Fighting the inevitable: infrastructure investment and coastal community adaptation to sea level rise

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Abstract

Coastal communities are crafting adaptation strategies to confront sea level rise (SLR). Unfortunately, cost-benefit analyses assessing SLR risks often fail to capture important political and social feedbacks. For example, adaptation measures (e.g. beach nourishment) can trigger greater development, undermining the value of adaptation infrastructure, incentivizing development, and increasing risks. We integrate diverse literature and data to develop a hypothesis and system dynamics model of coastal community responses to SLR. We apply the model to two U.S. communities, showing how political influence drives trajectories of infrastructure provision, cost, and vulnerability. We find that delayed feedbacks between perceived SLR risk and infrastructure investments mediate relationships between political capital, migration, and economic development. Community wealth and political influence may only delay the overshoot and collapse of its population and economy, as the "virtuous cycles" linking growth with infrastructure investment give way to "vicious cycles" of mounting infrastructure costs, political resistance to additional investment, and greater vulnerability.

Introduction

Sea level rise (SLR) poses a significant risk to coastal populations, infrastructure, and economies. Nearly 40 percent of the world's population lives within 100 km of the coastline (Moser, Williams, and Boesch 2012), and more than 50 percent of the U.S. population resides in coastal areas that may be affected by rising sea levels. SLR has already begun to transform low-lying coasts, disrupting daily life and economic activity. For example, coastal Virginia has experienced an increase in the frequency of "sunny-day" flooding (or "nuisance" flooding) from 1.7 days in 1960 to 7.3 days of flooding in 2014 (Behr et al. 2016). While these floods are often just 20-60 cm (1-2 ft.) deep, they can stop traffic, swamp basements, damage cars, kill forests, and contaminate wells with salt (Gillis 2016).

Significant research seeks to forecast the impacts of SLR (Hauer et al. 2016). Typically, this research has focused on future "end states," driven by rising sea levels that are understood to slowly inundate coastal communities (Horton et al. 2014; Rahmstorf 2007). By combining projections of a specific future amount of SLR with property values and other socio-demographic data, researchers have developed models and tools to determine which areas will likely be protected and which will likely be abandoned (Neumann et al. 2010). Such approaches to modeling usually estimate the adoption of protection and abandonment strategies by comparing the cost of building and maintaining protective physical infrastructure, such as seawalls, to the value of the property and assets at risk of inundation. Basing infrastructure investment decisions on cost alone, however, exacerbates existing inequalities by encouraging protection of the largest, wealthiest communities and abandoning small, disadvantaged communities (Martinich et al. 2013).

Several studies have begun to document the feedbacks between hazard protection and development (see McNamara, Murray, and Smith 2011), noting that efforts to protect coastal properties from hazard damage can have the unintended effect of encouraging more development in hazardous locations (Armstrong et al. 2016). As the economic value of vulnerable urban and economic infrastructure (roads, houses, commercial buildings, etc.) increases, the political and economic cases for protection are strengthened (Armstrong et al. 2016). As we will demonstrate in this paper, these political structures and behaviors create a powerful reinforcing feedback loop. The tendency for the initial "solution" to create additional challenges – increasing the number of people and assets at risk – suggests that coastal protection should be approached as a system dynamics problem (Moser, Williams, and Boesch 2012; Meadows and Wright 2008)

In this paper, we assess the dynamic feedbacks surrounding investment in coastal infrastructure (CI) protection to address two key questions: (1) How will infrastructure investment policies change in the face of climate change? and (2) How are both the social and natural hazard vulnerability of coastal communities affected by different infrastructure investment patterns in the face of unabated SLR? To do so, we integrate a broad range of community climate-response literature to establish a dynamic hypothesis that allows us to explore alternative trajectories of community vulnerability, economic activity, population, political influence, and infrastructure investment in the face of SLR. This hypothesis suggests the opportunity for several un-expected dynamic patterns to emerge, including over-shoot and collapse behavior, lagged political feedbacks, and nuanced links between population, migration, and infrastructure investment. We then construct a small, quantitative system dynamics simulation model (e.g., Fiddaman 2002) to test our hypothesis.

Our primary goal in this paper is to present a broader picture of the feedbacks affecting coastal community adaptation, infrastructure investment, and SLR risk. We endeavor to use system dynamics to consider the joint effects of several, independent causal relationships that have been identified in the rapidly-expanding coastal adaptation literature. However, it is important to highlight the complexity of this problem; previous studies, including work by Franck (2009) and Deegan et al. (2014), have demonstrated the complex model structures needed to realistically represent important aspects of adaptation dynamics, including differentiated CI (e.g., beach nourishment, sea walls), public finance mechanisms (e.g., bond ratings), and many other factors. In this paper, we use available data and literature to propose simplified causal structures around the complex feedbacks of community adaptation dynamics. Significant further work is needed to understand the nuances of CI construction, operations and maintenance, and the linkages between community tax-base and infrastructure investment, among other factors.

We begin by reviewing literature on coastal climate adaptation, CI investment strategies, and dynamic adaptive pathways. Next, we construct and explore a dynamic hypothesis that captures the causal relationships suggested by these literatures. We apply this hypothesis to two coastal regions with differing wealth, growth characteristics, and political influence. These study regions include North Carolina's Outer Banks barrier islands (Dare County, NC; high population growth and economic activity) and Dorchester County, Maryland (low population growth and economic activity).[1]

Finally, we construct a relatively simple, system dynamics model[2] to test vulnerability trajectories associated with investment strategies in these coastal regions. These applications aim to refine our understanding of the positive and negative feedback loops that drive CI investment strategies. We conclude with a discussion of insights that can be transferred to other regions facing unabated SLR. As coastal regions worldwide transform in advance of rising seas, the sustainability of these coastal landscapes, now and for decades to come, hinges on a well-grounded understanding of the strategies that communities can use to reduce their vulnerability to SLR.

Overview of climate adaptation policies

Adaptation behaviors in the face of SLR are typically classified into three categories, *retreat, protection*, and *accommodation* (Moser, Williams, and Boesch 2012; Butler, Deyle, and Mutnansky 2016; IPCC et al. 1990).

Retreat (sometimes called *abandonment*) typically occurs using construction setbacks (requirements to move construction away from hazard areas) and public land buyouts (Zavar 2015). Strong evidence suggests that long-term losses of shorefront development can only be

[1] In Supplementary Material 1, we apply our dynamic hypothesis to two additional regions with higher population densities, including the City of Chester, Pennsylvania (low income, high density) and New York, NY (high income, high density).
[2] The model is intended to be relatively simple compared to more sophisticated simulations of coastal community adaptation, such as that by Franck (2009).

avoided if retreat is incorporated into adaptation measures (Moser 2005). Retreating from hazardous areas eliminates risk rather than reducing it (Butler, Deyle, and Mutnansky 2016), making it an attractive, and perhaps the only, option over longer timeframes (Hino, Field, and Mach 2017). Comparing the costs and benefits of managed retreat and structural hardening in an English estuary, Turner et al. (2007) found that retreat was more economically efficient when considering timeframes of 25 years or longer. Nonetheless, many communities eschew retreat based on the high and immediate opportunity costs of foregone development (National Research Council 2014), as well as political and legal opposition to retreat policies (Butler, Deyle, and Mutnansky 2016).

Accommodation measures do not prevent floodwaters from entering a community, but instead aim to reduce the negative impacts of flooding. While local governments are generally hesitant to adopt retreat strategies, many propose or have implemented measures to reduce the risks caused by SLR through accommodation (Berrang-Ford, Ford, and Paterson 2011; Butler, Deyle, and Mutnansky 2016). Accommodation measures include flood insurance, efforts to elevate structures, and alterations to building codes to improve flood performance for new construction or, in some cases, modifications to existing structures. Local governments are well equipped to adopt and implement accommodation strategies since many of these approaches have been used for decades to reduce the risk of flooding (Butler, Deyle, and Mutnansky 2016). Perhaps as a consequence, Sahin and Mohamed (2013) found that local politicians generally prefer accommodation measures.

Protection includes the establishment of hardened infrastructure such as seawalls and "soft" structural protection measures such as beach nourishment. Along highly developed shorelines, structural protection has historically been the preferred option to prevent coastal flooding (Moser, Williams, and Boesch 2012; National Research Council 2014). Structural protection measures, such as seawalls, levees, dikes, have been found to protect property and lives (Brody et al. 2007; Zahran et al. 2008).

Some researchers argue that investments in protection strategies have been inadequate, leaving trillions of dollars of assets located in coastal areas exposed to flood damage from rising seas (Aerts et al. 2014). However, others argue that the benefits of structural measures come at high costs. Hardening shorelines can also lead to the loss of beaches and wetlands in front of protective structures, negatively affecting recreation and ecosystem services, such as fish nurseries, storm buffers, and bird habitat (Moser, Williams, and Boesch 2012). Additionally, structural flood protection measures can encourage further development in areas vulnerable to flooding. As a result, when a flood event does exceed the capacity of a flood control structure, the resulting costs of flood damages can be significantly higher (Brody et al. 2007). This phenomenon, which we discuss further below, is a prime example of a "moral hazard" and is commonly referred to as the "safe development" paradox (Burby 2006; Cutter and Emrich 2006), which we discuss further below.

Assessments of adaptation efforts globally have found that communities are currently prioritizing protection and accommodation measures, with relatively few pursuing retreat strategies (Berrang-Ford, Ford, and Paterson 2011). Table 1, adapted from Butler, Deyle, and Mutnansky

(2016), provides an overview of major land-use related adaptation planning strategies in the face of SLR.

[Insert Table 1 about here]

Considering vulnerability in the broader hazard context

Regardless of the approach adopted, local coastal adaptation planning processes often begin with an initial vulnerability assessment. Vulnerability carries multiple context-based definitions (Nguyen et al. 2016). We distinguish two-types: natural hazard vulnerability (bio-physical) and socio-economic vulnerability. For our purposes, we consider natural hazard vulnerability as an index connecting the probability of the hazard occurring (risk) and the exposure of assets (or population) to the hazard (population multiplied by probability). Socio-economic vulnerability is inversely related to the degree to which an individual or a community can respond to a hazard, which is highly correlated with both income and political power (Cutter and Finch, 2008). Given the vast literature on the inequities formed by emigration away from urban disamenities (e.g., Pulido 2000) and coastal hazards (Cutter and Emrich, 2006), we also consider the per-capita value of the natural hazard vulnerability index to be a proxy for socio-economic vulnerability. In both cases, we proxy vulnerability using the relationship between infrastructure supply and relative SLR, whether or not that infrastructure is protective or accommodative.

Case studies and data

We selected two coastal communities as case studies to aid us in developing our dynamic hypothesis. Data from these areas will also help calibrate and apply our dynamic model. We chose these study areas – as well as two additional areas discussed in Supplementary Material 1

– as the climate adaptation efforts or concerns in each have been a topic of detailed study (Woodruff and Stults 2016; Payne 2016). Dorchester County (Maryland) has notably engaged in local climate adaptation planning (Woodruff and Stults 2016), while the Outer Banks barrier islands, part of Dare County, North Carolina, have created hazard and coastal area management plans (Dare County 2017). These case study areas have different wealth levels and economic activities, growth rates, political power, and cultural values (Table 2).

[Insert Table 2]

Dorchester County, Maryland (low population growth and economic activity)

Dorchester County is located on Maryland's Eastern Shore. Compared to many other counties in Maryland, Dorchester County is more rural and has lower income (US Census 2016). Population has declined since 1970 in all but two of the incorporated towns in Dorchester; some areas have experienced more than 30 percent population loss. Since 1986, there has been a steady decline in manufacturing and warehouse jobs. Dorchester's limited economic, social and political resources constrain options for adapting to SLR (Miller Hesed and Paolisso 2015).

Approximately 60 percent of Dorchester County lies in the current 100-year floodplain, the vast majority of which is tidal. Due to the flat landscape, sea level increases as small as 7.6 cm could result in inundation over a hundred meters inland (Titus and Richman 2001). With Boesch et al. (2013) projecting a 110 cm increase in mean sea level by the end of the century, the bay shores may retreat up to ten kilometers inland (Miller Hesed and Paolisso 2015). In some low-lying areas, roads and homes are already at risk of flooding during high tides (Miller Hesed and Paolisso 2015). Road flooding forces residents to take alternative routes, while high water levels have also led to septic tank failures. Although these homes can still be occupied, a functional septic system is required to obtain a mortgage; tank failures drive down market value and make these homes virtually impossible to sell (Titus and Richman 2001). Consequently, abandoned homes are not uncommon.

In Dorchester, vulnerability to SLR is compounded by social and political isolation that inhibits access to sources of adaptive capacity (Miller Hesed and Paolisso 2015). Local action to reduce risk from SLR has thus far been limited. Proposals to require elevation of new construction have been introduced to the county council four times since 1990 and failed every time (Goldman 2010). In opposing elevation requirements, county councilmen cite concerns about restricting property rights, the cost of elevation, and limiting growth. To aid local government adaptation, the state has provided grant assistance, technical information, and has developed county specific sea level guidance. The guidance for Dorchester discusses the possibility of abandoning roads and other infrastructure that may be inundated. Maintenance, let alone elevation, of rural roads costs more than the value of the properties they service. The state recommends the establishment of policies to guide when abandonment will occur.

Dare County, North Carolina (high population growth and economic activity)

In contrast to Dorchester County, Dare County and North Carolina's Outer Banks barrier islands continue to receive state and federal funding to maintain infrastructure. For example, since the early 1990s, taxpayers have spent more than $30 million in state and federal funding to repair NC Highway 12, which runs the length of the Outer Banks and connects the island chain to the mainland (Browder 2012). Maintaining the road over the next century is estimated to cost more than $1 billion (Browder 2012). Currently, the high cost of maintaining this infrastructure may be warranted based on the $1 billion tourists spend annually in Dare County (Walker 2016), for which NC Highway 12 is vital.

Beyond their economic contribution, the Outer Banks are a cultural symbol of the State of North Carolina, giving them significant clout in comparison to inner coastal areas in the State, which have lower land values and less tourism. Dare County has also used its political clout to protect their development and economic interests, lobbying the state legislature to place a moratorium on the use of official rates of SLR for regulatory purposes (Bulla et al. 2017).

Demographic, infrastructure, and infrastructure cost data

To understand community responses to rising sea levels, we collected demographic, economic, and coastal hardening data for each case study community. Total population and per capita income were collected from the 1980, 1990, and 2000 decennial census. For 2005, 2010, and 2015, the data were collected from the American Community Survey (US Census 2016). Population and per capita income were multiplied to calculate “local area personal income,” a proxy for GDP we use in our model.

To operationalize the concept of “coastal infrastructure,” we used the US National Oceanic and Atmospheric Administration’s (NOAA) Office of Response and Restoration Environmental Sensitivity Index (ESI) Maps (NOAA 2018) to estimate “coastal hardening” in each community. The ESI summarizes coastal resources, including shoreline conditions, to identify risks of oil spills. Since ESI is a national dataset, it provides a consistent source to assess whether the shoreline is “hardened” (i.e., harbor structures, riprap, and seawalls) or “natural” (i.e., sandy, rocky, intertidal marsh) for our study areas. We downloaded the ESI Geographic Information Systems (GIS) data, which consists of a linear layer (a GIS line feature with type of shoreline) for each case study region. Using ArcGIS 10.5, we then clipped the ESI lines to the community boundary, calculated the length of each line segment (using the 2016 length as the baseline coastline length), and summed the length of the hardened shoreline segments. In all of our case study communities, data were available for at least two dates (1996 and 2016); however, dates varied by community (see Figure 1).

[Insert Figure 1 about here]

Operationalizing and estimating the cost of construction and maintenance for CI is difficult given the wide range of potential costs. At the extreme high end, the City of Charleston, SC estimated the 2015 cost of replacing a sea wall at approximately $22,840 per foot of wall ($74,915 per m; JMT 2015), while the 2013 replacement of the Elliot Bay seawall in Seattle, WA is estimated to cost $75,000 per linear ft ($246,000 per m; Beavers, Babson, and Schupp 2016). On the lower end, the 2016 Coastal Adaptation Strategies Handbook released by the US National Park Service estimates the cost of shore-parallel structures such as sea walls and bulkheads as $2,000 to $3,000 per linear ft (~$6,560—$9,840 per m; Beavers, Babson, and Schupp 2016). The NC Coastal Federation’s handbook on shoreline erosion (Seachange Consulting 2011) suggests that bulkhead construction can range from $100–$1,200 per linear foot ($328-$3940 per m), with residential prices around $135 per ft (~$445 per m).

For brevity, in this paper we assume constant (real) construction and annual maintenance costs on the lower end of this spectrum, at $900 per m and $100 per m, respectively. However, it is certainly possible that *marginal* construction and replacement costs could rise as SLR forces infrastructure to grow in size and sophistication. For instance, repair and replacement costs of deteriorating seawalls and bulkheads are often greater than new construction (Beavers, Babson, and Schupp 2016), suggesting the cost of CI will rise over time. Deegan et al. (2014) offer an excellent discussion of these costs and a more sophisticated effort to estimate cost accrual.

A dynamic hypothesis for the evolution of coastal community vulnerability

Since 1980, modeling which areas should be protected and which should be abandoned has been an active area in SLR research (Yohe and Schlesinger 1998; Fankhauser 1995). However, little work has comprehensively addressed the many feedback effects of conditioning whether, how, and why communities adapt to SLR. By integrating the feedbacks described in the literature, we can present a novel, more complete description of the dynamics of coastal community adaptation and vulnerability.

We iteratively construct a dynamic hypothesis using causal loop diagrams. The theory describes two sets of feedback loops, encompassing (1) the relationship between migration, economic activity, and CI development (the “safe development” paradox described above), and (2) the political feedbacks that constrain or enable future infrastructure spending and drive natural hazard and socio-economic vulnerability.

Migration, economic activity, and CI development feedbacks

Many early studies simplified analysis of coastal protection by assuming the choice is between abandonment and protection, ignoring accommodation options (Fankhauser 1995; Butler, Deyle, and Mutnansky 2016). Studies evaluating the “optimal” level of coastal protection further simplify the problem by ignoring changes in economic and demographic characteristics (Moser 2005; Sahin and Mohamed 2013; Balica, Wright, and van der Meulen 2012; Tol et al. 2004). For example, studies frequently overlay future scenarios of biophysical change on current demographic and socio-economic data, implicitly assuming these characteristics are stationary (Preston, Yuen, and Westaway 2011; Berry and BenDor 2015). Studies that fail to incorporate projected population and economic growth will underestimate the total population and value of assets at risk from future climate impacts, which can lead to non-adaptive or even maladaptive outcomes (Kashem et al. 2016).

Several studies attempted to model future population growth including migration to better estimate the number of people that will be exposed to future natural hazards (Neuman et al. 2015; Kleinosky, Yarnal and Fisher 2007). However, a major challenge in such studies is accounting for the interactions and feedbacks between environmental change and migration (Neuman et al. 2015). When vulnerability assessments do account for population growth, they usually rely on separate models of population growth and predicted flooding that are decoupled from models of infrastructure investment and decision-making. Typically, these studies assume past trends will continue, and that coastal cities will continue to grow; that is, growth is assumed to be unaffected by climate change (Balica 2012).

However, increased flooding and extreme events may reverse in-migration and discourage future investment in coastal areas. Migration and housing location decisions in flood hazard areas have been shown to be directly linked to perceptions of future risk (e.g., Bin and Landry 2013; Tripathi et al. 2014). A simple representation of this relationship is shown in Figure 2. Risk perception directly affects demand for CI (again, considered here generically as any structural investment or policy intervention). We refer readers to Franck (2009) for a much more in-depth discussion around modeling SLR risk perception and its relationship to storm frequency and other factors.

A factor missing from many of these models is the delay between increases in risk and resulting changes in migratory patterns and infrastructure investment. Increasing risk is abstract compared to the realization of risks after large scale events (e.g., hurricanes, storm surges; Adger et al. 2009).

[Insert Figure 2 about here]

Flood protection and development feedbacks

Several relevant studies treat some of the feedbacks that might lead to the aforementioned "safe development" paradox, in which structural flood protection measures can incentivize more development flood-vulnerable areas and drive up future costs of flood damages (Brody et al. 2007). The safe development paradox is an example of the general phenomenon of "moral hazard," in which actions to mitigate a risk or transfer its costs to others (such as providing insurance) create incentives for agents to increase their risk exposure (Arrow 1963; Pauly 1968). For example, in an analysis of beach nourishment and residential development in Florida, Armstrong et al. (2016) found that new development is concentrated in nourished zones. The results of resource investment can then lead to further wealth concentration that permits more focused application of resources in a positive feedback loop. This phenomenon mirrors long-standing problems with the United States' National Flood Insurance Program (NFIP), which provides subsidized flood insurance for homes built in floodplains, even those that are repeatedly lost to flooding (Shively, 2017). In both cases, CI construction and the NFIP program, designed to protect existing residents from the risk of catastrophic loss, increases risky behavior by discouraging existing residents from relocating to somewhere safer and encouraging new development and in-migration in hazard-prone areas, all at great cost to taxpayers elsewhere.

Research also suggests that the "development begets infrastructure" phenomenon should be augmented by a "damage begets infrastructure" dynamic. For example, Werner and McNamara (2007) modeled the construction (and costs) of new flood protection measures in New Orleans, as responses to damage from recent flooding. The authors represented the state of the landscape, the state of the local economy (modeling population growth, the supply, demand, and price of products, and the revenues for economic actors), feedbacks representing the impact of the landscape on the economy (via both repeated rapid damage events like hurricanes and slowly varying changes to the landscape), and feedbacks representing the impact of economic development on the landscape (via market-driven alterations to the landscape to mitigate damage).

Their coupled model accurately replicates the development of New Orleans over time, including spatial patterns of development and the location of flood protection measures. These feedbacks mirror Jay Forrester's hypothesis in his landmark 1969 *Urban Dynamics* study, in which growth begets growth as population attracts additional population and drives housing and job creation. However, as Forrester demonstrated for cities, these reinforcing feedbacks eventually break down as the city exhausts its undeveloped land; at that point, the reinforcing feedbacks can become vicious cycles as existing housing and businesses age and decay, reducing attractiveness and business formation still further, trapping the poor in substandard housing and underemployment. In our case, we will explore how infrastructure costs can slow population growth and shift these feedbacks from growth towards decline.

These studies illustrate the importance of capturing the feedback between flood protection and development (Figure 3). Protection from small scale floods encourages additional development in areas prone to disaster. The result is greater damage from low frequency flood events. In effect, small-scale floods that might deter settlement of the floodplain are suppressed, leading to additional development that amplifies the damage from less frequent, large floods. Figure 3 also expands our initial hypothesis into a more realistic representation that distinguishes private- and public-sector institutional perceptions and actions towards SLR risk (Grothmann and Patt, 2005).

[Insert Figure 3 about here]

Many of the studies we reviewed suggest an additional set of feedbacks in which "wealth begets infrastructure" through political relationships, whereby wealthy areas are seen as worthier of protection and have greater influence with the state and federal agencies and legislatures that fund CI. Because the cost of coastal protection via sea walls, beach nourishment, etc. are roughly constant per meter, traditional cost-benefit analysis will always find it worthwhile to protect highly developed areas in lieu of low-value lands, which will then need to be abandoned. These decision heuristics mean that the economic value of cities can be high enough to warrant full protection in virtually all SLR scenarios (Fankhauser 1995; Titus et al. 2009; Titus and Richman 2001; Martinich et al. 2013; Neumann et al. 2010).

Additional studies have attempted to better understand when coastal residents choose to retreat by using agent-based approaches that incorporate feedbacks related to investment (Werner and McNamara 2007; Smith et al 2009; Williams et al 2013). As one would expect, property values fall more rapidly and abandonment occurs much sooner under high SLR scenarios compared to low ones. More interesting, higher rates of SLR incentivize higher investments in protective infrastructure in the near term as the community seeks to protect itself, but even substantial investments do not significantly delay the time until abandonment, in part because extreme storm events with higher SLR can quickly overwhelm newly built protective CI, causing loss of assets and a financial decision to abandon rather than rebuilding and investing in yet additional protections (McNamara and Keeler 2013).

Furthermore, Martinichi et al. (2013) found that if decisions about protection and abandonment are based solely on property value, more land area is likely to be abandoned than protected in areas with lower economic value and high socio-economic vulnerability, while more land is likely to be protected in areas with higher economic value and lower socio-economic vulnerability. Because protection enhances economic value, the result is a reinforcing feedback through which many socially disadvantaged Americans living in coastal areas could be disproportionately affected by SLR.

These ideas are captured in the expanded dynamic hypothesis in Figure 4, which incorporates power differentials, the compounding effects of damage, non-linearity in the accumulation of infrastructure construction and maintenance costs, and the impacts of continued maintenance on the effectiveness of protective infrastructure. Figure 4 additionally incorporates our two types of vulnerability described by social (per-capita) and natural hazard vulnerability (biophysical).

[Insert Figure 4 about here]

Applying dynamic hypothesis to case studies

We selected Dorchester County to test our dynamic hypothesis based on the County's low population density and low political capital to leverage external infrastructure investment. As a result, we view this case as the simpler of our two case studies: all signs point to the long-term inability of Dorchester County to invest in infrastructure and promote a "virtuous cycle" of in-migration, economic activity (EA), and further protective CI investment. As shown in Panel A of Figure 5, continued SLR will lead to small investments in coastal hardening. We depict these investments as large and lumpy; as they come on, line they temporarily decrease hazard and socio-economic vulnerability and induce greater population and economic growth for a short period.

[Insert Figure 5 about here]

As infrastructure requirements increase, we theorize that political power will drop considerably, after which infrastructure investments will fall, increasing social and hazard vulnerability and causing an ensuing drop in population and EA (abandonment). As population falls, natural hazard vulnerability declines; however, we also theorize that socio-economic vulnerability (measured on a per-capita basis) will skyrocket for the remaining population as the infrastructure gap widens and the region becomes more susceptible to unabated hazards from SLR. Feedbacks linking the absence of political capital to limited development are frequently seen in urban planning, but our dynamic hypothesis suggests that it may also influence vulnerability to SLR.

More complex dynamics arise in applying our dynamic hypothesis to Dare County. First, we expect that, given the demonstrated ability of the region to demand external protective investment, the "virtuous cycle" of CI investments, development, greater need for protection and still more protective infrastructure will continue in the region. Compared to Dorchester county, we expect to see more protective investments, inducing greater development that drives hazard vulnerability higher over time (Figure 5, Panel B).

We expect that investment will continue until the incredibly high costs of maintaining protective infrastructure begin to overwhelm Dare County's economically-created political power. Combined with its relatively low population, the County will begin to be unable to continue to attract funds to construct new infrastructure. Unprotected from hazards, immigration declines and emigration increases, leading to population decline. As we saw in Dorchester County, population decline eventually causes hazard vulnerability to fall —because fewer people will be living in the flood zone—while socio-economic vulnerability rises for the remaining residents—because housing values, employment opportunities, and the local economy will shrink. The long-term growth of the Outer Banks may have inter-regional impacts; while continued development will likely increase the natural hazard vulnerability of the tourist-focused Outer Banks, protective infrastructure development may displace hazard impacts into neighboring, inner coastal areas, where most of the workforce serving the islands live. This could have the effect of exacerbating socio-economic vulnerability into this area lower income.

A system dynamics model of coastal community adaptation

To test these predictions, we develop a formal system dynamics model using the datasets described earlier. Figure 6 shows the model structure and Supplementary Material 2 provides full documentation. To consider changes in CI, we focus on the extent of coastal hardening (we will use the terms "coastal infrastructure (CI)" and hardening interchangeably). We measure an area's "economic activity (EA)" as "local area personal income," defined as the "…income received by, or on behalf of, all persons from all sources: from participation as laborers in production, from owning a home or unincorporated business, from the ownership of financial assets, and from government and business in the form of transfer receipts. It includes income from domestic sources as well as from the rest of the world" (BEA 2016).

[Insert Figure 6 here]

We characterize SLR over time using the median of the Representative Concentration Pathway (RCP) 2.6 scenario (a low emissions scenario) from Kopp et al. (2015), which assessed SLR along the North Carolina coast. This scenario predicts 22 cm of SLR over 2000 levels in 2030, 37 cm in 2050, and 70 cm in 2100. Assuming the current distribution of property and EA, Houser et al. (2015) estimate that by 2100, average annual insurable flood losses in North Carolina would very likely increase by 20-150 percent, while the '1-in-100 year' flood would be expected in 17 of 50 years after 2050 (Kopp et al. 2015). We use the same SLR scenario for both the Dare and Dorchester County study areas.

To abstract the relationship between SLR and EA and migration, we define a "SLR risk index" as the ratio of sea level rise to the fraction of hardened coastline (normalized by the 1985 values). The index increases as sea level rises and falls as the coastline is increasingly hardened. However, given the mixed metrics of SLR and coastline hardening, we need to scale each of these factors relative to their baseline values, such that we normalize values relative to the beginning of our study period:

$$SLR\ risk\ index = \frac{Current\ sea\ level \big/ Baseline\ sea\ level\ in\ 1985}{\%\ of\ coast\ hardened \big/ Baseline\ \%\ of\ coast\ hardened\ in\ 1985}$$

The SLR risk index affects the net rates of change of population and EA whereby lower risk increases growth. This occurs through hypothesized negative relationship linking risk to multipliers on population and economic growth rates. Population and EA are both modeled as stocks, each of which are altered through net flows determined by base rates, the SLR risk multiplier, and the stocks themselves:

$$Net\ change\ in\ Economic\ Activity\ (EA) = EA * Baseline\ EA\ growth\ rate * EA\ growth\ rate\ multiplier\ from\ SLR$$

The level of EA (total local area personal income) helps to determine the demand for coastal hardening, capturing the development-begets-infrastructure loop relationship from Figure 4. Additionally, demand is a function of the risk index – capturing the risk-begets-infrastructure relationship – as well as a baseline "level of service" measurement (BenDor et al., 2013) that aims to maintain a baseline level of infrastructure to EA:

$$\text{Demand for coastal infrastructure (CI)} = \text{EA} * \text{Baseline CI to EA ratio} * \text{SLR risk index}$$

While the stock of CI is determined by construction and deterioration (we hypothesize a 100-year lifetime), coastal hardening is inherently limited by the length of a region's coastline as marginal coastal hardening becomes increasingly difficult due to technical, legal, or practical implementation problems. Therefore, construction is taken as an effort to close the gap between current and demanded infrastructure that is slowed by construction delay and diminished by the coastline that is already hardened:

$$CI\ construction = (1 - Fraction\ of\ coast\ hardened)\frac{CI\ and\ CI\ demand\ gap}{Base\ delay\ to\ close\ CI\ gap * Political\ hesitance\ to\ close\ CI\ gap}$$

Construction delay is influenced by a stock of “political hesitance” to close the CI gap, which changes based on the relationship between the current and baseline values of the cost of CI relative to EA in a region:

$$Political\ hesitance\ to\ close\ CI\ gap = \int \frac{CI\ cost\ to\ EA\ ratio}{Baseline\ CI\ cost\ to\ EA\ ratio} \Big/ Time\ to\ change\ hesitancy$$

As a region’s EA increases relative to investments in CI, political hesitancy towards new infrastructure decreases (i.e., it becomes “worth it” to continue investing). Changes to the hesitancy stock are slowed by the time taken by political and funding entities to change their views towards constructing new infrastructure.

Finally, we model natural hazard vulnerability as the product of EA to SLR risk index due to the strong interaction effect on risk between SLR and EA in coastal areas. We represent socioeconomic vulnerability as the per-capita natural hazard vulnerability:

$$Natural\ hazard\ vulnerability = EA * SLR\ risk\ index$$

$$Socioeconomic\ vulnerability = Natural\ hazard\ vulnerability/Population$$

Model calibration and results

We calibrated the model to each case study area. We calibrated our model iteratively, aiming to determine a structure that reasonably and simply approximated a working relationship between

SLR risk index and population and EA. We hypothesized that increasing SLR risk would rapidly decrease net migration, eventually flattening as it turned negative to encourage out-migration. These qualitative relationships between the SLR risk index and economic and population growth resemble exponentially declining relationships, approximated by several theorized points. We estimated interpolated functions to roughly match (and smooth) these points, resulting in the logistic functions shown in Panels A and B of Figure 7.

We additionally explored differential inputs to two highly sensitive variables, including the base delay to close the GI gap and the baseline value (1985) for the political hesitance stock, which acts as a multiplier on the delay placed on constructing new CI. Based on our historical understanding of historic difficulties in obtaining funding for CI, we estimated this stock's initial value to be 225 and 1 for Dorchester and Dare Counties, respectively. For the same reasons, we also estimated the base delays for closing the GI gap to be 4 years and 3 years, respectively.

Calibration runs of our model between 1985 and 2015 (Figure 7, Panels C and D) matched fairly well with available data on economic activity (EA), population (P), and coastal hardening (%H; percentage of coastline) for both study areas. For each of these variables, we calculated the mean absolute deviation (MAD) and mean absolute percentage error (MAPE) between available data and calibration simulations for Dorchester and Dare Counties, respectively: $MAD_{EA} = 7.20x10^{7}$ and $4.37x10^{7}$; $MAPE_{EA} = 13.17\%$ and 6.12%; $MAD_{P} = 1027.7$ and 1663.4; $MAPE_{P} = 3.33\%$ and 5.68%; $MAD_{\%H} = 4.1515x10^{-3}$ and $2.88x10^{-2}$; $MAPE_{\%H} = 0.42$% and 29.72%. We note that our calibration of the model on the fraction of the coast that has been hardened was much more accurate for Dorchester County than Dare County; we hypothesize that this is the result of undershooting our estimate of the baseline 1985 value for Dare County, which was extrapolated from much later 1996 and 2011 values as there appeared to be a linear growth of coastal hardening in this region.

[Insert Figure 7 here]

After calibration we simulated Dorchester and Dare Counties from 1985 through 2100.

Dorchester County, Maryland

The Dorchester County simulation tells a similar story to that of our dynamic hypothesis, save for socioeconomic vulnerability, which decreases along with natural hazard vulnerability (Figure 8, Panel A).

[Insert Figure 8 here]

That pattern is primarily the result of slow, but continual, infrastructure increases initiated prior to the start of the collapse but were delayed due to high political hesitance to protective investment. We estimate that political resistance to protective investments is initially high in Dorchester due to the low initial level of EA and per capita income, and the low political influence of the county. Consequently, Dorchester has difficulty obtaining funding for infrastructure construction. Stagnating population leads to an early decline in infrastructure, which leads to additional population decline as SLR risk is perceived to rise. Increasing SLR risk in the face of continued difficulties in constructing infrastructure eventually triggers economic and population collapse. Eventually, as EA and population fall, SLR risk continues to rise—not because protection decreases, but simply because SLR increases at a rate that overwhelms any lingering efforts to continue infrastructure construction.

Dare County, North Carolina

Our simulation of Dare County shows continued increases in EA well past the point at which Dorchester County begins to decline (Panel B, Figure 8). EA continues to grow even though population growth slows before 2015. Population reaches just over 44,000 and remains nearly flat for almost two decades even as EA slowly begins to fall. The extent of CI stops growing as investment falls and only approximately offsets deterioration. SLR risk remains low due to the high growth in protective infrastructure facilitated by the low political resistance to funding protection for the region. However, as EA begins to decline, infrastructure construction slows, and population declines soon after. Natural hazard and socio-economic vulnerability decline, with natural hazard vulnerability declining faster as EA begins to collapse at an increasing rate after the late-2050s. Because Dare County is already highly developed, rising sea level induces significant investment in protection, which, by reducing the perceived risk level, induces additional growth. However, the inexorable rise in sea level eventually increases risk, even as the maintenance burden of the increased protective infrastructure raises the costs of additional protection. Thus, high rates of protective investment not only delay the inevitable, but by drawing more people and development in, lead to a larger loss of wealth and population when abandonment becomes inevitable.

Discussion and Conclusions

If we consider how hazard vulnerability is associated with encouraging larger populations to locate in high hazard areas, the “virtuous cycle” created as a result of the safe development paradox should be viewed as a trap. While the positive feedback loop linking development and coastal protection can operate as a virtuous cycle of asset protection and investment that increases the damage from extreme events, it inevitably hides an eventual, vicious cycle of disinvestment that reflects the unsustainability of defending communities against constant SLR. At some point, the on-going cost of protection will simply become too high, leading to eventual decline, collapse, and retreat. Furthermore, continued investment in CI could lead to widening inequalities between larger, wealthier communities and small, disadvantaged communities.

How can we break these cycles? The first major consideration concerns the scale of coastal protection decision-making (Moser 2005; McNamara, Murray, and Smith 2011). Currently, each municipality or local government operates by considering what is best for itself. The decentralized approach results in decisions focused on short-term and local benefits and the inequitable use of public resources. If decisions were made on a state level, investments in highly exposed coastal areas may not be appealing. The battle between municipal and state action is illustrated well in the Dorchester County case.

Second, traps created by reinforcing feedbacks involving protective investment, risk, and development are not unique to coastal issues. Similar dynamics occur in leveed river systems with developed floodplains (e.g. Flavelle 2018) and wildland-urban interfaces with wildfire suppression (Armstrong et al. 2016). In areas that are politically unable to adapt their communities to SLR hazards, recovery plans may be an opportunity for communities to rethink their priorities, explore alternative development patterns, or explore their understanding of the long-term effects of SLR. When taken as a whole, our theory and model demonstrate that our understanding of chosen community approaches to the threat of SLR – protection, accommodation, or retreat – are a function of socio-economic forces and political power dynamics. Key to many of the feedbacks within these systems are infrastructural and socio-economic vulnerabilities, as well as perceptions of both a community's economic value and of the risks posed by inundation. We argue that vulnerability assessments – an increasingly popular tool used by coastal states and governments to assess the impacts of SLR – are more likely to be helpful in guiding community decision-making if they are developed and situated within a broader political and social understanding of the patterns of development and socio-economic vulnerability within coastal communities.

Our primary goal in this paper has been to expand how we jointly consider the feedbacks affecting coastal community adaptation, infrastructure investment, and SLR risk. We have used system dynamics to consider the joint effects of multiple causal relationships that have been identified in the rapidly-expanding coastal adaptation literature. However, it is clear that more needs to be done to assess the consequences and more effectively model these multiple feedbacks.

First, we used dramatically simplified representations of the relationships between an SLR risk index and population and economic multipliers. Several factors were omitted from our simulation model. Specifically, more investigation needs to explore the precise mechanisms by which SLR risk affect insurance rates, immigration and emigration patterns, financial investments in infrastructure, and EA in coastal regions. Furthermore, additional steps could be taken to test our model more thoroughly against empirical evidence from communities that have experienced substantial investments in adaptation infrastructure due to SLR associated flooding already. Such tests would include both empirical investment and demographic data, but also a greater incorporation of qualitative assessments of risk perception and community adaptation decision-making processes. Finally, future work should also consider several SLR scenarios, not just the relatively low future emissions scenario that we employed (RCP 2.6), but infrastructure investment dynamics under higher emissions scenarios with more rapid SLR. These extensions would be helpful for not only addressing shortcomings of our model, but would be useful for specific policy analysis, testing and design. As communities both large and small, urban and rural respond to the impacts of rapid SLR, they must make adaptation decisions with large financial and social consequences that are challenging to understand. Models that address the feedbacks involved in the social-economic-policy-climate change interface are needed to provide policy support to make more effective community adaptation decisions.

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Table 1. Summary of adaptation strategies for sea level rise (SLR). Adapted from Butler, Deyle, and Mutnansky (2016).

Adaptation Approach	Strategies	Description
Protection Hard or soft engineering works designed to prevent flooding from SLR	Shoreline armoring	Seawalls, bulkheads, revetments to protect structures from higher flood elevations
	Green infrastructure for shoreline stabilization	Vegetated buffers, living shorelines, plants, reefs, restored natural features
	Beach and dune Nourishment	Beach and dune building and re-nourishment projects to counteract erosion
	Flood works	Dams and levees to protect vulnerable assets
Accommodation Alter existing assets to reduce vulnerability	Elevate	Raising the first floor of structures above current design flood elevations
	Flood proof	Changes to structures to reduce or eliminate flood damage
	Storm water system enhancements	Structures to counteract reduced storm water head differentials and backflow into storm water discharge pipes, e.g., tide gates, storm water discharge pumps
	Retrofit	Retrofit public facilities and infrastructure to enable continued functioning
Retreat Relocating existing assets to places less likely to be exposed to SLR	Post-disaster down zoning	Down zone built-out land in storm surge flood zones to prohibit redevelopment of properties damaged by flooding
	Post-disaster relocation	Relocate public facilities and infrastructures in anticipation of advancing hazards
	Rolling easements	Prohibit shoreline armoring and require that structures be moved landward or removed when mean high water line reaches a specified threshold

Table 2. Comparison of wealth, demographics, and densities of case study areas (Source: US Census 2016)

Dare County, North Carolina	Dorchester County, Maryland
Population: 35,663	Population: 32,384
Population Density: 35/km^2	Population Density: 23/km^2
Population Change: 19.0%	Population Change: 5.6%
Median HH Income: $54,496	Median HH Income: $47,093
Percent African American: 2.5%	Percent African American: 27.7%

Figure 1: Historic population, per-capita income, and coastal hardening (percentage of 2016 coastline length) for (A) Dorchester and (B) Dare Counties.

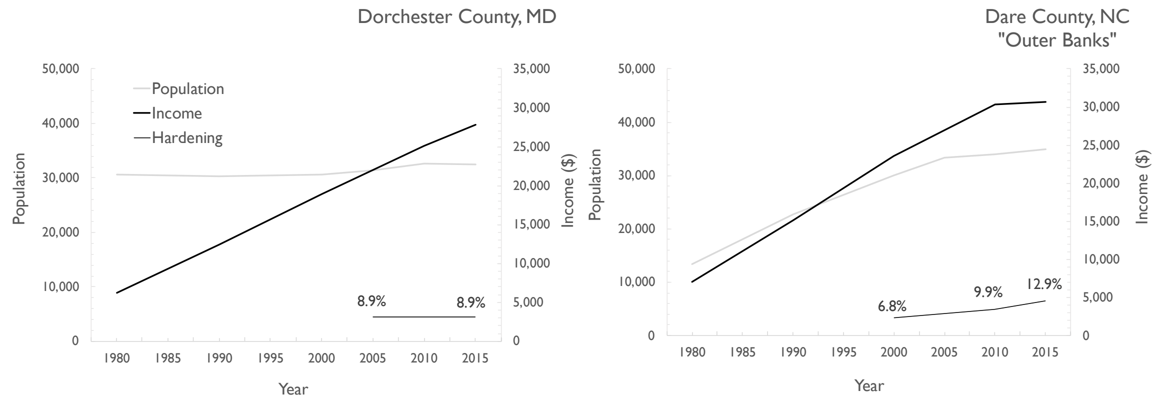

Figure 2: Feedbacks among hazards, perception, and coastal infrastructure (CI). [+]: reinforcing (positive) feedback loop; [-]: balancing (negative) feedback loop.

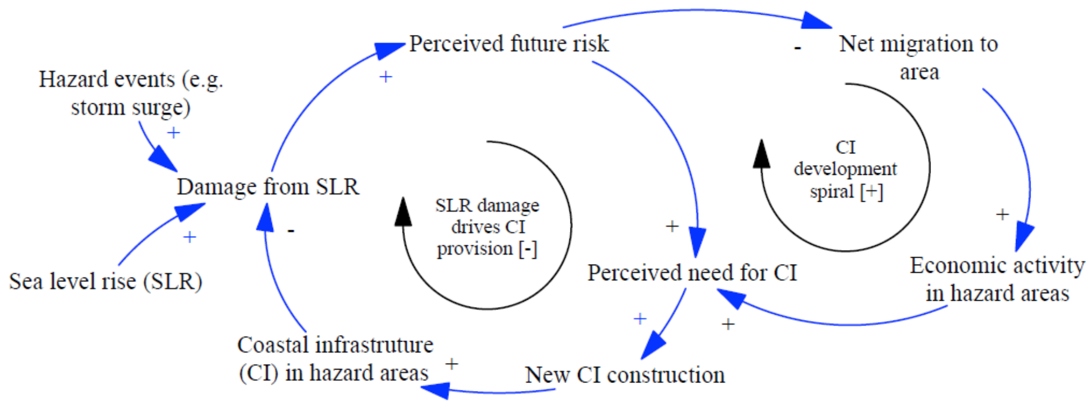

Figure 3: Feedbacks linking SLR hazards, migratory patterns, risk perception, and the stock of coastal protective infrastructure (CI).

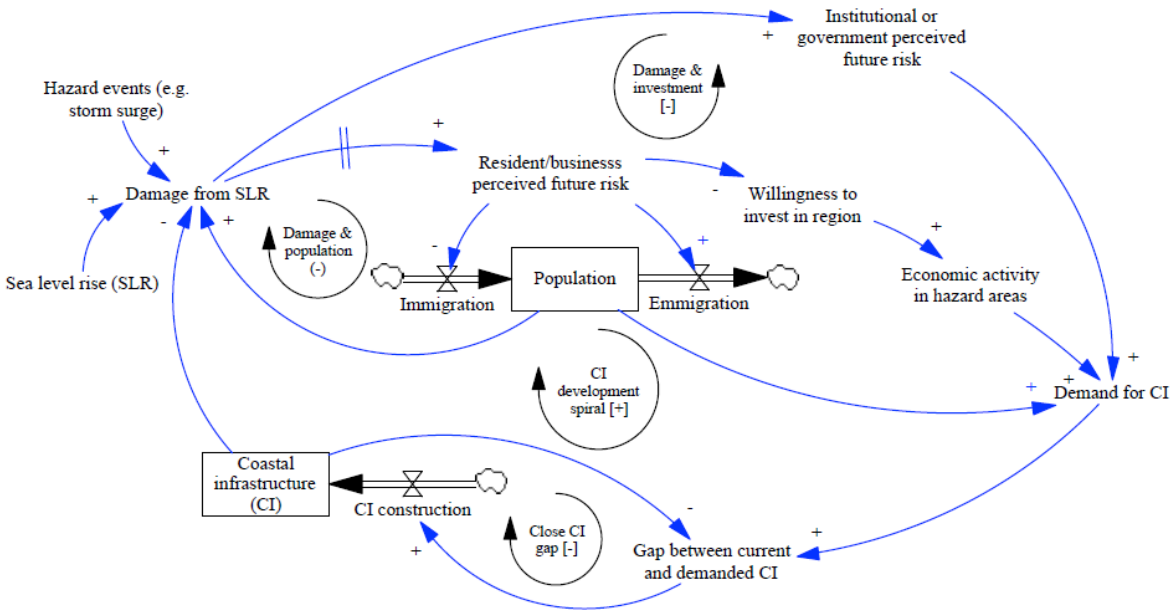

Figure 4: Full dynamic hypothesis, including impacts of political capital and perception of community cultural and economic value on ability to generate new CI and structures describing social and natural hazard vulnerability.

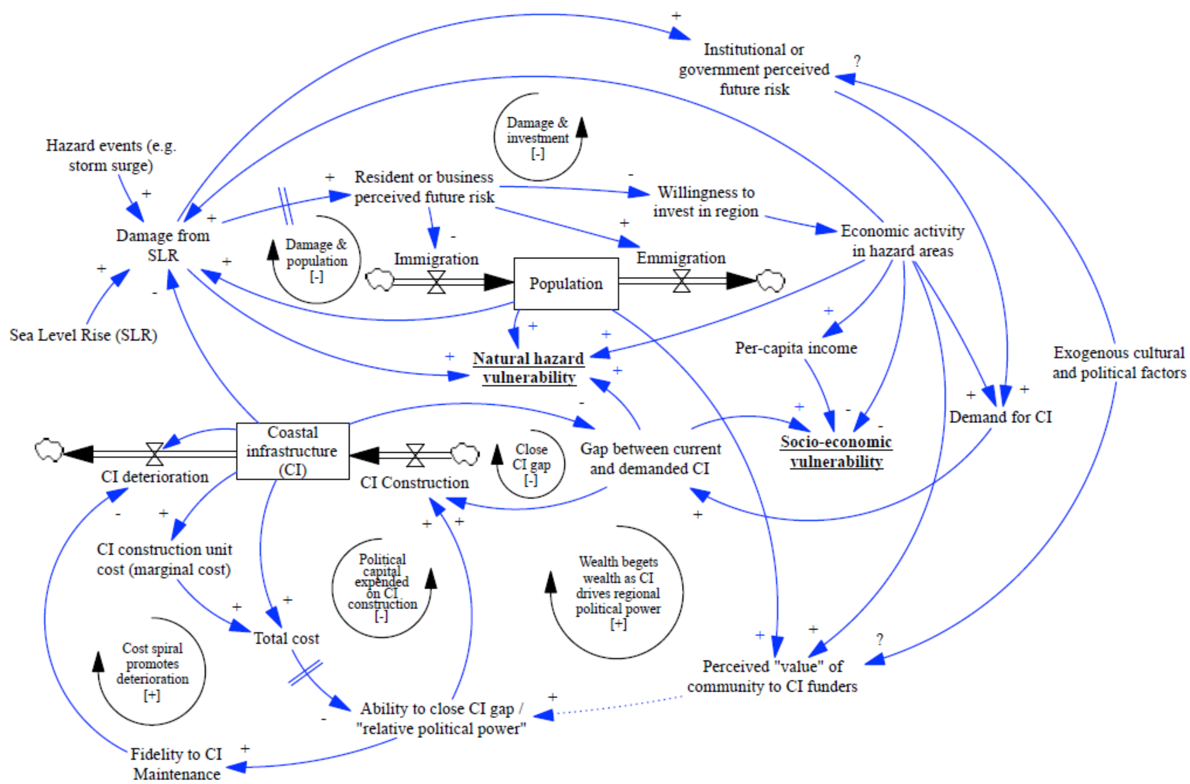

Figure 5: Hypothesized qualitative vulnerability trajectories for (A) Dorchester County, Maryland, (B) Outer Banks, North Carolina.

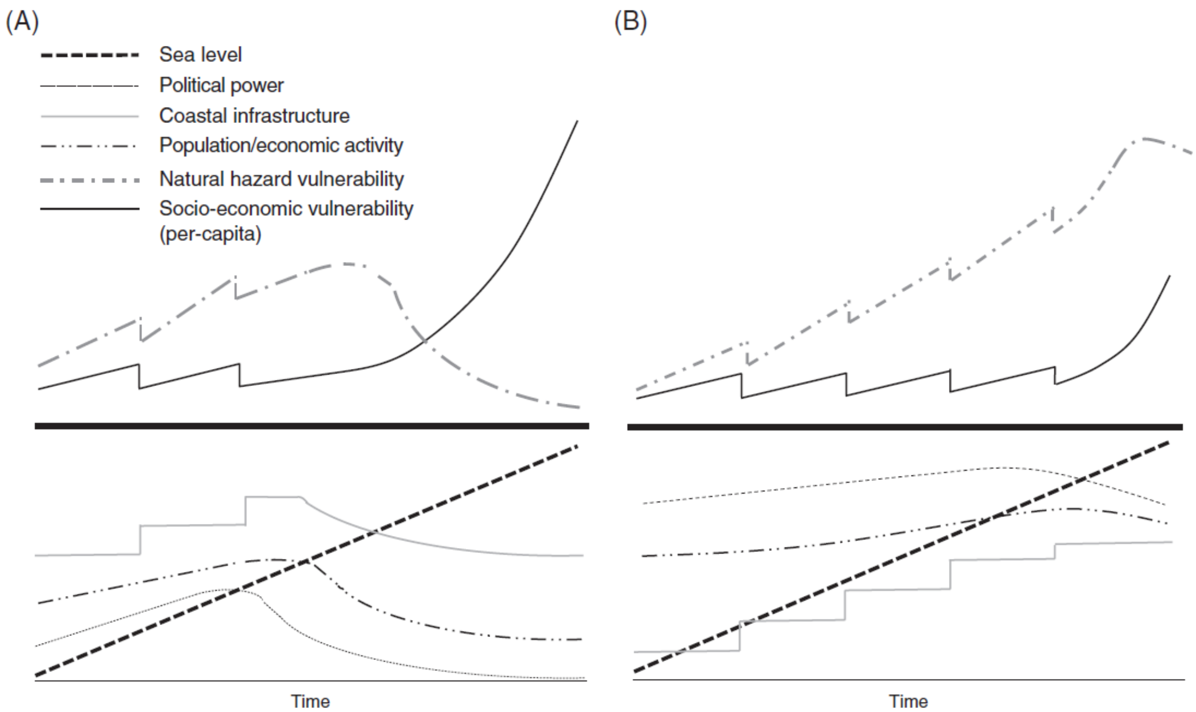

Figure 6: Simulation model capturing relationships among SLR risk, economic activity (EA), population, CI, infrastructure cost, and political perception of infrastructure investments. Gray variables are baseline inputs and italicized variables are model parameters.

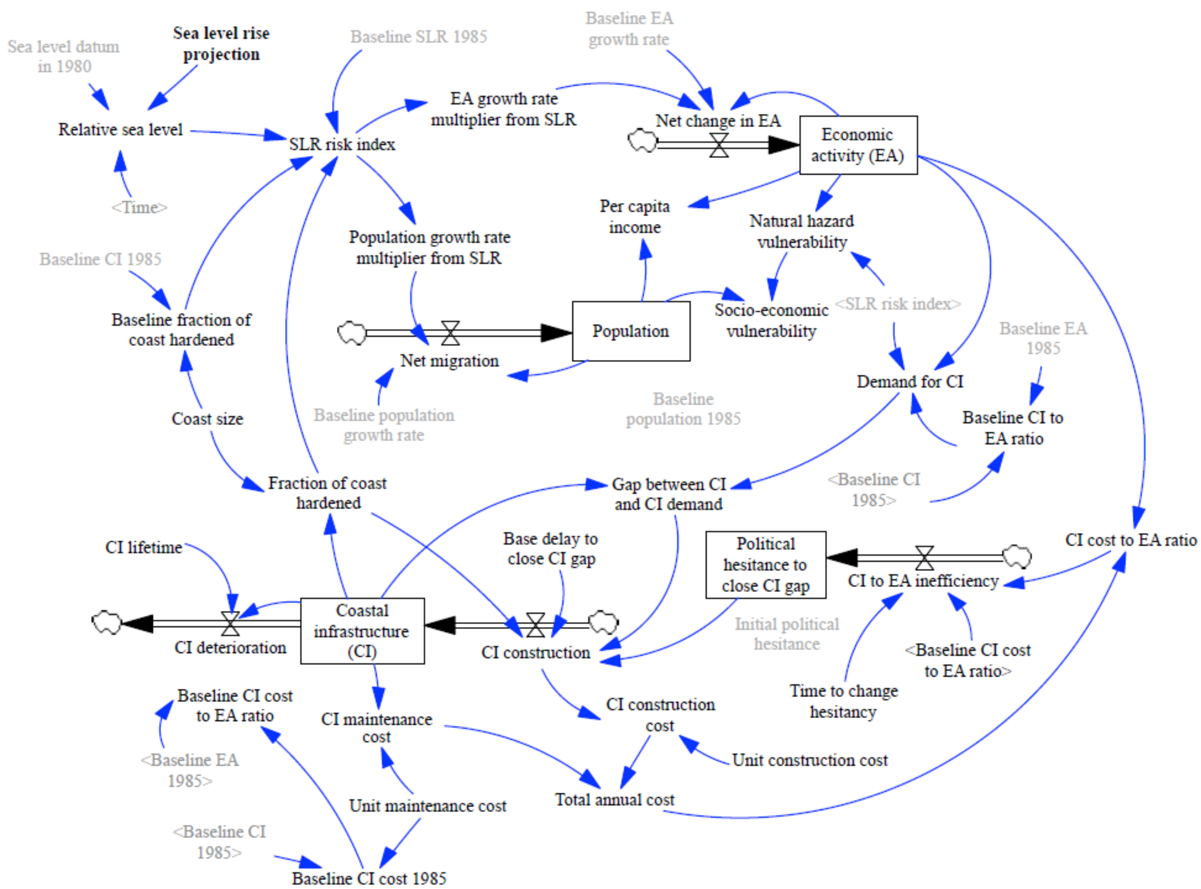

Figure 7: Initial point estimates and calibrated log-linear functions linking sea level rise (SLR) risk index and population and economic growth for (A) Dorchester County, Maryland and (B) Dare County, North Carolina. The model was calibrated for the 1985-2015 period on population, economic activity (EA), and percentage of coastline hardened for each region. Panels C and D compare model calibration to data for Dorchester and Dare counties, respectively.

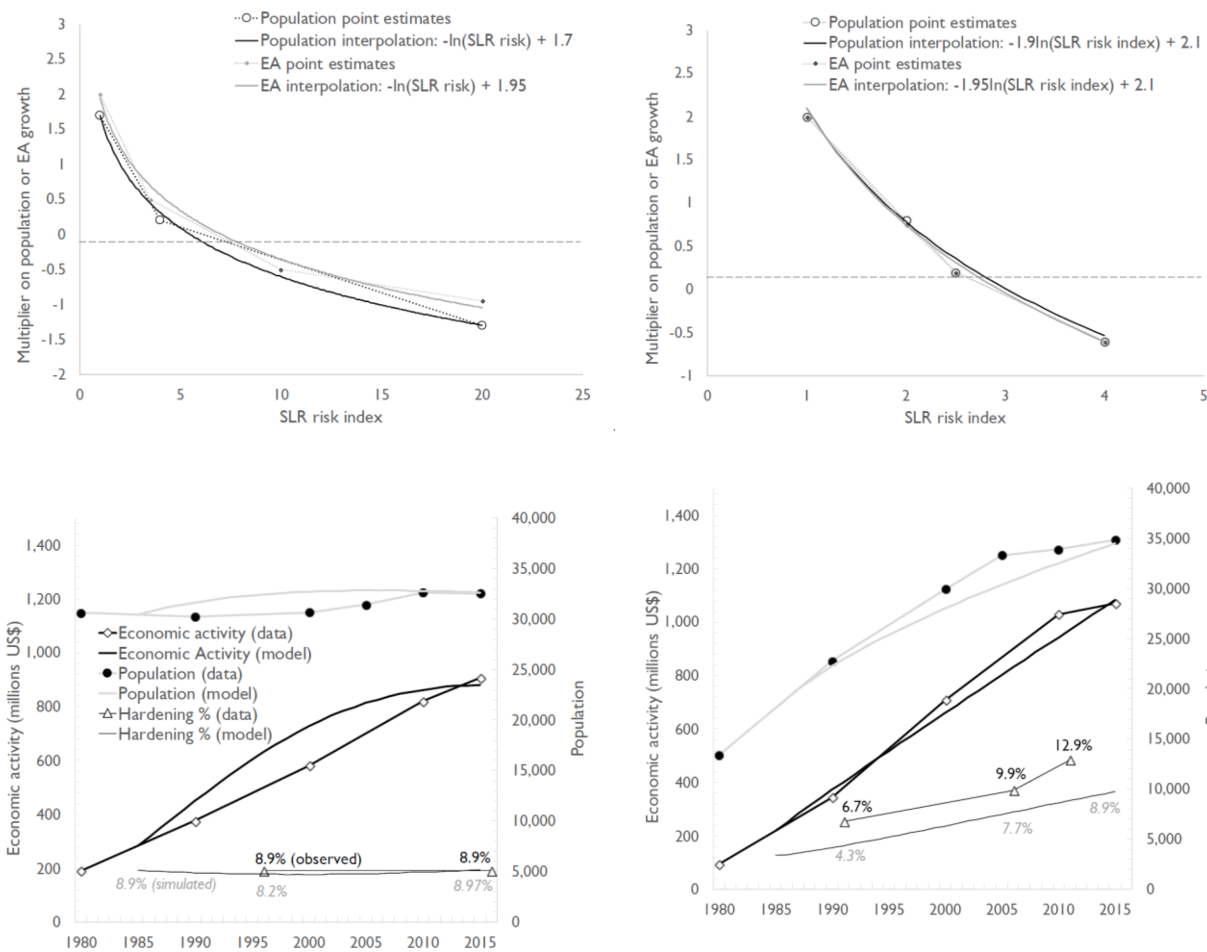

Figure 8: Simulated population, EA, coastal hardening, and vulnerability 1985-2100 for (A) Dorchester County and (B) Dare County. Dotted vertical line shows 2015 calibration endpoint. Initial, final, and maximum values are shown for percentage of coastline hardened (black), as well as initial and final values for SLR risk index (gray).