Is Shoreline Armoring a Response to Marsh Migration? Modeling Relationships Between Coastal Marshes and Private Adaptation Decisions

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September 14, 2021

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Running Title: *Modeling Shoreline Armoring Decisions*

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Abstract

The value and vulnerability of salt marshes has led to efforts to ensure their preservation, including the preservation of marsh transgression zones (uplands onto which marshes can migrate) and restrictions on shoreline armoring. Coastal armoring involves the placement of hardened structures such as revetments and bulkheads along the shoreline. These structures can prevent coastal marshes from migrating onto adjacent uplands as sea levels rise, thereby causing marsh loss over time. Hence, efficient targeting of efforts to ensure marsh sustainability requires an understanding of where and why coastal armoring is likely to occur. This article develops a random utility model that characterizes residential landowners' shoreline armoring decisions for beachfront and non-beachfront residential property, focusing on whether armoring is influenced by features related to marsh migration. The model is illustrated using parcel-level data from Accomack County, Virginia with armoring observations on each parcel for two time periods, 2002 and 2013. Independent models for the two time periods suggest that landowners in the case study area do not tend to construct armoring in ways that impede marsh migration—all else equal armoring is *less* likely to occur in areas suitable for marsh migration. Rather, armoring appears to be motivated primarily by factors associated with shoreline erosion risk such as high wave energy.

Keywords

Adaptation, Armoring, Coastal, Economics, Salt Marsh, Sea Level Rise

Introduction

The value of salt marsh ecosystems is recognized as an important motivation for coastal adaptation to sea-level rise (Barbier et al., 2011, 2013; Duran Vinent et al. 2019; Gopalakrishnan et al., 2018; Interis and Petrolia, 2016; Johnston et al., 2002a,b, 2005; Milon and Scrogin, 2006; Petrolia et al., 2014). Until recently salt marshes have been largely resilient to changes in sea level due to natural adjustments in elevation via vegetation growth and sediment accretion, and by migrating landward as sea levels rise (Kirwan et al., 2010, 2016a). However, there is increasing concern about impending loss of salt marsh given accelerated sea level rise, with regional and global analyses forecasting up to a 20–45% marsh loss by 2100 (Craft et al., 2009; McFadden et al., 2007).

Given limits in the extent to which salt marshes can build elevation naturally (and hence keep up with sea level rise in a single location), the natural migration of salt marsh onto neighboring uplands is necessary for marsh persistence in many areas, particularly under rapid sea-level rise. This migration requires the presence of marsh transgression zones—undeveloped and non-armored uplands onto which marshes can migrate landward as sea levels rise (Duran Vinent et al. 2019). Coastal armoring that prevents marsh migration (e.g., riprap revetments, bulkheads) can create a "coastal squeeze" wherein marshes progressively drown as they are trapped between these hardened structures and rising waters, leading to gradual reduction of marsh extent over time (Enwright et al. 2016; Kirwan and Megonigal, 2013; Torio and Chmura 2013). Potential barriers to marsh migration are significant, especially in regions such as the US Atlantic Coast, where over 40 percent of land within 1 meter above tidal wetlands is developed; this is expected to increase in the future (Titus et al., 2009).

From a purely biophysical perspective, shoreline armoring (e.g., the placement of bulkheads or revetments parallel to the shoreline) can exacerbate salt marsh losses over time. Yet despite the potential for detrimental impacts on marsh ecosystems, shoreline armoring may be viewed as an optimal decision from the perspective of private landowners seeking to protect property from erosion, flooding, marsh migration, or other hazards (Beasley and Dundas 2020). Because many of the goods and services provided by salt marshes are public or quasi-public goods (Duran Vinent et al. 2019), armoring decisions of this type may be privately optimal even if they lead to a net loss of social welfare due to diminished ecosystem services (Scyphers et al., 2015). However, recent calls for "urgent attention" and "pre-emptive planning to set aside key coastal areas for wetland migration" (Runting et al., 2017, p. 49) imply that ongoing development and armoring are occurring in ways that threaten marsh migration over time.

Public and private agencies have responded to these potential threats to coastal marsh persistence in multiple ways, many of which seek to prevent or attenuate the potential effects of development and armoring that occurs on privately owned land. For example, in our case study area of Virginia considerable effort has been made by public and private institutions to preserve salt marshes, recognizing the potential impact of private shoreline development and armoring decisions on existing marshes and future marsh migration (Bruce and Crichton 2014). Among public actions, the Virginia Department of Conservation and Recreation has created several natural-area preserves for marsh conservation. Additionally, Virginia state law requires permit authorization for any private shoreline development or armoring project that impacts wetlands.[1] However, although it is the state's responsibility to protect and manage coastal lands (through

[1] Per Subtitle III of Title 28.2 of the Code of Virginia, permits must be obtained from the Virginia Marine Resources Commission (VMRC) for any shoreline project that would potentially impact "subaqueous or bottomlands, tidal wetlands, and coastal primary sand dunes."

Virginia's Coastal Zone Management Program)[2] and armoring is controlled through the permitting process, armoring by private landowners has increased in recent years (see the Data section below for more detail). Potential shoreline armoring by landowners has direct implications for future marsh migration under sea-level rise, on the additionality of land preservation for future marsh migration, and hence on public agency decision-making for salt marsh preservation (Kirwan et al., 2016; Duran Vinent et al., 2019; Peterson et al. 2019).[3]

Yet despite the *potential* for future armoring to impact marsh loss over time (e.g., by preventing upland marsh migration), it is unclear whether human decisions to armor the coastline are currently being made in a way that threatens remaining marshes. Not all shoreline armoring affects potential marsh migration. For example, armoring structures built in areas subject to high wave energy and erosion potential may have minimal impact on marsh migration potential, because high-energy coastal areas of this type are not conducive to marsh survival (Hayes 1979; Mitchell et al. 2017). In contrast, other types of hardened structures—for example constructed directly upland of existing marsh systems—may serve as impediments to marsh migration, thereby causing a loss of marsh extent over time (Kirwan et al. 2016a, b). Kirwan et al. (2016b) provide illustrative examples of cases worldwide in which marshes are and are not impeded from migration due to the type of coastal armoring present in different locations. Analyses such as these show that the potential impact of shoreline armoring on coastal marshes depends on when and where these structures are built—both of which are determined by landowner behavior. Duran et al. (2019) demonstrate how landowners' choices to armor (or not) different types of

[2] The program, established in 1986, is a network of state and local agencies which administer the enforceable laws and regulations that protect coastal resources, including wetlands.

[3] Although this paper studies armoring decisions by private landowners, public agencies can also choose to construct shoreline armoring in ways that affect marshes, for example to prevent beach erosion or flooding of coastal communities (Gopalakrishnan et al. 2018). However, as most US coastal land is privately owned, actions to sustain coastal marshes tend to focus on preventing development and armoring on private land (cf., Duran Vinent et al. 2019).

coastal land directly influence optimal decisions regarding marsh conservation.[4]

Despite the importance of these issues for coastal marsh sustainability, the literature (perhaps surprisingly) provides little systematic, empirical insight into the factors influencing coastal armoring decisions by property owners over time and whether these factors encourage the construction of armoring in locations where it is likely to impede marsh migration (Gitman et al. 2015; Duran Vinent et al. 2019). Among the few studies to address armoring decisions in general are Beasley and Dundas (2020), Peterson et al. (2019), and Scyphers et al. (2015). However, as discussed below, these studies provide limited insight into relationships between armoring decisions and potential marsh impacts. Other studies develop conceptual or theoretical frameworks that can be used to characterize coastal decision-making in general situations but do not provide empirical results (e.g., Gopalakrishnan et al. 2018). Thus, while coastal armoring is widely acknowledged as a potential threat to salt marsh migration, past work provides limited empirical insight into coastal armoring decisions in general, and no direct information on whether armoring is likely to be constructed in ways that threaten salt marsh persistence.

To address this gap in the literature, the present article develops a theoretically grounded discrete-choice, random utility model to evaluate the extent to which the armoring of coastal property is motivated by factors related to marsh migration. We focus on coastal structures such as riprap revetments and bulkheads that are built roughly parallel to the shoreline and can hence serve as direct impediments to marsh migration. The model considers whether recent behavioral patterns suggest that armoring on residential parcels is being constructed in locations that are

[4] Application of the model in Duran et al. (2019) requires assumptions on the extent to which private landowners will choose to armor different types of coastal land—they discuss this issue explicitly in *Section 4.5. Portfolio optimization under additionality*. Because Duran et al. (2019) do not have estimates of armoring probability, they evaluate the sensitivity of model results to alternative assumptions on the likelihood of parcel armoring. Results developed here could enable the optimization of Duran et al. (2019) to proceed without the need for these assumptions or associated sensitivity analyses.

likely to impede marsh migration. It is estimated using geospatial and housing data from a case study of Accomack County, on Virginia's Eastern Shore, and capitalizes on a dataset with observations on shoreline armoring for two time periods, 2002 and 2013. Independent models are specified for each time period to determine the factors that motivated armoring in each period. These outcomes are modeled as a function of independent variables that quantify each parcel's exposure to erosion, flooding, and marsh migration, among other potential determinants of shoreline armoring. The main model evaluates determinants of armoring observed on parcels as of 2013 (the most recent date for which comprehensive armoring observations are available). We then test robustness with an additional, parallel model using armoring observations made roughly a decade prior, in 2002.

Results provide robust evidence that armoring is *less* likely to occur in areas suitable for marsh migration. The construction of armoring on or near a parcel is *positively* related to greater distances from salt marsh, smaller proportions of nearby salt marsh in the surrounding landscape, and areas that are poorly suited for salt marsh survival from an ecological perspective. These results are robust to alternative model specifications and time periods. Results further suggest that the primary motivation for armoring in the case study area is protection against erosion and high wave energy—factors negatively correlated with the presence of salt marsh. These combined results suggest that while shoreline armoring can unquestionably prevent marsh migration from a biophysical perspective, landowner behavior in the case-study area shows that recent armoring has not been constructed primarily as a response to this migration.

Understanding Drivers of Shoreline Armoring

Coastal armoring is widespread in the US, occupying 12 to 30 percent of the total shorelines of individual states and reaching proportions of 50 to 70 percent or more along urban coasts (Gittman et al., 2015). Conceptually, economists assume that armoring decisions by private landowners are motivated by anticipated benefits and costs, as a function of the potential losses anticipated on unarmored parcels and the costs of building and maintaining armoring structures (cf. Neumann et al., 2015; Yohe et al., 1996). For example, 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), providing an economic incentive for shoreline protection.[5] Beyond general expectations such as these, however, there is limited research that seeks to understand the systematic behavioral drivers of this activity—and whether these drivers tend to encourage armoring in locations that threaten particular types of coastal systems and services. Some of the major reported drivers of armoring include erosion, storm surge, and flooding (Dugan et al., 2011; Gittman et al., 2015; Peterson et al., 2019; Prosser et al., 2017), along with the structure's cost, effectiveness, and durability (Scyphers et al., 2015), although many of these arguments are not grounded in formal behavioral models of armoring decisions by landowners.

Among the few articles to develop a formal behavioral model of shoreline armoring decisions grounded in economic theory is Beasley and Dundas (2020), who study the installation of beachfront protective structures on the Oregon Coast. This prior work focuses on the potential for spatial spillovers in beachfront armoring decisions, relying on a panel dataset of annual parcel data from 1990 to 2015. They find that the installation of beachfront armoring is influenced by a variety of factors related to geomorphology and erosion rates, among other

[5] There is also evidence that homeowners with properties vulnerable to coastal risks (i.e., low elevation and an eroding shoreline) hold price premiums for the option to armor. Premiums of up to 22 percent were found for Oregon coastal homeowners, where state law prohibited armoring for properties developed after 1977 (Dundas and Lewis, 2020).

factors. They also find neighboring-parcel effects (or spillovers) to have an important influence.[6]

Perhaps the most closely related work to the present study is Peterson et al. (2019), who examine the determinants of armoring at the individual landowner level in an area where salt marsh is prevalent, along the Georgia estuarine coastline. Among the motivations for this prior study is to evaluate the drivers of armoring in a marsh-dominated landscape, motivated by potential impacts on marsh persistence. This study combines data on coastal land parcels from 2016, and bulkhead and revetment armored structures from 2006 and 2013 (identified through aerial imagery and on-the-ground field inspections). Using logistic regression similar to that presented here, the study finds that shoreline slope (elevation divided by the parcel's distance from the shoreline), high-energy shoreline environments, and the presence of armored neighbors increase the likelihood of armoring. Although the study provides insight into factors relevant to both armoring and marsh migration potential (such as wave energy), the influence of salt marsh (or variables directly related to marsh ecosystems) on armoring is not directly examined.

Earlier work by Scyphers et al. (2015, p. 42) uses data from a survey of coastal homeowners in Alabama to evaluate the "most influential criteria for [their] decisions to maintain or modify their shoreline (cost, effectiveness, durability, aesthetics, maintenance, environmental impact, water access, permitting)." Using tree-based empirical classification models, they argue that a neighbor's shoreline condition was the most powerful explanatory variable in predicting a homeowner's current shoreline condition. A few other studies analyze large-scale nationwide armoring patterns to explain drivers of habitat loss (e.g., percentage of armored shoreline measured over the entire US coastline at the kilometer scale; Gitman et al.

[6] 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 spillovers caused by the tendency of bulkheads and seawalls to deflect and transfer wave energy onto unarmored neighboring properties (Beasley and Dundas, 2020; Walsh et al., 2019).

2015). However, these studies are based solely on large-scale correlations and are not intended to characterize individual (e.g., property owner) decision-making.

Although past work of this type provides evidence regarding the factors influencing private landowners' armoring decisions, none of these prior studies provide insight into behavioral drivers of shoreline armoring directly related to marsh migration potential in a mixed coastal landscape. For example, both Beasley and Dundas (2020) and Scyphers et al. (2015) focus on the armoring of beachfront property, which provides no direct insight into the behavior of landowners with property frontage on coastal marshes rather than beaches. Conversely, Peterson et al. (2019) focus on the armoring of estuarine coastal property where over 92 percent is dominantly fronted by salt marsh, providing little variation in the armoring of parcels with and without salt marsh frontage. Hence, the study does not consider whether or how the presence of salt marshes (or the suitability of land for marsh migration) influenced armoring behavior.

Building on this prior work, this article presents an empirical model of armoring decisions in a heterogeneous coastal landscape where coastal marsh migration is common, and in which armoring could—at least in principle—be constructed in ways to prevent this migration. Among our primary research questions is whether armoring is constructed in locations that tend to affect marshes or potential marsh migration, or in other types of locations where marshes are unlikely to exist (now or in the future). We also consider potential drivers related to marsh migration potential, together with those related to erosion and storm surge/flood risk. The goal is to evaluate whether the primary motivator of armoring stems from preventing erosion, flooding, or marsh migration (as indicated by factors relevant to each).

The analysis is grounded in a theoretical model of landowners' shoreline armoring decisions with general parallels to prior work. However, there are important distinctions between the presented model and those found in prior work, reflecting differences in objectives, decision contexts, and data. For example, Peterson et al. (2019) do not present a formal theoretical model to underpin their empirical analysis. However, their choice of variables has conceptual grounding in microeconomic theory, with armoring installation specified as a function of variables associated with perceived risks and benefits, cost, and demographic/social factors. Despite these general similarities to the empirical specification presented here, the empirical model of Peterson et al. (2019) omits variables directly related to the current and potential future presence of marshes, which are primary focus of the present study.

As a second example, Beasley and Dundas (2020) emphasize the role of spatial spillovers in landowners' armoring decisions over time, using a long-term panel of annual observations on beachfront parcels in Oregon[7]. In contrast, our focus is on the effect of (largely time-invariant) dimensions of coastal geomorphology related to marsh presence and migration potential on the observed armoring of parcels as of 2002 and 2013. We hence orient the theoretical framework around a random-utility model of the armoring decision during each period, focusing primarily on the latter period. Unlike Beasley and Dundas (2020), we do not emphasize potential neighboring spillovers due to the armoring of nearby parcels, although a model of this type is illustrated in an appendix as a robustness check.

A Model of Landowner Armoring Decisions

We begin by outlining the theoretical framework that underlies empirical estimation. The empirical characterization of landowners' armoring choices is grounded in a simple random-

[7] Corresponding to this data structure, they develop a real-options framework of armoring decisions over time. This framework informs a reduced-form, panel-data regression model designed to address concerns such as the potential endogeneity of peer group formation over time, simultaneity of landowner decision-making, and the specification of peer effects (Beasley and Dundas 2020).

utility model of armoring decisions that emphasizes characteristics of the property relevant to marsh migration, among other potentially relevant factors. We assume that each landowner makes decisions for a single parcel, and focus on decisions made at any given time *t*. Within the context of this decision, the landowner's utility is specified $U(R(A, \boldsymbol{Z}, N), m - c)$, and is assumed to be a function of the net present value of anticipated future property losses on the parcel due to coastal hazards such as flooding, erosion, and marsh incursion, R, the capitalized total cost of armoring[8], c, and income, m.

The variable R in utility can be thought of as the capitalized value of the future flow of all anticipated losses on the parcel, as a function of armoring on the parcel (A), armoring on neighboring properties (N), and a vector of environmental, topographical, hydrodynamic, and other biophysical factors that influence these anticipated losses ($\boldsymbol{Z}$). Here, $A = 1$ denotes an armored parcel and $A = 0$ denotes an unarmored parcel.[9] In general, we anticipate that $\partial R(\cdot)/_{\partial A} \leq 0$, $\partial R(\cdot)/_{\partial N} \geq 0$, with the latter expectation motivated by the tendency of armoring on parcels to deflect wave energy and increase erosion on neighboring land, *ceteris paribus* (Beasley and Dundas 2020). The expected effect of elements of $\boldsymbol{Z}$ on R varies depending on the variable in question. We further assume that $\partial U(\cdot)/_{\partial R} \leq 0$ and $\partial U(\cdot)/_{\partial c} \leq 0$, so that utility declines with anticipated damage to the parcel and with expenditures on armoring. The marginal utility of income is assumed to be positive.

Given this model, we assume the landowner will armor the parcel if

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

where the absence of armoring implies no armoring cost ($c = 0$). That is, the landowner chooses

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[8] We assume that armoring costs include the present value of all construction and maintenance costs.

[9] We treat armoring as a binary outcome, and abstract from issues related to the proportion of the parcel that might be armored.

to install armor if the anticipated utility derived with armoring is greater than utility anticipated with an unarmored parcel, considering both the present value of anticipated property loss and armoring cost. Implicit in (1) is an understanding that this decision is made at a given time period *t* and that the decision is irreversible in the relevant planning horizon. That is, once a parcel is armored, we assume that it is prohibitively expensive to remove the armoring structure.

Modelling the Armoring Decision-Making Process

Grounded in this random-utility framework, we present a model in which all parcels are observed at a single time period *t*, at which point they are either observed to be armored or unarmored. To enable econometric analysis for this case, we rely on the standard assumption that utility is composed of a deterministic component, $V(.)$, and a stochastic component, ϵ. Equation (1) thus becomes

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

Grounded in (2), one can specify the probability that armoring will be installed as of $t=1$ (and hence observed), $P_{A=1}$, as

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

If one assumes that stochastic utility components follow a Type 1 extreme value distribution this probability may be modeled empirically using a conditional logit model with two choice alternatives (Greene 2003), where $P(\cdot)$ is specified as a logistic function of the observable utility difference for each landowner i, given by

$$\Delta V= V(R(A_i=1,\boldsymbol{Z_i}, N_i),m_i-c_i)-V(R(A_i=0,\boldsymbol{Z_i},N_i),m_i). \quad (4)$$

We make the simplifying assumptions that utility (and hence the utility difference) is linear in the parameters, and further that the damage function R may be specified in simple linear form as $R_{Ai} = \boldsymbol{Z_i} \cdot \boldsymbol{\mu_{0Ai}} + N_i\mu_{1Ai}$, for $A_i = \{0,1\}$, where $\boldsymbol{\mu_{0Ai}}$ and μ_{1Ai} are parameters (conforming vectors or scalars).[10] Because we are considering a relatively homogeneous set of armoring structures (bulkheads and revetments on one case-study area), we make an additional simplifying assumption that *per unit* (e.g., per linear meter) armoring costs do not vary across parcels.[11] Given these assumptions, the cost of shoreline armoring may be specified as a linear function of parcel shoreline frontage (or alternatively, size), F_i, where F_i is the relevant measure of parcel frontage or size that determines total armoring cost.

Finally, we assume that vector $\boldsymbol{Z_i}$ (biophysical factors that influence anticipated losses) is composed of a set of sub-vectors $[\mathbf{E_i}\ \mathbf{S_i}\ \mathbf{M_i}\ \mathbf{X_i}]$ and F_i. Here, $\mathbf{E_i}$ is a vector of variables affecting anticipated erosion risk, $\mathbf{S_i}$ is a vector of variables affecting anticipated flood risk, $\mathbf{M_i}$ is a vector of variables affecting the anticipated risk of marsh migration on the property, and $\mathbf{X_i}$ is a vector of additional conditions that influence the perceived benefits of armoring. Note that because parcel frontage F_i influences both the benefits and costs of armoring, the net effect of this variable on utility and hence armoring probability is ambiguous.

Grounded in this model, straightforward manipulations yield the empirical, reduced-form utility difference equation to be estimated,

$$\Delta V = \beta_0 + \boldsymbol{\beta_1} \cdot \mathbf{E_i} + \boldsymbol{\beta_2} \cdot \mathbf{S_i} + \boldsymbol{\beta_3} \cdot \mathbf{M_i} + \boldsymbol{\beta_4} \cdot \mathbf{X_i} + \beta_5 N_i + \beta_6 F_i + \epsilon_i, \quad (5)$$

where the betas represent reduced-form parameter vectors and scalars to be estimated.[12,13] As

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[10] Hence, the anticipated reduction in the net present value of loss, R, when the parcel becomes armored may be specified as $R_{Ai=1} - R_{Ai=0} = (\boldsymbol{Z_i} \cdot \boldsymbol{\mu_{0Ai=1}} + N_i\mu_{1Ai=1}) - (\boldsymbol{Z_i} \cdot \boldsymbol{\mu_{0Ai=0}} + N_i\mu_{1Ai=0}) = \boldsymbol{Z_i} \cdot (\boldsymbol{\mu_{0Ai=1}} - \boldsymbol{\mu_{0Ai=0}}) + N_i(\mu_{1Ai=1} - \mu_{1Ai=0})$.

[11] Cost information is unavailable for these structures and hence this assumption cannot be validated in the present study. However, prior work supports assumptions of this type, at least in general. For example, Beasley and Dundas (2020) find no significant parcel-level variation in the cost of armoring installation when examining 2,136 beachfront properties in Tillamook and Lincoln, Oregon.

[12] Theoretically, each of these reduced-form parameters to be estimated is defined as a function of underlying structural parameters. For example, based on the above specification and assumptions, the reduced form parameter β_5 (on N_i) may be defined as a theoretical function of underlying structural parameters $\theta(\mu_{1,A=1,i} - \mu_{1,A=0,i})$, where

noted above, the model is estimated as a two-alternative (binary) conditional logit model, with Huber-White robust standard errors. The dependent variable for estimation, A_i, is set equal to one if a (riprap or bulkhead) armored structure is installed on parcel i by a specified date, and zero otherwise.

The Data

The models are estimated using data from a case study in Accomack County. The county is part of a narrow peninsula between the Atlantic Ocean and the Chesapeake Bay on the Eastern Shore of Virginia, USA. This case study area was chosen due to its large areas of coastal marsh that are potentially vulnerable to a combination of sea-level rise and local decisions to armor the shoreline. Coastal wetlands (including salt marsh habitats) in this region are threatened by sea level rise and increasing rates of shoreline hardening (Duran Vinent et al. 2019) and are among the primary targets for local conservation (Bruce and Crichton 2014). Average annual sea-level rise in the Eastern Shore is estimated to be over twice the global average, leading to additional concerns over the sustainability of marsh ecosystems (The Nature Conservancy in Virginia, 2011a, 2011b).[14] Modeling in Duran Vinent et al. (2019) suggests that the extent of armoring on land suitable for marsh migration will be a critical determinant of future marsh extent in the area. A substantial portion of the Virginia shoreline is already armored or developed[15], and Accomack County has experienced a general upward trend in the number of permits issued to individuals

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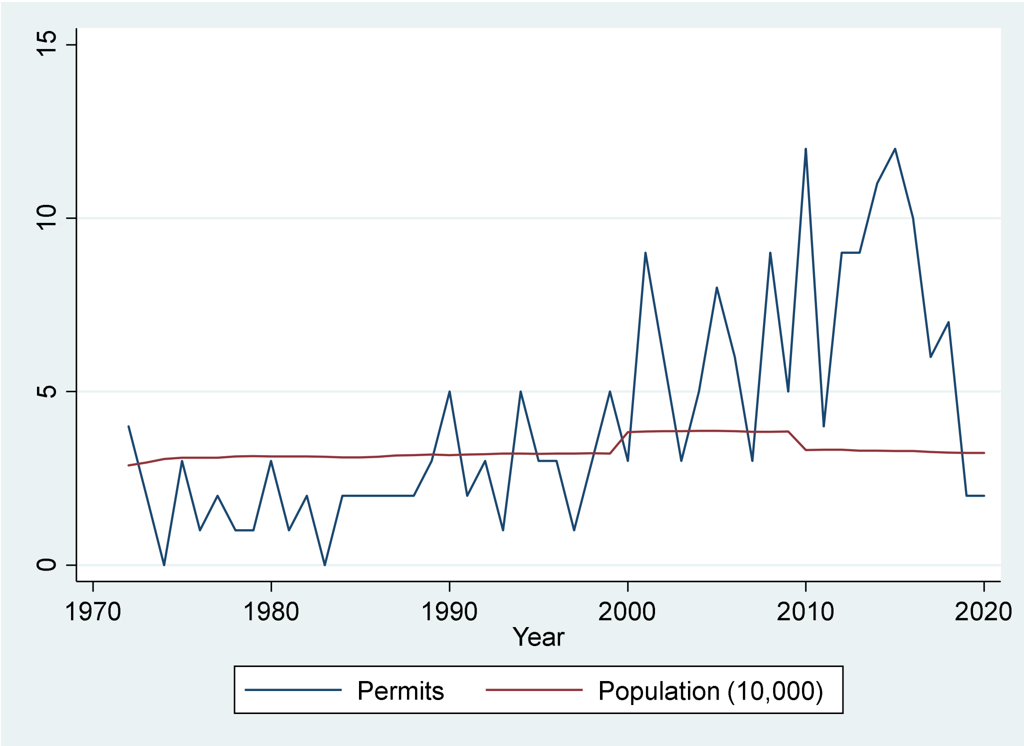
θ is the marginal utility of reductions in anticipated damage R. Available data do not allow the underlying structural parameters to be identified without additional maintained assumptions, so estimation focuses on the reduced form of the behavioral equation.

[13] Landowner income m_i does not depend on armoring status, and hence drops out of the linear utility difference equation ΔV.

[14] Average sea level rise in the Eastern Shore is approximately 4.0 millimeters per year compared to a global average of 1.7 millimeters per year.

[15] As of 2009, approximately 793 kilometers or 11 percent of Virginia tidal waters had been hardened or armored, with 29 kilometers of shoreline hardened each year. 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).

for the construction of riprap and bulkhead armored structures (Figure 1-1).[16, 17] While data suggest that shoreline armoring is ongoing, however, it is unclear whether these structures are being constructed in ways that potentially impact coastal marshes.



[*]Permit application data is taken from the Virginia Marine Resources Commission (VMRC). This information can be found at https://webapps.mrc.virginia.gov/public/habitat/. Historical county population data (by year) is taken from the U.S. Census Bureau. This information can be found at https://www.census.gov/en.html.

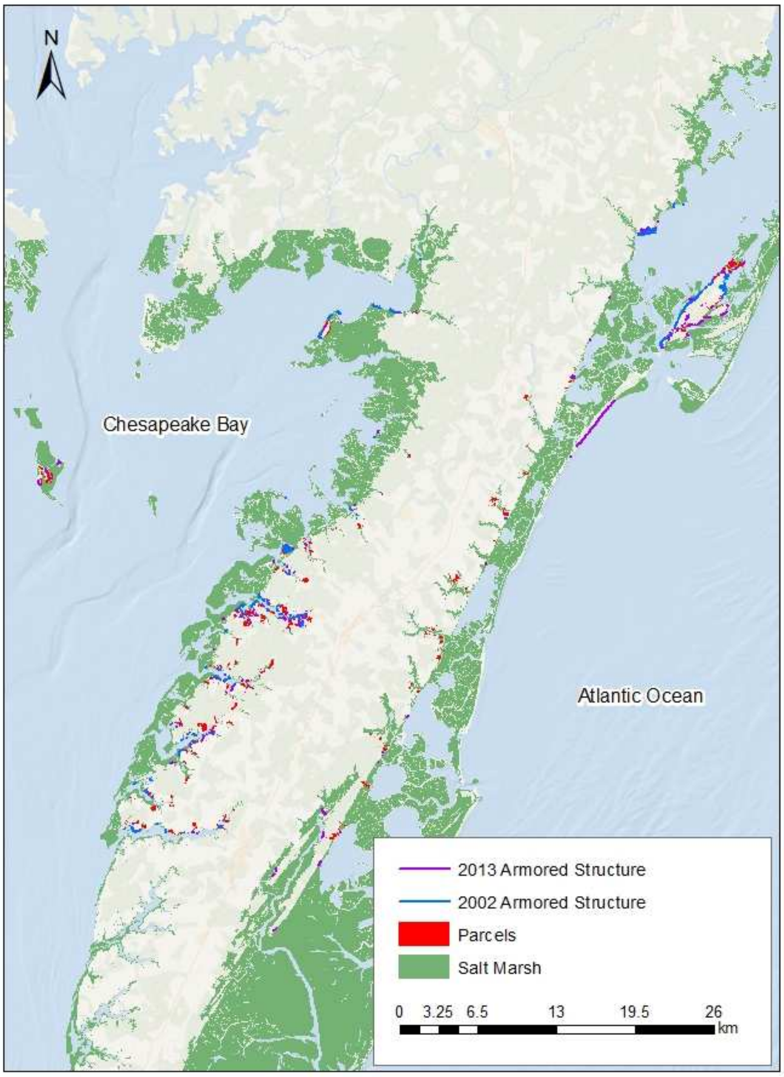
Figure 1-1 Permits Issued for Riprap and Bulkhead Structures in Accomack County Compared to the Population, 1972 – 2020[*]

[16] Our current data do not allow issued permits to be linked to specific observed armoring structures—hence we cannot determine the relationship between issued permits and observed armoring. However, there are multiple reasons why there is not a one-to-one relationship between issued permits and observed armoring in each year. For example, some permits allow multiple armoring structures to be built. In other cases, permits can be issued to restore or refurbish existing armoring structures rather than build new ones. For reasons such as these, determining relationships between observed armoring and issued permits would require historical analysis beyond the scope of the current data.

[17] Although recent years (2019-2020) have shown a decrease in the number of issued permits relative to some prior years, this may be part of the year-to-year fluctuations that have been occurring since the early 1990's (representing natural variation rather than a structural break in the long-term upward trend). However, it might also suggest changing trends on permit requests.

As noted above, we restrict the analysis to parcels classified as single-family residential. To ensure homogeneity, the data were further screened to include only parcels with a size of 20 acres or smaller, with homes built prior to 2013 (since the outcome of interest relies on changes in armoring status prior to that time). Parcels without coastal exposure were excluded, where exposure was defined to include all parcels within a 20-meter distance of the coast. We allow for non-zero distances (<20 meters), to accommodate the fact that the risk of future erosion, storm surge, flooding and marsh migration is not limited to parcels with current coastal frontage (0-meter distance). Preliminary models were estimated with different cutoffs for coastal exposure and frontage, showing largely robust results for different distances between 0 and 20 meters. After screening, the final sample includes 1,665 coastal single-family parcels. The size and location of the parcels, armored structures, and current salt marsh habitats are illustrated in Figure 1-2.

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



To evaluate the determinants of shoreline armoring for these parcels, an original dataset was developed combining information on single-family residential parcels, land cover, and shoreline structures. Data on single-family residential parcels was taken from the Accomack County Office of the Assessor using Virginia's GIS Clearinghouse (hosted by the Virginia

Geographic Information Network).[18] These data included tax parcel data and land ownership polygons with information such as the parcel location, dwelling value, land value, land use, property owner, acreage, improvements, and structural housing characteristics. Land cover information was obtained from sources including the National Wetlands Inventory and the Virginia Department of Conservation and Recreation. Flood zone information was taken from the Federal Emergency Management Agency.[19]

Information on shoreline structures was obtained from the Virginia Institute of Marine Science's (VIMS) Shoreline Inventory Reports (SIR) from 2002 and 2016 and Accomack County Shoreline Management Model (SMM) from 2016 (Berman et al., 2016a; Berman et al., 2016b).[20] The SIRs contained information on land use and shoreline conditions, the presence of beaches, and shoreline structures (these included bulkheads, riprap, wharfs, groins, jetties, and unconventional protection structures). The SMM contained data on the presence or absence of tidal marsh, forested riparian buffers, bank vegetation cover, wave exposure (fetch), and nearshore water depth (bathymetric data). Unlike the SIR data which included shoreline structure information at two points in time (2002 and 2013), the SMM data only included shoreline conditions at one point in time (2013). Due to this data limitation, we require the assumption that shoreline conditions remain effectively constant over the period covered by the analysis (i.e.,

[18] http://data.virginia.gov/datasets/8e222d4ffbea4f8ba552a089866ec11f.

[19] FEMA SFHA (Special Flood Hazard Area) flood zone designations are commonly used to define variables for economic valuation and other types of modeling, as done here. However, realized flood risks and economic effects (e.g., on housing values) for individual parcels can vary even within areas with the same (or similar) SFHA designations (Czajkowski et al., 2013; Johnston & Moeltner, 2019). Because the present data do not allow micro-scale quantification of flood risk beyond current SFHA designations, we proceed with analysis based on these designations. We acknowledge that improved measures of flood risk for each parcel could potentially support more refined estimates of flood-risk effects on armoring but leave such analysis for future work.

[20] The VIMS' SIR 2016 data was published in 2016 and includes shoreline structure information from the Spring of 2013 using aerial satellite imagery (Berman et al., 2016a; Berman et al., 2016b). The VIMS' SIR 2002 data was recorded through observations in the field taken by boat along the shoreline using a GPS tracker. This is based on correspondence with GIS Programmer/Analyst Tamia Rudnicky, a member of the team that compiled the shoreline data at the VIMS.

parcels armored by 2002 and parcels armored by 2013 are influenced by similar shoreline conditions). For this reason, we also consider the 2013 model to be more reliable and hence the primary model for deriving our results and conclusions.

As described above, the outcome of interest is whether a parcel is observed to have revetments (e.g., riprap) or bulkheads within 20 meters of the parcel edge, defined as an armored parcel. This allows for the possibility that relevant armoring structures may be observed in areas that are between a parcel and the water, but that are nonetheless outside of the legally recognized parcel boundary.[21] Alternative preliminary models were also estimated where a zero-distance threshold was used to identify armored parcels (armoring is observed within the legal parcel boundary). These models have poorer statistical fit than those with a 20-meter threshold, although results regarding salt marsh (see below) are largely robust.[22] Due to the improved empirical performance, we proceed with models that use a 20-meter threshold to assign armored status for purposes of defining the dependent variable(s). Models which use the alternative 0-meter threshold to assign armored status can be found in the Appendix.

Dependent variables are defined using these underlying armoring measures. *Arm13* is assigned a value of 1 if the parcel was observed to be armored by 2013 and a 0 otherwise, and *Arm02* is defined similarly for parcels armored by 2002.[23] Independent variables hypothesized to have potential influence on armoring decisions include environmental factors that increase the

[21] This also enables the data to capture the presence of armoring structures for which minor variations in geocoding or parcel boundaries within GIS data layers cause the structure to mistakenly appear as outside the parcel boundary, when in fact it is located on the parcel.
[22] The only exception regards proportions of salt marsh near the parcel. Although proportions of salt marsh within 100- or 200-meters of a parcel was found to influence armoring decisions in all of the 20-meter threshold models, this was never the case in the 0-meter threshold logit models. All other key results are robust, and the primary conclusions of the analysis do not change.
[23] Note that these dependent variables are defined based on physically observable armoring on the parcel. This eliminates the possibility of recall or other biases associated with the potential use of survey responses or other indirect approaches to identify armored parcels. In doing so, it is assumed that the owners of each parcel make decisions on whether to armor that parcel.

risk of property loss from erosion (*Wavenrgy_low*), storm surge/flood (*Fld*), and marsh migration (*marshplant*, *SMdist*, *SM100M*, *SM200M*), and factors that potentially mitigate these risks (*Elev*, *Forestshore*, *SMdist*, *SM100M*, *SM200M*, and *Beachdist*). Also included are non-environmental factors related to the parcel that influence these risks, such as its assessed dwelling value (*DwlgVall*)[24], and exposure to the coast (*Coast_Frnt*).

Lastly, parcel armoring might be affected by whether its neighbors' parcels are armored, and this is examined in *Neighb500M* and *Neighb1KM*, allowing for the possibility of spillover effects (Beasley and Dundas 2020). *Neighb500M* and *Neighb1KM* are defined as proportions[25] of neighbors armored within 500- and 1,000-meters of a parcel. Since the definition of "armored" changes between models, these spillover variables are altered accordingly (i.e., proportions of neighbors armored by 2013 and 2002 using either 20- or 0-meter distance thresholds between the parcel and the structure). These neighboring spillover variables are not included in the primary models in the main text but are included as a robustness check in the Appendix. Table 1.1 provides a list of variables used and their descriptions.

Table 1.1 Variable Descriptions

Dependent Variables	Description
Arm02	1 = parcel edge is within 20 meters of a revetment or bulkhead by 2002 (defined as armored) 0 = parcel edge is further than 20 meters from a revetment or bulkhead by 2002 (defined as not armored)
Arm13	1 = parcel edge is within 20 meters of a revetment or bulkhead by 2013 (defined as armored)

[24] This is defined as the assessed value of the dwelling itself (the structure), based on features such as the house size and quality of the building materials. We use dwelling value rather than property value in the model to allay endogeneity concerns related to potential two-way causal relationships between property values and the presence of armoring (see discussion in Beasley and Dundas 2020).

[25] Unlike counts of armored neighbors, proportions are not confounded by the density of a neighborhood.

	0 = parcel edge is further than 20 meters from a revetment or bulkhead by 2013 (defined as not armored)
Independent Variables	Description
DwlgVal1	Assessed dwelling value in $10,000, recorded in the fourth quarter of 2018
Acreage	The parcel acreage calculated from GIS parcel boundaries
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, defined to include all marine and estuarine intertidal wetlands as defined in the Cowardin et al. (1979) classification
Fordist	The Euclidean distance from the parcel edge to the nearest forest land cover
SM100M	The proportion of salt marsh within 100 meters of the parcel edge, defined as above
SM200M	The proportion of salt marsh within 200 meters of the parcel edge, defined as above
Marshplant[*]	1 = parcel overlaps an area that is ecologically suitable for marsh existence (or planting) 0 = otherwise
Wavenrgy_low[**]	1 = parcel is in an area with low wave energy 0 = parcel is in an area with moderate or high wave energy
Forestshore[***]	1 = parcel is in a forested shoreline 0 = otherwise
Elev	The mean elevation of the parcel in meters
Fld[****]	1 = parcel is in an AE or VE flood zone, based on FEMA SFHA (Special Flood Hazard Area) designations 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 in the town of 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 armored neighbors within 500 meters of the parcel centroid
Neighb1KM[*****]	The proportion of armored neighbors within 1 kilometer of the parcel centroid

[*] Suitability for the planting of salt marsh is defined following Berman et al. (2016a) using bathymetric measurements. If a 1-meter bathymetric contour is outside 10 meters of the shoreline, then it is considered 'shallow' and suitable for planting.
[**] Wave energy (erosion) risk is defined following Berman et al. (2016a) using a combination of fetch (the longest distance over water to the nearest shoreline) and the presence of a road or permanent structure near the shoreline. Areas without (with) a road or permanent structure near the shoreline and a fetch below 0.5 miles

are considered "low" ("moderate") wave energy environments. Areas with a fetch between 0.5 and 2 miles, and more than 2 miles are considered "moderate", and "high" wave energy environments regardless of the presence of a road or permanent structure near the shoreline.
*** The shoreline is considered forested if the riparian land use is considered forested or if there is a tree fringe greater than 100 feet (Berman et al., 2016a).
**** Homes within AE and VE designated flood zones have a 1-percent-annual-chance of inundation with the latter including additional storm surge hazards.
***** These variables use the same definition of becoming armored as the dependent variable used in the models.

Descriptive statistics shown in Table 1.2 highlight the differences between coastal single-family homes that were (*Arm13=1*) and were not (*Arm13=0*) armored by 2013. The 'Full Sample' includes both groups. For 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. On average, 23.1 percent of land within 200 meters of parcels was 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.

Approximately 50 percent of parcels were armored by 2013, showing considerable variation in this variable. As anticipated, an initial evaluation of variable means suggests systematic, univariate differences between parcels that were armored (or not). For example, the mean elevation (*Elev*) of parcels that become armored is lower at 1.019 meters compared to 1.390 meters for parcels that were never armored. Parcels that become armored also seem to be at higher risk of erosion relative to those that never have armor, since only 47.5 percent are in a shoreline with low wave energy (*Wavenrgy_low*) compared to 71.7 percent for parcels that were not armored. In another example, 59.2 percent of parcels that become armored are in areas suitable for planting salt marsh (*Marshplant*) compared to 98.0 percent for parcels that were not armored. Wilcoxon rank-sum tests are used to determine whether the (environmental and parcel) characteristics in the samples of armored and unarmored parcels are likely to derive from the same population. Results from these tests reject the null hypotheses ($p<0.01$) and indicate statistically significant differences in the observed characteristics.

Table 1.2 Summary Statistics*

	Full Sample		*Arm13*=1		*Arm13*=0	
Variable	Mean	S.D.	Mean	S.D.	Mean	S.D.
DwlgVal1	159,739	89,602	163,806	85,876	155,697	93,033
Acreage	1.744	2.816	0.942	2.063	2.541	3.211
Beachdist	9,477	7,965	7,975	7,679	10,970	7,967
SMdist	44.38	79.27	73.34	94.67	15.58	44.31
Fordist	41.47	69.89	68.56	84.13	14.54	35.39
SM100M	0.236	0.281	0.141	0.198	0.330	0.318
SM200M	0.231	0.252	0.174	0.203	0.289	0.281
Marshplant	0.786	0.410	0.592	0.492	0.980	0.141
Wavenrgy low	0.596	0.491	0.475	0.500	0.717	0.451
Forestshore	0.0679	0.252	0.0133	0.114	0.122	0.328
Elev	1.205	0.922	1.019	0.692	1.390	1.074
Fld	0.840	0.366	0.877	0.329	0.804	0.398
Lat	37.79	0.139	37.85	0.132	37.73	0.121
Long	-75.64	0.223	-75.56	0.219	-75.73	0.189
Chincoteague	0.274	0.446	0.419	0.494	0.1305	0.3371
Coast_Frnt	0.198	0.151	0.209	0.151	0.186	0.150
ChsBay	0.540	0.499	0.392	0.488	0.687	0.464
Neighb500M	0.202	0.235	0.248	0.274	0.157	0.177
Neighb1KM	0.205	0.194	0.238	0.220	0.171	0.156
N	1,665		830		835	

* For each of the above variables, Wilcoxon rank-sum tests reject the null hypothesis ($p<0.01$) that the sample, when grouped between parcels armored (Arm13=1) and unarmored (Arm13=0) by 2013 are from populations with the same distribution.

Robustness and Endogeneity

As discussed by prior works such as Lewis et al. (2011) and Beasley and Dundas (2020), analyses of spatial decisions such as these are complex, and it is important to verify the robustness of results to various types of statistical concerns. Recognizing this complexity, the presented models were developed after the estimation of multiple, alternative exploratory models to evaluate the robustness of our conclusions regarding the influence of coastal geomorphology on armoring, focusing on landscape attributes relevant to salt marsh migration. As noted above, we also present parallel models for our two time periods. Primary robustness checks and results are presented below and in the Appendix. For example, key model results and conclusions are unchanged regardless of the inclusion or exclusion of variables on the armoring of neighboring parcels (*Neighb500M* and *Neighb1KM*). Since these variables pose additional endogeneity concerns (see the Appendix for a detailed discussion) and do not influence our hypothesis tests on the effect of conditions related to marsh migration, our primary logit model results omit these variables. In general, all exploratory models and those used for robustness testing verify the key conclusions presented below.

Results

Table 1.3 presents conditional logit model results with the dependent variables *Arm13* and *Arm02*. Given that the latter model entails an additional caveat regarding the accuracy of its results[26], we focus the primary discussion on *Arm13* (the second column) and use *Arm02* (the first column) as a robustness check. A Wald chi-square test indicates that the overall model is significant ($\chi^2 = 449.94$, p<0.01). 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 probability of a riprap or bulkhead revetment being observed on or near the parcel as of 2013, as both conditions increase anticipated losses on unarmored parcels due to coastal hazards.

[26] Since data on shoreline characteristics were only available for 2013, this model requires the assumption that similar conditions held for armoring that took place by 2002.

Table 1.3 Logit Results on the Determinants of Installing Riprap and Bulkhead Revetments

Variables	Dependent Variable = *Arm02*	Dependent Variable = *Arm13*
DwlgVal1	-0.00201	0.0189**
	(0.00898)	(0.00830)
Acreage	-0.190*	-0.0221
	(0.111)	(0.0351)
SMdist	0.00339***	0.0105***
	(0.00106)	(0.00152)
Beachdist	0.000365***	0.000127***
	(0.0000551)	(0.0000292)
Fordist	-0.00201	0.00552***
	(0.00134)	(0.00174)
SM100M	-0.590	-1.150***
	(0.548)	(0.422)
SM200M	-3.213***	-0.393
	(0.642)	(0.503)
Marshplant	-1.571***	-2.652***
	(0.185)	(0.302)
Wavenrgy_low	-0.636***	-0.981***
	(0.172)	(0.165)
Forestshore	-2.731**	-1.043***
	(1.062)	(0.373)
Elev	-0.167	-0.299**
	(0.150)	(0.127)
Fld	-0.273	-0.188
	(0.241)	(0.184)
Lat	9.830***	7.345***
	(3.448)	(2.130)
Long	-1.883	-4.369**
	(4.155)	(2.174)

Chincoteague	2.036***	1.258***
	(0.514)	(0.422)
Coast_Frnt	1.156**	1.173**
	(0.513)	(0.480)
ChsBay	-2.473***	-1.298*
	(0.925)	(0.726)
Constant	-515.4	-606.1**
	(436.9)	(236.6)
Wald χ^2	336.44	449.94
P-value	0.0001	0.0001
N	1,665	1,665

*, **, and *** indicate levels of significance at 10, 5, and 1 percent levels, respectively. Huber-White robust standard errors are shown in parentheses.

Parameter estimates from the 2013 model suggest that many parcel features related to erosion, storm surge/flood, and marsh migration risk have statistically significant influences on armoring probability. For example, parcels located in areas with low wave energy (*Wavenrgy_low*), and hence, low erosion risk, are less likely to be armored. Similar results are found for parcels protected from erosion by a forested shoreline (*Forestshore*). Parcels with a higher elevation (*Elev*) are also less likely to be armored—this is intuitive because higher-elevation parcels are less vulnerable to many types of coastal hazards. Lastly, parcels further from beaches (*Beachdist*) are more likely to be armored, which may be due to erosion protection (in the case of wide beaches) and/or a desire to maintain the aesthetics of parcels closer to beaches (which may be devalued with armoring).[27,28]

The key hypotheses of interest, however, relate to whether armoring decisions are being

[27] Proportions of beach within 100- and 200-meters of parcels were included in preliminary models but were either not statistically significant or dropped due to a lack of nonzero observations (the average home was over 9-km from the nearest beach).

[28] Results for 2002 also suggest that larger parcels were less likely to be armored as of that year (*Acreage*). This effect, however, becomes insignificant as of 2013. It is possible that small parcels were more likely to be armored by 2002 because the structure/home in smaller parcels is more likely to be close to the shoreline, and hence more directly threatened by coastal flooding or erosion, *ceteris paribus*. However, as we do not have data on the specific location of housing structures within each parcel as of 2002, we do not have a means to test this assertion directly.

made in systematic ways that threaten salt marshes, for example that would prevent marshes from migrating onto suitable upland areas. Theory alone provides no clear expectation on the direction or magnitude of these effects. On the one hand, variables positively related to salt marsh migration could increase armoring likelihood, if landowners perceive future marsh migration is a risk to structures or property value. On the other hand, marsh presence can provide natural protection from storm surge and flooding, thereby reducing the need for armoring structures (Barbier et al. 2013). The net effect of marsh-related variables on parcel armoring depends on how landowners perceive and balance offsetting effects such as these.

This model draws insights on this question based on whether parcels were armored, or not, as of 2013. Results provide evidence that armoring is being constructed in systematic ways that tend *not* to threaten salt marshes. For example, the positive and statistically significant parameter ($p<0.01$) on *SMdist* suggest that parcels are more likely to have armored structures placed near them when located *further* away from salt marshes. The negative and significant ($p<0.01$) parameter estimate on *SM100M* suggests that larger proportions of marsh land cover within 100 meters are associated with a reduced probability of armoring. Similarly, the negative and significant parameter ($p<0.01$) on *Marshplant* indicates that armoring is more likely in areas that are *not* ecologically suitable for the survival of salt marsh. We also find evidence that armoring tends to be constructed in areas with moderate or high wave energy (*Wavenrgy_low* = 0)—areas that tend to be poorly suited to marsh sustainability.

Nearly all marsh-related results are robust when compared to those from a similar logit model predicting armoring by 2002, shown in the first column of Table 1.3. We find consistent results for *SMdist*, *Marshplant*, *Wavenrgy_low*, *Forestshore*, and *Coast_Frnt*. However, there are some differences in other results, suggesting that some types of armoring patterns may have changed over time. For example, the negative and significant ($p<0.01$) parameter estimate on *SM200M* in the 2002 model suggests that larger proportions of marsh land cover within 200 meters were associated with a reduced probability of armoring in 2002. Furthermore, *Elev* and *Dwlgval1* were not significant determinants of armoring during the earlier period.

These results suggest that armoring in the studied area tends not to be constructed in areas suitable for marsh migration. They do not imply that armoring *never* influences marshes in the case study area or that marsh preservation is not a relevant concern—only that the systematic component of armoring decisions observed in 2002 and 2013 led to the placement of armoring in locations that were less suitable for marsh migration, in general.

Conclusion

Although the empirical results presented above apply to the studied area on the US East Coast, the methods developed here can be potentially applied to any coastal location for which suitable observations on parcel armoring are available. Moreover, unlike methods such as those in Beasley and Dundas (2020) that require annual observations on parcel armoring for an extended period (data unavailable for most coastal locations), the presented approach only requires a single observation per parcel, at one time period. Hence, while we cannot provide the type of temporal insight possible with annual parcel armoring data over extended periods, the illustrated method is more broadly applicable. Although the present study focuses on marsh migration, this method could be adapted to study multiple topics of interest related to armoring decisions.

Focusing on our primary hypotheses of interest, results in the present case provide robust evidence that armoring in the studied area is motivated primarily by biophysical factors that influence hazard exposure, such as exposure to parcel erosion due to high wave energy. Results do not suggest that armoring is being constructed to reduce the risk of marsh migration onto a property. In fact, the opposite seems to be happening: Coastal properties are more likely to have riprap revetments or bulkheads (or be near these structures) 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). As shown in the Appendix, these results are robust to the inclusion of variables designed to capture neighboring spillover effects.

This finding does *not* imply that shoreline armoring is unimportant to future marsh migration or that actions should not be taken to preserve marsh transgression zones. For example, other types of human actions can negatively influence the potential upland migration of marshes and some types of armoring in the case-study area do affect marshes. However, results do imply the importance of understanding how and why landowners choose to armor their parcels, when designing policies and programs to sustain coastal marshes. For example, Duran Vinent et al. (2019) show that findings of this type affect the additionality of actions taken to ensure future marsh persistence.

There are multiple possible explanations for these observed patterns. First, as noted above, salt marsh is known to provide natural protection from coastal hazards such as flooding and erosion (Barbier et al., 2011, 2013). These ecosystem services may reduce the perceived need to armor a parcel against these other threats. Like Beasley and Dundas (2020) and Peterson et al. (2019) we find evidence that erosion is a primary concern when choosing whether to armor parcels. The same patterns may lead to tendencies *not* to armor near marshes. Second, as in many states, Virginia imposes monetary penalties and/or requires mitigation for shoreline armoring with negative marsh impacts ("Wetlands Mitigation-Compensation Policy And Supplemental

Guidelines", 2005).[29] These penalties provide a negative incentive for armoring in the vicinity of marshes. Finally, unlike erosion that can occur quickly (e.g., due to coastal storm events), marsh migration is a slow process that may be viewed as less of a risk to property value and structures. Hence, given the other factors discussed above, landowners may perceive less of an urgent need to armor against marsh migration, compared to other hazards.

Although these results provide useful and previously unavailable insight regarding the influence of marsh migration and other determinants of armoring in general, several caveats should be considered when interpreting model results. First, data collection methods used to identify armoring differed somewhat between the 2002 and 2013 data collection efforts, each with their own advantages and disadvantages.[30] These differences could be a potential source of unanticipated variation in the dependent variables. Second, results using the model of armoring by 2002 are only valid under the assumption that biophysical shoreline conditions in 2002 were similar to conditions in 2013. Major differences in shoreline conditions could lead to measurement error in some regressors. Third, although this research sheds light on whether armoring is taking place in locations that could potentially affect marsh migration, it says nothing about whether those revetment 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[31] and its placement on the landward-marsh edge (Fuller et al., 2011).

It is also important to recognize that these models are defined based on armoring

[29] See https://www.vims.edu/ccrm/wetlands_mgmt/_docs/permit_fees2020.pdf.
[30] The 2002 shoreline information was collected using direct visual inspection of structures. The 2013 shoreline information was collected via high-resolution remote sensing.
[31] 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.

observed "on the ground," not on reports of armoring by individual landowners. We do not have direct information on who made decisions to construct each armoring structure—only the parcels that are on or proximate to those structures. The model assumes, implicitly, that the owners of parcels made armoring decisions based on the characteristics of each parcel. Finally, the model does not include factors that may influence variations in the cost of armoring across parcels, including for example, the contractor used, its size and materials. Data on any potential variations in cost is unavailable and hence could not be included in the model. We leave extensions to address these and other potential limitations for future research.

Despite these caveats, the presented results have potentially important implications for policies designed to limit armoring with a goal of reducing impacts to salt marshes. 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 provide incentives to minimize marsh impacts or may reflect the natural protections offered by salt marshes. Regardless of the explanation, findings presented here highlight the importance of understanding the dynamics between armoring and marsh migration for conservation agencies and policymakers looking to preserve salt marshes. If coastal parcels remain unarmored and undeveloped into the future, land preservation may not be required to enable salt marsh migration under sea-level rise. To provide further guidance on where preservation may be needed, a dynamic model of armoring decision-making that can be tailored to future sea-level rise and land-use scenarios is required. Improved understanding of the forces that motivate parcel armoring decisions can help policies target actions that are likely to have the greatest net benefit in terms of protecting these valued systems.

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Appendix. Armoring Definitions, Neighboring Spillovers and Potential Endogeneity

To demonstrate the robustness of results presented in the main text, Tables A.1, A.2 and A.3 include alternative models that incorporate (1) different distance thresholds to identify armored versus unarmored parcels and (2) variables to capture neighboring spillover effects (Beasley and Dundas 2020), with the variables *Neighb500M* and *Neighb1KM* reflecting proportions of armored neighbors. Model A.1 reproduces the models in the main text with the addition of *Neighb500M* and *Neighb1KM*. Model A.2 reproduces the same models but defines an armored parcel based on the existence of armoring within 0 meters of the parcel edge, rather than the 20-meter threshold used for the primary models. Model A.3 incorporates both changes—neighboring spillovers and a revised distance threshold to define armoring. All models demonstrate the robustness of the general conclusions reported in the main text.

When considering neighboring spillover effects (Tables A.1 and A.3), it is important to recognize that regressors of this type can be endogenous, for example if an unobserved characteristic simultaneously influences armoring decisions on neighboring parcels (Lewis et al. 2011; Beasley and Dundas 2020). We also lack information on the precise year during which armored structures were placed—only whether they were present during 2002 and/or 2013. This leads to another potential source of endogeneity due to reverse (temporal) causation akin to a "reflection" effect (Manski 1993)—that is armoring on the parcel could have had a causal effect on the armoring of neighboring parcels. Although potential endogeneity of this type is often unacknowledged in empirical models, it can nonetheless influence results.

Common approaches to attenuate this type of endogeneity in panel-data models, such as the Mundlak-Chamberlain technique (Mundlak 1978; Chamberlain, 1982) or the use of lagged variables, do not apply to cases such as ours where each equation is estimated using only a single observation per parcel at one time period (cf. Beasley and Dundas 2020). While recognizing the potential for endogeneity of this type, however, it does not appear to influence our primary conclusions—key model results and conclusions related to salt marsh effects on armoring are unaffected by the inclusion or exclusion of variables on the armoring of neighboring parcels. Like Beasley and Dundas (2020) and Peterson et al. (2019), we find statistically significant neighborhood (or spillover) effects. Parcels with a greater proportion of armored neighbors are more likely to be armored themselves (this influence from neighboring parcels is significant within only 500 meters).

Like results of the primary models in the main text, results of the 0-distance threshold model (Table A.2) suggest that, all else equal, armoring is less likely to occur in areas suitable for salt marsh migration. For example, armoring is less likely to occur in areas suitable for salt marsh ecosystems (*Marshplant*) and in areas with low wave energy (*Wavenrgy_low*). Effects of currently proximate salt marsh (*SM100M*, *SM200M*) are only significant in the model using 2002 observations; the parameter for *SM200M* is negative, as anticipated, and statistically significant at $p<0.01$. However, the primary conclusions reported in the main text continue to hold.

Table A.1 Logit Results on the Determinants of Installing Riprap and Bulkhead Revetments with Neighboring Spillovers

Variables	Dependent Variable = *Arm02*	Dependent Variable = *Arm13*
DwlgVal1	0.00433	0.0146^{*}
	(0.0113)	(0.00880)
Acreage	0.0231	0.0288
	(0.0674)	(0.0314)
SMdist	0.00589^{***}	0.00786^{***}
	(0.00145)	(0.00153)
Beachdist	0.000229	0.0000203
	(0.000150)	(0.0000301)
Fordist	0.000717	0.00214
	(0.00177)	(0.00192)
SM100M	-0.763	-1.142^{**}
	(0.913)	(0.494)
SM200M	-1.827^{*}	-0.0237
	(0.995)	(0.542)
Marshplant	-1.244^{***}	-1.804^{***}
	(0.279)	(0.292)
Wavenrgy_low	-0.737^{***}	-0.583^{***}
	(0.259)	(0.187)
Forestshore	-2.152^{**}	-0.842^{**}
	(1.049)	(0.388)
Elev	-0.426^{***}	-0.218^{*}
	(0.149)	(0.126)
Fld	0.175	-0.115
	(0.287)	(0.194)
Lat	-14.21^{**}	2.130
	(6.840)	(2.022)
Long	23.10^{*}	-3.079
	(12.35)	(2.310)

Chincoteague	-0.00846	0.379
	(0.528)	(0.456)
Coast_Frnt	0.456	1.119**
	(0.691)	(0.533)
ChsBay	4.545***	-0.707
	(1.687)	(0.791)
Neighb500M	7.914***	3.905***
	(0.771)	(0.514)
Neighb1KM	-0.789	0.132
	(0.872)	(0.728)
Constant	2276.5*	-313.6
	(1181.2)	(239.6)
Wald χ^2	635.14	648.02
P-value	0.0001	0.0001
N	1,665	1,665

*, **, and *** indicate levels of significance at 10, 5, and 1 percent levels, respectively. Huber-White robust standard errors are shown in parentheses.

Table A.2 Logit Results on the Determinants of Installing Riprap and Bulkhead Revetments (Armoring within 0-meters of Parcel Edge)

Variables	Dependent Variable = *Arm02*	Dependent Variable = *Arm13*
DwlgVal1	-0.00227	0.0253^{**}
	(0.0109)	(0.0104)
Acreage	-0.324	-0.0811
	(0.201)	(0.0545)
SMdist	0.00127	0.00754^{***}
	(0.00121)	(0.00198)
Beachdist	0.000413^{***}	0.000160^{***}
	(0.0000955)	(0.0000354)
Fordist	0.000108	0.00612^{***}
	(0.00149)	(0.00228)
SM100M	-0.0795	-0.585
	(0.665)	(0.474)
SM200M	-4.166^{***}	-0.791
	(0.853)	(0.587)
Marshplant	-1.676^{***}	-2.844^{***}
	(0.217)	(0.336)
Wavenrgy_low	-0.746^{***}	-0.842^{***}
	(0.203)	(0.209)
Forestshore	-1.937^{*}	-0.648
	(1.122)	(0.459)
Elev	-0.185	-0.271
	(0.194)	(0.167)
Fld	-0.176	-0.384^{*}
	(0.263)	(0.229)
Lat	8.412^{*}	7.289^{***}
	(4.895)	(2.599)
Long	-0.501	-3.403
	(7.208)	(2.670)

Chincoteague	2.959***	1.005**
	(0.618)	(0.503)
Coast_Frnt	1.250**	1.938***
	(0.620)	(0.566)
ChsBay	-1.970	-1.764**
	(1.244)	(0.868)
Constant	-358.5	-531.3*
	(721.0)	(290.8)
Wald χ^2	522.90	327.94
P-value	0.0001	0.0001
N	1,310	1,310

*, **, and *** indicate levels of significance at 10, 5, and 1 percent levels, respectively. Huber-White robust standard errors are shown in parentheses.

Table A.3 Logit Results on the Determinants of Installing Riprap and Bulkhead Revetments with Neighboring Spillovers (Armoring within 0-meters of Parcel Edge)

Variables	Dependent Variable = *Arm02*	Dependent Variable = *Arm13*
DwlgVal1	0.0188	0.0257**
	(0.0143)	(0.0111)
Acreage	-0.0686	-0.0334
	(0.111)	(0.0463)
SMdist	0.00396**	0.00567***
	(0.00157)	(0.00202)
Beachdist	0.000198	0.0000565
	(0.000182)	(0.0000368)
Fordist	0.00402**	0.00231
	(0.00174)	(0.00250)
SM100M	0.482	-0.368
	(1.033)	(0.552)
SM200M	-1.969	-0.464
	(1.217)	(0.623)
Marshplant	-1.983***	-2.008***
	(0.319)	(0.318)
Wavenrgy_low	-0.847***	-0.423*
	(0.274)	(0.226)
Forestshore	-1.096	-0.500
	(1.008)	(0.476)
Elev	-0.392**	-0.195
	(0.186)	(0.157)
Fld	0.199	-0.259
	(0.330)	(0.245)
Lat	-12.72*	3.470
	(7.718)	(2.445)
Long	20.17	-2.645
	(14.36)	(2.687)

Chincoteague	0.674	0.304
	(0.616)	(0.565)
Coast_Frnt	0.658	1.968***
	(0.842)	(0.610)
ChsBay	5.941***	-0.885
	(1.952)	(0.897)
Neighb500M	7.198***	3.594***
	(0.962)	(0.658)
Neighb1KM	1.796	0.117
	(1.157)	(0.826)
Constant	1998.3	-331.7
	(1364.3)	(281.1)
Wald χ^2	851.24	458.72
P-value	0.0001	0.0001
N	1,310	1,310

*, **, and *** indicate levels of significance at 10, 5, and 1 percent levels, respectively. Huber-White robust standard errors are shown in parentheses.