surface elevation 1-m landward of the sill, SOM, and stem density of marsh macrophytes between each CI sill and the BACI sill using a one-sample t test. An alpha level of 0.05 was used for the individual site characteristic tests.

We compared nekton catch rates between sill, control marsh, and bulkhead-with-no-marsh sites using nested analyses of variance (ANOVAs) with treatment (sill vs. control vs. bulkhead) as a fixed factor and sampling month nested within each site.

We preferred a nested ANOVA over the matched paired analysis used to compare the sills and control marsh sites alone because unvegetated bulkhead sites could not be appropriately paired geographically to the sill and control marsh sites. Sequential Bonferroni corrections were applied as described for CI and BACI analyses of nekton catch rates (Appendix S2: Table S21).

Catch rates, density of marsh plants, and shoot density of seagrass were log-transformed prior to analysis to meet the assumptions of normality (Shapiro-Wilk Test, $P > 0.05$) and homogeneity of variance (Levene's test, $P > 0.05$). Analyses were conducted using JMP 10.0 (SAS Institute, Cary, North Carolina, USA).

Epibiotic cover data were pooled into three functional groups (bivalves, barnacles, and other foulers) and analyzed separately based upon the hypotheses that bivalve cover (oysters and mussels) should be higher on sills and along marshes than on bulkheads and that barnacle and other fouling organism cover would be lower at sites with a higher cover of bivalves. All fouling organisms other than barnacles (primarily sponges, bryozoans, and tunicates) were pooled together because their total proportion of cover was less than 0.1 across all treatments. The proportion of cover for each pooled group was zero-inflated and did not meet the assumptions of normality; therefore, we performed separate, nonparametric permutational multivariate analyses of variance (PERMANOVAs) on the Euclidean distance matrices of the univariate proportion of cover of bivalves, proportion of barnacles, and pooled proportion of other epibiota to decipher significant differences between sills, bulkheads, and control marshes. Performing a PERMANOVA on the Euclidean distance of a univariate response variable, such as total proportion of cover of barnacles, is equivalent to performing a univariate ANOVA, with the exception that the P values for a PERMANOVA are calculated using permutations rather than tabled P values, and thus do not assume normality of the data (Anderson 2005). Permutational dispersion (PERMDISP) was used to test for homogeneity of variances. PERMANOVA analyses were conducted using PRIMER-E software 6.1.1 with PERMANOVA+ 1.0.1 (Clarke and Gorley 2001, Anderson 2005).

Results

CI comparison

We found higher catch rates of fishes within the marsh at sill sites than at control sites (Fig. 2A, individuals per two fyke net sets, t ratio = −4.61, df = 14, $P > |t| = 0.0004$, and Fig. 2B, biomass per two fyke net sets, t ratio = −3.44, df = 14, $P > |t| = 0.004$). For crustaceans, we also caught more individuals per two fyke net sets within the marsh at sill sites than at control sites (Fig. 2A, t ratio = −4.13, df = 14, $P > |t| = 0.001$), but differences in crustacean biomass per two fyke net sets were nonsignificant between sill and control sites (Fig. 2B, t ratio = −1.83,

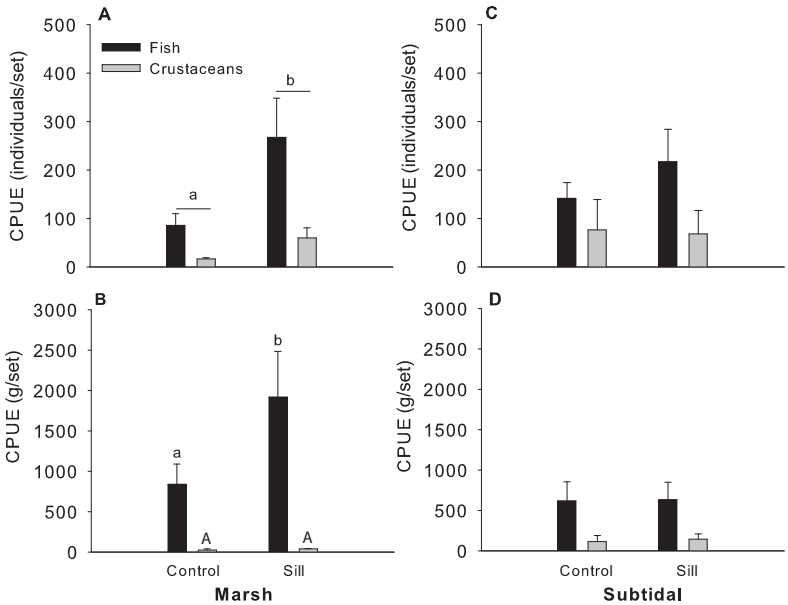

Fig. 2. Mean catch per unit effort (CPUE): (A) individuals per fyke net set in salt marsh; (B) biomass (g) per fyke net set in salt marsh; (C) individuals per seine net set in subtidal habitats; and (D) biomass (g) per seine net set in subtidal habitats. Error bars are standard error (SE). Black bars with different lowercase letters and gray bars with different uppercase letters are significantly different ($P < 0.05$).

df = 14, $P > |t| = 0.08$). The species diversity (H') of fishes within the marsh (two fyke net sets) at sill sites was greater than at control sites (t ratio = −3.83, df = 14, $P > |t| = 0.002$).

Transient fishes such as mullets (Mugil spp.), pinfish (*Lagodon rhomboides*), spot (*Leiostomus xanthurus*), mojarra (Eucinostomus spp.), flounders (*Paralichthys* spp.), speckled trout (*Cynoscion nebulosus*), pigfish (*Orthopristis chrysoptera*), and silver perch (*Bairdiella chrysoura*) dominated the fyke net catches within the marsh at both sill and control sites (making up 93% of the individuals and 92% of the biomass and 97% of the individuals and 95% of the biomass, respectively), although total abundance and biomass of each species was greater within the marsh at sill sites than control sites (Table 1). Marsh resident species, such as mummichogs (*Fundulus heteroclitus*) and striped killifish (*Fundulus majalis*), were also more abundant within the marsh at sill sites than control sites (Table 1). Marsh residents made up 7% of the individuals and 8% of the biomass caught within the marsh at sill sites and only 3% of the individuals

Table 1. Catch rates (individual [ind.] and biomass) and mean standard length (SL) of species caught in salt marsh habitat at CI sill and control marsh sites in North Carolina, USA.

	Sill			Control		
Species	Ind./6 h	Biomass (g/6 h)	SL (mm)	Ind./6 h	Biomass (g/6 h)	SL (mm)
Fishes						
Mugil spp. (T, P)	109.1 (65.9)	966.8 (490.6)	91.2 (1.8)	9.6 (6.0)	190.3 (124.5)	89.8 (4.0)
Lagodon rhomboides (T, P)	104.5 (7.9)	543.0 (134.9)	54.1 (0.8)	63.8 (16.5)	457.9 (134.9)	58.4 (1.0)
Leiostomus xanthurus (T, P)	18.4 (5.5)	72.1 (9.8)	56.4 (1.1)	5.7 (2.5)	19.9 (9.9)	51.5 (1.1)
Eucinostomus spp. (T, P)	9.7 (3.7)	23.9 (9.1)	43.0 (1.2)	1.1 (0.1)	1.9 (0.2)	46.0 (4.4)
Fundulus heteroclitus (R)	9.6 (4.1)	41.5 (20.4)	48.5 (0.8)	1.3 (1.0)	3.2 (1.8)	45.9 (1.9)
Fundulus majalis (R)	5.5 (1.8)	27.2 (10.5)	58.7 (2.1)	0.4 (0.1)	1.9 (0.8)	61.4 (4.9)
Menidia menidia (R)	2.0 (2.0)	2.0 (1.5)	45.5 (2.8)	0.1 (0.1)	0.1 (0.0)	41.0 (0.0)
Paralichthys spp. (T, P)	1.9 (0.7)	87.6 (8.7)	141.7 (17.3)	0.5 (0.2)	58.7 (36.2)	223.6 (50.0)
Cynoscion nebulosus (T, P)	1.4 (0.5)	10.9 (2.8)	63.7 (7.6)	0.4 (0.1)	19.4 (10.0)	117.6 (27.9)
Orthopristis chrysoptera (T)	1.4 (0.5)	21.2 (6.9)	80.7 (3.8)	0.7 (0.3)	14.7 (6.1)	89.5 (6.1)
Bairdiella chrysoura (T)	1.0 (0.1)	24.1 (5.5)	106.3 (5.2)	0.6 (0.2)	14.4 (2.7)	102.0 (10.9)
Menidia beryllina (R, P)	0.5 (0.3)	1.0 (0.7)	55.9 (3.5)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Cyprinodon variegatus (R)	0.4 (0.4)	1.4 (1.4)	42.3 (1.6)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Symphurus plagiusa (T, P)	0.4 (0.1)	1.3 (0.6)	59.5 (7.4)	0.1 (0.1)	0.1 (0.1)	41.3 (4.3)
Anchoa mitchilli (T, P)	0.4 (0.3)	0.2 (0.3)	48.7 (2.4)	0.1 (0.1)	0.4 (0.2)	69.0 (0.0)
Lutjanus griseus (T)	0.4 (0.2)	0.5 (0.3)	33.8 (5.0)	0.1 (0.1)	0.1 (0.1)	36.0 (1.0)
Sciaenops ocellatus (T, P)	0.2 (0.1)	20.6 (10.5)	181.7 (17.0)	0.1 (0.1)	15.8 (15.8)	245.5 (94.5)
Strongylura marina (T)	0.2 (0.0)	0.8 (0.3)	148.3 (24.9)	0.4 (0.3)	1.4 (1.4)	64.6 (32.3)
Anguilla rostrata (T)	0.1 (0.1)	11.8 (7.8)	413.0 (107)	0.1 (0.1)	20.7 (20.7)	468.5 (46.5)
Opsanus tau (R, P)	0.1 (0.1)	48.6 (48.6)	207.0 (37.0)	0.1 (0.1)	16.2 (16.2)	204.0 (0.0)
Archosargus probatocephalus (T)	0.1 (0.0)	25.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	
Chasmodes saburrae (T)	0.1 (0.1)	0.1 (0.1)	50.0 (0.0)	0.1 (0.1)	0.3 (0.3)	53.0 (0.0)
Hypsoblennius hentz (T)	0.1 (0.1)	0.1 (0.1)	45.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Sphyraena barracuda (T)	0.1 (0.1)	12.5 (12.5)	190.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Sphyraena borealis (T)	0.1 (0.1)	1.0 (1.0)	127.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Trachinotus falcatus (T)	0.1 (0.1)	0.1 (0.1)	35.0 (0.0)	0.1 (0.1)	0.0 (0.0)	0.0 (0.0)
Oligoplites saurus (T)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.1 (0.1)	0.1 (0.1)	35.0 (0.0)
Synodus foetens (T)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.1 (0.1)	0.3 (0.3)	83.0 (0.0)
Crustaceans						
Palaemonetes spp. (R, P)	31.9 (15.0)	7.1 (3.4)	22.0 (0.3)	2.3 (1.7)	0.4 (0.3)	21.6 (0.5)
Callinectes sapidus (T, P)	18.0 (5.6)	728.6 (70.1)	74.3 (1.9)	12.0 (2.1)	554.9 (120.6)	74.6 (2.3)
Penaeus spp. (T, P)	9.4 (1.0)	17.4 (5.0)	49.3 (1.4)	1.9 (0.5)	5.5 (1.5)	55.9 (3.2)
Menippe mercenaria (T)	0.1 (0.1)	14.3 (14.3)	196.0 (0.0)	0.1 (0.1)	17.1 (17.1)	79.0 (0.0)

Notes: All values are shown with standard error (SE) in parentheses. Catch rates were determined by setting nets out during a night spring high tide and recovering gear during the subsequent low tide, ~6 h later. Transient species are defined as fishes that spend only a portion of their life cycle in the estuary and are denoted with a T. Resident species spend their entire life cycle within the estuary and are denoted with an R, after Peterson and Turner (1994) and Hettler (1989). Species that were caught within the marsh at the before–after-control–impact Pine Knoll Shores (BACI PKS) sill site post-construction are denoted with a P. Standard length measurements were taken for fish and shrimp; SL values for crabs denote carapace length.

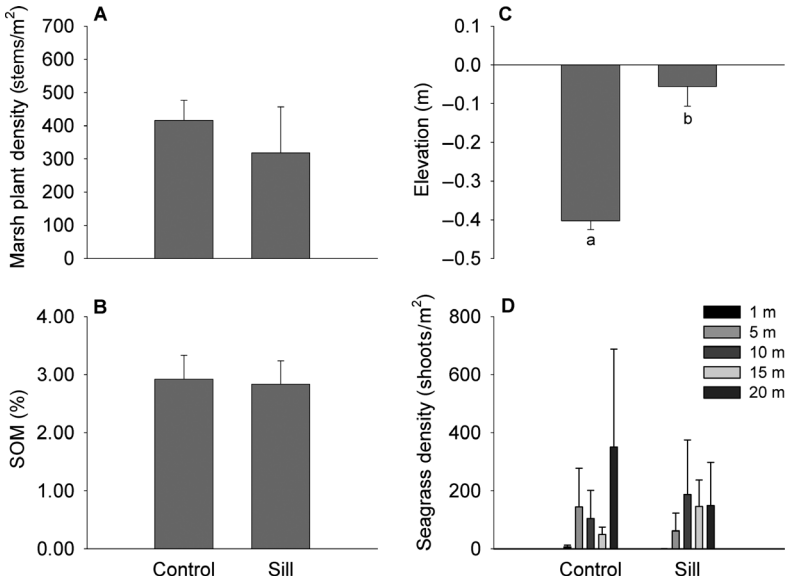

FIG. 3. Mean (A) total stem density across all species of marsh macrophytes; (B) sediment organic matter (SOM); (C) surface elevation (using North American vertical datum of 1988; NAVD88) of the mudflat within 1 m seaward of marsh edge; and (D) total seagrass shoot density across all species with increasing distance from the marsh edge (1–20 m) at CI control and sill sites. Error bars are SE. Bars with different lowercase letters are significantly different ($P < 0.05$).

and 5% of the biomass caught at control marsh sites. Crustacean catches within the marsh at both sill and control sites consisted of shrimp (Penaeid spp. and Palaemonetes spp.) and crabs (primarily blue crab, *Callinectes sapidus*), with catches of these species being greater within the marsh at sill sites than control sites (Table 1).

Catch rates and species diversity of nekton using seagrass patches or mudflat adjacent to sills or control sites were not significantly different based on seine net sampling (Fig. 2C, D, $P > 0.1$; Appendix S2: Table S22). *L. rhomboides* dominated seine net catches at both sill and control sites, making up 77% and 82% of the individuals, respectively.

Mean total density of marsh macrophyte stems and mean SOM within the marsh did not differ between sill and control sites (Fig. 3A, B, t ratio = 0.78, df = 2, $P > |t| = 0.51$ and t ratio = −0.92, df = 2, $P > |t| = 0.46$). Mean surface elevation of the unvegetated area between the sill and the landward marsh edge was greater than mean surface elevation within 1 m of marsh edge at control sites (Fig. 3C, t ratio = −6.16, df = 2, $P > |t| = 0.03$). Mean total density of seagrass shoots did not differ between sill and control marsh sites at any distance from the marsh edge (chi-squared = 0.25, df = 1, $P >$ chi-squared = 0.62, Fig. 3D).

BACI comparison

There was no effect of sill construction on nekton catch rates within intertidal (fyke net) or subtidal habitats (seine net) less than 1 yr post-construction at any of the sampled BACI sites (Fig. 4A–H, $P > 0.1$, treatment by time interaction, Appendix S2: Table S3).

CI and BACI sill comparison

The mean difference in fyke net catch rates of fishes within salt marsh habitat between older CI PKS sill sites (3–8 yr post-construction) and paired control marsh sites was greater than the difference between fyke net catch rates at the BACI PKS sill site (<1 yr post-construction) and paired control marsh site (Fig. 5A, $t = 14.4$, df = 2, $P > |t| = 0.005$). However, there was no analogous difference in crustacean fyke net catch rates ($t = 2.7$, df = 2, $P > |t| = 0.11$). Only three of six resident species caught in fyke nets at the CI sill sites were caught at the BACI sill site (Table 1). Surface elevation (m) landward of the CI sills was greater than surface elevation landward of the BACI sill (Fig. 5B, $t = 5.52$, df = 2, $P > |t| = 0.03$). SOM (%) landward of the CI sills was greater than SOM landward of the BACI sill (Fig. 5C, $t = 4.92$, df = 2, $P > |t| = 0.04$). Total stem density of marsh macrophytes was greater at CI sills than at the BACI sill; however, this difference was not significant (Fig. 5D, $t = 2.10$, df = 2, $P > |t| = 0.17$).

Comparison of sills, control marshes, and bulkheads

Catch rates (individuals and biomass per trap set) of fishes were greater along the unvegetated edge of

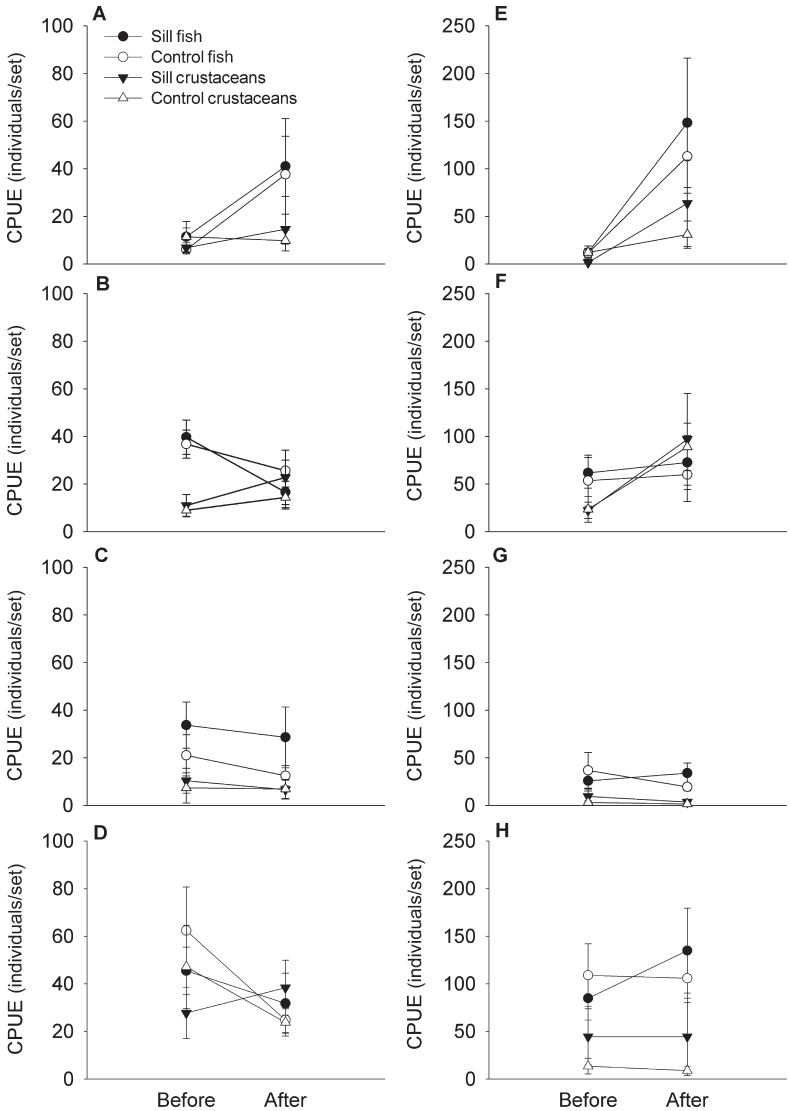

FIG. 4. Mean CPUE (individuals per set) before and after construction of the sill at Hatteras, Pine Knoll Shores, Jones Island, and Morris Landing in salt marsh (fyke net, A–D, respectively) and subtidal habitat (seine net, E–H, respectively). Error bars are SE.

sills than bulkheads (Fig. 6A, B, $P < 0.05$, Tukey's post hoc tests; Appendix S2: Table S24), while control marsh catch rates were not different from catch rates at marsh sill or bulkheaded sites (Fig. 6A, B, $P > 0.05$, Tukey's post hoc tests). Trap catch rates of crustaceans were not different along the unvegetated edge between sill, control marsh, and bulkheaded sites (Fig. 6A, B, individuals per trap set, $F = 1.14$, df = 2, $P = 0.38$, and biomass per trap set, $F = 0.04$, df = 2, $P = 0.95$). Resident marsh fishes made up 81% of the individuals and 76% of the biomass caught in traps at sill sites, while marsh residents made up only 11% of the individuals and 15% of the biomass caught at control marsh sites, and were completely absent from unvegetated bulkheaded sites (Table 2). Epibiotic cover differed between sills, bulkheads, and along the edge of the control marshes (Fig. 6C; Appendix S2: Table S25). The pooled proportion of cover by filter-feeding bivalves (oysters and mytilid mussels) was greater on sills than on bulkheads or along control marsh edges ($P < 0.05$, PERMANOVA pairwise tests). The proportion of cover by *Semibalanus* barnacles was greater on bulkheads than along control marsh edges ($P < 0.05$), but not different from sills ($P > 0.05$, PERMANOVA pairwise tests). The pooled proportion of cover by other epibiota (tunicates, sponges, and bryozoans) was greater on bulkheads than along control marsh edges and sills ($P < 0.05$, PERMANOVA pairwise tests).

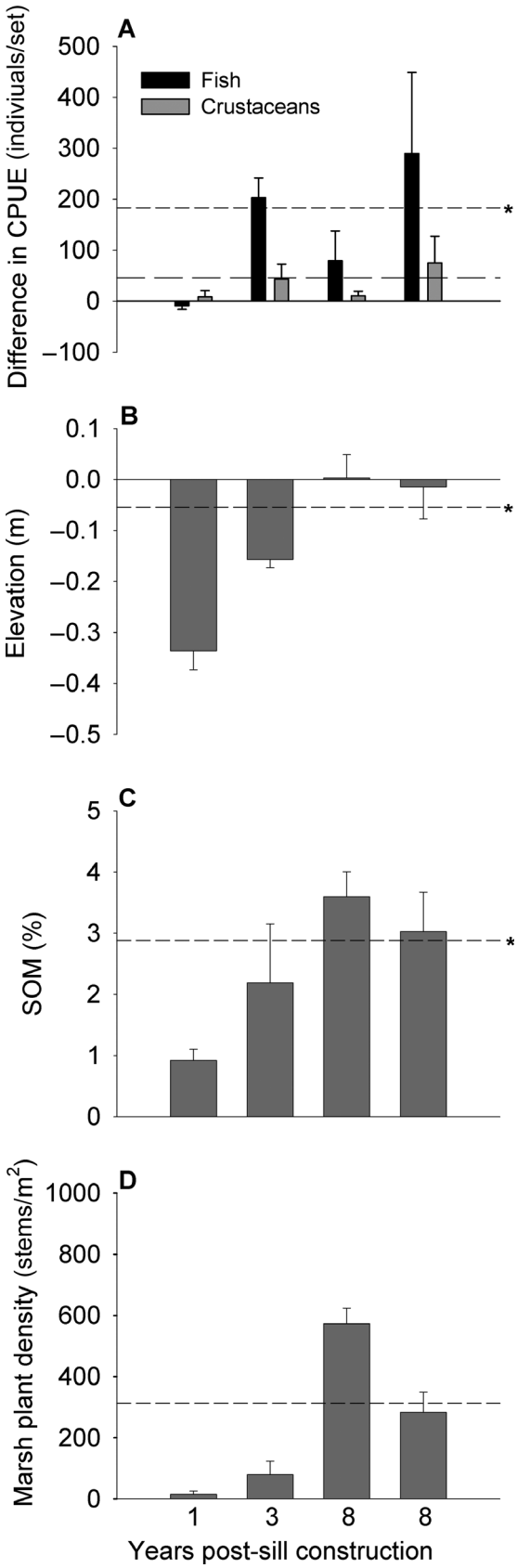

FIG. 5. (A) Change in fish CPUE (individuals per fyke net set) and crustacean CPUE between BACI (<1 yr post-construction) and CI (3 yr [one site] and 8 yr [two sites] post-construction) sill and control marsh sites in PKS. The short-dashed line represents the mean change in fish CPUE of the three CI sill sites and the long-dashed line represents the mean change in crustacean CPUE of the three CI sill sites. (B) Mean surface elevation (NAVD88) of the mudflat within 1 m landward of the sill; (C) mean SOM; and (D) mean density of marsh macrophytes at BACI and CI sill sites. The short-dashed line represents the mean surface elevation, SOM, or stem density of marsh macrophytes of the three CI sill sites. An asterisk indicates that this mean is significantly different from the mean of the BACI sill site one year after sill construction ($P < 0.05$). Error bars are SE.

DISCUSSION

Effects of sills on habitat use by fishes and crustaceans

Marshes with sills support higher abundances and diversity of fishes and higher abundances of crustaceans than marshes without sills three or more years post-construction (Figs. 2A, B and 6A, B), but this enhancement is not evident immediately after construction (≤1 year; Fig. 4A–H and 5A–D). A majority of the transient species that we caught were juveniles (Table 1), indicating that the fringing salt marshes at our sites probably serve as nursery habitat (Hettler 1989, Peterson and Turner 1994, Minello et al. 2003).

Marsh with sills may support higher abundances, biomass, and diversity of nekton via multiple mechanisms: (1) providing spatial refuges from predation for resident and juvenile fishes via increasing structural complexity of the habitat (Grabowski 2004); and (2) increasing food availability via the colonization and growth of epibiota on the sill itself and accumulation of organic material (Craft et al. 2003, Bulleri and Chapman 2010). Epibiota found on the sill (Fig. 6C), such as oysters (e.g., *Crassostrea virginica*), mytilid mussels, *Semibalanus* barnacles, and bryozoans (Bugula spp.) occur naturally on intertidal oyster reefs (Wells 1961, Fodrie et al. 2014) and may serve as food for many of the fish and crustaceans we caught, including *L. rhomboides* and *C. sapidus* (Peterson et al. 2003). We found no evidence that SOM was enhanced by the presence of a sill (Fig. 3B), rather SOM likely increased as a result of planting of marsh macrophytes landward of the sill. Therefore, the establishment of marsh seems necessary to provide SOM as trophic support for juvenile and resident nekton.

Differences in fish catch rates, particularly of marsh residents, between 1- and 3-year-old sills (Fig. 5A) may be a consequence of any of several physical and biological differences in <1-year-old BACI and ≥3-year-old CI sill sites. A lower mean surface elevation directly landward of the sill (−0.336 m NAVD88) at the PKS BACI sill site when compared to older PKS CI sill sites (−0.166 to 0.003 m NAVD88) meant greater water depths at high tide (Fig. 5B). Deeper water facilitates more access of large predators to the

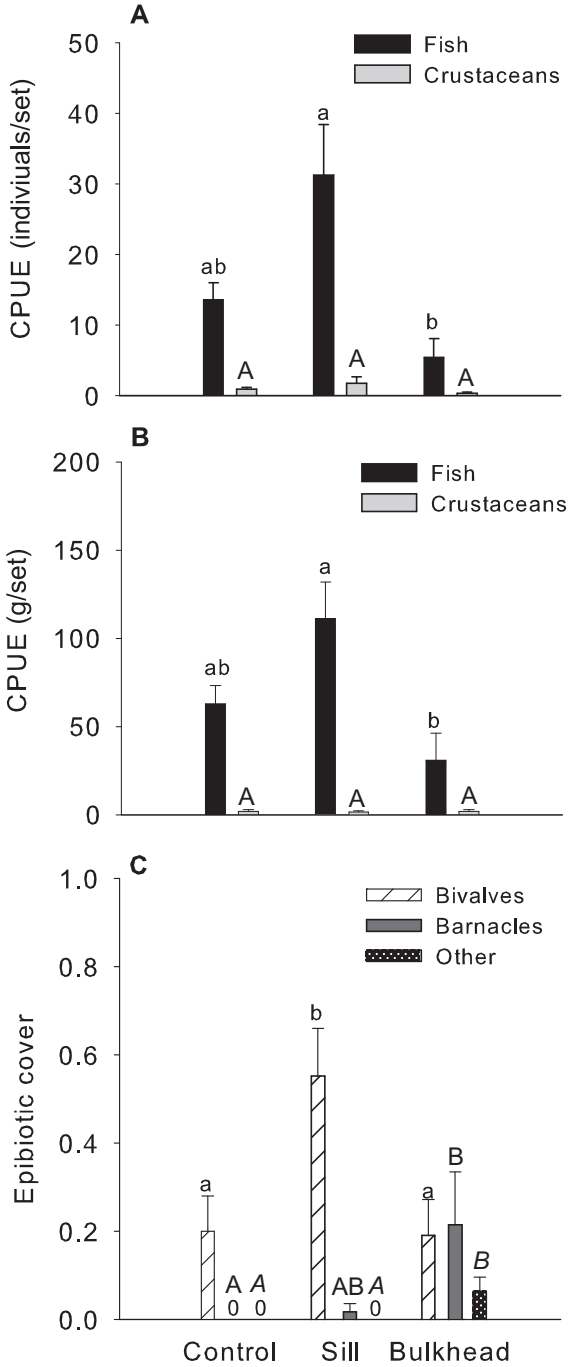

FIG. 6. Mean fish and crustacean CPUE: (A) individuals per trap set and (B) biomass (g) per trap set along the unvegetated edge of sills, control marshes, and bulkheads. (C) Proportion of coverage of bivalves (oysters and ribbed mussels), barnacles, and other epibiota (tunicates, bryozoans, and sponges) on stone sills, on the sand/mud substrate the edge of control marshes, and on bulkheads. Black bars or hatched bars with different lowercase letters, light gray bars or dark gray bars with different uppercase letters, and black dotted bars with different uppercase italic letters are significantly different ($P < 0.05$). Error bars are SE.

marsh and thus potentially reduces densities of small resident and juvenile fishes found along the marsh edge (via predation or behavioral avoidance by prey). Ruiz et al. (1993) found that densities and survivorship of juvenile fishes increased with decreasing depth and most predators of these species were found at a depth of 0.7 m or greater. This depth is approximately the equivalent mean depth during high tide at an elevation of −0.2 m NAVD88 at our PKS study sites. Thus, the <1-year-old PKS BACI sill had greater access for predators than the ≥3-year-old PKS CI sills. However, shallower depths along the marsh edge can also lead to reduced access for all nekton as the tide falls; therefore, this potential predation refuge may only be available at high tide. The PKS BACI sill site also had a lower SOM content than the older PKS CI sill sites (Fig. 5C), indicating that the PKS BACI sill provided less organic material and detritus for benthic-feeding species, such as Mugil spp. and Palaemonetes spp., to consume than the PKS CI sill sites. Fewer refuges from predation and lower food resource availability at the younger PKS BACI sill site as compared to the older PKS CI sill sites may have led to lower fish abundances. Finally, the PKS BACI sill site tended to have lower total stem densities of all marsh macrophytes, and therefore lower structural complexity, when compared to the PKS CI sill sites (Fig. 5D), although this difference was not statistically significant. Salt marsh macrophytes typically need multiple growing seasons to clonally expand and cover a site, and sediment surface elevation and SOM typically increase with salt marsh age, if sediment supply is adequate and subsidence is not occurring (Craft et al. 2002, 2003). We speculate that these results may indicate that the presence of a sill structure alone may not enhance fish use of intertidal habitat and that marsh macrophyte establishment (either through planting or natural recruitment) may be a critical aspect of enhanced of fish nursery habitat, although this hypothesis has yet to be tested.

We acknowledge that one of the shortcomings of control–impact designs is that observed differences between impact and control sites may be due to intrinsic differences in the sites, rather than differences caused by the "impact" of interest (Osenberg et al. 1994). However, as stated in *Methods*, we have made efforts to minimize site-specific differences that may affect nekton catch rates. There are also potential concerns (e.g., differences in sites) with CI (sill post-construction vs. control marsh) studies and with substituting space for time by comparing sill sites of varying ages to predict the trajectory of habitat development and nekton use of living shorelines. However, we used a combination of approaches (e.g., intensive sampling of nekton at multiple pairs of sill and control sites, measurements of multiple habitat characteristics) to evaluate the effects of living shorelines on nekton use. Despite these concerns, our results are consistent with the findings of other,

complimentary studies (no enhancement of nekton 1 year post-construction of sills [Currin et al. 2007], enhancement of nekton 2–3 years post-construction of oyster reefs [Scyphers et al. 2011, La Peyre et al. 2014]).

In contrast to the observed enhancement of fish and crustacean abundances and fish diversity within the marsh at older sill sites (fyke net data), seine data suggest that the presence of a sill does not increase abundance or diversity of nekton within seaward seagrass or mudflat habitats, regardless of the age of the sill (Figs. 2C, D, 4E–H). Although not directly comparable due to different gear types being used for sampling, the nekton community occupying seagrass patches seaward of the sills was dominated by the same species that dominated the salt marsh catches (e.g., Mugil spp., *L. rhomboides*, L. xanthurus, Eucinostomus spp., and Paralichthys spp.), although *L. rhomboides* made up a larger percentage of the catches in seagrass. This result may be a consequence of high variability in seagrass shoot density and patchiness of seagrass cover at the marsh sill and control sites (Fig. 3D). Additionally, the unvegetated corridor between the sill or control marsh and the beginning of a seagrass patch was typically 5 m or greater in width, which could have precluded nekton from crossing readily to utilize both structured habitats (Micheli and Peterson 1999, Gilliam and Fraser 2001). Sandflat or mudflat corridors between structured habitats may have higher predation rates than vegetated habitats and may serve as a barrier between habitats for juvenile nekton (Irlandi and Crawford 1997, Micheli and Peterson 1999, Jelbart et al. 2006, Rozas et al. 2011).

Comparison of sills to control marshes and bulkheads

Higher abundances of fishes at sill sites relative to bulkhead sites indicated that the unvegetated habitat adjacent to sills was serving as a more suitable habitat for fishes than the unvegetated habitat adjacent to bulkheads (Fig. 6A, B). The difference in catch rates was driven primarily by the absence of resident fishes such as *F. heteroclitus* and *F. majalis* at bulkhead sites (Table 2). There was a trend of increasing catch rates (individuals per trap set) of crustaceans from bulkheads to control marshes to sills, although overall catches were low across all shoreline types and differences in catch rates were not statistically significant. Although catch rates of crustaceans were not significantly different between bulkheads and marsh sills, Palaemonetes spp., another marsh resident, was notably absent from the bulkheaded sites (Table 2). Both resident and juvenile transient species benefit from unvegetated edge adjacent to salt marsh (Lipcius et al. 2005); however, resident species also utilize the interior marsh during high tide (Peterson and Turner 1994). This dependency on the marsh interior may explain the absence of resident species at bulkheaded sites.

Table 2. Catch rates (individuals and biomass) and mean standard length (SL) of species caught in salt marsh edge habitat at sill, control marsh, and bulkhead sites.

	Sill			Control			Bulkhead		
Species	Ind./4 h	Biomass (g/4 h)	SL (mm)	Ind./4 h	Biomass (g/4 h)	SL (mm)	Ind./4 h	Biomass (g/4 h)	SL (mm)
Fish									
Fundulus heteroclitus (R)	23.7 (9.0)	79.3 (30.3)	51.1 (0.6)	1.3 (0.6)	8.2 (4.1)	60.2 (29.8)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Lagodon rhomboides (T)	4.7 (2.7)	20.4 (7.5)	50.8 (1.1)	10.2 (2.7)	44.1 (15.3)	54.3 (1.6)	5.2 (2.4)	21.7 (12.2)	53.8 (0.9)
Fundulus majalis (R)	0.9 (0.2)	3.8 (2.5)	57.9 (5.3)	0.2 (0.2)	1.2 (1.2)	70.0 (15.8)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Orthopristis chrysoptera (T)	0.7 (0.2)	4.7 (1.9)	63.3 (2.4)	1.7 (0.2)	9.2 (2.8)	62.4 (21.9)	0.5 (0.2)	4.1 (2.2)	67.3 (8.7)
Cyprinodon variegatus (R)	0.5 (0.3)	1.0 (0.5)	38.3 (1.7)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Archosargus probatocephalus (T)	0.3 (0.3)	0.8 (0.8)	40.8 (1.5)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Eucinostomus spp. (T)	0.1 (0.1)	0.2 (0.3)	39.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Cynoscion nebulosus (T)	0.1 (0.1)	0.8 (0.8)	95.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Lutjanus griseus (T)	0.1 (0.1)	0.2 (0.2)	51.0 (0.0)	0.1 (0.1)	1.0 (1.0)	80.0 (0.0)	0.1 (0.1)	0.7 (0.6)	71.0 (0.0)
Symphurus plagiusa (T)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.1 (0.1)	0.1 (0.1)	151.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Anguilla rostrata (T)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.1 (0.1)	3.0 (3.1)	310.0 (0.0)
Hypsoblennius hentz (T)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.1 (0.1)	0.2 (0.1)	44.5 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Crustaceans									
Palaemonetes spp. (R)	1.5 (0.7)	0.3 (0.2)	23.4 (0.7)	0.3 (0.07)	0.1 (0.0)	23.5 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Penaeus spp. (T)	0.1 (0.1)	0.5 (0.3)	67.0 (4.0)	0.5 (0.1)	0.8 (0.7)	52.8 (3.1)	0.2 (0.2)	1.0 (1.1)	69.7 (5.7)
Panopeus herbstii (R)	0.1 (0.1)	0.5 (0.5)	29.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)

Notes: All values are shown with SE in parentheses. Catch rates were determined by setting traps 2 h before high tide and collecting 2 h after high tide (~4-h increment). Transient and resident species are as in Table 1.

Bivalves, such as *C. virginica* and mytilid mussels, were the dominant epibiota on sills, while barnacles formed a larger proportion of the cover on bulkheads (Fig. 6C). Thus, the epibiotic community on sills resembles that of an intertidal oyster reef more so than that on bulkheads (Wells 1961, Fodrie et al. 2014). Nekton that use intertidal oyster reefs for refuge and food resources, such as oyster toadfish (*Opsanus tau*) and *A. probatocephalus* (Peterson et al. 2003), would likely receive similar benefits from stone sills once the epibiotic community has become established. Additionally, the relief and geometry of a sill is closer to that of an oyster reef than is a vertical bulkhead's geometry. Therefore, a sill is likely to provide refuge and resources more similar to those provided by oyster reefs (Chapman and Blockley 2009, Scyphers et al. 2011). Grabowski et al. (2005) and Geraldi et al. (2009) found that restored oyster reefs adjacent to salt marshes did not enhance abundances and were functionally redundant as fish habitat. However, the reefs constructed in both of those studies were lower in vertical relief and overall footprint than the sills sampled in our study. The marsh vegetation in the Grabowski et al. (2005) and Geraldi et al. (2009) studies may have also been older and better established than the young, recently planted marshes in our study. Therefore, increases in habitat structural complexity in the previously studied restored oyster reefs may have been less than increases associated with stone sills in our study.

Design, site suitability, monitoring, and adaptive management of living shorelines

To ensure that our results guide improved coastal defense strategies, we identify several aspects of living shorelines that warrant further research. If one major goal of a living shoreline is to sustain or enhance multiple ecosystem services, then additional studies targeting the delivery of all those services are needed. A better understanding of the relationship between sill placement relative to marsh plantings and/or design (e.g., size, distance from shore, number of drop-downs or gaps, orientation relative to shore) and accessibility of intertidal habitat to nekton is needed. Factors such as tidal regime, shoreline geomorphology, local sediment supply, fetch, and storm frequency will influence the trajectory of ecosystem development of a living shoreline and should be considered further (Ruggiero and McDougal 2001, Cahoon 2006, Ranasinghe and Turner 2006). Finally, the type of shallow subtidal habitats (e.g., seagrass or mudflat) that would be replaced by a structure should also be identified and the costs and benefits of habitat trade-offs should be assessed (vis-à-vis ecosystem services; Peterson and Lipcius 2003).

Despite the need for additional research on living shorelines, our results allow us to make some specific recommendations for implementing ecologically sustainable coastal defense strategies. First, we suggest wherever feasible, living shorelines (i.e., vegetation alone or, if necessary due to higher rates of erosion, vegetation with a sill) be used to stabilize a shoreline in lieu of bulkheads to provide better habitat for nekton. Also, sites should be monitored for a minimum of three years after construction and periodically thereafter to ensure that vegetation has become established, epibiota have colonized structures, and nektonic organisms are able to access the marsh, using the methodology presented in this study. If vegetation has not become established after three years, additional planting may be required. If nekton access is compromised, additional openings or a reduction in the height of the structure may be necessary to increase water flow or decrease sedimentation. Careful design and management of living shorelines may sustain ecosystem services, such as habitat provision and erosion protection, even as sea levels rise (Rodriguez et al. 2014) and storm intensity or frequency increases (Arkema et al. 2013). Therefore, living shorelines should be considered further as a preferred option for shoreline erosion protection that simultaneously enhances the ecosystem service of habitat enhancement for fish and mobile crustaceans.

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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

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ABSTRACT

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).

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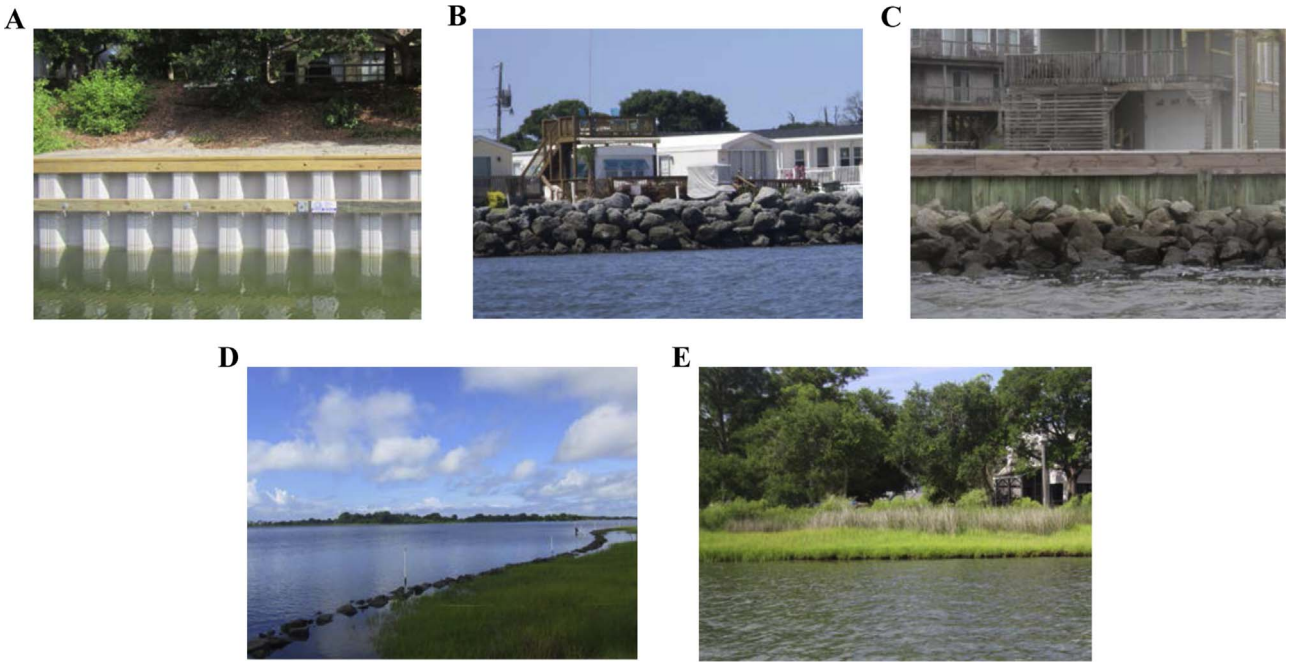

Fig. 1. Example shorelines: (A) bulkhead; (B) riprap revetment; (C) hybrid shoreline, combining a bulkhead with riprap; (D) sill with plantings; and, (E) natural marsh.

"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

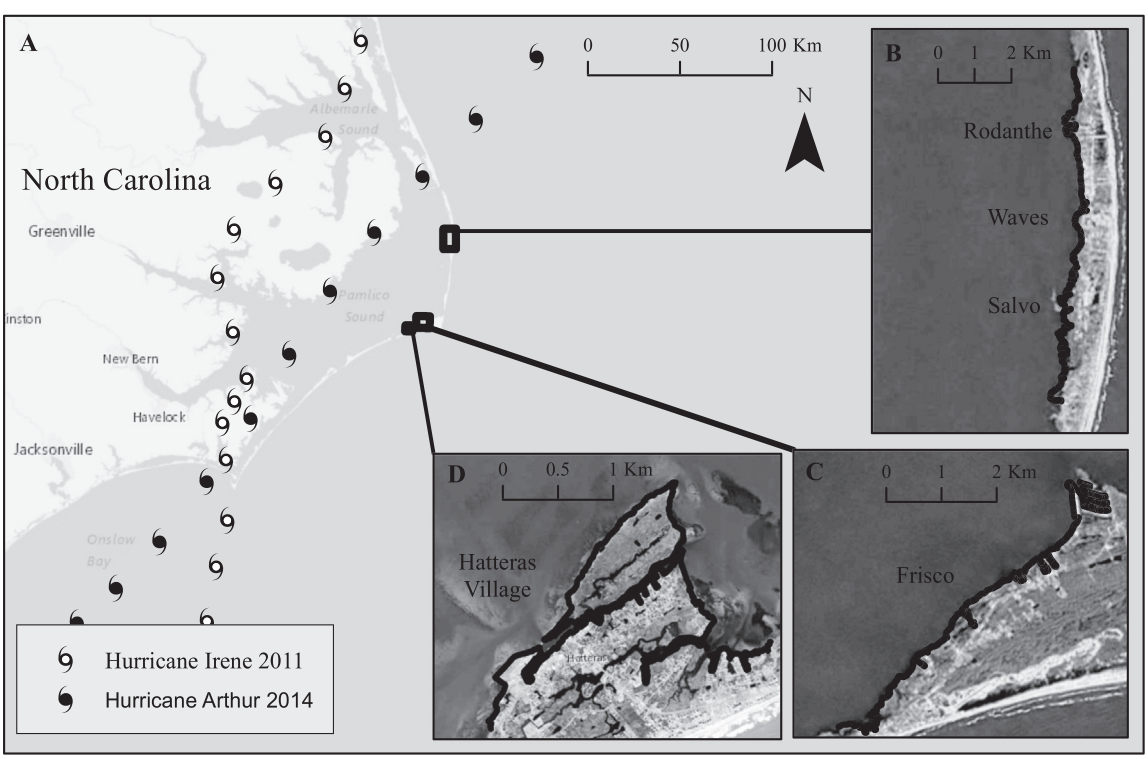

Fig. 2. (A) Map of the study area in NC, showing hurricane tracks for Irene (2011) and Arthur (2014) using location symbols in 1-h increments. Insets show damage assessment survey paths in: (B) Rodanthe, Waves, and Salvo; (C) Frisco; and, (D) Hatteras Village.

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

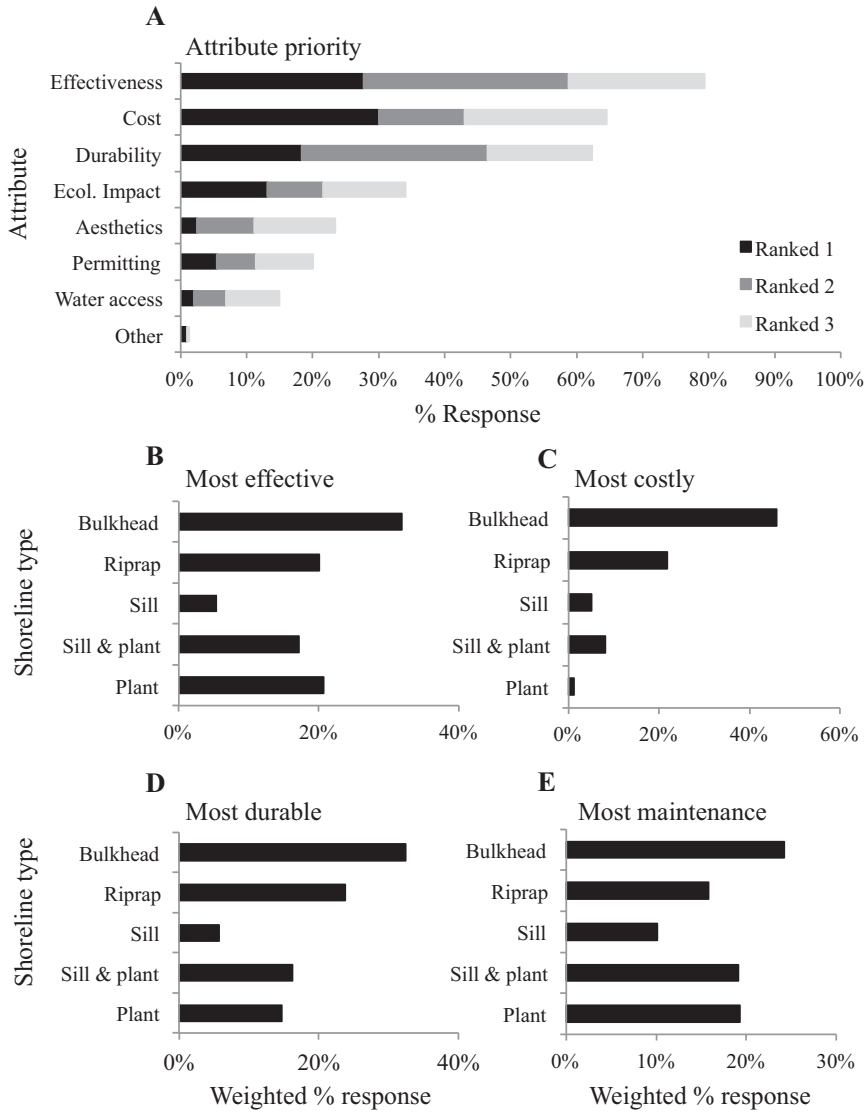

Fig. 3. (A) Priorities for shoreline protection schemes. (B-E) Perceived functions of different shoreline conditions weighted by ranking with weighted percent response shown.

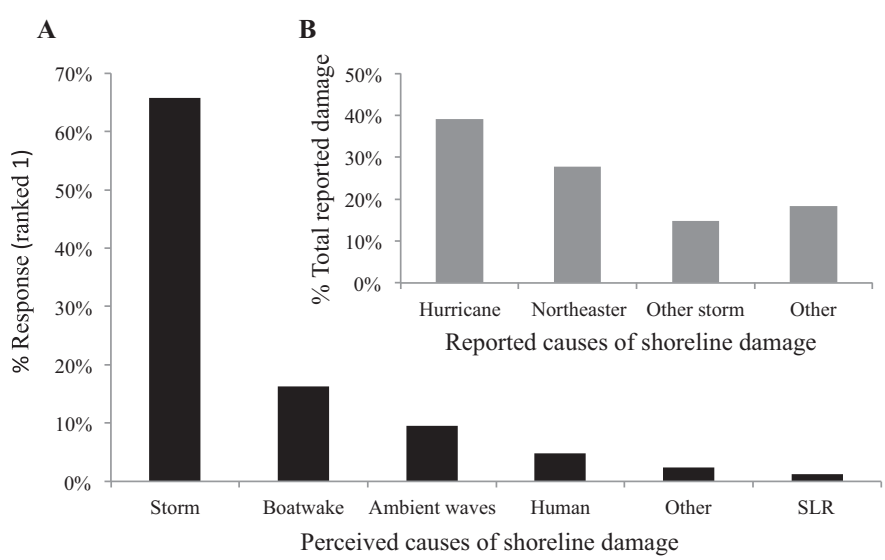

Fig. 4. (A) Perceived causes of shoreline damage shown as a percent of number 1 ranking. (B) Reported causes of shoreline damage shown as a percent of the total damage reported from all causes.

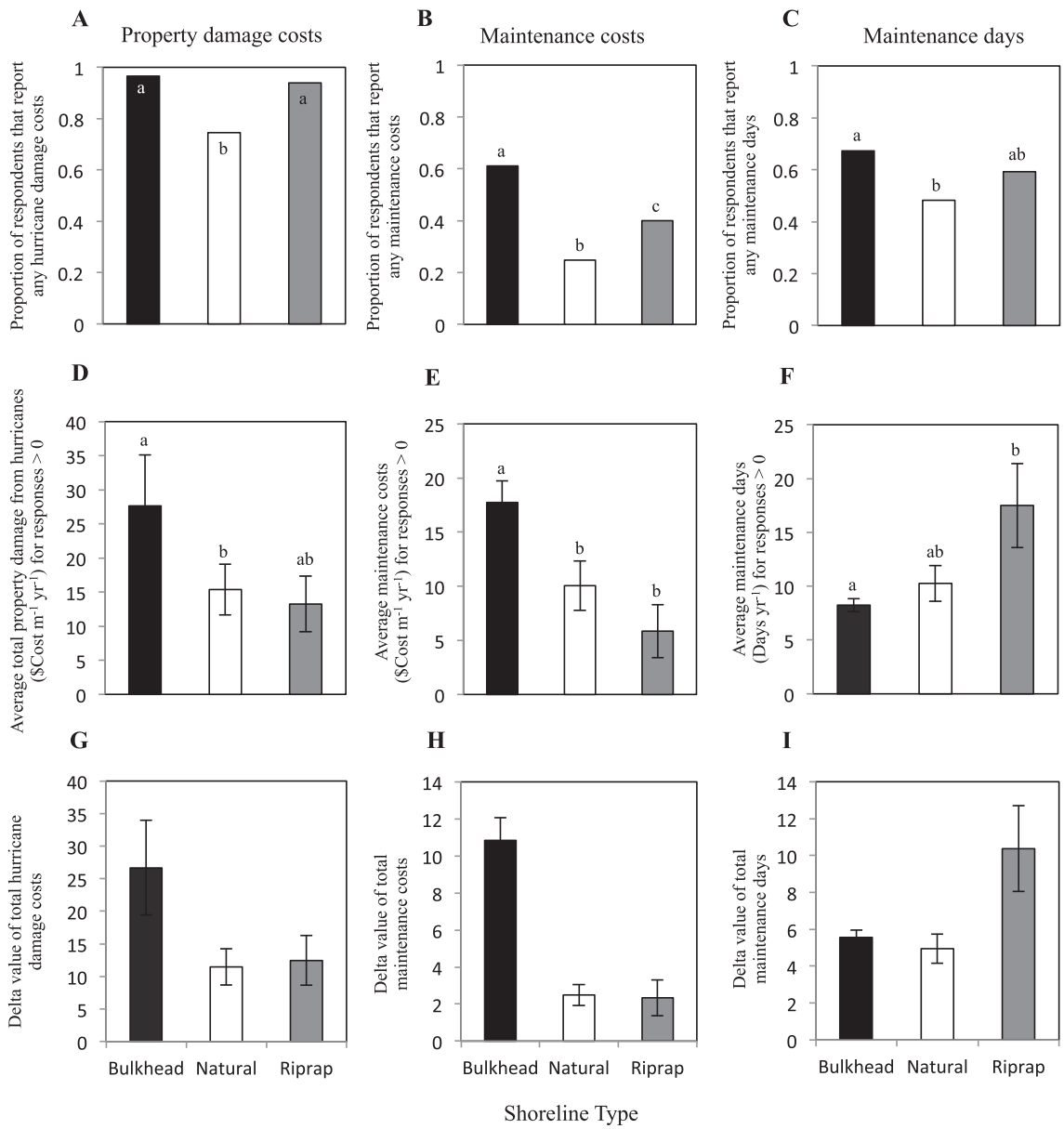

Fig. 5. Reported costs associated with hurricane damage and general shoreline maintenance (cost and time) as a function of shoreline type (bulkhead, natural, and riprap). Other shoreline types were excluded from this analysis because there were too few respondents. (A-C) show the percent of respondents 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

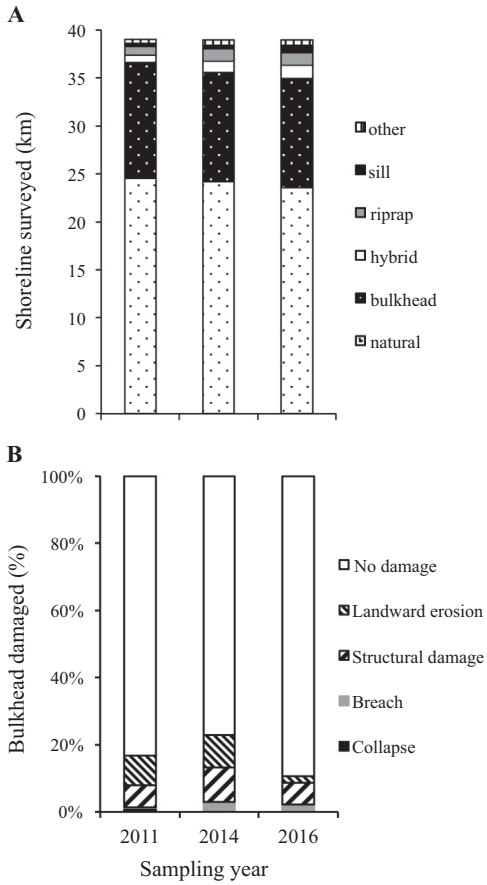

Fig. 6. (A) Total shoreline surveyed, broken down by structure type and (B) percent damage for bulkheads surveyed.

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.

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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.

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