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Title: **Adapting without Retreating: Responses to Shoreline Change on an Inlet-Associated Coastal Beach**

Shortened Title: **Adapting without Retreating**

Abstract

Coastal barrier systems around the world are experiencing higher rates of flooding and shoreline erosion. Property owners on barriers have made significant financial investments in physical protections that shield their nearby properties from these hazards, constituting a type of adaptation to shoreline change. Factors that contribute to adaptation on Plum Island, a developed beach and dune system on the North Shore of Massachusetts, are investigated here. Plum Island experiences patterns of shoreline change that may be representative of many inlet-associated beaches, encompassing an equivocal and dynamically shifting mix of erosion and accretion. In the face of episodic floods and fleeting erosive events, and driven by a combination of strong northeast storms and cycles of erosion and accretion, the value of the average Plum Island residence increases by 34% for properties on the oceanfront where protection comprises a publicly constructed soft structure. Even in the face of state policies that ostensibly discourage physical protection as a means of adaptation, coastal communities face significant political and financial pressures to maintain existing protective structures or to allow contiguous groups of property owners to build new ones through collective action. These factors mitigate against adapting to shoreline change by retreating from the coast, thereby potentially increasing the adverse effects of coastal hazards.

Keywords: adaptation; structural protection; coastal dune resource; tidal-associated inlet; hedonic pricing

Introduction

Worldwide, coastal communities have been impacted by shoreline changes associated with increases in the rate of relative sea-level rise (Sallenger, Doran, and Howd 2012; Church *et al*. 2013; Kensington and Han 2014), enhanced frequency and intensity of storms (Emanuel 2005; Webster *et al*. 2005; Elsner, Kossin, and Jagger 2008) and natural and human-induced changes in sediment delivery and supply (Blum and Roberts 2009; Hein *et al*. 2014). Many coastal communities in the United States now are flooded regularly by extreme high tides (such as perihelic-perigean spring tides) and storm surges. Moreover, fluvial sediment export to the US coast today is only about 80% of that prior to European settlement due to the effects of damming and urbanization (Syvitski *et al*. 2005). The resulting inundation and erosion can be very costly for coastal property owners; by mid-century (2050), 25% of property owners within 150m of the shoreline may be affected by property losses due to erosion (Kriesel, Landry, and Keeler 2000).

Yet this customary narrative of pervasive shoreline erosion is not globally applicable. Using information about coastal elevations, vertical land movements, and land covers, Lentz *et al*. (2016) found that 70% of the US Atlantic coast is able to respond dynamically to sea-level rise, suggesting that predictions of the submergence of many coastal lands may have been overstated. Hapke, Kratzmann, and Himmelstoss (2013) found that, although 68% of beaches along the US Northeast and Mid-Atlantic coasts are eroding, rates—and indeed directions—of shoreline change are highly variable. Proximal to tidal inlets, narrow waterbodies that bisect the mainland or adjacent islands and exchange water and sediment from the ocean to a backbarrier system (Hayes 1980), shoreline changes are amplified by dynamic interactions between complex morphologies and sediment transport patterns influenced by both waves and tidal currents (FitzGerald 1984, 1996).

The erosion of land and the damage to buildings as consequences of shoreline change imply significant economic losses. In order to mitigate potential damages, coastal communities have an enormous stake in identifying strategies for adapting to this change. Adaptive strategies can be focused on the physical system, through beach replenishment or the installation of jetties, groins, bulkheads, or revetments, or by modifications to buildings, such as raising their foundations with pilings, or by moving buildings further away from the shoreline.

Retreating from the coast is the ultimate adaptive option, but the economic benefits to property owners of adapting without retreating can be substantial. Further, the incentives encountered by local governments may be aligned with those of private property owners, as property abandonment through retreat could encompass lost property tax proceeds or an impaired ability to recover investments in capital infrastructures, such as sewers and roads. These issues are explored here for the case of a non-migrating coastal beach and dune system in New England.

Plum Island, Massachusetts

Plum Island, the longest barrier island in the Gulf of Maine, is located on the northeast coast of Massachusetts (Fig. 1). It is backed by the "Great Marsh," the largest US marsh system north of Long Island, New York. The northern-most 3km of the island is densely developed as part of the towns of Newburyport (the northern half) and Newbury. The southern 10km of Plum Island is undeveloped as part of the Parker River National Wildlife Refuge, which draws nearly 250,000 recreational visitors each year, especially during the summer months (Sexton *et al*. 2012).

Plum Island is unusual among US east coast barrier islands in that it is undergoing neither widespread erosion nor landward migration. Although short-term erosion of tens of meters of beach width can occur locally, on a longer, decadal scale, the shoreline of Plum Island has historically been stable (Fallon *et al*. 2015). Over the last 150 years, taken as an aggregate, Plum Island has experienced long-term erosion at the statistically insignificant rate of 0.09 ± 0.60 m/yr (Thieler *et al.* 2013). Nevertheless, 25-30 yr cycles in erosion and accretion along the Plum Island shorefront—driven by sediment bypassing mechanisms between the Merrimack Inlet ebb-tidal delta, nearshore sand bars, and the proximal beach—can greatly complicate decisions about the best practices for adaptation to short-lived shoreline changes along particular sections of the beach.

Plum Island and the coastal region surrounding the Great Marsh were settled by Europeans in the late 17th century. Through the 18th and 19th centuries, the Great Marsh was mowed for salt hay and used as a grazing area for livestock (Waters, Goodhue, and Wise 1905). By the 19th century, the town of Newburyport had become a commercially viable port on the Merrimack River (Labaree 1962), but Plum Island remained undeveloped. In 1806, the Plum Island Turnpike Bridge Corporation was established so that local residents and tourists could access the Plum Island beach more readily (Fig. 2). The Corporation constructed the first bridge and road connecting Plum Island to the mainland (later called the Plum Island Turnpike) and built the Plum Island Hotel, which was the only permanent structure on the barrier for many decades (Currier 1896). Plum Island did not fully develop as a vacation destination, however, for more than a century. In 1920, the Plum Island Beach Company purchased all land north of the turnpike and subdivided 567ha of the barrier into 12,000 lots (Anon. 1920).

The Merrimack River empties into the coastal ocean via a tidal inlet situated between Plum Island and, to the north, Salisbury Beach, Massachusetts. The complex morphology of tidal inlets allows them to temporarily store fluvial and nearshore sediment to be reworked onto adjacent beaches (FitzGerald, Nummedal, and Kana 1976). In the case of the Merrimack River Inlet, the interactions of waves, tides, sediment exchanges with upstream rivers, and longshore sediment transport create a flood-tidal delta upstream and an ebb-tidal delta downstream of the main inlet channel. Studies have shown that cycles of sediment bypassing through a tidal-inlet system are on the order of 4-8 yr in natural tidal inlets, and incorporate the growth of the ebb-tidal delta, ebb delta breaching due to channel avulsion, and subsequent landward bar migration and welding onto the adjacent beach (FitzGerald 1984; Guadiano and Kana 2001).

Historically, the Merrimack River Inlet underwent periods of river mouth migration, causing large shifts in the morphology of the northern-most *ca*. 2km of Plum Island (FitzGerald 1993; Hein *et al.* 2016). The ensuing navigation hazards prompted the US Army Corps of Engineers (Army Corps) to construct two inlet-stabilizing jetties, beginning in 1883 and completed by 1914. Even with this alteration, it has been necessary for the Army Corps to dredge the mouth of the Merrimack River on roughly a decadal basis to permit continued commercial and recreational boat traffic between the lower Merrimack River and the coastal Gulf of Maine (Plumb 2010).

Following jetty construction, and the gradual formation of the northeast fork of Plum Island (Hein *et al.* 2016; see location, Fig. 1), the 3km of Plum Island closest to the inlet began experiencing successive, small-scale changes (about 80-100m) in shoreline position (cycles of erosion and accretion) associated with the regular (once every 25-40 yr) formation and southerly alongshore migration of a localized erosion hotspot. This process has been attributed to the reorganization of inlet-beach dynamics driven by the stabilization of the river mouth and a shifting of the ebb-tidal delta offshore of its natural location, and thus into deeper water. This process altered the mechanisms and timescales of natural ebb-tidal delta breaching and sediment delivery to the downdrift beach, thereby contributing directly to the development of the 25-40 yr cycle of hotspot formation and migration (Fallon *et al.* 2015). For over half a century, these episodes of localized erosion along the Plum Island beach have drawn the attention of property owners, local governments, and state and federal agencies. As a consequence, northern Plum Island generally is now perceived as a coastal beach environment that increasingly will be at risk to a growing storminess and associated storm surges, extreme high tides, and rising sea levels (MCEC 2015).

Over the years, a variety of mitigation strategies have been employed to protect private properties along the Plum Island oceanfront from the effects of this erosion; most of these strategies have found limited success. Following the occurrence of hotspot-associated erosion in the 1950s, the Army Corps constructed a series of groins set perpendicular to a 500m stretch of the beach. These were followed by later attempts at hard shoreline stabilization, including a second set of groins and rip-rap seawalls in the late 1970s. Some of this infrastructure has been lost to erosion since then. Soft engineering approaches also were attempted: for example, the Army Corps replenished the beach in 1953, 1957, 1973, 1987, 1999, and 2010 (Haddad and Pilkey 1998; Plumb 2010).

In 1975, Newbury authorized and funded the pumping of sand from a former channel of the Merrimack River located between the two northern forks (the "Basin"; see location, Fig. 1) to the beach, a partial reconstruction by bulldozers of the fronting dune, the construction of a 400m wall of concrete blocks, and the placement 3,000 hand-filled sandbags in front of Northern

Boulevard (see location, Fig. 1). Much of the permanent infrastructure associated with this project persists today. In January of 1976, a 200m wall of 7,000 sand bags were filled and emplaced by the Massachusetts National Guard, disappearing in a storm the following month (Macone 2008). In March of 1976, 34 cement blocks, each weighing 2,500 kg, were positioned in front of an iconic property known as the “Salt Box Cottage.” Even with this protection, the cottage was destroyed and lost in a storm later that year (King 2010).

Localized erosion in Newbury, along Annapolis Way in the Southern Boulevard section immediately south of the Turnpike’s terminus (Fig. 1), resulted in soft dune stabilization measures, such as periodic beach scraping by property owners to create sacrificial dunes and the placement in 2008 by the town—with state funding—of large sand-filled, coir (coconut-fiber) bags on the beach, parallel to the shoreline and in front of the shorefront properties. A local, citizen-led, shoreline-hardening project, initiated in response to the most recent erosional period (2008 to present), has been highly controversial: rip-rap revetments were installed along the dune toe in 2013, fronting nearly two blocks of homes in the Southern Boulevard section (Fig. 1), including now empty lots on Annapolis Way where former homes had been lost to erosion or moved landward, between 2013 and 2015.

In the vicinity of Newbury’s Southern Boulevard, Plum Island is classified as a “coastal dune” resource, according to rules laid out under provisions of the Massachusetts Wetlands Protection Act (WPA). Properties located on a coastal dune in Massachusetts are subject to the WPA, implemented through bylaws at municipal levels, and administered by local Conservation Commissions, with possible appeals to the Massachusetts Department of Environmental Protection by permit seekers whose applications to modify the dune are denied. Under provisions of the WPA, shorefront properties located on a coastal dune are prohibited from erecting protective structures of any sort. Nevertheless, historical pre-WPA protective structures still exist on or near the coastal dune, and both Newbury and the Commonwealth have facilitated protection through the deployment of the coir bags or have acquiesced when property owners have undertaken temporary protections, such as beach scraping, or when they have built more permanent protections, such as the 2013 rip-rap revetment (Graikoski and Hoagland 2017).

In the next sections, a hedonic pricing model is specified and estimated in order to assess the values associated with properties on Plum Island, including the potential benefits of protective structures and the positioning of buildings. These values are used to help interpret the incentives faced by property owners and governments as they seek to adapt to the dynamic shoreline changes that take place on Plum Island's coastal beach and dune system.

Methods

Hedonic pricing models (HPMs) have been utilized for nearly a century to estimate the implicit prices of the individual attributes of multidimensional goods, including non-market attributes (Berry and Bednarz 1975). Freeman (1993) presented a general hedonic pricing model (HPM) for real estate in which the price of housing (P) is determined by attributes that fall into three general categories:

$$P = f\,(\boldsymbol{S}, \boldsymbol{N}, \boldsymbol{E}) \tag{1}$$

These categories comprise structural ($\boldsymbol{S}$), neighborhood ($\boldsymbol{N}$), and environmental ($\boldsymbol{E}$) attributes. The structural attributes describe a residential property, including its lot size, finished area, number of bedrooms, number of bathrooms, house type, among others. Neighborhood characteristics involve the identity of a municipality or localized municipal services. Environmental variables include proximal environmental amenities, such as a beach, a salt marsh, an estuary, or a river. The marginal implicit price of a housing attribute is roughly equal to an owner's marginal willingness-to-pay for that attribute. Consequently, for small changes in an attribute's quality, the estimated parameters from an HPM can be interpreted as measures of economic welfare changes (Smith 1985; Kriesel, Randall, and Lichtkoppler 1993).

These models have been used with increasing frequency to estimate the benefits of coastal amenities, such as proximity to beaches or water views, or the costs associated with coastal hazards, such as flooding or erosion (Jin *et al*. 2015; Shi 2016). Using an HPM approach, Kriesel, Landry, and Keeler (2000) conducted a far-reaching analysis of the economic risks of coastal erosion in the United States. The authors developed hedonic models for four different US regions: the Atlantic, the Gulf of Mexico, the Pacific, and the Great Lakes. The Atlantic model relied upon observations of properties in coastal counties from Delaware, North Carolina, South Carolina, Georgia, and Florida. (Notably, no observations were included from coastal counties in New England.)

Here, Freeman's model is extended to include information about the timing of previous sales in the Plum Island housing market (***M***), including seasonal and annual covariates, and measures of factors that represent coastal hazards and actions or policies to mitigate such hazards (***H***), including topography, setbacks, shoreline-change rates and their risks, and physical means of protecting properties, such as hard or soft structures or the elevation of buildings on pilings:

$$P = f(\boldsymbol{S}, \boldsymbol{M}, \boldsymbol{N}, \boldsymbol{E}, \boldsymbol{H}) \tag{2}$$

The Plum Island HPM follows the general approach taken by Jin *et al*. (2015). The model was developed to estimate the net benefits (or costs) of coastal hazards, environmental attributes, and measures to mitigate coastal risks. The following semilog form was estimated:

$$\ln(\mathrm{P}_i) = \beta_0 + \boldsymbol{\beta}_{\mathrm{S}}\mathbf{S}_i + \boldsymbol{\beta}_{\mathrm{M}}\mathbf{M}_i + \boldsymbol{\beta}_{\mathrm{N}}\mathbf{N}_i + \boldsymbol{\beta}_{\mathrm{E}}\mathbf{E}_i + \boldsymbol{\beta}_{\mathrm{H}}\mathbf{H}_i + \varepsilon_{\mathrm{i}} \tag{3}$$

where $\ln(P_i)$ is the natural logarithm of the assessed value of property i, and the $\boldsymbol{\beta}$'s are vectors of parameters to be estimated for the housing attributes in each general category.

Table 1 presents the full list of variables included in the model along with their descriptive statistics. The full data set comprises 959 properties. The data were trimmed to 736 properties because of missing values and emphases on single family residences (including three "duplexes," which are individual properties with two families in residence) with sale dates subsequent to 1990. The structural and market sales variables were compiled from town assessments carried out by the towns of Newbury and Newburyport, Massachusetts. A categorical neighborhood variable denoted whether a property was located in the town of Newbury (1) or in Newburyport (0). The environmental and coastal risk variables for each property were derived from publicly available geographic information system shapefiles, such as the Massachusetts MORIS system, data provided by MassGIS, the Federal Emergency Management Administration (FEMA), the US Geological Survey (USGS), or our own *in situ* measurements or observations (Fig. 4).

Most of the model variables are self-explanatory, including the response, the structural characteristics, the neighborhood (municipality), the dates of last sale (month and year), and the environment. Information about sales prices was complete only for 55% of the properties, and therefore the 2013 annual municipal property assessments from Newbury and Newburyport were utilized as the response (*cf.*, Freeman 1993; Bin *et al.* 2011; Shi 2017). For those properties with information about both sales price and assessed value, a fairly close relationship existed between the two, such that sales price increased about \$0.95 ± \$0.09 (95% c.i.) for every dollar increase in assessed value ($p << 0.01$, $R^2 = 0.31$). The towns of Newbury and Newburyport assess properties using approaches that combine information both from recent sales and from adjusted values of property characteristics. Typically, individual properties are assessed annually, but the assessments rely upon sales and value data from the previous year, so that there can be a lag of several months with respect to real estate market fluctuations. By 2012, the regional housing market had begun to recover from the effects of the 2007-09 recession. The 2013 assessments for Plum Island properties, relying upon mainly 2012 data, were likely lower than in several preceding years, being more reflective of housing prices from as much as a decade earlier before their pre-recession peak in 2005 (S&PDJI 2017).

Several variables relating to coastal risk were analyzed. These variables included measures of distance to a shoreline mapped in 1998 (or the "shoreline width"). Linear effects, increasing returns, and diminishing returns were assessed for the 1998 shoreline width. Further, both short-term and long-term measures of net shoreline change were examined. A positive net shoreline change distance comprised net accretion, and a negative net shoreline change distance comprised net erosion. The short-term net shoreline change was measured as the loss or gain of shoreline width over 30 yrs (the position of the shoreline from the mid-1970s to 2007-09), and the long-term net shoreline change was measured as the loss or gain of shoreline width over 125 yrs (the position of the shoreline from the mid-1800s to 2007-09). These time windows were selected to illustrate the importance of dynamic shoreline change, where erosion or accretion on annual or even longer timescales often may be only an ephemeral feature of an otherwise generally stable barrier system.

Beaches fronting Plum Island residential properties exhibited a wide range of width changes, reflecting periods dominated by net erosion to net accretion over both short and long time periods. Although shoreline change was highly variable over both the short- and long-terms, an average property experienced erosion (-9.5m) over the short-term; in contrast, an average property experienced accretion (17.2m) over the long-term. Over the entire (*i.e.*, untrimmed) dataset, and assuming unequal variances, this difference is highly significant in a paired *t*-test ($t = 6.58$; $n = 958$; d.f. = 1,278; $p \ll 0.01$) (Ruxton 2006). The wide range of shoreline changes, exhibiting long-term accretion on average, is characteristic of a stable barrier beach. Notably, flooding and erosion risks still are present in low-lying areas and along stretches of the beach for certain periods of time.

Measures of shoreline change rates and their variabilities over those same time periods also were analyzed, using data compiled for Plum Island by the USGS and the Massachusetts Office of Coastal Zone Management (Hapke et al. 2011). These rates ranged from negative (implying erosion) to positive (implying accretion). Following Kriesel, Landry, and Keeler (2000), measures of time-to-inundation, where the land between a building and the shoreline has been permanently lost to erosion, also were investigated. Time-to-inundation consisted of the distance to the shoreline in 1998 divided by the shoreline change rate, in both the short-term and long-term. Observed accretion for a property, characterized by a positive shoreline change rate, would logically imply that permanent inundation due to erosion could never occur. Several variable transformations and model alternatives were explored, including rescaling the time-to-inundation values to range continuously from low (erosion) to high (accretion) and analyses of subsets of properties that experienced erosion only.

Human actions to mitigate the risks of coastal flooding or erosion also were examined. These actions included the natural elevation of a property (a siting decision), elevation on pilings, and the construction of protective structures. Importantly, building regulations require that new, expanded, or rehabilitated commercial or residential structures be elevated on pilings (Klein and Freed 1989). An interaction between elevation and shoreline width also was tested.

Protective structures comprised seawalls, groins, or beach nourishments that utilized the full range of materials utilized for hard to soft structures (concrete, stone, wood, sand bags, and sand). Seawalls were distinguished on the basis of their heights and whether they underwent public or private construction (and therefore public or private ownership and ongoing maintenance).

Finally, the locations of residential properties in flood zones AE, AO, VE, or none, as designated on the flood insurance rate maps (FIRMs) for both towns, were investigated. With respect to a 100-year flood, zone VE comprises lands that have a one percent risk of flooding and are susceptible to high wave velocity; zone AE comprises lands that have a one percent risk of flooding; and zone AO comprises lands that have a one percent chance of shallow flooding. Although it was not possible to characterize whether individual properties were covered by flood insurance policies, 508 properties in Newbury (98% of the total) and 565 properties in Newburyport (78% of the total) were covered (FEMA 2016a). Neither municipality qualifies under FEMA's Community Rating System program for recognizing voluntary community floodplain management activities that exceed the National Flood Insurance Program's minimum standards (FEMA 2016b). Such qualification would allow a potential reduction in flood insurance premiums. Annual flood risk varies according to location, but during the last 39 years, paid claims per claiming property per year amounted to only \$368/property/yr in Newbury and \$223/property/yr in Newburyport.

The model was estimated using a stepwise regression procedure in the SAS System, including corrections for heteroscedasticity. A preferred model was selected, but eight other models with a variety of alternative specifications and covariate transformations were examined (Appendix, Table A-1), demonstrating the robustness of the results in the preferred model.

Pairwise correlations among covariates were examined, and three variables were dropped from the preferred model because of high correlations with other variables (Appendix, Table A-2). Given the semi-log form, the estimated model parameters comprised percentage changes in assessed property values with changes in the relevant covariate. After estimation, changes in the expected value of a property with changes in each of the covariates were investigated, holding the values of other predictors at their means.

Results

Results of the hedonic regression (Table 2) indicated that the effects of the structural characteristics were consistent with the outcomes of most studies of real estate markets (*cf.*, Monson 2009). Value is added to the average residence though increases in the number of bathrooms and bedrooms, the finished area, or a property's lot size. A small diminishing return to lot size was observed. Only the contemporary housing style added value to an average residence; all other styles either had no effect or subtracted value, with the older, less finished, year-round and seasonal "camp" styles valued respectively at 17% and 21% less, on average.

The variables describing the timing of the most recent sales of houses revealed that the Plum Island housing market tended to peak in November and to be significantly lower than average in February. In both 2008 and 2012, the recorded dates of last sale were significantly higher than average. The 2008 finding was not unexpected, as the recession—triggered by a decline in housing prices nationwide—had officially taken hold by the end of 2007. Home prices in the region declined through 2008, but by 2012 the real estate market had already reached its bottom and had begun its recovery (S&PDJI 2017).

Residences in Newbury commanded a 12% premium relative to Newburyport. This premium likely reflected the physical location of a larger number of Newbury properties positioned with water views and beach access in both the northerly and southerly directions. This effect also could represent a potential difference in applications of property assessment approaches as carried out by the two municipalities.

As seen in the effects of the environmental variables, locations of residences proximate to waterbodies of any type added value to the average residence. Location near the beach added the most value at 21%, followed by the Basin (15%) and the back-barrier (13%). Location near the salt marsh generated a premium of only 5%.

The distance of a property to the 1998 shoreline detracted from its value, but this effect diminished with increasing distance. The net distances of shoreline changes were significant both in the long-term (125yrs) and short-term (30yrs), adding (subtracting) very slight value to the average property when such distances increased (decreased) in both the short and long terms.

Several transformations of variables representing time-to-inundation on Plum Island were explored (not shown in Table 2). None were found significant. To further investigate time-to-inundation, we separated out the properties exhibiting erosion only from the full dataset, dividing them into (overlapping) categories of properties that experienced short-term (726 properties) and long-term (668 properties) erosion. These categories overlapped because some properties experienced erosion in the short-term but accretion in the long-term (or vice versa). Even for these erosion-only properties, parameters on the time-to-inundation variables were insignificant, indicating that concerns about erosion leading to potential damages were not incorporated into assessed values for Plum Island properties.

Three different types of protective structural options were considered: no seawall, a *privately* built and maintained hard structure on the Basin, or a *publicly* built and maintained soft structure on the ocean (Fig. 3a). A hard structure on the Basin that was privately constructed and maintained added about 18% to the value of an average property. This value nearly doubled (to 34%) for properties on the oceanfront, where protection comprised a soft structure (the large coir bags) that was publicly emplaced and maintained.

Elevation of a property above sea level occurs naturally when a building is built on higher ground and artificially when a building is constructed or rebuilt upon pilings. Natural elevation contributed positively and at an increasing rate with height above sea level. Properties that were elevated on pilings added about 6% to the value of an average property.

The VE zone was the only flood management zone found to be significant; a property in the VE zone was worth about 4% *more* than the average home on Plum Island. This result was unexpected, and an explanation is attempted in the next section.

Discussion

Actions that property owners can take to mitigate coastal risks while sustaining proximity and access to environmental amenities have significant value for properties on Plum Island. This value likely affects the way in which property owners approach adaptation to shoreline change. It also likely affects how governments manage important resources, such as designated coastal dunes, in response to those actions.

Table 3 shows the estimated effects of changes in the factors that comprised environmental or coastal change risks on the assessed values for an average property on Plum Island. These effects appear to be sizable, but they are consistent with effects observed by other authors (*cf*., Kriesel, Landry, and Keeler 2000). Property locations on the beach, Basin, or back-barrier contributed most significantly to hedonic value on Plum Island, as it is common for waterviews or proximity to coastal amenities to bear a premium. In the case of Plum Island, waterfront premiums may be buoyed in two ways: the apparent long-term stability of the beach and dune system, and a political environment that enables both property owners and government agencies to put in place either temporary or permanent protective structures to mitigate inundation and consequent property damages in the short-term.

The effect of net distance change in shoreline position was positive for both the short- and long-term measures. Notably, geological studies of the Plum Island beach have observed erosion in localized areas, but these have been characterized as short-term perturbations of a longer, much more stable beach on multi-decadal scales (Hubbard 1976; Fallon *et al*. 2015). In both the long and short terms, the implicit prices of the net shoreline change distance were not very consequential (0.05% in the long-term to 0.09% in the short-term for a 1m change in distance). Because these time periods overlap, if 1m of accretion occurred in both the long- and short-term, the combined effect would be an economic benefit of 0.14% (0.05% + 0.09%). In contrast, if a 1m accretion occurred in the long-term and a 1m erosion occurred in the short-term, the combined effect would be -0.04% (0.05% - 0.09%), namely an economic loss. Notably, both estimates imply only small losses from erosion or benefits from accretion.

An increase in the variability of the long-term *rate* of shoreline change was observed to have a negative effect on property values. This effect was expected where such variability would imply higher levels of uncertainty about the potential for erosion.

The elevation of nearshore properties on pilings has become increasingly common along US coasts, and property values reflect the reduction in flood risks due to this construction technique. In Massachusetts, formal implementation of policies for elevating damaged properties and new construction began as early as 1990, depending upon the promulgation of local by-laws. Foundation pilings allow the free flow of flood waters through a property, both to decrease hydraulic forces and to minimize structural damage. On Plum Island, the difference between the assessed values of a property with pilings compared to one without is about $23,000.

A property in the VE flood management zone is worth about $15,000 *more* than the average property. This increase in value may be due in part to the existence of widespread flood insurance coverage, even though there is a heightened risk of flooding from storm surges in the VE zone. It is important to note, however, that flood insurance does not cover a loss due to coastal erosion, unless it is determined to be the consequence of a flooding event. The inclusion of the flood zone variable has produced mixed results due to the entanglement of two opposing effects: recreational benefits (*i.e.,* it is easier to access coastal amenities) versus flood hazards. Atreya and Czajkowski (2014) found that amenity effects dominated home values. Bin *et al.* (2008) showed that a three-dimensional measure of ocean views accounting for natural topography could be used to isolate risk factors from spatial amenities.

On Plum Island, the presence of hard or soft structural protections is valued significantly more highly than in their absence. The economic benefit of shoreline protection for the average property ranges from about $72,000 for those associated with a privately owned and maintained hard structure on the Basin to about $133,000 for those associated with a publicly owned and maintained soft structure (sand-filled coir bags) on the oceanfront. Without a doubt, protective structures provide a (possibly misguided) sense of safety and security from storm surges and flooding. The premium attached to public protection may relate to the perceived security of large-scale, government-funded shoreline protection projects, including episodic beach nourishments undertaken by the Army Corps. Further, a public structure would be maintained by government agencies, or by the collective action of a contiguous group of property owners, implying that the costs of protection also would be covered by those agencies or spread over the members of that group.

In recent years, sections of the beach that have undergone erosion during the ongoing hotspot cycle—and where only soft mitigation structures, in the form of sand-filled coir bags, were emplaced—have nevertheless experienced significant damages to adjacent oceanfront properties. For example, during a series of northeast storms occurring over the winter of 2013 (prior to installation of the private rip-rap revetment later that year), eight Annapolis Way residences in the Southern Boulevard section proximate to the coir bags were lost to erosion, and several more were damaged significantly (Schworm 2013; Packer, p.c., 2016). This raises a question about why there is such a large premium associated with a publicly owned soft structure in that area.

In addition to the public construction and maintenance of soft protection, it is likely that the premium reflects the tolerance exhibited by government agencies with respect to adaptive responses undertaken by the shorefront property owners on a designated coastal dune resource. For example, on several occasions during the last decade, shorefront property owners along that section of the beach have been allowed by the town and state agencies to "scrape" the sand with bulldozers, forming sacrificial dunes that serve as temporary protection against flooding and erosion prior to approaching storms. Recently, a more permanent adaptation was carried out by shorefront property owners, who emplaced the rip-rap revetment fronting the beach along the Southern Boulevard section, from Fordham Way in the south to Annapolis Way in the north.

Undeniably, the town has an incentive to ensure that the properties along the coast continue their tax and utility payments. The assessed value of each the 40 properties along Fordham Way and Annapolis Way averaged $561,405. At the current property tax rate in Newbury of $10.61 per thousand dollars of assessed value, the average residence pays nearly $6,000 in property tax to the town each year. At a discount rate of 2%, the capitalized tax base along this section of the beachfront is on the order of $12 million. (The eight residences lost in 2013 comprised a loss of capitalized tax payments of nearly $2.4 million to the town.) Further, the town also needs the property owners to continue as rate payers for the municipal sewer system, which was mandated as a consequence of the contamination of drinking water by overburdened or poorly maintained septic systems on Plum Island—clear evidence of resident and visiting populations that exceeded the barrier's carrying capacity.

In many US coastal locations, often the risks of flooding and erosion are conflated, making it difficult to sort out the relative risks of either hazard (*cf.*, Kriesel, Landry, and Keeler 2000). Elevating buildings, either on pilings or with natural topography, and flood insurance help to lessen the risks of damage due to inundation. Construction and maintenance of protective structures, abetted by local and regional governments, help to mitigate the damages of the fleeting erosion that can occur during storms. Multiple means of hedging natural hazards may comprise a form of coastal adaptation sometimes referred to as "resistance, redundancy, and contingency" (Muir-Wood 2016). On Plum Island, protective structures comprise resistance, the elevation of buildings comprises redundancy, and flood insurance comprises contingency. In rare cases, a further contingency exists in the expectation of federal disaster assistance payments that may be forthcoming in the wake of very significant storm events, such as those associated with storm surges from tropical cyclones.

The Plum Island case offers three main insights for coastal managers in Massachusetts and elsewhere. The first is that an understanding of the degree of environmental change may be capitalized into coastal property values. In particular, measurements of erosion rates demonstrate the stability—in the long-term—of the inlet-associated beach system of Plum Island, and this stability is reflected in Plum Island's property assessments. As scientific information about coastal environmental change and sensitivity to ongoing and accelerated changes in sea level, storminess, and sediment-delivery rates becomes increasingly available to coastal communities around the world, its effect on property values is expected to become more evident. Knowledge of how advances in scientific understanding can influence property values is essential for adaptive management.

Second, statewide policies with respect to generic resource areas, such as designated "coastal dunes" in Massachusetts, may be written too broadly to accommodate atypical, context-dependent local systems, such as the 25-40 yr cyclical pattern of inlet-associated erosion and accretion observed at northern Plum Island. State coastal managers have been justifiably concerned over the potential broader precedent that may have been set by the scofflaw nature of adaptation undertaken by property owners in the Southern Boulevard beachfront section of Plum Island. Yet Plum Island, as an example of an inlet-associated beach and dune system, comprises a unique set of geological characteristics that may not easily mesh with an inflexible broader policy framework that lacks the ability to put in place context-dependent adjustments.

Finally, and perhaps most importantly, the problem of coastal adaptation often has been cast simply as one of individual property owners following parochial interests, leading to the imposition of significant costs on society when catastrophic natural events occur. While there is some truth to that depiction, the case of Plum Island shows that the interests of the wider community may be more complex than previously appreciated, with incentives for local institutions and managers closely aligned to those of beachfront property owners. Adaptation therefore may be more problematic than simple suggestions that property owners ought to retreat from the coast. In this view, adaptation comprises a much more difficult problem of getting *both* the individual property owners and the broader community and its institutions to consider the potential net benefits of adaptation in the context of their mutual interdependencies. Even in cases where the benefits to individual property owners of retreat clearly exceed the costs, community policies acceding to or directly implementing structural protections may continue to persuade property owners to stand their ground.

Conclusions

Similar to other studies that have analyzed the economic aspects of shoreline change, property values on Plum Island decrease with distance from the shoreline, albeit at a small but diminishing rate. The dynamic nature of inlet-beach interactions along Plum Island leads to short-term cycles of localized erosion and accretion, the positions of which may shift over time, thereby making it problematic for property owners to assess explicitly the costs associated with the risks of shoreline change. A time-to-inundation variable was unrelated to assessed property values, and the net distance of shoreline change over both short- and long-term exhibited very small impacts on property values.

Public protective structures on the oceanfront contributed significantly to property values on Plum Island, exceeding the value of private protective structures on the Basin. Until recently, the costs of building and maintaining the public projects were shouldered mainly by government agencies, so that the protected residential properties bore only a fraction of the costs of construction, maintenance, and repair. Perceptions held by property owners of lower erosion risks may be misguided, however, as the coir bags have been ineffective in preventing erosion, and the groins and jetties may disrupt sediment transport patterns in ways that may be difficult to predict, thereby heightening erosion or flooding risks in ways that are not fully transparent to or recognized by property owners. Nevertheless, there appears to be a tacit understanding, reinforced by consistent sets of economic incentives, that both property owners and governments will continue to collaborate in adapting to shoreline changes on Plum Island by protecting existing properties, using both soft and hard structures.

Plum Island provides an example of the complex interactions of dynamic shorelines and coastal development that may not be uncommon among inlet-associated beaches. Recently, the long-term stability of Plum Island has been overlooked, as public attention has been focused on the frequent impacts of northeast storms to only a small number of residences in a localized oceanfront area. In the near future, the economic incentives comprising adaptation without retreating imply that the emplacement of protective structures, the elevation of buildings, and the purchase of flood insurance will continue to be both implemented by property owners and supported by governments. In the much longer run, however, when sea levels have risen sufficiently, Plum Island property owners and their coastal communities inevitably may be forced to reconsider the practicality of adaptation by retreat.

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Figures and Tables

Fig. 1: Study site: Plum Island, Massachusetts is a 13km barrier island in the western Gulf of Maine (figure modified from Hein *et al*. 2012). Only the northern 25% of the island's total length—that most directly influenced by the bounding Merrimack River to the north—has been developed. Inset: zoom-in of northern Plum Island highlights the locations and structures discussed in the text.

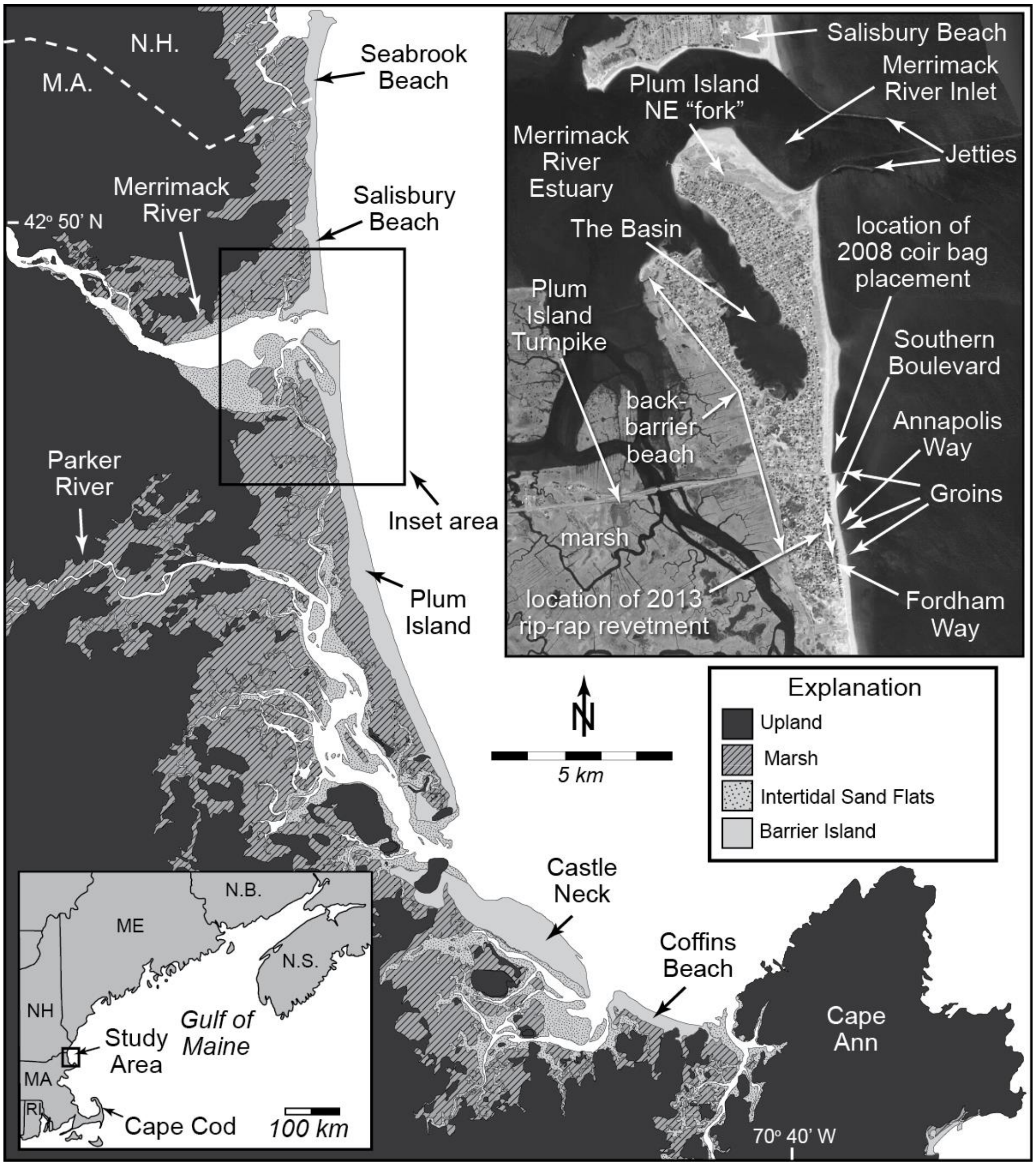

Fig. 2: Timeline of development of the Newburyport section of Plum Island. The development of Plum Island on Newburyport began in 1895, aided by the existence of the Plum Island Turnpike (connecting the beach to the mainland by road) by the street railway company. In 1920, the Plum Island Turnpike Bridge Corporation bought the land north of the turnpike, initiating the rapid growth of Plum Island until the 1970's when growth slowed from ~300 homes in 50 years to <150 homes in 40 years.

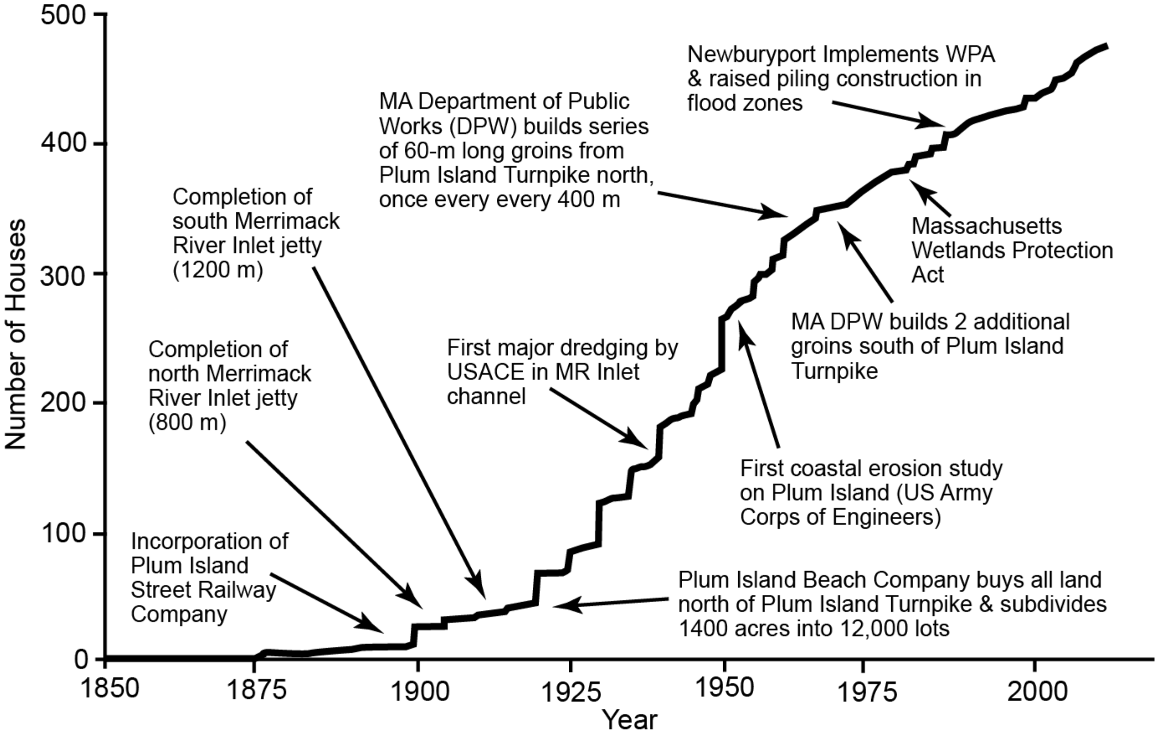

Fig. 3: Panel a: Locations of homes (green dots) and protective structures (red lines) on northern Plum Island. The thin black lines show the locations of shore-perpendicular transects along which the impact of shoreline change on housing values was evaluated. The red lines depict the locations of protective structures (“seawalls”) on the Basin (hard structures) and on the oceanfront (coir bags). The diagonal gray line bisecting northern Plum Island is the political boundary between the towns of Newburyport (north) and Newbury (south). Panel b: the locations of properties in the VE flood zone (red).

(a) (b)

Table 1: Descriptive statistics

Variable	Units	Minimum	Mean	Maximum	s.d.
Response					
Assessed Value	$ (2013)	187,500	412,110	1,142,800	149,660
Assessed Value (natural log)		12.14	12.93	13.95	11.92
Structural Characteristics					
Bedrooms	rooms	1	2.56	8	0.87
Bathrooms	rooms	0	1.54	4.50	0.66
Finished Area	m^2	254	1,929	7,410	1,038
Finished Area (squared)		64,516	4,795,880	54,908,100	5,515,591
Lot Size	m^2	1,764	7,161	41,174	4,373
Lot Size (squared)		3,111,696	70,374,180	1,695,298,276	121,822,551
Contemporary		0	0.07	1	0.25
Old Style		0	0.04	1	0.19
Cape Cod		0	0.06	1	0.24
Bungalow		0	0.01	1	0.11
Ranch		0	0.13	1	0.34
Two-family Conversion		0	0.02	1	0.12
Year-round Camp		0	0.22	1	0.41
Seasonal Camp		0	0.08	1	0.27
Duplex		0	0.004	1	0.06
Old-style Colonial		0	0.01	1	0.07
Raised Ranch		0	0.01	1	0.09
Neighborhood					
Newbury		0	0.51	1	0.50
Newburyport		0	0.49	1	0.50
Environment					
Beach		0	0.08	1	0.27
Basin		0	0.12	1	0.32
Back-barrier		0	0.06	1	0.23
Marsh		0	0.26	1	0.44
Coastal Risk Factors					
Long-term (125yr) Net Distance of Shoreline Change	ft	-400.98	60.01	1,591.44	393.31
Long-term Shoreline Change Rate	ft/yr	-2.89	0.31	10.73	2.92
Long-term Shoreline Change Rate Variability	ft	0.12	2.89	12.71	3.08
Short-term (30yr) Net Distance of Shoreline Change	ft	-282.51	-31.03	521.46	164.19
Short-term Shoreline Change Rate	ft/yr	-8.30	-0.64	16.93	5.28
Short-term Shoreline Change Rate Variability	ft	0.11	9.22	69.93	9.97
Long-term time-to-inundation	yr	13.96	72.18	1,482.39	139.59
Short-term time-to-inundation	yr	40.62	54.84	78.33	3.57
Distance to the Shoreline in 1998	m	4.58	139.28	474.94	75.99
Distance to the Shoreline in 1998 (squared)	m^2	20.96	25,166.66	225,565.53	28,898.97
Distance to the Shoreline in 1998 (square-root)	$m^{0.5}$	2.14	11.33	21.79	3.31
Land Elevation (squared)	m^2	1.29	14.11	72.64	11.19
Land Elevation (square-root)	$m^{0.5}$	1.07	1.85	2.92	0.32
Distance to the Shoreline x Land Elevation	m^2	5.79	482.47	2,585.46	294.33
Seawall Height (< 5)	ft	0	0.01	1	0.10
Seawall Height (5-10)	ft	0	0.01	1	0.10
Seawall Height (10-15)	ft	0	0.20	1	0.40
Private Hard Structure on Backbay		0	0.20	1	0.40

Public Soft Structure on Oceanfront	0	0.31	1	0.46
Elevation on pilings	0	0.10	1	0.30
Location in VE Flood Zone	0	0.27	1	0.45
Location in AE Flood Zone	0	0.23	1	0.42
Location in AO Flood Zone	0	0.12	1	0.33
Dates of Last Sale				
January	0	0.08	1	0.27
February	0	0.05	1	0.22
March	0	0.08	1	0.27
April	0	0.09	1	0.28
May	0	0.08	1	0.28
June	0	0.10	1	0.29
July	0	0.09	1	0.28
August	0	0.08	1	0.28
September	0	0.09	1	0.28
October	0	0.10	1	0.31
November	0	0.07	1	0.26
1990	0	0.01	1	0.10
1991	0	0.01	1	0.10
1992	0	0.03	1	0.17
1993	0	0.01	1	0.11
1994	0	0.03	1	0.16
1995	0	0.03	1	0.17
1996	0	0.02	1	0.15
1997	0	0.03	1	0.16
1998	0	0.04	1	0.19
1999	0	0.04	1	0.18
2000	0	0.03	1	0.18
2001	0	0.03	1	0.16
2002	0	0.06	1	0.23
2003	0	0.05	1	0.21
2004	0	0.06	1	0.23
2005	0	0.05	1	0.21
2006	0	0.05	1	0.21
2007	0	0.06	1	0.24
2008	0	0.04	1	0.21
2009	0	0.04	1	0.20
2010	0	0.04	1	0.21
2011	0	0.08	1	0.27
2012	0	0.09	1	0.29
2013	0	0.08	1	0.27

Table 2: Regression of the natural log of assessed property values on factors affecting those values for residential properties located in Newbury and Newburyport on Plum Island.

Predictor	**Parameter Estimate**	**Standard Error**
Intercept	12.35	(0.04)***
Structural Characteristics		
Bedrooms	0.02	(0.01)***
Bathrooms	0.08	(0.01)***
Finished Area	1.1×10^{-4}	(9.7×10^{-6})***
Lot Size	2.4×10^{-5}	(3.0×10^{-6})***
Lot Size (squared)	-4.4×10^{-10}	(8.5×10^{-11})***
Contemporary	0.05	(0.02)**
Old Style	-0.05	(0.03)*
Cape Cod	-0.07	(0.02)***
Bungalow	-0.09	(0.03)***
Ranch	-0.14	(0.01)***
Two-family Conversion	-0.16	(0.04)***
Year-round Camp	-0.17	(0.02)***
Seasonal Camp	-0.21	(0.02)***
Dates of Last Sale		
February	-0.05	(0.02)**
November	0.04	(0.02)*
2008	0.06	(0.03)*
2012	0.03	(0.02)**
Neighborhood		
Newbury (vs. Newburyport)	0.12	(0.02)***
Environment		
Beach	0.21	(0.02)***
Basin	0.15	(0.02)***
Back-barrier	0.13	(0.03)***
Marsh	0.05	(0.01)***
Coastal Risk Factors		
Long-term Net Distance of Shoreline Change	1.5×10^{-4}	(2.5×10^{-5})***
Long-term Shoreline Change Rate Variability	-8.3×10^{-3}	(0.003)***
Short-term Net Distance of Shoreline Change	2.8×10^{-4}	(4.5×10^{-5})***
Distance to the Shoreline in 1998 (square-root)	-0.01	(0.002)***
Land Elevation (squared)	0.001	(5.2×10^{-4})**
Private Hard Structure on Backbay	0.03	(0.01)**
Public Soft Structure on Oceanfront	0.13	(0.02)***
Elevation on Pilings	0.06	(0.02)***
Location in VE Flood Zone	0.04	(0.01)***
n	736	
R^2	0.84	

*, **, and *** denote statistical significance at 10, 5, 1% levels, respectively.

Table 3: The effects of categorical variables on the assessed value of an average Plum Island property ($384,100). Results were derived from estimated parameters and standard errors. Each value is calculated by assessing property value with the presence of that variable (1) in comparison to the value at the mean of the relevant variable (somewhere from 0-1, see Table 1). Confidence intervals comprise 95% of the estimated parameter distributions.

ENVIRONMENTAL/ COASTAL RISK FACTOR	EFFECT ON ASSESSED VALUE
Beach	$81,080 ± $17,438
Basin	$59,516 ± $15,157
Public Soft Structure on the Oceanfront	$51,604 ± $15,110
Back-barrier	$51,131 ± $20,496
Elevation on Pilings	$23,004 ± $14,504
Marsh	$21,059 ± $10,747
Location in VE Flood Zone	$15,110 ± $10,924
Private Hard Structure on Basin	$12,195 ± $9,818