Environmental Science and Policy 101 (2019) 46–53

Contents lists available at ScienceDirect

Environmental Science and Policy

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

Past hurricane damage and flood zone outweigh shoreline hardening for predicting residential-scale impacts of Hurricane Matthew

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ARTICLE INFO

Keywords:
Coastal resilience
Bulkhead
Hurricane
Saltmarsh
Flooding
Shoreline hardening

ABSTRACT

Hurricanes and tropical storms are among the most frequent and costly natural disasters in the United States, and their impacts are expected to intensify in the future. Understanding the best predictors of hurricane damage in coastal areas is of paramount importance for reducing recovery costs and protecting coastal infrastructure and human lives. This project used surveys of 295 homeowners in coastal North Carolina to evaluate damage to estuarine shorelines and homes caused by Hurricane Matthew in 2016. Specifically, we were interested in the following questions: 1) did homes with hardened shorelines (e.g. bulkheads and riprap revetments) experience more or less damage than homes with natural shorelines during the storm; and, 2) what were the strongest predictors of hurricane damage to shorelines and homes. Overall, we found that past hurricane damage to shorelines was the strongest predictor of shoreline damage during Hurricane Matthew and that flood zone and past hurricane damage to homes were the strongest predictors of home damage. However, homes with bulkheads also sustained more hurricane damage than homes with natural shorelines, perhaps because homes with bulkheads were on average 2 times closer to the shoreline than homes with natural shorelines. Our results show patterns of repeated shoreline and home damage during hurricanes and indicate that environmental context and vulnerability can outweigh individual residents' shoreline management decisions.

1. Introduction

Over coming decades, climate change will have severe and disproportionate impacts in coastal areas, predominantly because rising sea levels are predicted to inundate low-lying coastal landscapes (IPCC, 2018). Furthermore, several models predict that warming sea surface temperatures will lead to an increase in the frequency and severity of storm events (Webster et al., 2005; Bender et al., 2010). Even without an increase in storminess, it is likely that sea level rise (SLR) will worsen flooding events caused by storms (Strauss et al., 2014) and economic costs associated with maintaining coastal hazard protection infrastructure will increase rapidly (Hinkel et al., 2014). Adding context to these considerable risks, coastal population densities are nearly three times higher than inland population densities (Small and Nicholls, 2003), and the proportion of the global population living in the coastal zone is expected to grow (Neumann et al., 2015). This simultaneous increase in both risk and vulnerability underscores the importance of understanding which coastal hazard mitigation and adaptation strategies are the most effective at protecting infrastructure and lives.

One of the most common coastal hazard mitigation strategies is the placement of hard engineered structures (e.g. seawalls, bulkheads, groins) along estuarine and oceanfront shorelines (henceforth referred to as shoreline hardening; Walker, 1988). The unprecedented scale of shoreline hardening in recent decades has led to over 50% hardening in many urban areas across the globe (Chapman and Bulleri, 2003) and 14% of the total United States shoreline being hardened (Gittman et al., 2015). Shoreline hardening is projected to spread as coastal populations continue to expand (Douglass and Pickel, 1999; Gittman et al., 2015), with known and unanticipated implications for social and economic resilience. For instance, at a broad societal scale, it is clear that coastal development trajectories will further increase the amount of infrastructure that is vulnerable to coastal hazards and may even encourage additional human settlement in high-risk areas by making them appear safer (i.e. "safe development paradox"; Burby, 2006); this may increase the potential for any natural hazard event to turn into a long-term social disaster. Furthermore, in Alabama, Scyphers et al. (2015a, 2015b) found that the condition of a homeowner's shoreline was most strongly predicted by the condition of their neighbor's shoreline. This could be the result of spatial contagion (Hunter and Brown, 2012) or shoreline hardening triggering increased erosion of neighboring properties;

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https://doi.org/10.1016/j.envsci.2019.07.009
Received 22 April 2019; Received in revised form 11 July 2019; Accepted 15 July 2019

regardless, either case could lead to a cascade in shoreline hardening and thus environmental degradation.

Shoreline hardening is often implemented with the goal of enhancing resistance to natural hazards (e.g. erosion, storms, floods, tsunamis) and reducing property damage and human casualties; however, shoreline hardening ultimately erodes coastal resilience by undermining the ability of shorelines to adapt and regenerate (Smith et al., 2018). Furthermore, the extensive transformation of naturally sloping coastal habitats into vertical walls fundamentally alters the land-water interface, and has been shown to negatively impact habitat sustainability and the delivery of ecosystem services (Titus, 1998; Peterson et al., 2008; Gittman et al., 2016; Dugan et al., 2018), thus eroding natural capital and increasing future vulnerability to natural hazards (Arkema et al., 2013). While prior research demonstrates frequent and repeated damage to shoreline stabilization structures during hurricane events (Nichols and Marston, 1939; Morton, 1976; Thieler and Young, 1991; Gittman et al., 2014; Smith et al., 2017, 2018), these studies have typically focused on oceanfront shorelines (Nichols and Marston, 1939; Morton, 1976; Thieler and Young, 1991) rather than sheltered estuarine shorelines, or exclusively on damage to the shorelines themselves rather than damage to infrastructure behind the shoreline (Gittman et al., 2014; Smith et al., 2017, 2018). In contrast, more recent studies have shown that natural coastal habitats can buffer storm damage to upland infrastructure (Narayan et al., 2017; Tomiczek et al., 2017).

Coastal property damage costs have risen over recent decades (Zhang et al., 2000). To curb future damage expenditures, a better understanding of the environmental factors that lower damage during storm events is needed, as is a better understanding of the factors that best predict shoreline and home damage. Despite frequent damage to hardened estuarine shorelines (Gittman et al., 2014; Smith et al., 2017, 2018), homeowners continue to perceive vertical walls as being more durable and requiring less maintenance than other forms of shoreline protection, including nature-based options (Scyphers et al., 2015b; Smith et al., 2017). The continual investment and repair of shoreline structures may be an acceptable trade-off to the coastal homeowners and municipalities that are investing in them, so long as hardened shorelines offer superior protection for upland infrastructure; but, this link has rarely, if ever, been investigated along residential estuarine shorelines.

In the United States, the National Flood Insurance Program (NFIP) subsidizes development in flood-prone areas by creating Flood Insurance Rate Maps (FIRMs) that designate Special Flood Hazard Areas (i.e. flood zones) in which residents are required to obtain flood insurance. Notably, standard NFIP flood insurance policies do not cover damages to estuarine shoreline stabilization structures, like bulkheads (FEMA, 2011). Flood zones are based predominantly on elevation and are generally assumed to be an accurate predictor of actual flood risk during extreme events (Horney et al., 2010; Wallace et al., 2016); however, coastal storm events are difficult to predict and FIRMs are rarely validated after storms (National Research Council, 2009), even though they are often criticized for being out-of-date and of varying quality (Burby, 2001; Michel-Kerjan, 2010). Furthermore, studies in North Carolina have shown that nearly one half of coastal residents cannot correctly identify their flood zone (Horney et al., 2010), and more generally that homeowners tend to underestimate their vulnerability to flood hazards (Horney et al., 2010; Wallace et al., 2016). This disconnect between public and expert risk assessments is common and problematic (Slovic, 1987) because public perceptions of risk are thought to drive policy just as much as scientific and technological risk assessments (Correia et al., 1998; Tierney et al., 2001).

To gain a better understanding of the efficacy of hurricane damage mitigation strategies along estuarine shorelines in the United States and more generally to understand which factors predict vulnerability to storms, we conducted an address-based, dual-mode survey of residents in three coastal counties of North Carolina after Hurricane Matthew in 2016. Our surveys were designed to address the following questions:

1) Did homes with hardened shorelines experience more or less damage than homes with natural shorelines during Hurricane Matthew?
2) What were the strongest predictors of shoreline damage and home damage during Hurricane Matthew?

2. Methods

2.1. Description of study area

North Carolina is a model study system because it will be extremely vulnerable to the impacts of climate change in the future, and it is frequently impacted by major storm events. Even under low emission scenarios, North Carolina is expected to face up to 1 m of SLR by 2100 (Zervas, 2004; Rahmstorf, 2007), which will inundate many low lying coastal communities and severely exacerbate rates of flooding and damage to coastal structures and homes. Over 2000 square miles of land in North Carolina has an elevation less than 1.2 m above the high tide line, within which property values are estimated at almost $9 billion dollars (Strauss et al., 2014). By 2100, the Union of Concerned Scientists predicts that the number of North Carolina county subdivisions that are experiencing chronic inundation (i.e. where at least 10% of usable land is inundated at least 26 times per year) will grow from 6 communities at present to 49 communities under an intermediate emissions scenario (1.2 m SLR), and this does not account for any additional flooding associated with storms (Union of Concerned Scientists, 2017). Furthermore, since 1851, 83 tropical cyclones have made direct landfall in North Carolina and an additional 289 storms have passed within 150 miles of the coast and had some effect on the state (North Carolina State Climate Office, 2018). These factors together have made it a priority in North Carolina to create effective damage mitigation strategies.

This study focuses predominantly on damages associated with Hurricane Matthew, which was a tropical cyclone that formed in late September of 2016. After peaking at Category 5 intensity in the Caribbean, Matthew weakened as it traveled up the East Coast of the United States. Matthew made landfall in South Carolina as a Category 1 hurricane on October 8th, but then moved offshore of North Carolina where it remained through October 9th. While Matthew never made direct landfall in North Carolina, it brought hurricane-force winds and heavy rains to many areas of the coast and caused extensive flooding and damages along estuarine shorelines in the Outer Banks. In North Carolina, the storm had maximum sustained winds of 67 knots with gusts up to 87 knots near Nags Head and a maximum sound side storm surge of over 1.8 m in Hatteras. Twenty-five deaths were attributed to the storm in North Carolina alone, and estimated property damage in Eastern North Carolina was valued at over $1.5 billion (Matthew and Stewart, 2016).

2.2. Survey distribution

Our approach involved a targeted dual-mode (online and by mail) survey of waterfront property owners in coastal North Carolina. We did not expect that the sociodemographics of our target population (i.e. waterfront property owners) would be representative of the larger regional population (Supplementary material S1), but in comparing our results to previous surveys of waterfront homeowners in North Carolina and Alabama (Scyphers et al., 2015b; Smith et al., 2017) we have confidence that the survey sample is generally representative of the population of waterfront residents. Property-owner addresses were collected using county tax assessor websites, and a total of 1459 surveys were distributed. We used ArcGIS to visually verify that properties were located along estuarine shorelines, and we used the United States Postal Service to verify that addresses were correct and deliverable. The surveys were equally distributed among three coastal counties (Dare, Carteret, and Brunswick), which were chosen because they represent

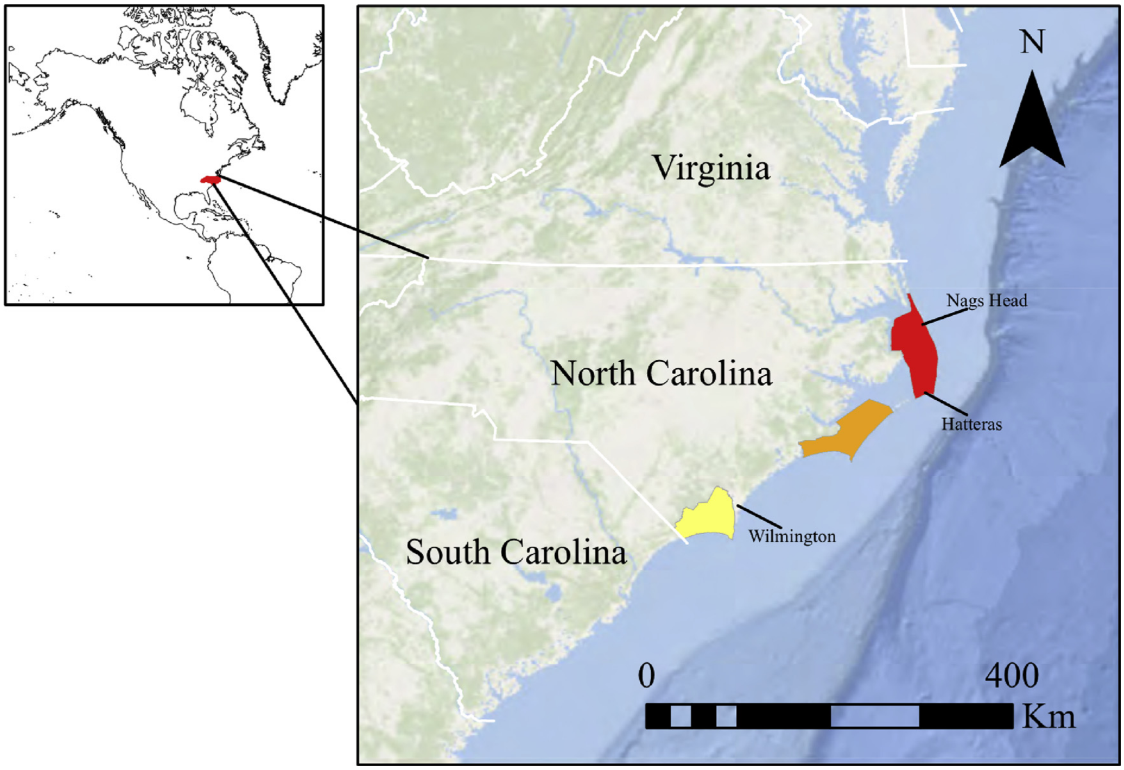

Fig. 1. Map showing the study location. The three coastal counties in North Carolina where the surveys were distributed are highlighted in red (Dare County), orange (Carteret County), and yellow (Brunswick County).

three distinct coastal geographies with expansive estuarine shorelines (Fig. 1). Dare County, North Carolina's easternmost county, encompasses several barrier islands that are part of the Outer Banks and border the Albemarle/Pamlico Sound. The sound is a predominantly wind driven system with a relatively small tidal range but high fetch. The residential estuarine shorelines of Carteret County have lower fetch than Dare County, but a larger tidal range. In Brunswick, North Carolina's Southernmost county, fetch is typically limited because there are no expansive inland bodies of water in the region, but the tidal range is the largest of the three counties (Supplementary material S1). Once properties were selected, survey participants were recruited using a modified Dillman method (Millar and Dillman, 2011) involving an initial mailing of letterhead invitations to complete an online survey (with a link to the online survey) and one follow-up reminder letter. We offered a random raffle drawing of prizes (e.g. Five $25 - $100 Amazon.com gift cards) as incentive to take part in the study. The online survey was hosted and administered by Qualtrics Research Suite (Qualtrics, Provo, UT), and printed surveys were mailed to all individuals who requested them; once returned, these surveys were manually entered into Qualtrics. Survey responses were recorded from May through September 2017.

2.3. Survey composition

We developed a 44-question survey instrument, which was tested by an interdisciplinary team of scientists, coastal managers, and coastal residents. This manuscript focuses on responses to a subset of 12 questions that focused on respondent demographics, property characteristics, and self-reported damage to shorelines and homes during recent hurricanes (Supplementary material S2). Residents were asked to describe their waterfront type (i.e. exposed sound, sheltered sound, man-made canal, etc.), the current state of their shoreline (i.e. bulkhead, natural, riprap, living shoreline, etc.), and whether or not their shorelines and homes had been damaged during Hurricane Matthew (2016) or during previous hurricanes (i.e. Arthur (2014), Irene (2011), and Floyd (1999)). For each hurricane, homeowners could indicate that their shoreline/home experienced no damage, minor damage, or major damage, but for analyses we combined the minor and major damage categories because we were not confident that the breakdown between minor and major damage was consistent across shoreline types (for the full distribution of data see Supplementary material S3). Only homeowners that reported living in their current home at the time of each of the previous storms were included in the analysis. Experiences with previous hurricanes (i.e. Arthur, Irene, and Floyd) were combined to create a new variable indicating whether or not the shoreline/home had ever been damaged during a previous hurricane. Analyses were conducted using this composite variable.

2.4. Environmental parameters

To supplement the homeowner reported data, we calculated additional environmental parameters based on the address where the initial survey invitation was sent. We used ArcGIS to measure the distance between homeowners' houses and the shoreline as defined by the North Carolina Department of Environmental Quality shoreline shapefiles (NC DEQ, 2018). This shapefile was created by digitizing aerial imagery of the entire North Carolina coast and approximating the location of the interface between structure/water, land/water, or vegetation/water (Mcverry, 2012). In addition, we used tax parcel and flood zone layers to extract land parcel values and flood zone for each property (North Carolina OneMap GeoPortal, 2018). Flood zones were categorized as (in order of increasing risk): X = minimal flood risk, 500-year = 0.2% annual chance of flooding; AE = Special Flood Hazard Area (i.e. 1% annual chance of flooding); and, VE = Special Flood Hazard Area with an increased hazard associated with wave velocity (National Research Council, 2009). We used the fetchR package in R (Seers, 2017) to calculate the average fetch (the average of 72 evenly spaced vectors), maximum fetch, and direction of maximum fetch (i.e. North, South, East, or West) for each shoreline. Finally we used a combination of Google Streetview, and real estate websites Trulia.com and Zillow.com to evaluate whether or not houses were elevated (defined as room to fit a car underneath the house; *sensu* Kennedy et al., 2011).

2.5. Statistical analyses

For analyses based on shoreline type, we only included homeowners with bulkhead, natural, and riprap shorelines, because all other shoreline types combined represented less than 10% of respondents. Fisher's Exact Tests (FET) were used to investigate relationships between shoreline type and shoreline or home damage during Hurricane Matthew. When statistically significant, the FET was followed by a post hoc pairwise comparison. For multivariate analyses, we used Chi-squared Automatic Interaction Detection (CHAID) trees to examine the most powerful predictors of shoreline type, shoreline damage, and home damage during Hurricane Matthew. Trees were restricted to 3 levels, with parent nodes containing at least 50 cases and child nodes containing at least 25. The tree for shoreline type included the following variables: distance between the house and shoreline, county, average fetch, maximum fetch, direction of maximum fetch, flood zone, and parcel value. The tree for shoreline damage included the following variables: past hurricane damage to the shoreline, county, average fetch, maximum fetch, direction of maximum fetch, shoreline type, and flood zone. The tree for home damage included the following variables: county, average fetch, maximum fetch, direction of maximum fetch, shoreline type, shoreline damage during Hurricane Matthew, home damage during a previous hurricane, flood zone, distance between house and shoreline, and whether or not the house was elevated. Analyses were conducted in SPSS Version 25 and R Studio Version 1.1.423.

3. Results

3.1. Survey sample

Two hundred and ninety-five homeowners completed our survey (20.2% response rate). Compared to regional sociodemographics (Supplementary material S1), our respondents were mostly male (72%), older (average age = 66 years), educated (73% had a Bachelor's degree or higher), and of higher economic status (56% reported making over $100,000 in 2016). Respondents were split between Brunswick (31%), Carteret (39%), and Dare Counties (30%) and most commonly described their waterfront access as either exposed sound (fetch > 1 mile; 31%) or man-made canal (30%), followed by natural creek (14%), sheltered sound (fetch < 1 mile; 12%), or other (13%). Fifty percent of homeowners had a bulkhead shoreline, followed by natural shoreline (34%) and riprap shoreline (6%); all other shoreline types were represented by less than 10% of homeowners combined. Homes with bulkheads, riprap shorelines, and natural shorelines were an average of 42 ± 46 m (mean ± SD), 49 ± 25 m, and 81 ± 66 m from the shoreline, respectively.

3.2. Hurricane damages

There was no difference in homeowner reported shoreline damage from Hurricane Matthew among shoreline types (FET, $p = 0.07$; Fig. 2A), but there was a statistically significant difference in reported home damage by shoreline type ($p = 0.02$; Fig. 2B). Homeowners with bulkheads reported more home damage than homeowners with natural shorelines ($p = 0.02$), but not significantly more damage than homeowners with riprap ($p = 0.13$). There was no statistical difference in home damage between homeowners with riprap and natural shorelines ($p = 0.69$).

The CHAID classification tree revealed that the strongest predictor of shoreline type was distance between the house and shoreline (Fig. 3).

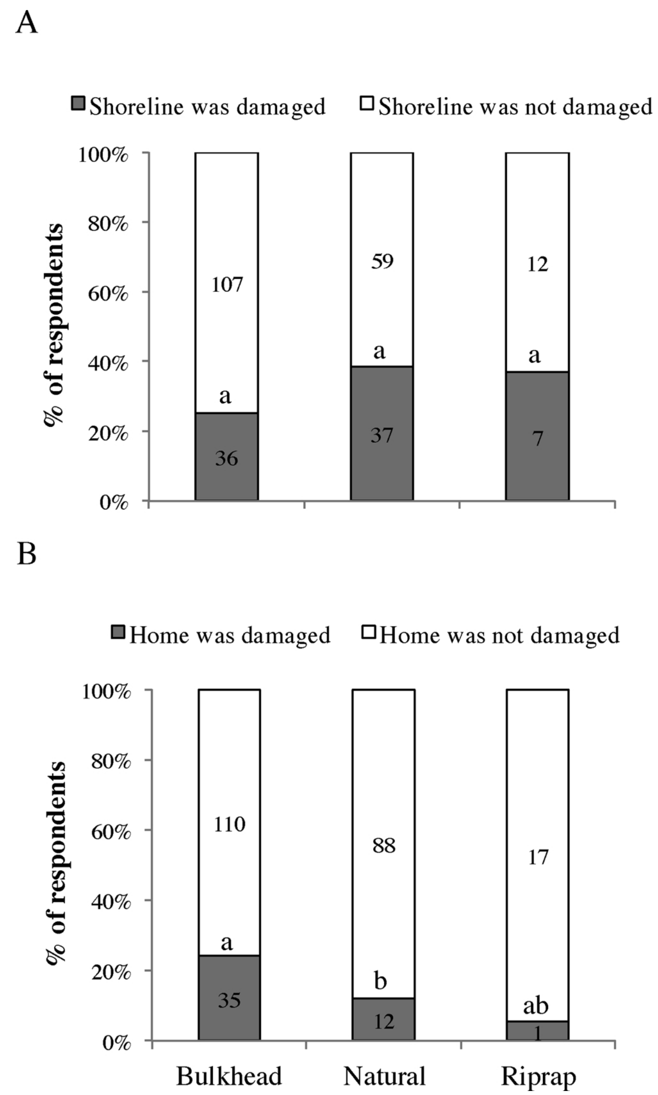

Fig. 2. Percent of survey respondents that reported shoreline damage (A) and home damage (B) during Hurricane Matthew by shoreline type. Numbers inside of the bars represent the total number of survey respondents and different lower case letters indicate significant differences among shoreline types.

Bulkheads were the most common shoreline type when the house was relatively near the shoreline (< 35.7 m from the shoreline), whereas natural shorelines were the most common shoreline type when the house was relatively far from the shoreline (> 68.6 m from the shoreline). For houses that were between 44.1 and 68.6 m from the shoreline, parcel value was a statistically significant predictor of shoreline type, with more shoreline hardening when parcel values were above $444,900.

Thirty-three percent of survey respondents reported shoreline damage from Hurricane Matthew, and the strongest predictor of damage was whether or not the shoreline had been damaged during a previous hurricane (Fig. 4). Shorelines that had been damaged during hurricanes in the past were three times as likely to have experienced subsequent damage during Hurricane Matthew (49% versus 16%), and of those shorelines, more damage was reported to natural shorelines than to bulkhead and riprap shorelines.

Twenty percent of survey respondents reported water damage to their homes from Hurricane Matthew, and the strongest predictor of damage was flood zone, with Special Flood Hazard Area VE (which indicates an increased hazard over AE due to wave velocity) grouping separately from all other flood zones (Fig. 5). Of the homes that were

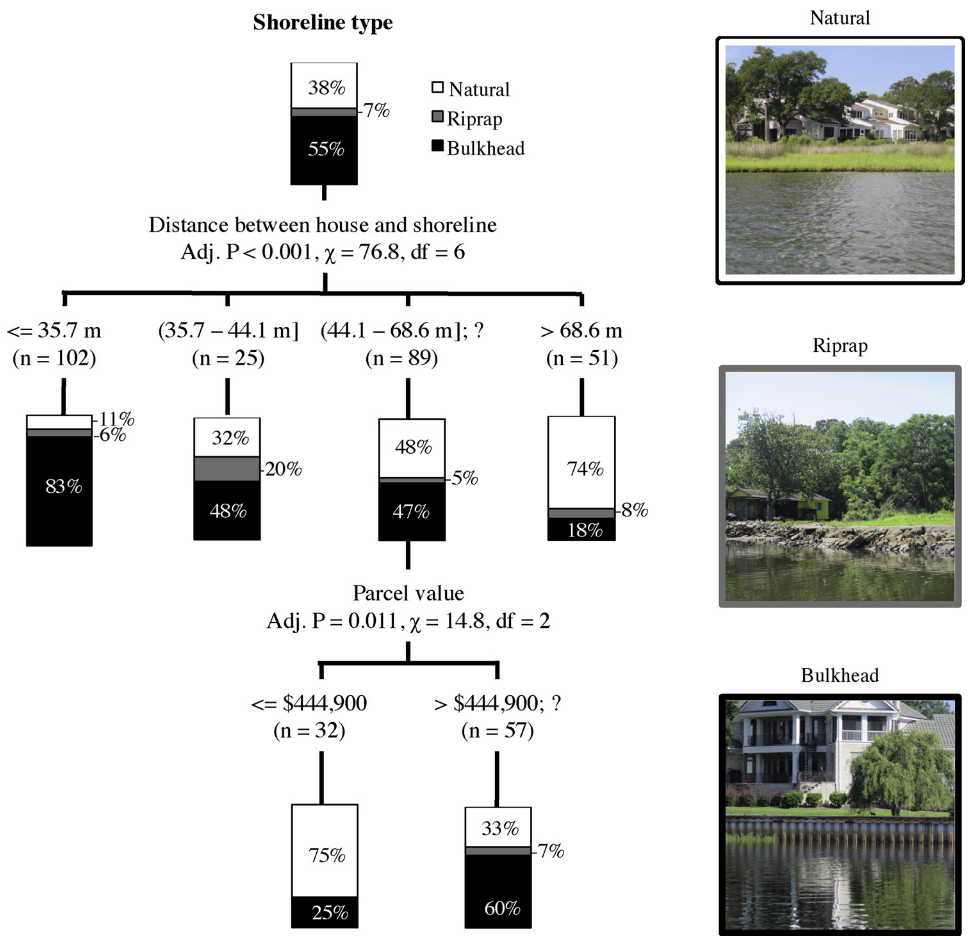

Fig. 3. Classification tree analysis showing the strongest predictors of shoreline type for our survey respondents along with example photographs of each shoreline type. Question marks indicate where missing values group.

not in flood zone VE, past home damage during hurricanes was a statistically significant predictor of damage during Hurricane Matthew, with homes that had been damaged previously five times more likely to have experienced damage (20% versus 4%).

4. Discussion

Shoreline and home damage during previous hurricanes was a significant predictor of both shoreline and home damage during Hurricane Matthew, potentially suggesting ineffective adaptive action after previous hazard events. Successful climate change adaptation and hazard mitigation will be largely predicated on acknowledging and addressing vulnerability, which is a product of exposure (i.e. the stress placed on a system), sensitivity, and the capacity for adaptive action (Adger, 2006). Climate change will increase exposure to hazards in most coastal areas, and thus we will need to employ strategies that lessen sensitivity to hazards and bolster the ability of social-ecological systems to evolve. The adaptive capacity of communities relies in part on understanding and modifying stakeholder decision-making (Schultz, 2011) as societal and stakeholder engagement is critical for the long-term success of hazard mitigation strategies (Kelly and Adger, 2000). Moreover, the longer communities wait to adopt sustainable hazard mitigation and adaptation strategies, the more expensive it will be and less likely to succeed (Titus, 1998).

Damage to homes that are covered by NFIP flood insurance policies are subsidized by the government and taxpayers and repetitive loss properties have received approximately 24% of claim payments over the history of the NFIP, despite making up less than 2% of insured properties (Congressional Budget Office, 2009). While we do not know how many survey respondents in this study were covered by flood insurance, our data show that many of the shorelines and waterfront homes had been repeatedly damaged by storms. Damage to protective shoreline infrastructure is not covered under any NFIP Standard Flood Insurance Policies (Federal Environmental Management Agency, 2011), which means that the costs of repeated damages to shorelines is carried by individuals and municipalities. Bulkhead replacement costs upwards of $460 per linear meter (Gittman and Scyphers, 2017); this carrying cost could become a significant financial burden, especially in an era of rising sea levels and increased storminess.

Our results show that homes with bulkheads had significantly more damage than homes with natural shorelines; however, our data cannot infer causality nor do we think it is likely that bulkheads are causing home damage. While previous studies have shown that shoreline type does not necessarily track with shoreline vulnerability (e.g. natural shorelines and hardened shorelines are often interspersed in the Outer Banks of North Carolina, even in high fetch areas; Smith et al., 2017), the relationship between home damage and shoreline type in our study may reflect home vulnerability. For example, homes with bulkheads in our study were on average two times closer to the shoreline than homes with natural shorelines. In fact, distance between the home and shoreline was the best predictor of shoreline type. Homeowners with bulkheads that are living closer to the water are increasing their exposure and relying on their shoreline structure to reduce their sensitivity to hazards, though our results show that bulkheads do not reduce sensitivity to the point of eliminating upland home damage. Nevertheless, resilience to an individual homeowner might mean resisting storm impacts enough to be able to build back after a storm, but that might come at the cost of increasing long-term social vulnerability.

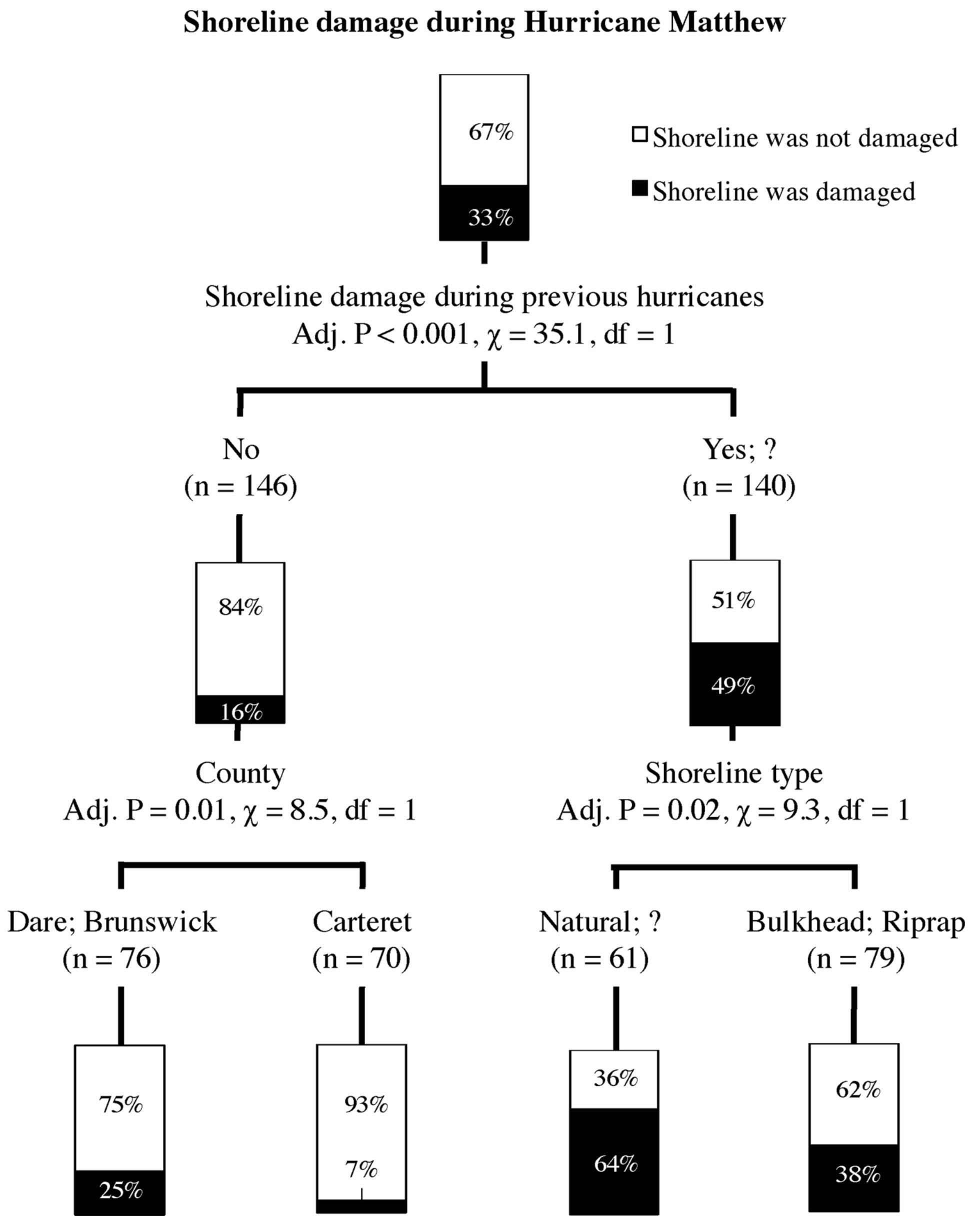

Fig. 4. Classification tree analysis showing the strongest predictors of shoreline damage during Hurricane Matthew. Question marks indicate where missing values group.

The observation that homes with bulkheads were closer to the water than other shoreline types could reflect the fact that: 1) closer proximity to water leads to increased concern for storms or erosion and thus triggers shoreline hardening; 2) the presence of a vertical wall leads to unfounded confidence in the safety of an area and potentially encourages development in a risky area (Burby, 2006); 3) the pervasive construction of engineered canal systems in NC, which generally have high rates of shoreline hardening and small property parcels, pre-date home construction; or, 4) when homes are too close to the water, or when the waterfront has a steep slope, there is not enough space to allow for a gently sloping natural shoreline (or a sloping riprap revetment) and thus a vertical wall is the only option. If numbers 3 or 4 are true, bulkhead shorelines may not necessarily be the preferred option for some homeowners, but in fact the only option if they want to continue living where they do. Furthermore, if a home is located in a vulnerable location (e.g. low elevation, too close to the water, etc.), hardening the shoreline may not ultimately protect the home from storm damage but it may enable the homeowner to build back and continue living in that vulnerable location. For example, current permitting for bulkheads allows for homeowners to build a bulkhead back in the same position where it was initially constructed within two years of the damage (USACE Nationwide Permit 13), resulting in no land lost, even if that property is underwater after the storm. Conversely, if a natural shoreline is damaged (e.g. eroded away) it is often impossible or unlawful to replace that property. This inability to "maintain" natural shorelines may act as an incentive for property owners to harden their shorelines.

It is worth noting that not all hardened shorelines are created equal. Homes with riprap shorelines in our study experienced lower rates of damage than homes with bulkheads. Additionally, when compared to bulkheads, riprap shorelines have been shown to be less expensive to maintain (Smith et al., 2017), cause less seaward scour (Nielsen et al., 2000), and have fewer ecological consequences (Seitz et al., 2006; Bilkovic and Roggero, 2008; Scyphers et al., 2015a). Thus, riprap may be a cheaper and more environmentally stable alternative to bulkheads along shorelines where some kind of hardening is needed or preferred; but, any hardened shoreline ultimately lowers the potential for sustainability when compared to natural or nature-based shorelines,

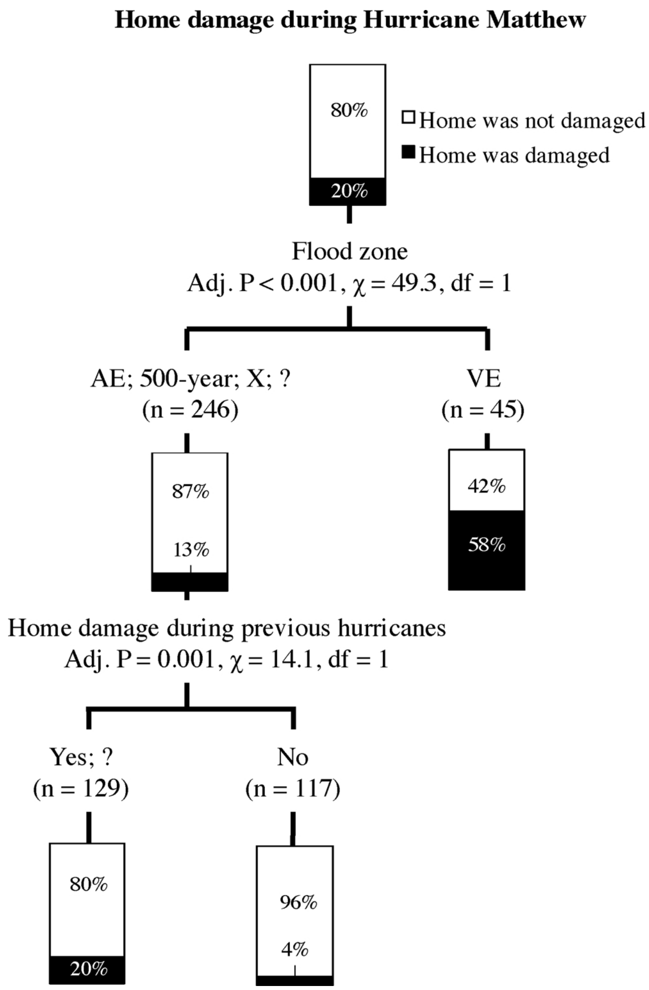

Fig. 5. Classification tree analysis showing the strongest predictors of home damage during Hurricane Matthew. For flood zone, AE = Special Flood Hazard Area with a 1% annual chance of flooding, 500-year = 0.2% annual chance of flooding, X = minimal flood risk, and VE = Special Flood Hazard Area with a 1% annual chance of flooding plus an increased risk associated with wave action. Question marks indicate where missing values group.

because hardened shorelines lack the capacity for self-recovery after a perturbation and will necessarily require maintenance and repairs (Smith et al., 2017, 2018).

In this study, the strongest predictor of home damage during Hurricane Matthew was flood zone. The NFIP has been heavily criticized in recent years, with those in opposition arguing that flood risk maps are not accurate, that coverage encourages development in high-risk areas, and that repeated losses account for a large amount of claims (Burby, 2001; Michel-Kerjan, 2010); however, North Carolina is recognized for having some of the highest coverage of high-quality flood hazard data in the country (National Research Council, 2009). While flood zone was a good predictor of damage during Hurricane Matthew, only flood zone VE (which carries an increased risk associated with wave action) grouped separately. Zones AE and VE are both Special Flood Hazard Areas with an estimated 1% annual chance of flooding; the fact that we saw higher rates of damage in VE zones may indicate that the added exposure to wave action was a major driver in home damage during Hurricane Matthew. Nevertheless, our study predominantly investigated the effects from one storm, Hurricane Matthew, which never made direct landfall in North Carolina and was in many ways an unusual storm associated with a record amount of rainfall and flooding (Matthew and Stewart, 2016), both of which can be very destructive to bulkheads. Trends of damage might be very different with other storms that have different inundation regimes. Thus, many more data are needed, particularly studies that compare results across multiple storms and evaluate the predictive power of flood maps after different types of storms and in different locations.

In recognition of many growing coastal hazards, managers and policy-makers are trying to rapidly develop coastal adaptation plans that will strengthen the ability of communities to respond to a variety of natural and anthropogenic disturbances. Individual interest in risk mitigation strategies, ranging from compliance with evacuation orders to investment in damage mitigation strategies, will depend on an accurate perception of risk. Thus, understanding how experience with hurricanes correlates with risk perceptions and decision-making will be an important component of outreach plans and the promotion of new policy. Risk perception and awareness have been shown to be highest directly after an event and then fade over time (Wachinger et al., 2013). Therefore, the best time for hurricane hazard education and the promotion of new mitigation strategies and policy may be directly after a storm. Hurricanes can also serve as signaling events that help communities make decisions relating to more spatially and temporally nebulous threats, like SLR (Retchless, 2018). More research is needed that looks at the difference between short-term resilience to storms versus long-term resilience to storms and SLR.

5. Conclusion

Our results show that many homeowners in our study have experienced repeated damages from hurricanes. This suggests that homeowners are either not investing in damage mitigation strategies after their properties are damaged or that the strategies that they are investing in are not effective. Our results also show that homes with bulkheads were much closer to the water and were damaged more frequently than homes with natural shorelines, suggesting that shoreline hardening may not be a consistently effective storm damage mitigation strategy. This is not to imply that natural shorelines are a better option, but rather that having a bulkhead in front of a home in a vulnerable location does not appear to eliminate the vulnerability of that home. In locations where common damage mitigation strategies, such as shoreline hardening, prove to be ineffective or increasingly cost-prohibitive, discouraging or outlawing shoreline hardening may deincentivize risky coastal development (Titus, 1998; Kittinger and Ayers, 2010). Over coming decades, hazard mitigation and climate adaptation is certain to remain a high priority for coastal communities (Hinkel et al., 2014), but more research is needed to ensure that chosen strategies are living up to expectations.

Acknowledgements

We would like to thank C. Peterson, I. Neylan, J. Harrison, M. Gregory, T. Miller, W. Jenkins, and R. Gittman for offering valuable input towards the development of this survey. This research was funded by a North Carolina Sea Grant and North Carolina Sentinel Site Cooperative Graduate Student Fellowship and a UNC Chapel Hill Royster Society Fellowship to C. Smith. Research activities posed no more than minimal risk to human subjects and received an expedited IRB review compliant with UNC Chapel Hill Policies (IRB Number: 17-0455).

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.envsci.2019.07.009.

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