The Determinants of Shoreline Hardening:
Armoring as a Response to the Threat of Marsh Migration

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Abstract

Salt marsh habitats have been under significant human threat due to climate change induced sea level rise and shoreline armoring (structures that prevent marsh migration such as revetments, riprap, bulkheads, seawalls, and wharfs). This leads to a gradual reduction of salt marsh habitats as they "drown" over time. Ironically, many of the benefits obtained from armoring, such as erosion control and to a lesser extent, flooding, are also provided by salt marshes. Although there exists a sizable literature on the ecological effects of armoring, there is little written about the influences on armoring. This study explores the determinants of armoring focusing particularly on responses to salt marsh migration. Logit and Heckman probit models are developed to evaluate whether the armoring of coastal property (via the installation of riprap or bulkhead revetments) is primarily motivated by erosion and/or flood control, or marsh migration prevention, as indicated by various factors (e.g., wave energy, flood zone, elevation, etc.). The study is located in Accomack County, Virginia, and includes data on parcel-level coastal residential housing, and shoreline characteristics from 2002 and 2013. A parcel's armoring is defined in several ways: (1) whether the parcel became armored by 2013, (2) whether the parcel became armored by 2002, and (3) whether the parcel became armored between 2002 and 2013. Armoring is modeled as a function of potentially relevant factors: risk factors such as erosion, flooding, and marsh migration, and mitigating factors such as forested shorelines, large beaches, and higher elevation. Empirical results show that armoring is *less* likely to occur in areas suitable for marsh migration. A parcel is more likely to have a riprap or bulkhead revetment built near it by 2013 the further away it is from salt marsh, when there are smaller proportions of nearby salt marsh (within 100-meters from the parcel), and when it is in an area less suited for planting salt marsh (unlikely areas for marsh migration). Similar results are found for parcels that armored by 2002, and parcels that armored between 2002 and 2013. Results provide evidence that riprap and bulkhead armored structures are not being built near parcels due to the threat of marsh migration but, rather, due to the threat of erosion. This suggests that the preservation of salt marshes through transgression zone purchases (unarmored and undeveloped upland likely to become salt marsh in the future) may be unnecessary for reasons other than the property's expected development, in the study area. It highlights the importance of understanding the dynamic between armoring and marsh migration for conservation agencies and policymakers looking to preserve salt marshes.

Keywords: salt marsh; marsh migration; residential property; transgression zone

JEL Codes: Q24, Q28, Q51, Q57

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Introduction

Salt marsh habitats provide a wide variety of valuable ecosystem services, some of which include flood abatement, erosion control, water purification, and habitat for aquatic species (Barbier et al., 2011). The value of these ecosystem services has been well established in the literature (Barbier et al., 2013; Gopalakrishnan et al., 2017; Interis & Petrolia, 2016; Johnston et al., 2002a; Johnston et al., 2002b; Petrolia et al., 2014; Saleh & Weinstein, 2016). And there are many examples of public agencies investing in salt marshes as a natural and cost-effective method of flood protection (Gedan et al., 2009; Temmerman et al., 2013; Zedler & Kercher, 2005). Despite these benefits, salt marsh habitats have been under significant human threat due to climate change induced sea level rise and shoreline armoring—the construction of revetments made of wood, stone, or concrete placed parallel to the shoreline. Rising seas, combined with structures that prevent migration (e.g., riprap, bulkheads, seawalls, and wharfs) create a gradual reduction of salt marsh habitats as they "drown" over time (Kirwan & Megonigal, 2013; Torio & Chmura, 2013).[1] Barriers to marsh migration are significant in many areas, especially along the Atlantic Coast where 42 percent of land within 1 meter above tidal wetlands is developed; this is expected to only increase in the future (Titus et al., 2009). Similarly, marsh migration is limited in the Pacific United States, and along estuaries in the Gulf of Mexico coast of the United States, partly due to urban encroachment (Borchert et al., 2018; Thorne et al., 2018).

[1] Armoring structures may lead to other detrimental effects on salt marsh including habitat loss, and reductions in habitat quality and productivity (Dugan et al., 2017; Scyphers et al., 2015).

Studies have shown, through simulations, the future loss of salt marsh due to sea level rise with global losses ranging between 20 and 90 percent of current salt marsh habitats for low and high sea level rise scenarios, but it has also been shown that these losses can be greatly reduced or even reversed with enough space for marsh migration (Kirwan et al., 2016b; Schuerch et al., 2018). However, coastal homeowners may prefer to armor their property even if they are aware of the negative impact this action has on salt marshes.[2] This was found to be the case for some coastal homeowners in Mobile Bay, Alabama who recognized the Bay's decline due to armoring and still opposed any new regulation to the management of residential shorelines (Scyphers et al., 2015).

The widely recognized value and vulnerability of salt marshes has led to worldwide efforts to ensure their preservation, often through the purchase of transgression zones—undeveloped and unarmored areas where marsh migration is likely to occur (Kirwan & Megonigal, 2013; Kirwan et al., 2016a; Temmerman et al., 2013; Thorne et al., 2012; Zedler & Kercher, 2005). However, the purchase and preservation of transgression zones may not always be necessary, and depends, in part, on whether private landowners armor or develop their property as a response to marsh migration threat or otherwise.

Although there exists a sizable literature on the ecological effects of armoring, there is little written about the influences on armoring. Coastal property is often valuable due to its limited supply and amenity benefits (such as its scenic views) encouraging its preservation. In the U.S., armoring is widespread, occupying 12 to 30 percent of the total shorelines of individual

[2] This is possible if the property owners can justify its construction (e.g., through erosion damage to the property that cannot be otherwise avoided) and gain permit authorization. In the study area, the authorizing body is the Virginia Marine Resources Commission.

states and reaching proportions of 50 to 70 percent or more along urban coasts (Gittman et al., 2015).

Some of the major drivers of armoring are erosion, storm surge, and flooding (Dugan et al., 2011; Gittman et al., 2015; Prosser et al., 2017). There is evidence that houses near a rapidly eroding shore decline in value by 10 to 20 percent when compared to similar houses near stable shorelines (Dunn et al., 2000; Kriesel et al., 2000). The relative viability of alternatives to armoring, such as beach nourishment, and the maintenance of marshland also play a role in the installation decision. These options vary in their use and effectiveness for the mitigation of flooding and erosion (serving as imperfect substitutes) and depend on the geomorphology surrounding a parcel. Structural approaches are often more effective than nonstructural approaches at protecting shorelines in areas with greater wave energy, deeper water, and higher rates of erosion (Luscher & Hollingsworth, 2007). The level of protection provided by beaches depends on their proximity and width, and maintaining their size through beach nourishment is often viewed as an unsustainable solution, especially when wave energy is high (Jin et al., 2013; King et al., 2016; Landry & Hindsley, 2011). The flood defense and erosion control provided by coastal salt marshes depend nonlinearly on their size (Barbier et al., 2008; Temmerman et al., 2013). In addition to these biophysical factors, neighboring spillovers can also play a role in the armoring decision. For example, an unarmored landowner can be influenced by the perceived success or failure of his neighbor's armoring choice. There is also the possibility of a negative spillover resulting from particular kinds of armoring, as bulkheads and seawalls tend to reflect wave energy and often transfer erosion issues onto unarmored neighboring properties (Beasley & Dundas, 2018; Walsh et al., 2019). Lastly, the armoring decision is also influenced by the structure's cost, effectiveness, and durability (Scyphers et al., 2015).

This paper develops a logit model to evaluate whether the armoring of coastal property (via the installation of riprap or bulkhead revetments) is primarily motivated by erosion and/or flood control, or marsh migration prevention, as indicated by various factors (e.g., wave energy, flood zone, elevation). Using Accomack County, Virginia as a case study, geospatial and housing data is taken from coastal single-family homes. The outcome of interest, a parcel's armoring, is defined in several ways: (1) whether the parcel became armored by 2013, (2) whether the parcel became armored by 2002, and (3) whether the parcel became armored between 2002 and 2013. The outcome of interest is modeled as a function of factors potentially relevant to armoring: risk factors such as erosion, flooding, and marsh migration, and environmental factors that protect against these risks such as forested shorelines, large beaches, and higher elevation. Some factors, however, play both roles. For example, greater amounts of nearby salt marsh results in protection against both erosion and flooding, but also higher marsh migration risk. Neighboring effects are also examined, particularly the influence of neighbors whose property also becomes armored.

Empirical results show that armoring is *less* likely to occur in areas suitable for marsh migration. A parcel is more likely to have a riprap (granite or concrete stones or boulders placed at an angle) or bulkhead (wooden, concrete, or vinyl walls) revetment built near it by 2013 the further away it is from salt marsh, when there are smaller proportions of nearby salt marsh (within 100-meters from the parcel), and when it is in an area less suited for planting salt marsh (unlikely areas for marsh migration).[3] These results are further supported when examining Virginia Marine Resources Commission (VMRC) Joint Permit Application forms for armoring construction, with no applicants citing marsh migration as a reason for installation, and are

[3] Similar results are found for parcels that armored by 2002, and parcels that armored between 2002 and 2013.

robust to a variety of specifications, armoring installation definitions, and the inclusion of neighborhood spatial effects.

The likelihood of armoring installation is influenced by the parcel's geomorphological features that protect against or exacerbate the risk of property loss, especially from erosion. For example, higher elevation, relatively low wave energy, being located near larger proportions of salt marsh, and being located near a forested shoreline reduce the risk of erosion and flooding, and hence the likelihood of armor installation. In contrast, parcels at a higher risk of property loss (e.g., from erosion and flooding) with more of their boundaries exposed to the coast have a higher likelihood of armor installation. Lastly, greater proportions of armored neighbors also increase its likelihood. This may be due to an increase in erosion risk from wave energy reflected onto the property and/or a learning effect where property owners learn from their neighbor's armoring experience.

The paper proceeds as follows. First, is a description of the permitting application process for the installation of armored structures in the study area, Accomack County, Virginia. Second, is a review of the armoring literature. Third, is a descriptive analysis of armoring decision-making for permit applicants who were issued a permit in the county. Fourth, is a model of armoring decision-making. Fifth, is a description of the study area and data. Sixth, are the results, which include subsections on the main logit model, an alternative model using a Heckman probit approach, and model predictions for parcels becoming armored in the future. Seventh, lastly, this is followed by the conclusion which includes a summary of the results, limitations of the study, and a brief discussion of policy implications.

The Permitting Application Process

In 1972, the Commonwealth passed the Tidal Wetlands Act which declared that it was the Commonwealth's responsibility to:

"…preserve the wetlands, and to prevent their despoliation and destruction and to accommodate necessary economic development in a manner consistent with wetlands preservation" (Ecology et al., 1993).

This act gave the Virginia Marine Resources Commission (VMRC) the responsibility of issuing tidal wetlands permits. Any proposed construction, including armoring, that involves tidal and/or non-tidal wetlands requires a Joint Permit Application (JPA), or in the case of tidal waters or wetlands impact, a Tidewater JPA. The application is generally reviewed and authorized by the VMRC, the Department of Environmental Quality (DEQ), the U.S. Army Corps of Engineers (USACE)[4], and/or the Local Wetlands Boards (LWB).

Applicants must provide a description of the project, its purpose, and any measures that will be taken to avoid and minimize impacts to, among other things, wetlands. If there are no impacts to wetlands, the permit can be issued or denied by the VMRC without needing to be submitted to the LWB (acceptance by the LWB is required for construction that impacts wetlands). If the Local Wetlands Board determines the project is necessary and wetland losses are unavoidable, the parcel owner must either provide wetland mitigation or pay a fine of $12 per square foot of impact (in the case of Accomack County, this goes to the Vegetated Wetlands Mitigation Account). According to the VMRC Wetland Guidelines, shoreline protection structures are justified only if there is active, detrimental shoreline erosion which cannot

[4] The USACE (along with the Environmental Protection Agency) is given the responsibility of regulating the discharge of dredged or fill materials into wetlands under Section 404 of the Clean Water Act (the primary vehicle for Federal regulation of activities that occur in wetlands).

otherwise be controlled, rapid sedimentation adversely affecting marine life or impairing navigation which cannot be corrected by upland modifications, or a need to accrete beaches (for beach nourishment).

Neighbors are also involved in the permitting process. When determining whether to grant or deny a permit, the VMRC considers the effects of a proposed project on nearby properties. Property owners adjacent to the construction site are notified of the project (either by the permit applicant, VMRC, or LWB) and they may air any objections (e.g., due to an increased risk of erosion from reflected wave energy) either to the LWB or in a public hearing held by the VMRC.[5] The entire permitting process can take up to three months depending on the complexity of the project.

The Determinants of Armoring Literature

There is a sparse literature on the determinants of armoring. To my knowledge, the only study to directly examine the determinants of armoring is Beasley and Dundas (2018). They explore private coastal land-use decisions to alter the coastline through the installation of beachfront protective structures, using the Oregon Coast as a case study. Deed and tax records which contain structural and sales transaction information are combined with permit data containing armoring information. This is further supplemented with spatial data on coastal erosion and other topographical features (e.g., beach width, development setback, and sand/gravel classification). Using a correlated random effects model, they find that a parcel's geomorphology, and severe storm events influenced the installation of beachfront property structures. The likelihood of

[5] In the case where a LWB does not exist a public hearing may be held by the VMRC where protested applications for VMRC permits can be resolved.

armoring was found to increase with higher erosion rates, shorter coastal distances, and larger, more valuable parcels.

In a related study, Scyphers et al. (2015) use a stated-preference survey of coastal homeowners in Alabama to examine the rationale for beachfront protective structure installation. The criteria that were most influential in homeowners' armoring decisions were effectiveness, cost, and durability. When homeowners were asked about their current preference if faced with an eroding shoreline, more than 75 percent of homeowners with an armored shoreline stated that they would select the same type of structure while only 5 percent preferred it to remain natural. In contrast, 45 percent of the unarmored homeowners would install an armored structure (a vertical wall or revetment) and 41 percent would prefer it to remain natural.

Neighborhood effects were found to play a significant role in the likelihood of armoring. Beasley and Dundas (2018) examine the influence of neighbors on beachfront protective structure installation decisions and strategic decision-making through coalition formation between neighbors (encouraged through a sharing of fixed construction costs and the negative externalities associated with neighboring installation). Neighboring effects are captured in several ways: (1) through a variable measuring the number of neighbors armored at the time a homeowner applies for an armoring permit; (2) through a variable identifying the number of armored neighbors within concentric ring buffers of a parcel up to 2-kilometers away; (3) and through spatial lag models. They find a clustering effect where armored parcels were around nearly 61 other armored parcels in a 2-kilometer radius and unarmored parcels were unlikely to be near any armored parcels. They also find neighboring and coalition parcel effects to be even more influential than geomorphology in armoring decision-making, where more armored neighbors within 2-kilometers and the ability to join a coalition increase the likelihood of armoring. Scyphers et al. (2015) also find neighbor-related effects on the armoring installation decision of coastal beachfront property owners. Using tree-based classification models, they find that a neighbor's shoreline condition was the most powerful explanatory variable in predicting a homeowner's current shoreline condition. Among homeowners neighbored by a shoreline with a vertical wall, the probability of also having a shoreline protected by a vertical wall was greater than 90 percent. Neighboring shoreline conditions were also found to be the most powerful predictor in a homeowner's current armoring preference. Among homeowners neighbored by a shoreline with a vertical wall, the probability of choosing a vertical wall was 75 percent. These results highlight the influence of spatial spillovers in armoring decision-making.

This study adds to the literature on the determinants of shoreline hardening in several ways. (1) Unlike Beasley and Dundas (2018) and Scyphers et al. (2015), this study looks at all coastal property owners and is not restricted to beachfront property or beachfront protective structures; (2) Also, this study considers not only factors relevant to erosion and storm surge/flood risk, but also those relevant to marsh migration. The goal of the paper is to evaluate whether the primary motivator of armoring stems from preventing erosion, flooding, or marsh migration (as indicated by factors relevant to each).

Armoring Decisions Using Evidence from VMRC Permit Applications

VMRC permits can be used to examine who is armoring, the type of structure chosen and its cost, when the armoring took place, and why the armoring took place. The following results are based on VMRC permit applicants from Accomack County, Virginia who were issued a permit for either construction of a riprap or bulkhead armored structure between the start of 2010 and the end of 2017.[6] The data was filtered to only include permits given to individuals (applications from the county, town, or corporations are removed).

During the 7-year time frame 49 permits were issued to individuals by the VMRC for riprap or bulkhead construction projects (no permits were denied by the VMRC or LWB during this time). The data shows an increase in the number of permits issued over this time with only 22 percent given between 2010 and 2013 and 88 percent given between 2014 and 2017. The median length of these structures were 68 feet, with 95 percent of construction projects being under 355 feet. The median and average cost per linear foot were $160.65 and $158.18, respectively, and ranged between $63.83 and $379.31 (with a standard deviation of $80.14).[7] Projects took on average, 4.5 months to complete and ranged between 1 and 14 months.[8]

Table 1.1 shows armoring statistics for these permit applications that include the structure built, reason for construction, and wetland impact mitigation. The majority of these were for bulkhead construction projects rather than riprap, with bulkhead projects occurring 6.8 times more often. There were in general, three reasons given for a construction project: (1) 'Erosion', for erosion control, (2) 'Ease of Access', to improve ease of access to the water, and (3) 'Storm', to repair storm damage or prevent future storm damage. Out of the 27 applicants that provided a reason for construction 70.37 percent cited erosion control as being an issue. There were only 5 cases (18.52 percent) where people were affected by storms (Hurricane Sandy and Hurricane Irene) or worried about storm surge. Lastly, access was a minor concern, only being a primary

[6] Permits issued prior to 2010 were not included due to a lack of data. The data is made publicly available and can be obtained from the VMRC Habitat Management Permits and Applications using the following link: https://webapps.mrc.virginia.gov/public/habitat/.
[7] This is based on 25 observations when excluding the cost for more complex projects that included the construction of other things besides riprap and bulkheads (e.g., breakwaters, jetties, piers).
[8] In some cases, people recorded the completion dates as 'Fall' or 'Spring' of the given year. In these cases, I used the middle of the season, October for the Fall and May for the Spring. If the permits were issued later than October or May, I used the end of the season instead (December and June, respectively).

issue in 3 cases (11.11 percent) and secondary to that of erosion control. Marsh migration risk was *not* an issue in any of the permit applications.

People took several actions to reduce the impact their armoring would have on existing salt marsh habitats. This can be seen in their impact mitigation efforts which can be categorized into (1) ‘Unnecessary’, no action needed (no salt marsh is near the site of construction), (2) ‘BMP’, the use of Best Management Practices, (3) ‘Build from Upland’, construction taking place from upland, and (4) ‘Pay Fine’, the payment of an impact penalty. Among the applicants, 45.61 percent of people stated they would work from upland to avoid wetland impacts, while 25.71 percent stated they would use proper Best Management Practices, and 8.57 percent would pay the penalty due to unavoidable wetland impacts. The remaining 20.00 percent were not near salt marshes and did not need to take any mitigative action.

A Model of Armoring Decision-making

In general, past literature examines the armoring installation decision as a function of the net present value of the benefits less costs to the property owner (Beasley & Dundas, 2018; Neumann et al., 2015; Yohe et al., 1996). For example, armoring takes place when the cost of its construction and maintenance is less than the protection against damages incurred through storm surge, sea level rise, erosion, and marsh migration (otherwise, the property owner may choose to either pay the cost of repairing the damaged property or abandon it). In short, the benefits gained in terms of reduced damages to the property should exceed the cost of armoring. Beasley & Dundas (2018) extend the model to include the impact of learning from neighbors in decisions to armor. However, the direction of this learning effect is ambiguous. Property owners may observe effective erosion control from armored neighbors and/or suffer damages due to erosion spillovers encouraging armor installation, but armor installation may also be discouraged if the structure is observed as having failed to adequately protect the neighboring property or hamper access to beaches.

This literature is used to guide the development of a theoretical model of armoring decision-making that emphasizes characteristics of the property relevant to marsh migration. The basic theoretical model adapts a Random Utility Model approach from McFadden (1974) which outlines the general procedure for formulating an econometric model of choice behavior using a utility maximization decision rule. The theoretical model is given in equation (1):

$$U(R(A=1,\boldsymbol{Z},N),m-c) > U(R(A=0,\boldsymbol{Z},N),m) \quad (1)$$

In the equation above, U represents the utility of the property owner, which is a decreasing function of the anticipated present value of property loss, R, and the cost of armoring, c, and an increasing function of income, m. R itself is a decreasing function of armoring, A, an increasing function of armored neighbors, N (in general, unarmored property owners cannot free-ride from their neighbor's armoring and may face an increased risk of erosion)[9], and an increasing or decreasing function of nearby environmental factors, $\boldsymbol{Z}$ (e.g., R decreases if the property has a higher elevation which provides protection against flooding and marsh migration risk but increases if the property is in a high wave energy environment which exacerbates erosion risk). The property owner chooses to install armor if the utility derived in the scenario with armoring is greater than the utility in the scenario without it. In other words, for armoring to take place at time t, the gain in utility from the reduction in the expected present value of

[9] In theory, there may be situations in which an unarmored property owner adjacent to an armored neighbor may indirectly benefit, due to the position and shape of their parcels, and their environmental surroundings. However, these situational circumstances are almost never met. This is based on the expert opinion of Hank Badger of the VMRC.

property loss must be sufficiently larger than the loss in utility due to the cost of armoring, so that it leads to an improvement over the utility in the status quo scenario.

However, utility cannot be directly observed and is separated into a deterministic component, $V(.)$, and a stochastic component, ϵ. Equation (1) becomes:

$$V(R(A=1,\boldsymbol{Z},N),m-c)+\epsilon_{A=1}>V(R(A=0,\boldsymbol{Z},N),m)+\epsilon_{A=0} \quad (2)$$

By rearranging (2) the probability that the property owner chooses to install armor is given by:

$$P_{A=1}\equiv P(\epsilon_{A=0}-\epsilon_{A=1}<\ V(R(A=1,\boldsymbol{Z},N),m-c)-V(R(A=0,\boldsymbol{Z},N),m)) \quad (3)$$

This necessitates the specification of a probability distribution for the error terms. When the errors follow a type 1 extreme value distribution a logit model is used (an alternative to this is the probit model which assumes errors are normally distributed). Using a logit model, the probability of armoring can be written in terms of the log odds. When $V_{A=1}=V(R(A=1,\boldsymbol{Z},N),m-c)\equiv log\left(\frac{P(A_i=1)}{P(A_i=0)}\right)$, the empirical specification is given by:

$$P(A=1|\epsilon_{A=1})=\frac{e^{V_{A=1}}}{1+e^{V_{A=1}}} \quad (4)$$

where, following common practice, $V_{A=1}$ takes on a linear form,

$$V_{A=1}=E_i{}'\beta_1+S_i{}'\beta_2+M_i{}'\beta_3+X_i{}'\gamma+\alpha N_i+c_i+\epsilon_i \quad (5)$$

the outcome of interest, A_i, equals one if a (riprap or bulkhead) armored structure is installed close to parcel i by 2013, and zero if parcel i is not close to an armored structure by this date. The likelihood of an armored structure being installed near a parcel is hypothesized to be an increasing function of environmental factors affecting erosion risk, E, flood risk, S, and marsh migration risk, M (factors which place the property at increased risk of deterioration). E decreases when parcels are protected by salt marshes, wide beaches, and/or a forested shoreline, and when the parcel is in a low wave energy environment. S decreases if the parcel has a higher elevation and is protected by salt marshes but increases if it is in a flood zone. M decreases if the parcel has a higher elevation and increases if the parcel is surrounded by more salt marsh. The likelihood of armoring installation is also influenced by N, neighboring parcels that have armored structures built near them (e.g., from the possible increased risk of erosion, and/or the perceived success of the neighbors' installations). X_i is a vector of other geospatial and parcel-specific factors that could impact the likelihood of armoring (e.g., whether the parcel is located in a cluster where armoring is likely to take place, and the parcel's exposure to the coast). Lastly, when assuming the average cost of armoring per linear foot is approximately equal across parcels in the sample, a lack of variation causes the construction cost of armoring, c_i, to drop out of the logit (and probit) models.

After testing various probit and logit model specifications with distance variables truncated at varying thresholds[10] and finding consistent results, a logit specification was chosen for the main model based on the Pseudo-R Squared goodness of fit.[11] Due to issues of heteroskedasticity, as indicated by a Breusch-Pagan Test, all models are run with robust standard errors.

Two empirical approaches are used to model the armoring decision-making process. In the first approach, the dependent variable is defined to capture all parcels which were armored by the end of 2013. This has the advantage of producing the cleanest results since the dependent variable is not based on changes in armoring between 2002 and 2013, which rely on different

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[10] Truncated distances reflect an expectation that the effect these variables have on a parcel's armoring status may become zero beyond a certain threshold.

[11] Probit model results can be found in Tables A.3 and A.4 of the Appendix.

data collection methods.[12] In the second approach, a Heckman probit model is used to predict whether parcels unarmored in 2002 become armored in 2013 (Heckman, 1979; Van de Ven & Van Praag, 1981). Although results from this approach may be more subject to measurement error, it has several advantages over the previous one. Unlike the former approach which assumes the armoring process to be the same for parcels armored by 2002, and parcels armored between 2002 and 2013, the Heckman probit model allows this process to differ.[13] Another advantage of this approach is that it can be used to predict the probability of armoring for those parcels that have not armored by 2013.

The second approach requires additional explanation. The Heckman probit model assumes an underlying relationship between some latent model and the probit model being estimated, where the dependent variable, in this case, becoming armored between 2002 and 2013, is not always observed (Heckman, 1979); this change in armoring status is not observed for parcels already armored in 2002. The chance of a parcel's being armored in 2002 can be predicted through a probit model in the first step (which, often called a 'selection equation', is typically used to account for sample selection).[14] In the second step, another probit model is estimated which predicts whether the parcel becomes armored between 2002 and 2013. This model includes as a regressor, a transformation[15] of the predictions of a parcel's armoring in 2002. These two probit equations allow for different factors to influence the armoring of a parcel

[12] See footnote 14 in the data section below.

[13] When assuming the armoring process to be the same across time, an ordered logit or probit model can be used to predict when parcels are likely to armor (before 2002, between 2002 and 2013, and after 2013). This is shown in Table A.5 of the Appendix.

[14] The Heckman model has the advantage of correcting for sample selection, since a model predicting the probability that a parcel will become armored between 2002 and 2013 only considers parcels that are unarmored by 2002. For this reason, a standard probit model would produce biased estimates.

[15] This regressor is called the 'inverse Mills Ratio' and is the ratio between the standard normal probability density function and the standard normal cumulative density function evaluated at the model predictions of being armored by 2002.

in these time periods. However, for empirical reasons, there are some key rules in how these equations are specified. The first step probit model should be specified to include any explanatory variables in the second step probit equation (this avoids issues of inconsistency) and include at least one explanatory variable that is not (this is necessary to distinguish between sample selection and mis-specification) (Wooldridge, 2016).

Ideally, the two probit equations would be differentiated by some variable (or variables) that influences armoring differently over time. However, many of the factors that influence a parcel's armoring status in 2013 are also expected to influence its armoring status in 2002. This makes it difficult to satisfy the exclusion restriction in the first step probit model. In order to circumvent this issue, preliminary models are used to examine the variables that are consistently significant in the first step probit equation but never significant in the second step probit equation. These variables are then dropped from the second step probit equation and incorporated into the first step equation.

Data

The study takes place in Accomack County, Virginia. The county resides in the northern part of the Eastern Shore of Virginia and is part of a narrow peninsula bordering the Atlantic Ocean and the Chesapeake Bay. The Eastern Shore is home to large areas of productive wetlands which total over 280,000 acres in the Chesapeake Bay alone (Chesapeake Bay Program, n.d.). Unfortunately, the persistence of wetlands (including salt marsh habitats) in this region is threatened due to sea level rise and increasing rates of shoreline hardening. The Eastern Shore contains one of the most vulnerable coastal regions due to rising sea levels, estimated to be three to four times the global average (Coastal Resilience: Virginia Eastern Shore, n.d.). According to a report conducted by the VIMS in 2009, approximately 793 kilometers or 11 percent of Virginia tidal waters has been hardened with 29 kilometers of shoreline hardened each year (Bilkovic et al., 2009). If current shoreline hardening trends continue, 9 to 18 percent of additional shoreline is predicted to be hardened 50 to 100 years into the future (Bilkovic et al., 2009). The impact on salt marsh habitats is significant with the same report estimating 38 percent of marshes being made vulnerable to sea level rise due to adjacent development, and only 62 percent of marshes having opportunities for migration. These issues may be more prominent in the Chesapeake Bay where 18 percent of the tidal shoreline is hardened (Bilkovic et al., 2014). Figure 1-1 illustrates that within Accomack County alone there has been a substantial upward trend in the number of permits issued by the VMRC to individuals for the construction of riprap and bulkhead armored structures. The study area was selected for its many threatened salt marsh habitats, and its significant shoreline hardening activity.

An original dataset was developed combining single-family residential home, land cover, and shoreline structure information. Data on single-family residential homes was taken from the Accomack County Office of the Assessor using Virginia's GIS Clearinghouse (hosted by the Virginia Geographic Information Network).[16] This included tax parcels and land ownership polygons from 2018 Q4 with information such as the parcel location, dwelling value, land value, land use, property owners, acreage, improvements, and structural housing characteristics. Land cover information was taken from several sources including the National Wetlands Inventory for salt marshes, and the Virginia Department of Conservation and Recreation for beaches. Information regarding shoreline structures is taken from the Virginia Institute of Marine

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[16] The Virginia GIS Clearinghouse can be reached at the following link: http://data.virginia.gov/datasets/8e222d4ffbea4f8ba552a089866ec11f.

Science's (VIMS) Shoreline Inventory Reports from 2002 and 2016 and Shoreline Management Model (SMM) from 2016 (Berman et al., 2016b; Berman et al., 2016a).[17] This includes information on (1) the immediate riparian zone evaluated for land use, (2) the bank along the shore, evaluated for height, cover, and natural protection, and (3) the shoreline, describing the presence of shoreline structures.

The data is filtered in several ways. First, the parcel land use code and land use descriptions are used to select only single-family residential homes. Parcels with residential homes built later than 2013 are excluded since the outcome of interest relies on changes in armoring status prior to that time. Only coastal parcels are chosen for the analysis which is based on coastal exposure and a distance threshold. Parcels that were not fronting the coast were excluded since armoring is not a consideration for these parcel owners (e.g., for parcels that are behind other parcels that front the coast). Several cutoffs are tested with the strictest cutoff selecting parcels with a zero distance from the coast and the most lenient cutoff selecting parcels within 20-meters from the coast. Next, salt marsh land cover is screened to include all marine and estuarine intertidal wetlands as defined in the Cowardin et al. 1979 classification system. Lastly, armored structures are screened to only include those structures that may prevent marsh migration, riprap and bulkheads. When omitting observations with missing or erroneous information, the sample that only includes parcels within 20-meters from the coast consists of 1,665 coastal single-family homes.[18] The size and location of the parcels, armored structures, and current salt marsh habitats are illustrated in Figure 1-2.

[17] The VIMS' SMM 2016 data was published in 2016 and includes shoreline structure information from the Spring of 2013 using aerial satellite imagery. The VIMS' SMM 2002 data was recorded through observations in the field taken by boat along the shoreline using a GPS tracker.
[18] Parcels that were greater than 20 acres in size were dropped due to the high likelihood of them being miscategorized as single-family homes. According to the Accomack county assessor, land use codes of 100 or 200

Several indicators are used to define the outcome of interest, a parcel's becoming armored.[19] Using the logit approach, the indicator gives a 1 to parcels that were armored by 2013 and a 0 to unarmored parcels. However, this approach does not take advantage of the armoring information in 2002 (parcels that armored by 2002 are treated the same as parcels that armored between 2002 and 2013). The Heckman approach allows these to be disentangled. Using this approach, in the first step probit equation, the indicator gives a 0 to parcels that were armored in 2002 and a 1 to parcels that were unarmored as of that date.[20] In the second step probit equation, the indicator gives a 1 to parcels that were armored between 2002 and 2013 and a 0 to parcels that were unarmored by 2013. One major drawback of these definitions is that because the armoring installation is based a parcels' proximity to structures, it cannot be said for certain that parcel owners are the individuals making those decisions (since any nonzero distance would associate parcels with armoring just off the property). However, this is a necessary compromise due to the limited available permit data for the county. The issue is mitigated when using a distance threshold of zero.

Spatial calculations for variables including armoring status, proximity and area measurements, and neighboring spillover effects are made in ArcGIS. Spatial calculations involving proximity measures include distance to the coast, distance to the nearest beach, distance to the nearest forest, and distance to the nearest salt marsh. Spatial calculations involving size measures include the proportion of beach and salt marsh within 100- and 200-

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for single-family residential homes can only have up to 20 acres. These errors are most likely due to differences between GIS acre and legal acre measurements.

[19] Distance thresholds between 0 and 20 meters of the parcel edge to the armored structure were used to determine if a parcel was near an armored structure and considered 'armored'. Distance thresholds beyond 20 meters were not used due to the risk of measurement error where parcels might mistakenly be considered armored.

[20] The reason for this is that the first equation also accounts for whether an observation is used in the second equation which is only the case for parcels that had not armored by 2002.

meter buffers of the parcel edge. Lastly, neighboring effects are quantified through the proportion of neighbors who became armored out of the total number of neighbors during the 2002 to 2013 time period within 500- and 1,000-meter buffers of the parcel. Compared to how Beasley and Dundas (2018) measured neighboring effects (by counting number of armored neighbors within concentric ring buffers) this is a superior measure because it is not confounded by the number of neighbors surrounding a parcel. Table 1.2 provides a list of variables used and their descriptions.

The descriptive statistics shown in Table 1.3 highlight the differences between coastal single-family homes that 'Always Armored', 'Installed Armor', and 'Never Armored' within 20 meters of the coast. The 'Always Armored' category includes parcels that were armored by 2002, the 'Installed Armor' category includes parcels that installed armor between 2002 and 2013, and the 'Never Armored' category includes parcels that never armored. 'Full Sample' includes all three groups. The dependent variable in the logit model takes on a one for parcels in the 'Always Armored' and 'Installed Armor' groups and a zero for parcels in the 'Never Armored' group. In comparison, the dependent variable in the Heckman model's second step probit equation takes on a one for parcels in the 'Installed Armor' group and a zero for parcels in the 'Never Armored' group.

When focusing on the 'Full Sample' the average parcel had a dwelling value (*DwlgVal1*) of $159,739 in 2018 USD, and was on average, 1.744 acres (*Acreage*) in size. Parcels were on average much further away from beaches (*BeachDist*) compared to forest land (*Fordist*), and salt marshes (*SMdist*) with distances of 9,477 meters, 41.47 meters, and 44.38 meters. Similarly, parcels were near smaller proportions of beach relative to salt marsh, having on average 6.47 percent of land within 200 meters as beach (*Beach200M*) compared to 23.1 percent as salt marsh

(*SM200M*). Most parcels were in flood zones (*Fld*) and in areas with low wave energy (*wavenrgy_low*), at 84.0 percent and 59.6 percent, respectively. Lastly, parcels had on average 20.2 percent of their neighbors (within 500 meters) armored by 2013.

When comparing the 'Installed Armor' to 'Never Armored' groups, 29.5 percent of parcels that were not already armored in 2002 became armored in 2013 (*Arm_Inst_1*).[21] An initial evaluation of variable means suggests that there are some systematic differences between parcels that were armored (or not) at different time periods. For example, the mean elevation (*Elev*) of parcels that become armored is lower at 1.072 meters compared to 1.390 meters for parcels that never have armor. Parcels that become armored also seem to be at higher risk of erosion relative to those that never have armor, since only 44.7 percent are in a shoreline with low wave energy (*wavenrgy_low*) compared to 71.7 percent for parcels that never have armor. In another example, 70.8 percent of parcels that become armored are in areas suitable for planting salt marsh (*marshplant*) compared to 98 percent for parcels that never have armor. However, because these findings only consider pairwise comparison of mean values, they are insufficient to draw definitive inferences regarding factors that increase or decrease the likelihood of armoring across the sample, ceteris paribus. This necessitates a more rigorous regression analysis using the logit and Heckman probit models of armoring.

Results

Table 1.4 compares results from three alternative logit model specifications that include factors important to the installation of riprap or bulkhead revetments. These include environmental

[21] When combining the 'Always Armored' and 'Installed Armor' groups, 49.8 percent of parcels became armored by 2013 (*Arm_Inst_2*).

factors that increase the risk of property loss from erosion (*wavenrgy_low*), storm surge/flood (*Fld*), and marsh migration (*marshplant*, *SMdist*, *SM100M*, *SM200M*), and factors that mitigate these risks (*Elev*, *forestshore*, *SMdist*, *SM100M*, *SM200M*, *BeachDist*, *Beach100M*, *Beach200M*). Also included are non-environmental factors related to the parcel that influence these risks, such as its dwelling value (*DwlgVall*), and its exposure to the coast (*Coast_Frnt*). Lastly, the parcel's becoming armored may be affected by whether its neighbors' parcels become armored, and this is examined in *Neighb500M* and *Neighb1KM*. The outcome of interest, *Arm_Inst_2*, allows us to determine which factors significantly influence the likelihood of a parcel being located within 20 meters of a riprap or bulkhead revetment by the end of the 2013 time period.[22] Columns (1) through (3) show results at varying truncated distances.

In all cases, results for statistically significant variables comport with prior expectations derived from theory and intuition. For example, higher dwelling values and greater coastal exposure raise the likelihood (or log odds) of a riprap or bulkhead revetment being placed near a parcel. Parcel position is significant (*Lat* and *Long*) but this may be because there are relatively more coastal parcels in the northeast of the Eastern Shore that could potentially have an armored structure placed nearby.

Many of the parcel's natural features that influence the risk of erosion, storm surge/flood, and marsh migration are significant. For example, parcels located in areas with low wave energy (*wavenrgy_low*), and hence, low erosion risk, are less likely to have a riprap or bulkhead revetment built nearby. Similar results are found for parcels protected from erosion by a forested

[22] Most of the primary results related to salt marshes are consistent when using a distance threshold of zero in *Arm_Inst_3* (the only exception is for *SM100M* which becomes insignificant). However, many of the parcel's natural protective features are now insignificant (this may be due to the loss of observations and greater chances of measurement error). Results from this model using a distance threshold of zero, can be found in Table A.1 of the Appendix.

shoreline (*forestshore*). Parcels with a higher elevation that are more protected from flooding and marsh migration are also less likely to be near one of these structures. Some natural features, however, may mitigate some risks while exacerbating others; such is the case for salt marshes which protect against erosion, and flooding, but increase the risk of marsh migration. Results indicate that parcels are more likely to have armored structures placed near them when located *further* away from salt marshes, when near *smaller* proportions of salt marsh (only within 100 meters of the parcel), and when located *outside* of areas suitable for planting salt marsh (areas less suited to marsh migration). However, not all environmental factors had a significant effect. For example, although wide beaches provide some protection against erosion and flooding, the parcels being on average 9,477 meters away were unlikely to receive this benefit. Lastly, neighborhood effects are found to be very influential as well. Parcels near greater proportions of neighboring parcels that also have an armored structure placed nearby are more likely to have one placed near them (this influence from neighboring parcels is significant within only 500 meters).

Armoring Predictions Using a Heckman Probit Approach

In the Heckman two-step model, the first and second step probit equations are very similar, since the same factors that influence armoring at the end of the 2002 to 2013 time period (predicted by the second step probit equation) are likely to influence armoring at the start of the period (predicted by the first step probit equation). For the coefficients of the second step probit to be interpretable however, the explanatory variables must be a subset of the ones used in the first step. This leads to the removal of *BeachDist*, *Beach100M*, and *Beach200M* from the second step probit equation, and the inclusion of *BeachDist* in the first step.[23] Table 1.5 shows the Heckman Probit results when distance is untruncated in 'Heckman Probit 1', and when distance is truncated at 500 meters in 'Heckman Probit 2'. The 'First Stage' shows the first step probit results and 'Second Stage' shows the second step probit results.

A parcel's predicted armoring status in 2002 was shown to be significant in its likelihood of becoming armored between 2002 and 2013. This is indicated by both statistically significant Inverse Mills Ratios (ρ), and Wald Tests.[24] Results are broadly consistent between the two Heckman models. The only exception is the significance of *Fld* in 'First Stage' of 'Heckman Probit 2'. However, considering its lack of significance in all other models, this is most likely a spurious result. In both models, the results from the 'First Stage' follow intuition. When comparing signs between statistically significant natural protection variables, the 'First Stage' results have signs opposite of those found in the 'Second Stage'. This is the case because the omitted parcels in 'Second Stage' were already close to an armored structure at the start of the 2002 to 2013 time period, so factors that make a parcel *more* likely to be near armoring in 2002 make it *less* likely to appear in the dataset in 'Second Stage'. When focusing on the 'First Stage', parcels which were further away from salt marshes were more likely be near armoring at the start of the time period and hence, omitted. Similarly, parcels which were more protected early in the time period (e.g., as indicated by *Elev*, *forestshore*, and, *SM200M*) were less likely to be near armoring and less likely to be omitted. *BeachDist* is a very significant factor in determining whether a parcel is selected into the dataset. One possible explanation for this is that parcels that

[23] The decision was made on an empirical basis using the data in the sample. Also, the variables *Beach100M* and *Beach200M* are not included in the selection equation model because all of the omitted parcels are further than 200 meters away from beaches, and hence, have beach proportions of zero.
[24] The Wald Tests rejected independence between the first and second step probit equations at the 10 percent and 5 percent levels for 'Heckman Probit 1' and 'Heckman Probit 2', respectively.

were already near an armored structure in 2002 were on average 8,373 meters away from beaches. Lastly, neighborhood effects (mainly *Neighb500M*) play a significant role; parcels around larger proportions of neighbors that had armored structures built between 2002 and 2013 were less likely to already be near an armored structure in 2002, and less likely to be omitted.

Results from the 'Second Stage', are largely consistent with the logit model results shown in Table 1.4. Parcels are more likely to have an armored structure built within 20 meters of them between 2002 and 2013 when the dwelling value is higher, and when a larger proportion of the parcel's boundary fronts the coast. Also, there is evidence that these armored structures are not being built in order to prevent marsh migration, as indicated by *SMdist*, and *marshplant*. In contrast, despite their benefits in erosion, marsh migration and flood protection, *Elev*, *forestshore*, and *wavenrgy_low* are insignificant.

Armoring Installation Predictions

Models based on the change in armoring status can be used to predict the likelihood of armoring for parcels that were not armored by 2013. For example, the models which use *Arm_Inst_1* as the dependent variable can be used to predict the likelihood that an armored structure is built within 20 meters of a parcel. The Heckman probit model in Table 1.5 was chosen for this purpose. Predictions of armored structures being built within 20 meters of (835 unarmored) parcels is shown in Figure 1-3.

When examining all unarmored parcels, armoring is unlikely with a median probability of only 10.95 percent, and 90 percent of parcels with probabilities under 40 percent. But even among this group, the probability of parcels armoring near salt marsh is low at under 10 percent.

Although there are exceptions, for most of the parcels shown the probability does not rise higher than 20 percent.

Conclusion

This paper examines the determinants of armoring using riprap and bulkhead revetments through a unique spatial dataset that combined residential housing data with shoreline characteristics, and land cover information. By comparing the geospatial characteristics between coastal single-family residential homes that had armored to those that did not, the influence of marsh migration as well as other factors relevant to the installation of these structures are examined.

Results provide evidence that armoring is not taking place against the threat of salt marsh encroachment. In fact, quite the opposite seems to be happening: Coastal properties are more likely to be near riprap or bulkhead revetments when they are located further away from salt marsh, around smaller proportions of salt marsh, and in areas less suited for planting salt marsh (areas less likely to have marsh migration). There may be many reasons for this including: (1) salt marsh's benefits in the form of erosion control and flood mitigation more than offset the increased risk of marsh migration, (2) the potential penalties incurred for armoring that impacts wetlands deter its construction, or (3) both. Other environmental factors that protect against the loss of property value from erosion, storm surge/flood, and marsh migration also play a role in whether coastal properties are near these structures. For example, similar to findings from Beasley and Dundas (2018), results provide evidence that properties with higher elevation (which are more protected against flooding and marsh migration) and properties located in areas with low wave energy (with a reduced risk of erosion) are less likely to be near an armored structure. In comparison, there is some, albeit, weaker evidence that properties are less likely to be near an armored structure when protected by a forested shoreline. Characteristics of the parcel itself that increase the value or risk of property loss (e.g., the value of the dwelling, and how much of the property is exposed to the coast) increase the likelihood of it being near an armored structure. Lastly, consistent throughout all specifications, neighboring effects play a role in whether an armored structure is near a property; a property that has a larger proportion of its neighbors near an armored structure is more likely to be near one as well.

Although these results provide useful information regarding the influence of marsh migration and other determinants of armoring in general, there are several limitations in the analysis. First, *Arm_Inst_1* is based on whether a property has a riprap or bulkhead revetment placed near it in 2013 where one did not exist in 2002, but since the VIMS' data collection methods differ between the 2002 and 2013 structural information[25] some of the changes in armoring status may be due to these differences (however, results are generally consistent with the *Arm_Inst_2* model which does not rely on comparisons in these datasets). Two, although this research sheds light on whether armoring is taking place due to the threat of marsh migration, it says nothing about whether those riprap or bulkhead structures *actually prevent* marsh migration. There are many factors that make these structures more or less effective in this regard, such as its relative height when compared to the tidal range[26], and its placement on the landward-marsh edge (Fuller et al., 2011). Three, since there is no information on the exact timing of when these armored structures were placed, the direction of neighboring effects cannot be determined

[25] The 2002 shoreline information was collected from a boat based on structures that were visible. Structures could have been missed, for example with a wide enough marsh. In contrast, the 2013 shoreline information was collected in a lab using high-resolution imagery. It is possible that structures could have been missed, for example, if they were hidden by vegetation or tree shadows.
[26] Tidal wetlands only grow up to 1.5 times the tidal range in all of Virginia with few exceptions in the Chincoteague Bay area of Accomack County (where the tidal range is under 1 foot). This is based on the expert opinion of Hank Badger of the VMRC.

(results only indicate a positive spatial correlation in parcels located near armored structures). Four, results should not be interpreted as factors influencing the parcel *owner's* decision to install armor. When comparing even the number of properties that had an armored structure built adjacent to them, there is a large discrepancy between the number of individuals issued permits by the VMRC (256 parcels had a structure built adjacent to them during the 2002 to 2013 time period while only 11 permits were issued during the same time frame). Fifth, the model does not incorporate property insurance against flooding or erosion, which would lower the need to be protected by an armored structure and place a downward bias on measures of flood and erosion risk. However, this is not considered a major problem since riprap and bulkhead revetments are designed to protect against erosion rather than flooding and erosion insurance does not exist (Walsh et al., 2019).[27] Lastly, the model does not include factors that may influence the cost of armoring, including for example, the contractor used, its size and materials. If the cost of armoring per linear foot is not assumed equal across parcels, this would bias the results. These limitations leave room for further research.

Despite its limitations, these results have significant implications for policies designed to limit armoring and reduce impacts to salt marshes and wetlands in general. Although this study looks at the armoring of developed property, it is reasonable to assume that similar findings would occur in the case of undeveloped property since they face the same risks of property loss from erosion, flooding, and marsh migration. The finding that armoring is less likely to occur near salt marsh may indicate the success of current policy restrictions (such as through permit authorization) that limit the impact to wetlands in the study area. But whether this is due to the

[27] The Federal Emergency Management Agency's (FEMA) National Flood Insurance Program only covers erosion damage indirectly through flood-related erosion. More information can be found at https://www.fema.gov/erosion.

policy restriction and/or the natural protections offered by salt marshes (or some alternative reason), this suggests that the preservation of salt marshes through transgression zone purchases may be unnecessary for reasons other than the property’s expected development, in the study area. This highlights the importance of understanding the dynamic between armoring and marsh migration for conservation agencies and policymakers looking to preserve salt marshes. With global warming, urban development, and the increasing trend of armoring, actions taken to preserve salt marsh habitats will only grow in importance.

References

Barbier, E. B., Georgiou, I. Y., Enchelmeyer, B., & Reed, D. J. (2013). The value of wetlands in protecting southeast Louisiana from hurricane storm surges. *PLoS One, 8*(3), e58715.

Barbier, E. B., Hacker, S. D., Kennedy, C., Koch, E. W., Stier, A. C., & Silliman, B. R. (2011). The value of estuarine and coastal ecosystem services. *Ecological monographs, 81*(2), 169-193.

Barbier, E. B., Koch, E. W., Silliman, B. R., Hacker, S. D., Wolanski, E., Primavera, J., . . . Cramer, L. A. (2008). Coastal ecosystem-based management with nonlinear ecological functions and values. *science, 319*(5861), 321-323.

Beasley, W. J., & Dundas, S. J. (2018). Holding the Line: Identifying the influential determinants of a land-owner's decision to install coastal armoring.

Berman, M., Nunez, K., Kileen, S., Rudnicky, T., Bradshaw, J., Angstadt, K., . . . Hershner, C. H. (2016b). *Accomack County, Virginia - Shoreline Inventory Report: Methods and Guidelines*. Retrieved from: <https://scholarworks.wm.edu/data/50/>

Berman, M., Nunez, K., Killeen, S., Rudnicky, T., Bradshaw, J., Angstadt, K., . . . Hershner, C. (2016a). *GIS Data: Accomack County Shoreline Management Model*. Retrieved from: https://doi.org/10.21220/V5543F

Bilkovic, D. M., Greiner, J., Horan, J., & Stubbs, Q. (2014). *Designing Sustainable Coastal Habitats*. Retrieved from Edgewater, MD:

Bilkovic, D. M., Herschner, C. H., Rudnicky, T., Nunez, K., Schatt, D. E., Kileen, S., & Berman, M. (2009). Vulnerability of shallow tidal water habitats in Virginia to climate change.

Borchert, S. M., Osland, M. J., Enwright, N. M., & Griffith, K. T. (2018). Coastal wetland adaptation to sea level rise: Quantifying potential for landward migration and coastal squeeze. *Journal of Applied Ecology, 55*(6), 2876-2887.

Chesapeake Bay Program. (n.d.). *Wetlands.* Retrieved from https://www.chesapeakebay.net/state/wetlands

Coastal Resilience: Virginia Eastern Shore. (n.d.). Retrieved from http://coastalresilience.org/project/virginia-eastern-shore/

Dugan, J., Airoldi, L., Chapman, M., Walker, S., Schlacher, T., Wolanski, E., & McLusky, D. (2011). 8.02-Estuarine and coastal structures: environmental effects, a focus on shore and nearshore structures. *Treatise on estuarine and coastal science, 8*, 17-41.

Dugan, J. E., Emery, K., Alber, M., Alexander, C., Byers, J. E., Gehman, A., . . . Sojka, S. (2017). Generalizing ecological effects of shoreline armoring across soft sediment environments. *Estuaries and Coasts*, 1-17.

Dunn, S., Friedman, R., & Baish, S. (2000). Coastal erosion: Evaluating the risk. *Environment, 42*(7), 36-45.

Wetland Guidelines, (1993).

Fuller, R., Ferdaña, Z., Cofer-Shabica, N., Herold, N., Schmid, K., Smith, B., . . . Taylor, P. (2011). Marshes on the move; A manager's guide to understanding and using model results depicting potential impacts of sea level rise on coastal wetlands.

Gedan, K. B., Silliman, B. R., & Bertness, M. D. (2009). Centuries of human-driven change in salt marsh ecosystems.

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

Gopalakrishnan, S., Landry, C. E., & Smith, M. D. (2017). Climate change adaptation in coastal environments: modeling challenges for resource and environmental economists. *Review of environmental economics and policy, 12*(1), 48-68.

Heckman, J. J. (1979). Sample selection bias as a specification error. *Econometrica: Journal of the econometric society*, 153-161.

Interis, M. G., & Petrolia, D. R. (2016). Location, location, habitat: how the value of ecosystem services varies across location and by habitat. *Land Economics, 92*(2), 292-307.

Jin, D., Ashton, A. D., & Hoagland, P. (2013). Optimal Responses to Shoreline Changes: An Integrated Economic and Geological Model with Application to Curved Coasts. *Natural Resource Modeling, 26*(4), 572-604. doi:http://onlinelibrary.wiley.com/journal/10.1111/%28ISSN%291939-7445/issues

Johnston, R. J., Grigalunas, T. A., Opaluch, J. J., Mazzotta, M., & Diamantedes, J. (2002a). Valuing estuarine resource services using economic and ecological models: the Peconic Estuary System study. *Coastal Management, 30*(1), 47-65.

Johnston, R. J., Magnusson, G., Mazzotta, M. J., & Opaluch, J. J. (2002b). Combining economic and ecological indicators to prioritize salt marsh restoration actions. *American Journal of Agricultural Economics, 84*(5), 1362-1370.

King, P. G., McGregor, A. R., & Whittet, J. D. (2016). Can California Coastal Managers Plan for Sea-Level Rise in a Cost-Effective Way? *Journal of Environmental Planning and Management, 59*(1-2), 98-119. doi:http://www.tandfonline.com/loi/cjep20

Kirwan, M. L., & Megonigal, J. P. (2013). Tidal wetland stability in the face of human impacts and sea-level rise. *Nature, 504*(7478), 53-60.

Kirwan, M. L., Temmerman, S., Skeehan, E. E., Guntenspergen, G. R., & Fagherazzi, S. (2016a). Overestimation of marsh vulnerability to sea level rise. *Nature Climate Change, 6*(3), 253.

Kirwan, M. L., Walters, D. C., Reay, W. G., & Carr, J. A. (2016b). Sea level driven marsh expansion in a coupled model of marsh erosion and migration. *Geophysical Research Letters, 43*(9), 4366-4373. doi:doi:10.1002/2016GL068507

Kriesel, W., Landry, C., & Keeler, A. (2000). Coastal erosion hazards: the University of Georgia’s results. *Evaluation of erosion hazards*.

Landry, C. E., & Hindsley, P. (2011). Valuing beach quality with hedonic property models. *Land economics, 87*(1), 92-108.

Luscher, A., & Hollingsworth, C. (2007). Shore Erosion Control: the Natural Approach. USDA National Resource Conservation Service and MD Department of Natural Resources. In.

McFadden, D. (1974). Conditional Logit Analysis of Qualitative Choice Behaviour". In Frontiers in Econometrics, ed. P. Zarembka.(New York: Academic Press).

Neumann, J. E., Emanuel, K., Ravela, S., Ludwig, L., Kirshen, P., Bosma, K., & Martinich, J. (2015). Joint effects of storm surge and sea-level rise on US Coasts: new economic estimates of impacts, adaptation, and benefits of mitigation policy. *Climatic Change, 129*(1-2), 337-349.

Petrolia, D. R., Interis, M. G., & Hwang, J. (2014). America's wetland? A national survey of willingness to pay for restoration of Louisiana's coastal wetlands. *Marine Resource Economics, 29*(1), 17-37.

Prosser, D. J., Jordan, T. E., Nagel, J. L., Seitz, R. D., Weller, D. E., & Whigham, D. F. (2017). Impacts of coastal land use and shoreline armoring on estuarine ecosystems: an introduction to a special issue. *Estuaries and Coasts*, 1-17.

Saleh, F., & Weinstein, M. P. (2016). The role of nature-based infrastructure (NBI) in coastal resiliency planning: A literature review. *Journal of environmental management, 183*, 1088-1098.

Schuerch, M., Spencer, T., Temmerman, S., Kirwan, M. L., Wolff, C., Lincke, D., . . . Brown, S. (2018). Future response of global coastal wetlands to sea-level rise. *Nature, 561*(7722), 231-234. doi:10.1038/s41586-018-0476-5

Scyphers, S. B., Picou, J. S., & Powers, S. P. (2015). Participatory conservation of coastal habitats: the importance of understanding homeowner decision making to mitigate cascading shoreline degradation. *Conservation Letters, 8*(1), 41-49.

Temmerman, S., Meire, P., Bouma, T. J., Herman, P. M., Ysebaert, T., & De Vriend, H. J. (2013). Ecosystem-based coastal defence in the face of global change. *Nature, 504*(7478), 79-83.

Thorne, K., MacDonald, G., Guntenspergen, G., Ambrose, R., Buffington, K., Dugger, B., . . . Rosencranz, J. (2018). US Pacific coastal wetland resilience and vulnerability to sea-level rise. *Science Advances, 4*(2), eaao3270.

Thorne, K. M., Takekawa, J. Y., & Elliott-Fisk, D. L. (2012). Ecological Effects of Climate Change on Salt Marsh Wildlife: A Case Study from a Highly Urbanized Estuary. *Journal of Coastal Research, 28*(6), 1477-1487.

Titus, J. G., Hudgens, D. E., Trescott, D. L., Craghan, M., Nuckols, W. H., Hershner, C. H., . . . Wang, J. (2009). State and local governments plan for development of most land vulnerable to rising sea level along the US Atlantic coast. *Environmental Research Letters, 4*(4), 044008. doi:10.1088/1748-9326/4/4/044008

Torio, D. D., & Chmura, G. L. (2013). Assessing coastal squeeze of tidal wetlands. *Journal of Coastal Research, 29*(5), 1049-1061.

Van de Ven, W. P., & Van Praag, B. M. (1981). The demand for deductibles in private health insurance: A probit model with sample selection. *Journal of econometrics, 17*(2), 229-252.

Walsh, P., Griffiths, C., Guignet, D., & Klemick, H. (2019). Adaptation, Sea Level Rise, and Property Prices in the Chesapeake Bay Watershed. *Land economics, 95*(1), 19-34.

Yohe, G., Neumann, J., Marshall, P., & Ameden, H. (1996). The economic cost of greenhouse-induced sea-level rise for developed property in the United States. *Climatic Change, 32*(4), 387-410.

Zedler, J. B., & Kercher, S. (2005). Wetland resources: status, trends, ecosystem services, and restorability. *Annu. Rev. Environ. Resour., 30*, 39-74.

Table 1.1 Armoring Statistics from Joint Permit Applications (2010 – 2017)

Variable		Percentage	Total Responses
Armored Structure	Bulkhead	84.67	49
	Riprap	12.24	
	Both	4.08	
Reason Given	Ease of Access	11.11	27
	Erosion	70.37	
	Storm	18.52	
Impact Mitigation	BMP	25.71	35
	Build from Upland	45.71	
	Unnecessary	20.00	
	Pay Fine	8.57	

Note: ‘Total Responses’ are not equal due to incomplete responses in how people filled out the Joint Permit Application form.

Table 1.2 Variable Descriptions

Dependent Variables	Description
Arm_Inst_1	1 = newly installed riprap or bulkhead revetment between 2002 and 2013 within 20 meters of the parcel edge 0 = parcel is further than 20 meters away from either structure
Arm_Inst_2	1 = parcel has a riprap or bulkhead revetment within 20 meters of its edge by 2013 0 = parcel is further than 20 meters away from either structure
Arm_Inst_3	1 = newly installed riprap or bulkhead revetment between 2002 and 2013 within 0 meters of the parcel edge 0 = parcel is further than 0 meters away from either structure
Arm_Inst_4	1 = parcel has a riprap or bulkhead revetment within 0 meters of its edge by 2013 0 = parcel is further than 0 meters away from either structure
Independent Variables	**Description**
DwlgVal1	Dwelling value in $10,000 recorded in 2018 Q4
Acreage	The GIS parcel acreage
BeachDist	The Euclidean distance from the parcel edge to the nearest beach
SMdist	The Euclidean distance from the parcel edge to the nearest salt marsh
Fordist	The Euclidean distance from the parcel edge to the nearest forest
SM100M	The proportion of salt marsh within 100 meters of the parcel edge
Beach100M	The proportion of beach within 100 meters of the parcel
SM200M	The proportion of salt marsh within 200 meters of the parcel edge.
Beach200M	The proportion of beach within 200 meters of the parcel edge
marshplant*	1 = parcel is located in an area suitable for marsh planting 0 = otherwise
wavenrgy_low	1 = parcel is located in an area with low wave energy 0 = parcel is located in an area with moderate or high wave energy
Forestshore**	1 = parcel is located in a forested shoreline 0 = otherwise
Elev	The mean elevation on the parcel in meters
Fld	1 = parcel is in a FEMA flood zone 0 = otherwise
Lat	The latitudinal coordinate of the parcel's centroid in decimal degrees
Long	The longitudinal coordinate of the parcel's centroid in decimal degrees
Chincoteague	1 = parcel is located in Chincoteague 0 = otherwise
Coast_Frnt	The proportion of the parcel perimeter fronting the coast
ChsBay	1 = parcel is located on the Chesapeake Bay side of the coast 0 = otherwise

Neighb500M***	The proportion of neighbors who became armored between 2002 and 2013 within 500 meters of the parcel centroid
Neighb1KM***	The proportion of neighbors who became armored between 2002 and 2013 within 1 kilometer of the parcel centroid

* Based on bathymetric measurements from the VIMS. A 1-meter bathymetric contour is used to determine if the nearshore is suitable for marsh planting. If the contour is outside 10 meters of the shoreline then it is considered 'shallow' and suitable for marsh planting.

** The shoreline is considered forested if the riparian land use is considered forested or if there is a tree fringe greater than 100 feet.

*** These variables use the same definition of becoming armored as the dependent variable used in the models.

Table 1.3 Summary Statistics

Variable	Full Sample Mean	Full Sample S.D.	Always Armored Mean	Always Armored S.D.	Installed Armor Mean	Installed Armor S.D.	Never Armored Mean	Never Armored S.D.	t-statistics*	
DwlgVal1	159,739	89,602	162,340	78,931	165,827	94,698	155,697	93,033	-1.6992	0.5772
Acreage	1.744	2.816	0.659	1.597	1.331	2.522	2.541	3.211	6.2775	4.6864
BeachDist	9,477	7,965	8,373	7,532	7,428	7,856	10,970	7,967	7.0038	-1.7525
SMdist	44.38	79.27	81.91	91.43	61.52	97.87	15.58	44.31	-11.1143	0.9989
Fordist	41.47	69.89	71.71	75.48	64.22	94.72	14.54	35.39	-13.1287	-1.2661
SM100M	0.236	0.281	0.101	0.158	0.197	0.230	0.330	0.318	7.0547	7.1321
Beach100M	0.0612	0.230	0	0	0.0576	0.210	0.0979	0.289	2.3559	6.0192
SM200M	0.231	0.252	0.121	0.143	0.247	0.247	0.289	0.281	2.3980	9.2638
Beach200M	0.0647	0.225	0	0	0.0742	0.205	0.0980	0.283	1.4229	7.9472
marshplant	0.786	0.410	0.507	0.500	0.708	0.455	0.980	0.141	15.5594	5.9139
wavenrgy low	0.596	0.491	0.495	0.500	0.447	0.498	0.717	0.451	9.1222	-1.3615
forestshore	0.0679	0.252	0.00208	0.0456	0.0287	0.167	0.122	0.328	5.0622	3.3228
Elev	1.205	0.922	0.981	0.564	1.072	0.835	1.390	1.074	4.9517	1.8580
Fld	0.840	0.366	0.873	0.333	0.883	0.322	0.804	0.398	-3.2848	0.4042
Lat	37.79	0.139	37.86	0.134	37.83	0.128	37.73	0.121	-12.4706	-3.6103
Long	-75.64	0.223	-75.53	0.207	-75.59	0.231	-75.73	0.189	-11.4421	-3.4015
Chincoteague	0.274	0.446	0.4158	0.4934	0.4241	0.4949	0.1305	0.3371	-11.8003	0.2380
Coast_Frnt	0.198	0.151	0.221	0.154	0.194	0.146	0.186	0.150	-0.8248	-2.4931
ChsBay	0.540	0.499	0.356	0.479	0.441	0.497	0.687	0.464	8.1491	2.5049
Neighb500M	0.202	0.235	0.112	0.122	0.434	0.314	0.157	0.177	-19.2209	20.4929
Neighb1KM	0.205	0.194	0.140	0.0887	0.375	0.269	0.171	0.156	-16.2475	17.8829
N	1,665		481		349		835			

*The ‘Always Armored’ category summarizes statistics for those parcels that were armored (within 20 meters of the parcel edge) prior to 2002. The ‘Installed Armor’ and ‘Never Armored’ categories summarize statistics for those parcels that were armored between 2002 and 2013, and those parcels that were not. The t-statistics in the first column are based on a comparison between the averages of variables for the ‘Installed Armor’ and ‘Never Armored’ categories, and the t-statistics in the second column are based on a comparison between the averages of variables for the ‘Always Armor’ and ‘Never Armored’ categories.

Table 1.4 Logit Results on the Determinants of Installing Riprap and Bulkhead Revetments by 2013

	Dependent Variable = Arm_Inst_2		
Variables	(1)	(2)	(3)
DwlgVal1	0.0153*	0.00845*	0.0153*
	(0.00880)	(0.00493)	(0.00881)
Acreage	0.0285	0.0160	0.0279
	(0.0316)	(0.0171)	(0.0315)
SMdist	0.00827***	0.00474***	0.00938***
	(0.00154)	(0.000887)	(0.00174)
BeachDist	-0.0000278	-0.000577	0.000574
	(0.0000404)	(0.000626)	(0.00523)
Fordist	0.00165	0.000877	0.00158
	(0.00189)	(0.00101)	(0.00214)
SM100M	-1.076**	-0.646**	-1.052**
	(0.494)	(0.271)	(0.510)
SM200M	-0.0186	0.0778	-0.0486
	(0.545)	(0.294)	(0.554)
Beach100M	-1.161	-0.410	-0.876
	(1.347)	(0.758)	(1.307)
Beach200M	-1.174	-0.849	-0.715
	(1.533)	(0.833)	(1.513)
marshplant	-1.856***	-1.028***	-1.825***
	(0.291)	(0.151)	(0.288)
wavenrgy_low	-0.572***	-0.316***	-0.577***
	(0.189)	(0.103)	(0.188)
forestshore	-0.826**	-0.437**	-0.833**
	(0.387)	(0.200)	(0.390)

Elev	-0.229*	-0.111*	-0.217*
	(0.128)	(0.0667)	(0.123)
Fld	-0.144	-0.0548	-0.142
	(0.195)	(0.111)	(0.195)
Lat	4.837*	2.725*	5.010*
	(2.487)	(1.404)	(2.588)
Long	-7.286**	-3.860**	-7.003**
	(3.175)	(1.781)	(3.288)
Chincoteague	0.639	0.327	0.719
	(0.447)	(0.251)	(0.467)
Coast_Frnt	1.078**	0.625**	1.066**
	(0.539)	(0.296)	(0.537)
ChsBay	-0.876	-0.642*	-1.145
	(0.785)	(0.379)	(0.709)
Neighb500M	3.907***	2.293***	3.911***
	(0.516)	(0.281)	(0.522)
Neighb1KM	0.0804	0.116	-0.00165
	(0.718)	(0.371)	(0.708)
Constant	-733.4**	-394.6**	-718.8**
	(325.2)	(183.8)	(339.2)
Distance Truncated	No	500 M	200 M
N	1,665	1,665	1,665
Pseudo-R^2	0.4728	0.4731	0.4720

Table 1.5 Heckman Probit Results on the Determinants of Installing Riprap and Bulkhead Revetments Between 2002 and 2013

Dependent Variable = Arm_Inst_1

Variables	Heckman Probit 1 (Second Stage)	Heckman Probit 1 (First Stage)	Heckman Probit 2 (Second Stage)	Heckman Probit 2 (First Stage)
DwlgVal1	0.0144***	-0.00631	0.0146***	-0.00909*
	(0.00548)	(0.00530)	(0.00553)	(0.00536)
Acreage	0.0101	0.0610	0.0109	0.0560
	(0.0183)	(0.0380)	(0.0182)	(0.0377)
SMdist	0.00388***	-0.00386***	0.00399***	-0.00428***
	(0.00115)	(0.000735)	(0.00110)	(0.000798)
BeachDist		-0.000132***		-0.00641***
		(0.0000175)		(0.000674)
Fordist	-0.000056	-0.00230***	-0.000114	-0.00325***
	(0.00118)	(0.000851)	(0.00117)	(0.000934)
SM100M	-0.723***	0.430	-0.760***	0.143
	(0.266)	(0.275)	(0.268)	(0.300)
SM200M	0.0465	0.904***	0.0151	1.260***
	(0.299)	(0.315)	(0.300)	(0.340)
marshplant	-0.434	1.131***	-0.471*	1.295***
	(0.314)	(0.122)	(0.280)	(0.128)
wavenrgy_low	-0.256**	0.520***	-0.274**	0.583***
	(0.115)	(0.113)	(0.113)	(0.110)
forestshore	-0.201	1.271***	-0.204	1.225***
	(0.193)	(0.427)	(0.194)	(0.430)
Elev	-0.0834	0.182**	-0.0939	0.262***
	(0.0743)	(0.0808)	(0.0731)	(0.0776)
Fld	0.156	0.123	0.155	0.287**
	(0.134)	(0.128)	(0.135)	(0.133)

Lat	2.242***	-4.096***	2.449***	-6.532***
	(0.855)	(1.224)	(0.836)	(1.193)
Long	-1.716*	-0.102	-1.676*	5.605***
	(0.976)	(1.411)	(0.970)	(1.584)
Chincoteague	-0.0638	-1.269***	-0.105	-1.380***
	(0.234)	(0.226)	(0.228)	(0.209)
Coast_Frnt	0.809**	-0.0955	0.831***	-0.0339
	(0.323)	(0.342)	(0.321)	(0.331)
ChsBay	-0.461	0.0272	-0.448	-0.242
	(0.306)	(0.465)	(0.302)	(0.358)
Neighb500M	1.976***	3.248***	1.907***	3.059***
	(0.377)	(0.461)	(0.383)	(0.463)
Neighb1KM	0.594	0.343	0.552	-0.104
	(0.491)	(0.535)	(0.490)	(0.504)
Constant	-215.5**	147.3	-220.0**	672.6***
	(96.97)	(148.7)	(97.12)	(161.2)
Distance Truncated	No	No	500 M	500 M
ρ	0.707*		0.589**	
N	1,665	1,184	1,665	1,184

Figure 1-1 Permits Issued in Accomack County Compared to the Population (1972 – 2018)

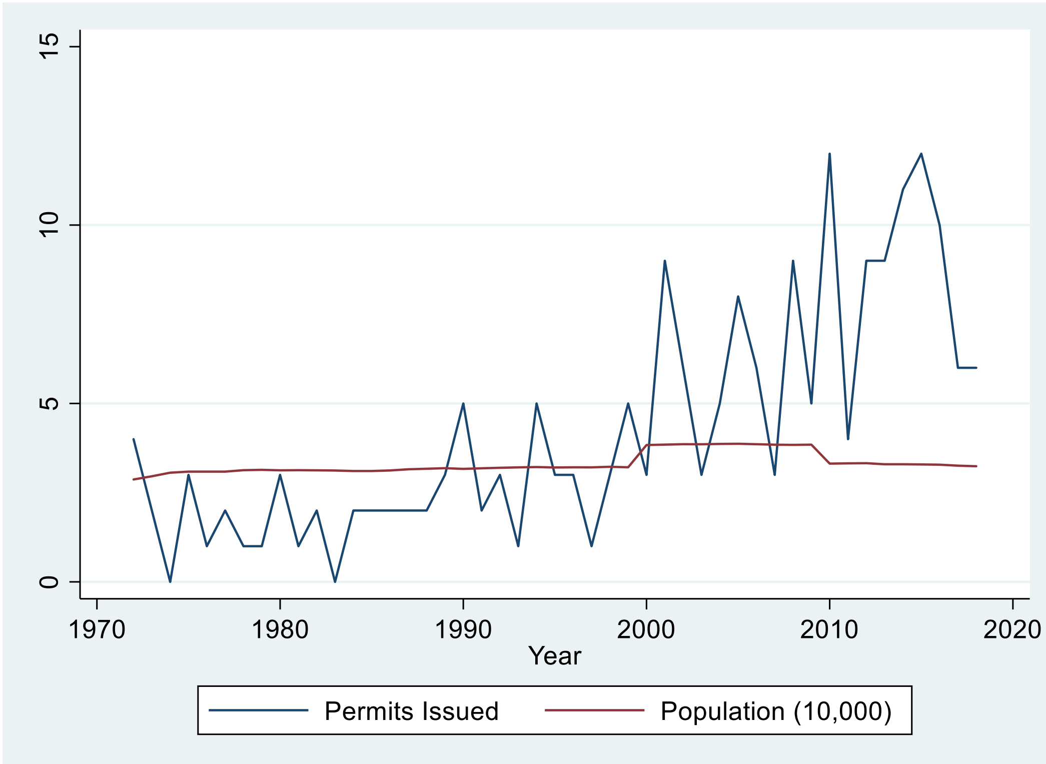


Figure 1-2 Map of Accomack County with armored structures and salt marshes

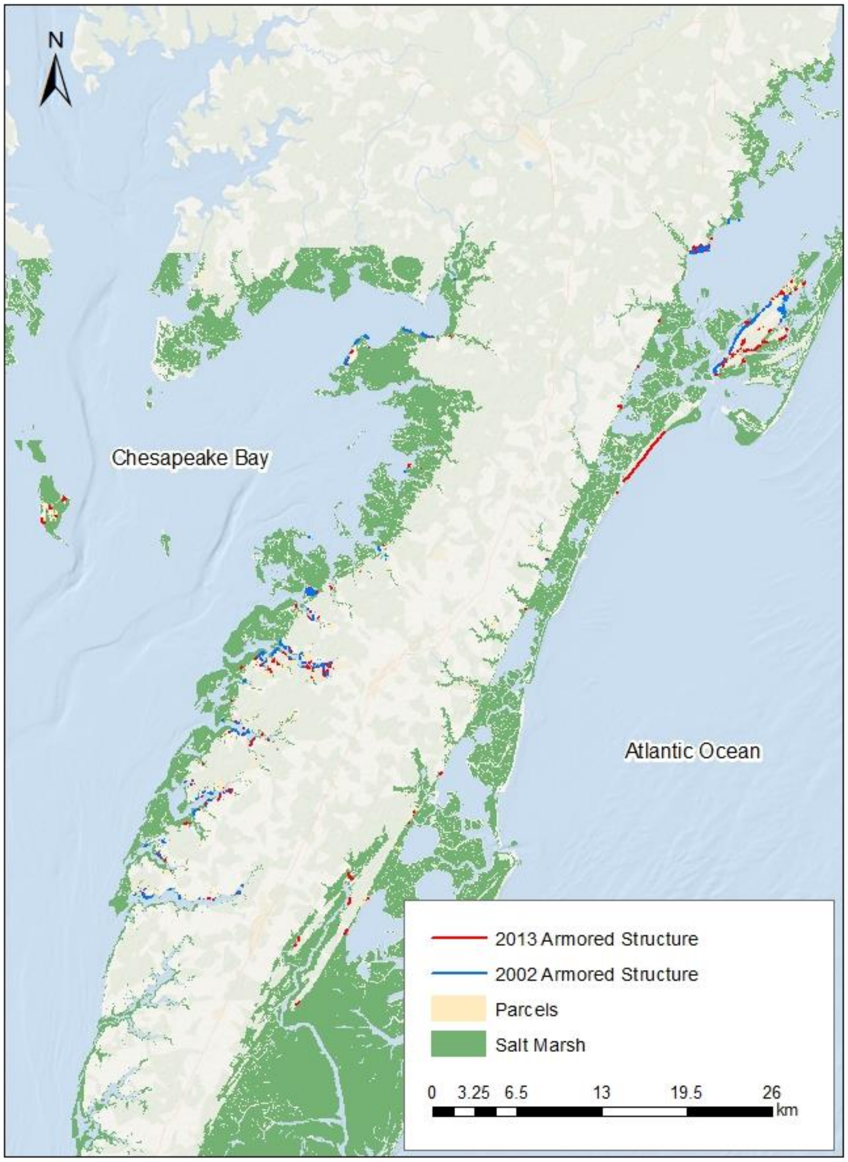
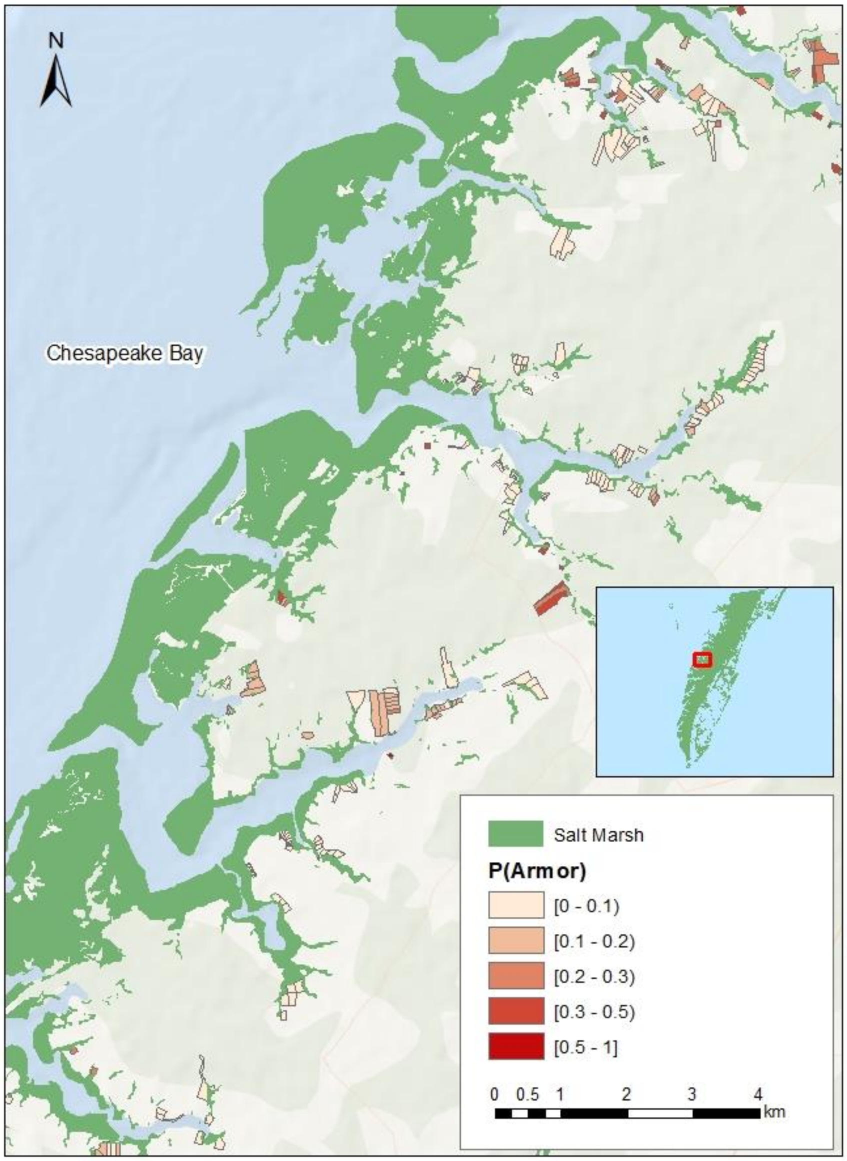


Figure 1-3 Predictions for Armored Structures Installed within 20m of Parcels



APPENDIX

Table A.1 Logit Results on the Determinants of Installing Riprap and Bulkhead Revetments by 2013 (within 0 meters of the parcel edge)

	Dependent Variable = Arm_Inst_4		
Variables	(1)	(2)	(3)
DwlgVal1	0.0263** (0.0112)	0.0134** (0.00608)	0.0274** (0.0111)
Acreage	-0.0301 (0.0456)	-0.0100 (0.0225)	-0.0221 (0.0447)
SMdist	0.00594*** (0.00201)	0.00305*** (0.00102)	0.00780*** (0.00222)
BeachDist	0.0000239 (0.0000480)	0.000141 (0.000656)	0.00502 (0.00496)
Fordist	0.00232 (0.00246)	0.00101 (0.00125)	0.00354 (0.00250)
SM100M	-0.391 (0.554)	-0.286 (0.298)	-0.238 (0.541)
SM200M	-0.348 (0.624)	-0.0881 (0.328)	-0.386 (0.612)
Beach100M	0.724 (1.803)	0.248 (0.894)	0.148 (1.647)
Beach200M	-2.424 (1.643)	-1.561* (0.888)	-1.533 (1.661)
marshplant	-2.048*** (0.320)	-1.183*** (0.167)	-2.064*** (0.329)
wavenrgy_low	-0.410* (0.230)	-0.226* (0.121)	-0.429* (0.230)
forestshore	-0.495	-0.258	-0.471

	(0.474)	(0.233)	(0.471)
Elev	-0.205	-0.115	-0.267*
	(0.158)	(0.0797)	(0.154)
Fld	-0.278	-0.0954	-0.326
	(0.244)	(0.142)	(0.241)
Lat	5.064*	3.171*	5.489*
	(3.069)	(1.655)	(3.061)
Long	-5.306	-3.597*	-6.244
	(3.970)	(2.085)	(3.903)
Chincoteague	0.494	0.287	0.612
	(0.565)	(0.296)	(0.567)
Coast_Frnt	1.928***	1.021***	1.905***
	(0.614)	(0.335)	(0.617)
ChsBay	-0.958	-0.485	-0.772
	(0.908)	(0.438)	(0.822)
Neighb500M	3.579***	2.064***	3.490***
	(0.663)	(0.351)	(0.679)
Neighb1KM	0.118	0.158	0.152
	(0.824)	(0.412)	(0.807)
Constant	-592.8	-392.0*	-680.7*
	(404.7)	(215.5)	(401.6)
Distance Truncated	No	500 M	200 M
N	1,310	1,310	1,310
Pseudo-R^2	0.5038	0.5037	0.5066

Table A.2 Heckman Probit Results on the Determinants of Installing Riprap and Bulkhead Revetments Between 2002 and 2013 (within 0 meters of the parcel edge)

Dependent Variable = Arm_Inst_3

Variables	Heckman Probit 1 (Second Stage)	Heckman Probit 1 (First Stage)	Heckman Probit 2 (Second Stage)	Heckman Probit 2 (First Stage)
DwlgVal1	0.0172** (0.00705)	-0.00791 (0.00582)	0.0173** (0.00703)	-0.0120** (0.00578)
Acreage	-0.0122 (0.0257)	0.0920 (0.0705)	-0.0120 (0.0257)	0.0927 (0.0639)
SMdist	0.00299** (0.00123)	-0.00221*** (0.000835)	0.00306** (0.00122)	-0.00215** (0.000928)
BeachDist		-0.000208*** (0.0000565)		-0.00692*** (0.000794)
Fordist	-0.000684 (0.00153)	-0.00279*** (0.000931)	-0.000656 (0.00152)	-0.00361*** (0.000965)
SM100M	-0.460 (0.302)	0.0406 (0.354)	-0.455 (0.303)	-0.363 (0.354)
SM200M	-0.158 (0.369)	1.523*** (0.408)	-0.175 (0.366)	2.033*** (0.433)
marshplant	-0.859*** (0.237)	1.363*** (0.142)	-0.850*** (0.233)	1.518*** (0.150)
wavenrgy_low	-0.130 (0.134)	0.680*** (0.129)	-0.138 (0.136)	0.675*** (0.127)
forestshore	-0.113 (0.242)	0.830* (0.481)	-0.114 (0.242)	0.764* (0.461)
Elev	-0.0996 (0.0854)	0.203* (0.106)	-0.105 (0.0854)	0.269*** (0.0993)
Fld	0.0534 (0.179)	0.0948 (0.147)	0.0455 (0.179)	0.342** (0.150)

Lat	2.921***	-0.890	2.971***	-6.056***
	(1.056)	(3.077)	(1.045)	(1.436)
Long	-0.731	-4.963	-0.677	5.785***
	(1.142)	(4.694)	(1.151)	(1.907)
Chincoteague	-0.456*	-0.955***	-0.470**	-1.236***
	(0.240)	(0.300)	(0.239)	(0.258)
Coast_Frnt	1.444***	-0.175	1.472***	-0.0741
	(0.362)	(0.416)	(0.360)	(0.397)
ChsBay	-0.349	0.206	-0.335	0.0172
	(0.350)	(0.661)	(0.351)	(0.431)
Neighb500M	1.713***	2.158***	1.698***	1.521***
	(0.471)	(0.508)	(0.470)	(0.500)
Neighb1KM	0.540	1.390**	0.538	0.814
	(0.572)	(0.636)	(0.575)	(0.578)
Constant	-166.2	-340.9	-164.0	668.2***
	(117.6)	(468.1)	(118.0)	(194.6)
Distance Truncated	No	No	500 M	500 M
ρ	0.300		0.261	
N	1,310	974	1,310	974

Table A.3 Probit Results on the Determinants of Installing Riprap and Bulkhead Revetments by 2013

	Dependent Variable = Arm_Inst_2		
Variables	(1)	(2)	(3)
DwlgVal1	0.00871*	0.00845*	0.00867*
	(0.00492)	(0.00493)	(0.00492)
Acreage	0.0176	0.0160	0.0169
	(0.0169)	(0.0171)	(0.0169)
SMdist	0.00472***	0.00474***	0.00536***
	(0.000883)	(0.000887)	(0.000996)
BeachDist	-0.0000197	-0.000577	0.000432
	(0.0000226)	(0.000626)	(0.00266)
Fordist	0.000864	0.000877	0.000831
	(0.000994)	(0.00101)	(0.00111)
SM100M	-0.621**	-0.646**	-0.608**
	(0.264)	(0.271)	(0.268)
SM200M	0.0535	0.0778	0.0395
	(0.289)	(0.294)	(0.291)
Beach100M	-0.703	-0.410	-0.472
	(0.780)	(0.758)	(0.748)
Beach200M	-0.733	-0.849	-0.431
	(0.828)	(0.833)	(0.863)
marshplant	-1.047***	-1.028***	-1.026***
	(0.152)	(0.151)	(0.151)
wavenrgy_low	-0.327***	-0.316***	-0.329***
	(0.103)	(0.103)	(0.102)
forestshore	-0.430**	-0.437**	-0.435**
	(0.199)	(0.200)	(0.200)
Elev	-0.123*	-0.111*	-0.115*

	(0.0697)	(0.0667)	(0.0668)
Fld	-0.0639	-0.0548	-0.0619
	(0.112)	(0.111)	(0.111)
Lat	2.882**	2.725*	2.951**
	(1.385)	(1.404)	(1.423)
Long	-4.312**	-3.860**	-4.067**
	(1.769)	(1.781)	(1.811)
Chincoteague	0.355	0.327	0.405
	(0.247)	(0.251)	(0.253)
Coast_Frnt	0.614**	0.625**	0.612**
	(0.296)	(0.296)	(0.295)
ChsBay	-0.482	-0.642*	-0.669*
	(0.430)	(0.379)	(0.380)
Neighb500M	2.280***	2.293***	2.275***
	(0.277)	(0.281)	(0.280)
Neighb1KM	0.139	0.116	0.0897
	(0.376)	(0.371)	(0.372)
Constant	-434.9**	-394.6**	-419.1**
	(181.7)	(183.8)	(187.0)
Distance Truncated	No	500 M	200 M
N	1,665	1,665	1,665
Pseudo-R^2	0.4774	0.4774	0.4766

Table A.4 Probit Results on the Determinants of Installing Riprap and Bulkhead Revetments by 2013 (within 0 meters of the parcel edge)

	Dependent Variable = Arm_Inst_4		
Variables	(1)	(2)	(3)
DwlgVal1	0.0133**	0.0134**	0.0145**
	(0.00614)	(0.00608)	(0.00601)
Acreage	-0.0105	-0.0100	-0.00721
	(0.0225)	(0.0225)	(0.0220)
SMdist	0.00305***	0.00305***	0.00424***
	(0.00102)	(0.00102)	(0.00116)
BeachDist	0.00000496	0.000141	0.00341
	(0.0000261)	(0.000656)	(0.00272)
Fordist	0.000981	0.00101	0.00195
	(0.00127)	(0.00125)	(0.00131)
SM100M	-0.296	-0.286	-0.179
	(0.295)	(0.298)	(0.290)
SM200M	-0.0809	-0.0881	-0.123
	(0.327)	(0.328)	(0.323)
Beach100M	0.346	0.248	0.149
	(0.976)	(0.894)	(0.892)
Beach200M	-1.617*	-1.561*	-0.869
	(0.884)	(0.888)	(0.937)
marshplant	-1.179***	-1.183***	-1.179***
	(0.166)	(0.167)	(0.168)
wavenrgy_low	-0.223*	-0.226*	-0.235*
	(0.121)	(0.121)	(0.121)
forestshore	-0.258	-0.258	-0.245
	(0.234)	(0.233)	(0.233)
Elev	-0.111	-0.115	-0.147*

	(0.0819)	(0.0797)	(0.0807)
Fld	-0.0918	-0.0954	-0.128
	(0.142)	(0.142)	(0.140)
Lat	3.143*	3.171*	3.230*
	(1.655)	(1.655)	(1.665)
Long	-3.496	-3.597*	-3.689*
	(2.131)	(2.085)	(2.121)
Chincoteague	0.281	0.287	0.366
	(0.298)	(0.296)	(0.304)
Coast_Frnt	1.022***	1.021***	1.010***
	(0.334)	(0.335)	(0.336)
ChsBay	-0.529	-0.485	-0.451
	(0.491)	(0.438)	(0.442)
Neighb500M	2.067***	2.064***	2.008***
	(0.347)	(0.351)	(0.352)
Neighb1KM	0.151	0.158	0.137
	(0.425)	(0.412)	(0.418)
Constant	-383.2*	-392.0*	-401.8*
	(218.1)	(215.5)	(218.7)
Distance Truncated	No	500 M	200 M
N	1,310	1,310	1,310
Pseudo-R^2	0.5051	0.5051	0.5087

Table A.5 Ordered Logit and Probit Results on the Determinants of Installing Riprap and Bulkhead Revetments

	Dependent Variable = Arm_Inst_5*	
Variables	(Ordered Logit)	(Ordered Probit)
DwlgVal1	-0.00837 (0.00742)	-0.00368 (0.00410)
Acreage	-0.000804 (0.0313)	-0.00639 (0.0174)
SMdist	-0.00481*** (0.000915)	-0.00275*** (0.000524)
BeachDist	0.00000554 (0.0000375)	-0.000000851 (0.0000203)
Fordist	0.00408*** (0.00117)	0.00208*** (0.000647)
SM100M	1.440*** (0.433)	0.793*** (0.236)
SM200M	0.200 (0.470)	0.0487 (0.249)
Beach100M	-0.935 (1.529)	-0.596 (0.768)
Beach200M	4.550** (1.826)	2.226** (0.876)
marshplant	0.943*** (0.160)	0.586*** (0.0910)
wavenrgy_low	0.288* (0.159)	0.193** (0.0858)
forestshore	1.120*** (0.401)	0.556*** (0.205)
Elev	0.128	0.0893

	(0.111)	(0.0608)
Fld	0.0705	0.0272
	(0.196)	(0.104)
Lat	-9.498***	-4.296***
	(2.331)	(1.283)
Long	12.52***	5.729***
	(2.913)	(1.599)
Chincoteague	-0.824**	-0.378*
	(0.407)	(0.220)
Coast_Frnt	-1.390***	-0.730***
	(0.444)	(0.246)
ChsBay	1.973**	0.891**
	(0.772)	(0.412)
Neighb500M**	-4.131***	-2.452***
	(0.414)	(0.233)
Neighb1KM**	-0.355	-0.186
	(0.546)	(0.298)
N	1,665	1,665
Pseudo-R^2	0.3526	0.3547

* Arm_Inst_5 takes on a 1 if armoring occurs by 2002, 2 if armoring occurs between 2002 and 2013, and 3 if armoring did not occur. A parcel is considered ‘armored’ if it is within 20 meters of a structure.

** Neighborhood variables are the proportions of neighboring parcels that were armored between 2002 and 2013 within 500 meters and 1 kilometer of a parcel.