University of Southampton

Faculty of Environmental and Life Sciences

Geography and Environmental Science

Exploring unintended feedbacks between coastal hazard, exposure, and vulnerability

by

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Thesis for the degree of Doctor of Philosophy (PhD)

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Abstract

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Coastal zones are more densely populated than any other landscape on Earth. These regions are also dynamic places that naturally change shape and position, especially in response to sea-level rise, leaving the infrastructure that sustains high coastal populations exposed to natural coastal hazards. Therefore, to make exposed infrastructure less vulnerable to damage, shorelines are deliberately altered with hazard protections. Some developed coasts have been altered on such spatial scales that they no longer act like natural coastlines. Instead, they function as coupled human-landscape systems, where shoreline dynamics reflect interactions and feedbacks between human alterations and natural coastal processes. The Atlantic Coast of the USA has over 2500 km of developed coastline, and is arguably the largest coastal coupled human-landscape system in the world, and is dominated by beach nourishment: a type of coastal hazard protection that involves widening an eroding beach with imported sand. Beach nourishment buffers exposed infrastructure from coastal hazards, and also serves as a stock of natural capital for tourism economies. However, despite ubiquitous nourishment along the US Atlantic since the 1960s, coastal risk continues to increase. This dynamic is an expression of the "safe development paradox", in which exposure to hazard continues to rise, despite increased efforts to protect against hazard impacts. This thesis explores unintended feedbacks between coastal hazard, exposure, and vulnerability evident along the US Atlantic Coast. My work examines why beach nourishment might have the counter-productive consequence of increasing risk. This thesis also presents a conceptual framework that may enable future models of coastal risk to incorporate "big data" approaches to illuminate and explore the "safe development paradox", and to test whether prospective management strategies might mediate coastal risk or exacerbate it.

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Research Thesis: Declaration of Authorship

Print name:	Scott Armstrong

Title of thesis:	Exploring unintended feedbacks between coastal hazard, exposure, and vulnerability

I declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Parts of this work have been published, the declaration for the authors contributions are as follows:

Paper 1: Armstrong, S. B., and Lazarus, E. D., 2019a. Masked Shoreline Erosion at Large Spatial Scales as a Collective Effect of Beach Nourishment. *Earth's Future*, **7**(2), 74–84. DOI: 10.1029/2018EF001070

Armstrong S.B. and Lazarus E.D. conceived of the study, designed the analysis and wrote the paper. Armstrong S.B. performed the analysis.

Paper 2: Armstrong, S. B., Lazarus, E. D., Limber, P. W., Goldstein, E. B., Thorpe, C., and Ballinger, R. C., 2016. Indications of a positive feedback between coastal development and beach nourishment. *Earth's Future*, **4**(12), 626–635. DOI: 10.1002/2016EF000425

Armstrong S.B., Lazarus E.D., and Limber P.W. conceived of the study and designed the analysis; Armstrong S.B., Limber P.W., and Thorpe C. performed the analysis; Lazarus E.D., Goldstein E.B., and Ballinger R.C. contributed to interpretation and synthesis of results; Armstrong S.B. and Lazarus E.D. wrote the paper, with contributions from all co-authors.

Paper 3: Armstrong, S. B., and Lazarus, E. D., 2019b. Reconstructing patterns of coastal risk in space and time along the US Atlantic Coast, 1970–2016. *Natural Hazards and Earth System Sciences Discussions*, **In review**. DOI: 10.5194/nhess-2019-159

Armstrong S.B. and Lazarus E.D. conceived of the study, designed the analysis and wrote the paper. Armstrong S.B. performed the analysis.

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Much of my research relies on open published data. While I reference all of the data I use in this thesis, I would like to thank the following organizations for making public such a wealth of data: the Program for the Study of Developed Shorelines (PSDS); United States Geological Survey (USGS); the Florida Geographic Data Library (FGDL); IPUMS National Historical Geographic Information System (NHGIS); and the Permanent Service for Mean Sea Level (PSMSL).

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Chapter 1 Introduction

1.1 Preamble

Coasts are dynamic places, where energy from waves, tides, currents and storms allow water to move sediment, altering shoreline position. Coasts can also be developed places: While only 2% of the global landmass is less than 10 m above sea-level, 10% of the world's population live in this "low-elevation coastal zone", and the population and assets within it are growing faster than national averages worldwide (McGranahan et al., 2007; Wong et al., 2014). By building infrastructure in dynamic coastal zones – and placing hazard protections to protect that infrastructure – human alterations have changed natural coastal geomorphology over such spatial extents that alterations can no longer be considered simply as localised aberrations at the case-study scale (Nordstrom, 1994).

Beach nourishment, for example, is a form of hazard protection that involves widening an eroding beach with imported sand. A nourished beach is intended to buffer coastal infrastructure from chronic erosion and storm damage, and also supply the local coastal economy with a stock of natural capital (NRC, 1995; Smith et al., 2009). In the USA, beach nourishment has been used ubiquitously since the 1960s. Yet despite over 1850 beach nourishment projects since 1960 (PSDS, 2017), the value of property at risk from coastal hazards continues to rise (AIR Worldwide, 2013; Union of Concerned Scientists, 2018; Wong et al., 2014). How might beach nourishment have the unintended consequence of increasing, rather than reducing, coastal risk?

This thesis investigates the US Atlantic Coast as a fundamentally coupled human-landscape system, defined by reciprocal feedbacks between landscape change and societal decisions (Lazarus et al., 2016; Werner and McNamara, 2007). Given its spatial scale – the distance from Maine to South Florida extends over 2500 km – the US Atlantic Coast is arguably the largest coastal coupled system in the world (Figure 1.1). I use this coupled-systems lens to explore the effects of beach nourishment on the dynamics of developed coasts, and on the economic value of property at risk from coastal hazards.

Figure 1.1 Map of US Atlantic Coast, black dots denote shoreline settlements, with labels for major cities. Insets show examples of heavily developed coastline: Long Beach (image by Christopher Michel, from https://en.wikipedia.org/wiki/Long_Beach,_New_York); Atlantic City (image from https://www.cmlf.com/things-do-atlantic-city); Virginia Beach (image by Sherry V. Smith, from https://www.timeout.com/virginia-beach/things-to-do/best-things-to-do-in-virginia-beach); and Miami Beach (from https://www.getyourguide.co.uk/miami-beach-l33437).

My work synthesises geospatial data in novel ways to explore open and topical questions about the unintended consequences of coastal protection. I present this thesis in the form of three manuscripts – two published (Armstrong et al., 2016; Armstrong and Lazarus, 2019a), and one currently in "discussion" at *Natural Hazards and Earth System Sciences* (Armstrong and Lazarus, 2019b). The first two papers presented in this thesis, Chapter 2 and Chapter 3 (Armstrong et al., 2016; Armstrong and Lazarus, 2019a), are large-scale empirical studies that test existing theory for coupled human–coastal systems (Lazarus et al., 2016; Nordstrom, 1994) by examining spatial correlations in "big data" datasets of geomorphological and economic/social elements. The third paper, Chapter 4 (Armstrong and Lazarus, 2019b), takes a more exploratory approach, using a data-driven model to examine trajectories of coastal risk between 1970 and 2016 at the county scale for the entire US Atlantic Coast.

Together, these papers represent complementary approaches to understanding why it is so difficult to reduce the risk of damage to coastal hazards along developed coastlines. My research provides evidence that feedbacks between physical processes, hazard protection, and development patterns are at play along the US Atlantic Coast, and advances the argument that widespread coastal protection may inadvertently exacerbate coastal risk.

1.2 Background

1.2.1 Humans as agents of geomorphic change

The dynamics of developed coasts are fundamentally different from those of natural coasts:

> “Landforms are created, reshaped or eliminated to suit human needs. These alterations affect the mechanisms of change, freedom of movement, locations of sources and sinks for sediment, internal structure, outward appearance and spatial and temporal scales of landscape evolution….Evidence suggests that human alterations are an integral component of landscape evolution.”
>
> **Nordstrom (1994) pg. 497**

Indeed, humans are agents of geomorphic change, responsible for moving more soil and rock than any other natural process of geomorphic transport (Hooke, 1994). Whether moving material for construction, mining, agriculture, or for any other ends, humans are an integral part of Earth’s geomorphological system (Church, 2010; Haff, 2003, 2010, 2012, Hooke, 1994, 2000; Marsh, 1869; Murray et al., 2009). This observation has prompted calls to integrate anthropic alterations into the study of geomorphology (A. G. Brown et al., 2016; Church, 2010; Haff, 2003, 2012; Murray et al., 2009). In the case of developed coasts, specifically, calls have been made to fully integrate human geomorphic alterations into coastal dynamics (Elko et al., 2016; Lazarus, 2017; Nordstrom, 1994, 2000). Along the US Atlantic Coast, human interventions have made a significant and measureable difference to natural coastal processes: Recent rates of shoreline change show a shift from erosion to accretion that is strongest in areas of concentrated coastal development (Hapke et al., 2013).

1.2.2 Beach nourishment alters geomorphology

The US Atlantic Coast is a mostly low lying, passive margin, typified (from New York south) by barrier islands that would naturally consist of ocean-facing beaches, developed dunes, and back-barrier marshes (Dolan et al., 2016; Dolan and Ferm, 1968; Dolan and Lins, 1986; Fenster et al., 2016; Limber et al., 2007; Milliman et al., 1972; NOAA, 1975; Pilkey and Thieler, 1992; Stockdon et al., 2002; Thieler et al., 2014). However, where permanent infrastructure and development is fixed along the shoreline, beaches that would tend to migrate landward are instead narrowed – a phenomenon known as coastal squeeze (Doody, 2004; Pontee, 2013).

Beach nourishment is a form of coastal hazard protection that involves importing sand to widen an eroding beach (NRC, 1995). Nourished sand can be imported from afar, or dredged from the seafloor nearby (NRC, 1995), sand is then pumped onto the beach and earth moving equipment shape it into a new, wider beach (ASBPA, 2007; Dean and Dalrymple, 2001; Finkl and Walker, 2006; Hanson et al., 2002; Leonard et al., 1990; NOAA, 2006; NRC, 1995). Costs of beach nourishment depend on sand availability and the distance over which that sand must be imported (Hoagland et al., 2012; McNamara et al., 2011; NRC, 1995). Beach nourishment is a strategy applied globally (Cooke et al., 2012; Hanson et al., 2002; Nordstrom, 2000; Walker and Finkl, 2002), but in the US, beach nourishment overtook hard structures as the prevailing form of coastal protection in the 1960s (NRC, 2014; Pilkey and Clayton, 1989; PSDS, 2017; Trembanis et al., 1999; Valverde et al., 1999). Along the US Atlantic there have been over 1220 beach nourishment episodes, involving ~285 million m^3 of sand, between 1960 and 2007 (PSDS, 2017).

Natural coastal sediment transport is complex (Ashton and Murray, 2006a; Galgano, 1998; Galgano and Leatherman, 2006; Jackson and Nordstrom, 2019), operating on low-lying, open coasts across a range of scales in space and time (Ashton and Lorenzo-Trueba, 2018; Ciarletta et al., 2019; Elsayed and Oumeraci, 2017; Houser et al., 2018; Kraus and Galgano, 2001; Lazarus, 2016; Lazarus, Ashton, et al., 2011; Lazarus and Armstrong, 2015; Masselink and Van Heteren, 2014; National Academy of Sciences Engineering and Medicine, 2018; Vitousek, Barnard, Limber, et al., 2017; Wernette et al., 2018). As a nourished beach erodes, sand moves onshore, offshore, and/or alongshore, altering the sediment budget acted upon by coastal sediment transport mechanisms (Dean and Dalrymple, 2001). The protection afforded by beach nourishment lasts until the added beach width itself erodes, in the order of 1-10 years, after which the same beach may need to be re-nourished (Dean and Dalrymple, 2001). Some beaches have multi-decade programs of regular re-nourishment (NRC, 2014). The nourished profile of a beach erodes at a faster rate than the natural beach profile, as a nourished beach is effectively a wedge of additional sand with a steeper profile and more seaward excursion than the surrounding shoreline (Dean and Dalrymple, 2001; Strauss et al., 2009). By altering the cross-shore and alongshore sediment fluxes of the littoral cell in which it sits, beach nourishment affects both local and non-local shoreline changes that mean sand deposited in one reach of the coastline may influence shoreline fluctuations elsewhere in the littoral cell (Ells and Murray, 2012; Gopalakrishnan, McNamara, et al., 2016; Lazarus, McNamara, et al., 2011; Williams et al., 2013).

1.2.3 Coastal risk

Beach nourishment is intended as a means of reducing risk along developed coasts. Risk can be defined in many different ways (e.g., Brooks, 2003; Haimes, 2009; Kaplan and Garrick, 1981; Samuels and Gouldby, 2009), by researchers and practitioners in a range of fields from finance (e.g., Dionne, 2013) to medicine (e.g., Ahmed et al., 2012; Day and Wilson, 2001). While there may be benefits to each definition, for the purpose of the research presented in this thesis, I consider the definition of risk set out by the National Research Council (NRC, 2014), adapted from (Samuels and Gouldby, 2009), more specific to coastal settings. In this definition:

> “[R]isk is represented as the probability of a hazard multiplied by the consequence…[where] consequence may be expressed as a function of the exposure… (the density of people, property, systems, or other elements present in hazard zones) and the vulnerability… which is a system’s potential to be harmed.”
>
> **NRC (2014) pg. 18**

In Chapter 4, on trajectories of risk over time along the US Atlantic Coast (Armstrong and Lazarus, 2019b), I adapt this definition to address risk as a function of three components: hazard, exposure, and vulnerability.

1.2.3.1 Hazard

At the coast, hazard can either describe the probability of a hazard occurring, or, in the case of chronic hazard, the rate of that chronic hazard (e.g., sea-level rise or chronic erosion). Sea levels have been rising globally over recent decades and the rate of sea-level rise is projected to increase in future (Cazenave and Cozannet, 2013; Church et al., 2013; Church and White, 2011; Wong et al., 2014). Rates of sea-level rise vary along the US Atlantic Coast, but there is a hotspot of increased sea-level rise in the central to northern stretch of the US Atlantic (Sallenger et al., 2012). The response of the shoreline to the chronic hazard of sea-level rise is not straightforward

(Carter et al., 2014; Cazenave and Cozannet, 2013; Church et al., 2013; Church and White, 2011; FitzGerald et al., 2008; Passeri et al., 2015; Peek et al., 2015; Witze, 2018; Wong et al., 2014). While the entirety of every coast will not respond by retreating, shorelines will retreat overall as a result of rising sea levels (Brooks et al., 2016; Gutierrez et al., 2011; Vitousek, Barnard, and Limber, 2017). Permanent infrastructure fixes barrier islands in place, preventing them from migrating landward and up the continental shelf in response to rising sea-levels through overwash processes (Ciarletta et al., 2019). By migrating up the continental slope, a natural barrier island can keep above rising sea-levels without changing volume, whereas a developed barrier island may be submerged, even where infrastructure is protected with beach nourishment (Figure 1.2).

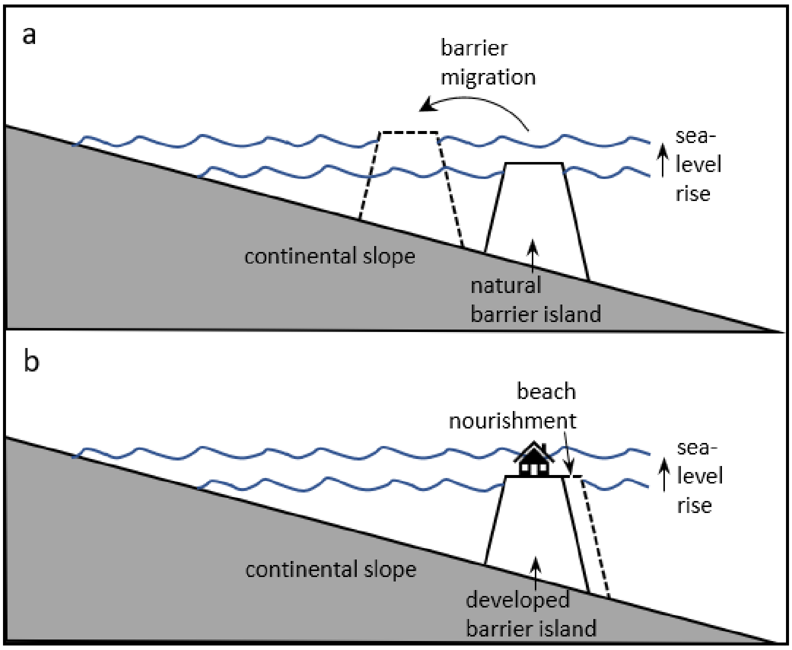

Figure 1.2 (a) Natural barrier islands migrate landward up the continental shelf in response to sea-level rise, maintaining a barrier that is above a higher sea level. (b) Developed barrier islands, with permanent infrastructure, are fixed in place, often by widening the barrier with beach nourishment, which does not allow the barrier island to migrate and maintain its elevation above a higher sea level.

Along the US Atlantic and Gulf Coasts, hurricanes are an acute, "event-driven" hazard that cause damage through high winds, flooding from storm surge, and shoreline erosion from wave attack (Blake et al., 2011; Pielke Jr. et al., 2008; Stockdon et al., 2007; Vecchi and Villarini, 2012; Woodruff et al., 2013). Sea-level rise can compound acute hazards by increasing the baseline sea level that underpins storm surges, so that a 1 m storm surge acting on 1 m higher sea level affects the coast in the same way that a 2 m storm surge above the original sea level might (Ezer and Atkinson, 2014; Strauss et al., 2014, 2012; Tebaldi et al., 2012; Vitousek, Barnard, Fletcher, et al., 2017; Wahl et al., 2015; Witze, 2018; Woodruff et al., 2013).

For the analysis in Chapter 4 (Armstrong and Lazarus, 2019b), I consider only chronic hazard, in terms of rates of shoreline change, derived both from U.S. Geological Survey shoreline position surveys, and from changes in sea-levels measured by tide gauges.

1.2.3.2 Exposure

Exposure represents people (in number), buildings, or infrastructure (in number or economic value) that coastal hazards could negatively impact (NRC, 2014). Coastal populations in the USA are increasing at a higher rate than the national average (Crossett et al., 2004; NOAA, 2012a, 2012b, 2013), concentrating development pressures in coastal hazard zones (AIR Worldwide, 2005, 2013; Lins, 1980; Union of Concerned Scientists, 2018). Development in low-lying coastal zones along the US Atlantic Coast is likewise increasing, with land-use plans showing that development is expected on nearly 60% of land below 1m elevation (Titus et al., 2009).

I consider only the value of exposed property for the analysis in Chapter 4 (Armstrong and Lazarus, 2019b), keeping my risk calculations as a measure of the risk of monetary loss in the event of hazard.

1.2.3.3 Vulnerability

The third and final component of risk – vulnerability – describes how susceptible exposed people and property are to coastal hazards (NRC, 2014; Wu et al., 2002). Vulnerability can be reduced by protecting the shoreline with hazard defences, creating a buffer between the hazard and whatever is exposed to that hazard. In the case of beach nourishment, that buffer can be considered in terms of the width of a beach, whereby a recently nourished wide beach offers an effective buffer, but that buffer is only temporary as it gets eroded away (Dean and Dalrymple, 2001).

In Chapter 3, I make the case that beach nourishment is where the coupling happens between hazard and exposure in terms of the size and number of homes exposed to natural coastal hazards (Armstrong et al., 2016). In Chapter 4 (Armstrong and Lazarus, 2019b), I express vulnerability in terms of beach width, where a wide beach reduces vulnerability, and beaches are widened by beach nourishment, but are eroded by natural coastal processes. I discuss the nature of this coupling in further detail in Section 1.2.4.

1.2.3.4 Coastal risk management in the US

There are different levels of governance for risk management in the USA, from national to local scale, and federal subsidies available for decisions at all levels. The National Flood Insurance Program (NFIP) is a program established in 1968 that subsidises flood insurance for those living in the 1 in 100 year floodplain (King, 2013). However, the program is contentious for a number of reasons. The subsidy that it creates is unevenly distributed both spatially (in terms of where it applies) and economically (in terms of who benefits from it), and, because disaster costs continue to increase, so too does the cost of the NFIP, which runs at a loss (Holladay and Schwartz, 2010; King, 2013; Kriesel and Landry, 2004; Michel-Kerjan, 2010). Another contention with the NFIP is that by subsidising insurance in the floodplain, it drives risky development by reducing the risk to developers, representing a "moral hazard" in which people do not bear the full costs associated with the decisions they make (Bagstad et al., 2007; Brody et al., 2016; Cutter and Emrich, 2006).

Another national risk management program is the Federal Emergency Management Agency (FEMA) Disaster Relief Fund, initiated in 1979 (Burby, 2006; Michel-Kerjan, 2010; NRC, 2014; Platt et al., 2002), which provides funds to rebuild after disasters. The Disaster Recovery Reform Act was signed in 2018, but it is too early to tell what effect it will have: one of its main reforms is investment in pre-disaster mitigation (FEMA, 2018).

Beach nourishment programs are typically commissioned on the local level, with municipalities taking the decision to nourish (Nordstrom, 2000; NRC, 1995; Pilkey and Dixon, 1996). If a municipality does decide to nourish, it can apply for the United States Army Corps of Engineers (USACE) to carry out the work, and can qualify for a federal subsidy of 65% on developed shorelines and 50% on undeveloped shorelines, so long as the beach has public access (NRC, 1995, 2014; Pilkey and Dixon, 1996; USACE, 2000, 2015). Even when beach nourishment is commissioned on the local level, federal funding may be involved. At a community level, erosion-hazard mitigation can increase uptake of flood insurance (Landry and Jahan-Parvar, 2011).

Should the rate of sea-level rise continue to increase, it is not expected that beach nourishment can continue to protect infrastructure in the long-term (e.g., Keeler et al., 2018; Parkinson and Ogurcak, 2018; Woodruff et al., 2018), and managed retreat will need to be considered as an option (Neal et al., 2017). Managed retreat has been trialled in one New Jersey community after Superstorm Sandy, where a cluster of properties were bought-out so that the land could be cleared and left undeveloped to reinstate a coastal buffer (Schwartz, 2018). Gaining co-operation for this buy-out was hard fought, and only became appealing to residents after Superstorm Sandy damaged properties (Schwartz, 2018). Buying out at-risk properties on a large scale in U.S. will likely require a shift in attitudes about property ownership and perceptions of coastal risk.

1.2.3.5 Coastal risk modelling

Coastal risk modelling studies fall into several categories: case studies (e.g., Smallegan et al., 2016; Taylor et al., 2015), future projections of risk (e.g., Brown et al., 2014, 2016b, 2018; Hinkel et al., 2010, 2014; Neumann et al., 2015; Nicholls et al., 2018), or exploratory resource economics coupled models (e.g., Gopalakrishnan et al., 2016; McNamara and Werner, 2008a, 2008b; McNamara et al., 2015; Smith et al., 2009). The case studies tend to focus on hazard in great detail, whereas future projections of risk focus on the population susceptible to global flooding due to sea level rise in different climate model scenarios, and resource economics coupled models that compare developed and natural shorelines do not explicitly examine risk. I discuss resource economics coupled models in more detail in Section 1.2.5.

1.2.4 Unintended consequences of beach nourishment

Because natural coastal geomorphology is complex and beach nourishment as a risk-reduction strategy actively interacts with coastal processes, beach nourishment can result in unintended consequences (Neal et al., 2018; Nordstrom, 2000). Here, I highlight the main unintended consequences that I consider in this thesis. First among them is the emergence of developed coastlines as coupled human–landscape systems.

1.2.4.1 Unintentionally coupled human-landscape systems

Developed coasts are an example of a dynamic coupled system in which human interventions at the shore and natural physical coastal processes are related by inherent feedbacks. In this case, the mechanisms of the human system component are manifest in economics, politics, and psychology. The mechanisms of the landscape system component are manifest in physical processes including sediment transport, wave climate, storm regime, and sea-level change. When the human system alters the coastline, it affects the landscape system, which in turn affects the environmental conditions to which the human system must respond. Beach width, for example, changes as a function of both system components at the temporal scale of 1 – 10s of years, with the human system nourishing to widen a beach as the landscape system erodes it (Lazarus et al., 2016; Lazarus, McNamara, et al., 2011; McNamara and Lazarus, 2018; Smith et al., 2009; Werner and McNamara, 2007). The definition of a coupled human-landscape system that I use in this thesis states:

> “Humans and landscapes are coupled via a range of mechanisms. Humans impact landscapes by directly transporting sediment, indirectly through enhancing erosion by agriculture and construction or deposition by damming streams and flood control, by altering vegetation and animal life through harvesting and manipulation, by modifying the chemical and microbiological context for landscape processes, and by changing climate. Landscape processes impact humans in two primary ways: at short time scales, natural disasters such as hurricanes, floods, slope failures and earthquakes cause

> widespread economic damage and human suffering. At long time scales, landscape processes and configurations provide a context for human settlement patterns (Davis, 2002), cultural development (Fagan, 2004) and genetic evolution (Hewitt, 2000)."
>
> **Werner and McNamara (2007) pg. 398**

According to Werner and McNamara (2007), certain conditions determine whether the coupling in a coupled system is strong or weak:

> "…[H]umans-landscape coupling should be strongest where fluvial, oceanic or atmospheric processes render significant stretches of human-occupied land vulnerable to large changes and damage, and where market processes assign value to the land and drive measures to protect it from damage. These processes typically operate over the (human) medium scale of perhaps many years to decades over which landscapes become vulnerable to change and over which markets drive investment in structures, evaluate profits from those investments and respond to changes in conditions."
>
> **Werner and McNamara (2007) pg. 399**

Following the definition set out by Werner and McNamara (2007), Lazarus et al. (2016) describe beach nourishment along developed coasts as an exemplar of a coupled human-landscape system, made up of four parts (Figure 1.3):

> "(1) natural littoral processes of alongshore and cross-shore sediment transport …. create spatial patterns of beach accretion and erosion; (2) coastal development built to benefit economically from the natural capital of a wide beach (3) becomes vulnerable to damage from coastal hazards; risk exposure (4) drives investment in hazard mitigation and shoreline protection. Where beach erosion is persistent, this cycle (1–4) repeats on a multi-annual to decadal cycle."
>
> **Lazarus et al. (2016) p. 83**

I use this exemplar coupled human-landscape system to further develop a framework to conceptualise interactions between system components in Section 5.1.

Figure 1.3 Beach nourishment as an exemplar of a coupled human-landscape system: (1) natural littoral processes; (2) coastal development; (3) risk exposure; and (4) hazard mitigation. From (Lazarus et al., 2016).

Large scale studies of coupled human-landscape systems generally cover either beach nourishment, or development, but tend not to link the two (Crossett et al., 2004; Johnson et al., 2015; Luijendijk et al., 2018; NOAA, 2012a, 2013). Using United States Geological Survey (USGS) shoreline surveys of erosion rates along the northeastern US Atlantic Coast, Hapke et al. (2013) highlighted a link between coastal development and reduced erosion at the scale of 10^1 – 10^3 km, but did not explicitly establish a link between beach nourishment and reduced erosion. Instead, Hapke et al. (2013) found that erosion rates are more strongly correlated with the amount of development present than with the natural geomorphological setting.

Coupled human-landscape systems can switch between periods of being driven more by one system over another. For example, landscape system changes due to hurricanes can drive disaster relief investment in the human system, including hazard mitigation (Burby, 2006). An example of a period when the human system can be the stronger driver is the global reduction of coastal development pressure following the 2008 economic downturn (Cooper and McKenna, 2009).

Human-landscape systems are described in geomorphology literature, but may go by different names (Table 1.1). There are also other types of coupled systems in different fields and disciplines that involve a human and a natural element. In this thesis, I exclusively use the term ‘coupled human-landscape system’, but this is synonymous with most other coupled-systems terminology (Table 1.1).

Table 1.1 Different names for coupled systems, and the literature that uses them.

System Family	System Name	Literature
Human-natural systems	Human-landscape systems	(Kondolf and Podolak, 2014; McNamara and Lazarus, 2018; McNamara and Werner, 2008a, 2008b; Werner and McNamara, 2007)
	Human-coastal systems	(Brown et al., 2014; Lazarus et al., 2016; Miselis and Lorenzo-Trueba, 2017; Murray et al., 2013)
	Natural-human coastal systems	(Lazarus et al., 2019; National Academy of Sciences Engineering and Medicine, 2018)
	Coupled human and natural systems (CHANS)	(Alberti et al., 2011; An et al., 2016)
	Human-environment systems	(Bauch et al., 2016; Lazarus, 2014)
Economic and coastal systems	Coupled physical and economic systems	(Gopalakrishnan et al., 2011; McNamara and Keeler, 2013)
	Coupled economic and coastline systems	(Lazarus, McNamara, et al., 2011; McNamara et al., 2011; Williams et al., 2013)
	Coupled economic geomorphological systems	(Gopalakrishnan et al., 2010; Smith et al., 2009)
Socio-ecological systems	Socio-ecological (or social-ecological) systems	(Filatova et al., 2013; Verburg et al., 2015)
	Fisheries	(Steneck et al., 2011; Wilson, 2006)
	Social ecological traps	(Berkes et al., 2006; Boonstra and de Boer, 2014; Steneck et al., 2011)
Socio-natural system	Socio-natural systems	(Cioffi-Revilla and Rouleau, 2010)
	Socio-hydrology	(Di Baldassarre et al., 2013)
	Coevolution of deltas	(Welch et al., 2017)

1.2.4.2 Unintended consequences – other concepts

Safe development paradox – The most expensive hurricanes in history have been recent ones (Blake et al., 2011), and the economic cost of coastal disaster continues to grow (Union of Concerned Scientists, 2018). Mileti (1999) describes this phenomenon as “disasters by design”, in which the rising cost of disaster events occurs despite better scientific understanding of disaster dynamics and post-event response, and despite increased spending on hazard mitigation. The *safe development paradox* is a concept that explores why disaster costs continue to rise, despite increased hazard mitigation, and describes a feedback in which increased development makes its own case for hazard protection, and investment in hazard protection contributes to a perception of safety in hazard-prone areas (Brody et al., 2007; Burby, 2006; Keeler et al., 2018; McNamara and Lazarus, 2018; Mileti, 1999; Nordstrom, 2000; Werner and McNamara, 2007).

Jevons' paradox – The safe development paradox is conceptually related to *Jevons’ paradox*, which describes how gains in efficiency can be offset or overwhelmed by increased production and/or use (Jevons, 1865; Sorrell, 2009). Noting that coal consumption was not reduced when steam engines become more efficient, Jevons (1865) theorised that gains in efficiency, which should reduce the consumption of coal, can be countered by increased demand, a so-called 'rebound effect' (Alcott, 2005; Polimeni et al., 2008; Sorrell, 2009). Rebound effects, both direct and indirect, are illustrated for the case of fuel-efficient cars (Figure 1.4). When rebound effects exceed 100% of an efficiency gain, then overall energy consumption increases: this is known as 'backfire' (Sorrell, 2009). This theory from resource economics has been used in resource management (Dumont et al., 2013), though it remains controversial among environmental economists because the patterns are notoriously difficult to isolate empirically (Sorrell, 2009).

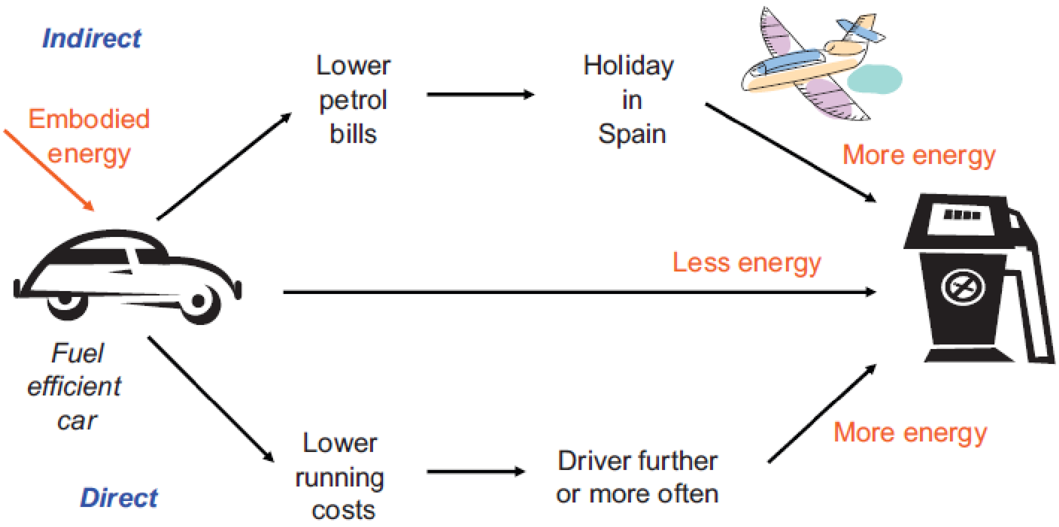

Figure 1.4 An illustration of Jevons' paradox: Conceptual figure showing how direct and indirect rebound effects can reduce the savings in fuel consumption expected by introducing more fuel efficient cars. From (Sorrell, 2009).

Coastal geoengineering – Climate geoengineering is defined as:

> "deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change."
>
> **Royal Society (2009) pg. 1**

While this definition focuses on counteracting climate change, geoengineering can also take place to counteract environmental effects of climate-driven change. This definition is less specific to climate systems:

> "the direct, large-scale, purposeful intervention in or manipulation of the natural environments of this planet, e.g., land, lakes, rivers, atmosphere, seas, ocean, and/or its physical, chemical, or biological processes."
>
> **Verlaan (2009) pg. 446**

The definition of "marine geoengineering" specifically considers the effects of climate change, and is set out by the London Protocol as:

> "a deliberate intervention in the marine environment to manipulate natural processes, including to counteract anthropogenic climate change and/or its impacts, and that has the potential to result in deleterious effects, especially where those effects may be widespread, long-lasting or severe."
>
> **IMO (2015) pg. 5**

Coastal geoengineering, then, involves the deliberate manipulation of the coastal environment to counteract the impacts of anthropogenic climate change, including sea-level rise and increased storminess, which could potentially result in deleterious effects. Coastal geoengineering can occur accidentally, through the collective result of individual actions along developed coasts (Smith et al., 2015). The main deleterious effect in coastal geoengineering would be a termination effect – the impact that would manifest if coastal adaptation were to suddenly stop, for example because of lack of funding (Finkl, 1996; Neal et al., 2017; Parkinson and Ogurcak, 2018).

Systems traps – The threat of a termination effect arises in *systems traps*, or system archetypes with structures that manifest in problematic behaviour (Meadows and Wright, 2008). The *addiction system trap* (also referred to as "shifting the burden") is one such system archetype in which an intervention to fix a problem addresses only a symptom of the problem. By only relieving the symptom of a problem and not addressing the cause, the addiction system trap can result in masking the original problem, while dependence on the intervention continually increases (Meadows and Wright, 2008; Senge, 2006). In the case of hazard protection masking the underlying causes to the problem of coastal flooding and erosion, this could alter the perception of risk for municipalities, developers, and individuals at the coast (Di Baldassarre et al., 2013; Brown et al., 2014; Filatova et al., 2011; Mileti and Gailus, 2005; Peacock et al., 2005; Petrolia et al., 2013).

In this thesis I explore: non-local effects of beach nourishment; collective and cumulative beach nourishment as a form of coastal geoengineering; whether the US Atlantic has fallen into a system trap by masking the true state of coastal erosion; the existence of a feedback between coastal development and beach nourishment; whether this feedback has wiped out the risk-reduction gains of beach nourishment through a form of Jevons' paradox; and how beach nourishment contributes to the safe development paradox.

1.2.5 Progress in modelling coastal coupled human-landscape systems

Reviews of coastal coupled models cover the breadth of models in the literature (Lazarus et al., 2016; McNamara and Lazarus, 2018; Murray et al., 2013). Here I will highlight those models that use coastal coupled systems to explore unintended consequences of beach nourishment.

Related to coastal geoengineering, the non-local effects of beach nourishment were modelled by Lazarus et al. (2011b), illustrating that the spatially myopic nourishment decisions of one town affects those of towns alongshore, resulting in an emergent spatial pattern of nourishment developing over time. Non-local effects of beach nourishment were also addressed by Williams et al. (2013), who created a game-theory based model that explored how two neighbouring towns can either gain free sand from their neighbour (free-rider), or pay to help nourish their neighbour (sucker). If a free-rider is a wealthier town than a sucker, this can act to reinforce wealth inequality (Williams et al., 2013), as too can a wealthier town depleting local sand resources by nourishing more frequently than necessary, increasing sand prices and making nourishment less accessible to less wealthy neighbouring towns (McNamara et al., 2011).

Some models indirectly explore the safe development paradox by attributing economic value to beaches. Adapting a forestry model of optimal cycles for timber harvesting (Hartman, 1976), Smith et al. (2009) set up a model of beach nourishment as a capital accumulation problem, where beach width is related to value, and decisions to nourish are based on finding the optimal time to balance spending with the dividends of beach width. They found that because a wide beach increases property value, a feedback between beach width and development, wealthier towns counterintuitively have an economic incentive to nourish more frequently (Smith et al., 2009). A further model built up from this base explored the effect of policy changes on beach value (Gopalakrishnan et al., 2011). In another value-driven model, McNamara et al. (2015) explored the inflation of coastal property value by insurance subsidy. They found that removing the effect of beach nourishment could reduce property values by 17% for wealthy regions and 34% elsewhere in coastal North Carolina and New Jersey, under historical erosion and storm intensity (McNamara et al., 2015).

To date, there are no systems models that explicitly explore the addiction system trap, among other traps, related to beach nourishment. The closest is perhaps a coupled barrier island-resort model by McNamara and Werner (2008a), which demonstrates how protecting and preserving infrastructure in place does not allow the barrier island to migrate landward, effectively pinning barrier islands at an unnaturally low elevation and leading to the eventual abandonment of barrier-island resorts. Woodruff et al. (2018) formed a systems modelling 'hypothesis' for community response to coastal hazards, which includes beach nourishment. This hypothesis represents a good conceptual starting point for systems models to explore the unintended consequences of beach nourishment, with stocks, flows, delays, and feedbacks (Meadows and Wright, 2008).

1.3 My contributions to the literature

In my work, I have aimed to address several gaps in the literature about unintended feedbacks between hazard, exposure, and vulnerability at large spatial scales.

First, while some empirical studies consider developed coasts on spatial scales that are significantly larger than case studies (Hapke et al., 2010, 2013; Morton and Miller, 2005; Pilkey and Clayton, 1989; Pilkey and Cooper, 2014; PSDS, 2017; Trembanis and Pilkey, 1998; Valverde et al., 1999), none explicitly examine how beach nourishment may drive feedbacks between hazard and exposure.

Second, while some models explore a link between coastal development and beach nourishment (Gopalakrishnan et al., 2010, 2011; McNamara et al., 2015; McNamara and Werner, 2008a, 2008b; Smith et al., 2009; Williams et al., 2013), my research is the first large-scale empirical study that links coastal development patterns and beach nourishment.

Finally, while Mileti (1999) explains that interactions between natural forcing, hazard protection, and the built environment may lead to unintended consequences of "disasters by design", literature on coastal risk still does not adequately capture feedbacks between risk components (hazard, exposure, and vulnerability) that emerge over time (Brown et al., 2016; Hinkel et al., 2014; Neumann et al., 2015; NRC, 2014; Samuels and Gouldby, 2009).

The contributions compiled in this thesis address the above gaps in existing literature by examining the US Atlantic Coast as a strongly coupled human-landscape system.

1.3.1 Chapter 2: Masked erosion at large spatial scales as a collective effect of beach nourishment (Armstrong and Lazarus, 2019a)

Nota bene – This article was selected by journal editors as a research highlight.

The objective of this paper was to study how beach nourishment affects the shoreline geomorphology of a developed coast at large spatial scales (>10^2 kms).

Short-term rates of shoreline change along the US Atlantic Coast, based on the two most recent surveys, between 1962-1988 and 1997-2007, are significantly less erosional than the long-term rates, spanning from 1830 – 2007 (Hapke et al., 2010; Morton and Miller, 2005). Driven by this unexpected observation, previously attributed in general terms to coastal development (Hapke et al., 2013), this paper examined whether beach nourishment, specifically, has influenced rates of shoreline change. Because beach nourishment has been used ubiquitously along the US Atlantic Coast since 1960, we used 1960 as a cut-off date to calculate "historical" and "recent" shoreline change rates for transects taken every km along the US Atlantic Coast, from USGS surveys (Figure 1.5). We hypothesised that if recent erosion is less than historical erosion, then the erosion signal since 1960 has been suppressed.

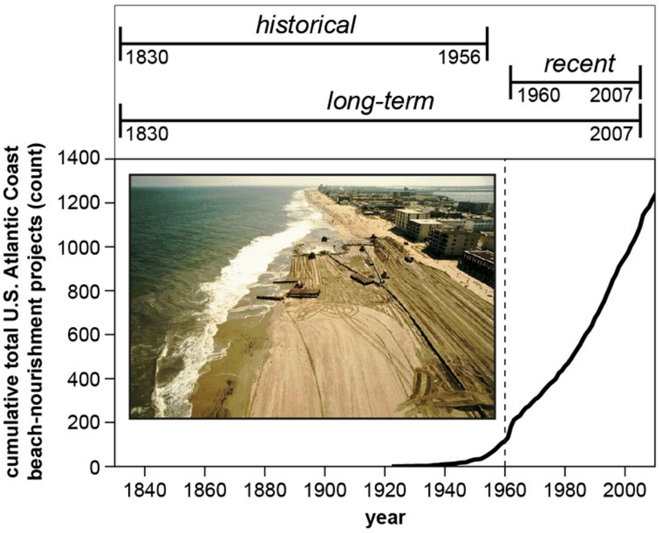

Figure 1.5 Uptake of beach nourishment since 1960 along the US Atlantic Coast, and illustration of the USGS shoreline survey years included in our analysis. Dotted line at 1960 indicates the temporal cut-off between historical and recent shoreline change rates. Inset photo of a beach nourishment project (courtesy of NOAA). From (Armstrong and Lazarus, 2019a).

Our main findings were that:

- Over the whole US Atlantic Coast, mean historical shoreline change rate is strongly erosional (-55 cm/yr), while mean recent shoreline change rate describes accretion (+5 cm/yr), representing a mean erosion reduction of 60 cm/yr since 1960.
- The volume of sand imported into the US Atlantic shoreline by beach nourishment projects since 1960 could account for the 60 cm/yr reversal of mean erosion.

- Both historical and recent shoreline change rates are correlated to coastal development pressure, as measured by population density, but the greatest erosion reduction occurs in the middle range of population density.
- The number of nourishment projects peaks within this same middle range of population density, explaining the corresponding erosion reduction.
- Erosion is reduced up to ~16 km from a beach nourishment project, and 74% of the US Atlantic shoreline is within this distance of a nourishment project.
- Findings of this study provide evidence that the uncoordinated, cumulative use of beach nourishment along the US Atlantic Coast since 1960 could be responsible for altering erosion rates for the whole coastline. This would represent a case of unintended coastal geoengineering that effectively masks true erosion rates.
- An “addiction” system trap could emerge if true coastal erosion rates are masked by beach nourishment, an intervention to the problem of chronic erosion.

1.3.2 Chapter 3: Indications of a positive feedback between coastal development and beach nourishment (Armstrong et al., 2016)

Nota bene – This article was selected by journal editors as a research highlight.

The objective of this paper was to compare detailed data for coastal development with beach nourishment across a large spatial scale (>10^2 km) to explore potential indications of an emergent feedback (Gopalakrishnan et al., 2010, 2011; McNamara et al., 2015; McNamara and Werner, 2008a, 2008b; Smith et al., 2009; Williams et al., 2013).

Using Florida as an exemplar of development in coastal hazard zones, this paper compared the size and number of single family beachfront homes in nourishing zones versus those in non-nourishing zones along both the Atlantic and Gulf Coasts of Florida. Zones were delimited by ZIP code area, and spatially joined to beach nourishment records maintained by the Program for the Study of Developed Shorelines (PSDS) (PSDS, 2014). Using nourishing versus non-nourishing zones as a filter, we compared parcel-scale tax record property data for the beachfront row of single family homes (FGDL, 2014). Beach-nourishment sites were included if a nourishment project had ever occurred at that site (Figure 1.6).

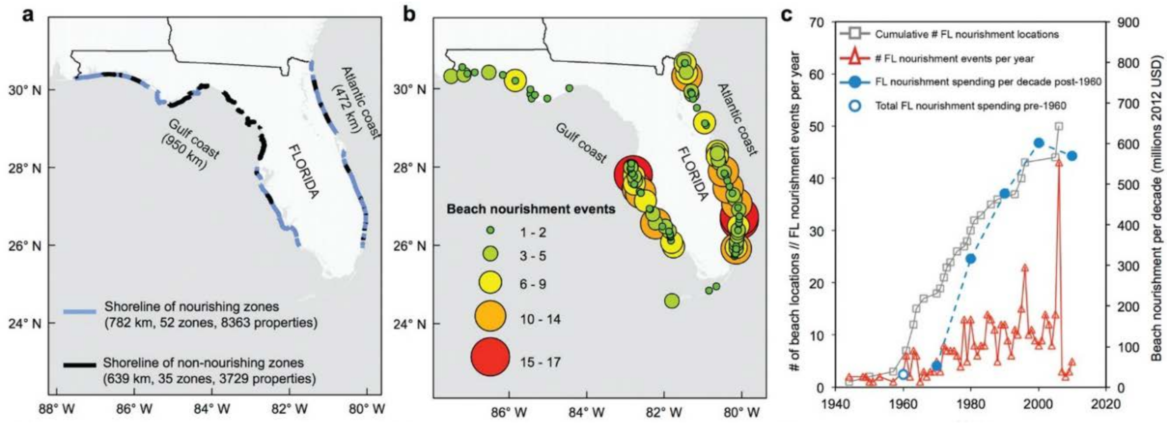

Figure 1.6 (a) Shoreline of beach nourishing zones in Florida. (b) Beach nourishment events in Florida between 1940 – 2010. (c) Cumulative number of beach nourishment locations in Florida between 1940 – 2010. From (Armstrong et al., 2016).

Our main findings were that:

- Beachfront houses on both the Gulf and Atlantic Coasts of Florida are larger, more numerous, and more densely distributed in nourishing zones, compared with non-nourishing zones.
- The difference in mean house size is more pronounced in the largest houses: Houses are larger in nourishing zones, but the biggest houses (in the 91st – 100th percentile) are much larger in nourishing zones.
- The difference in mean house size increases with the decade that houses are built: Newer houses are much larger in nourishing zones.
- Findings of this study indicate a feedback between property development and beach nourishment.
- This feedback may cause the reduction in risk delivered by nourishing beaches to be negated because nourishment encourages further development that increases the value of property exposed to coastal hazards, which could be seen as an example of the backfire effect described by Jevons' paradox (Sorrell, 2009).

1.3.3 **Chapter 4: Reconstructing patterns of coastal risk in space and time along the US Atlantic Coast, 1970–2016** (Armstrong and Lazarus, 2019b)

The objective of this paper was to explore how risk can increase over time as a result of feedbacks between human and landscape systems within risk components. This begins to explore how the safe development paradox emerges over time, as risk increases despite hazard mitigation, and the unintended consequence of beach nourishment, specifically, as a potential mechanism for increasing rather than reducing risk.

This paper presents a data-driven model of the entire US Atlantic Coast that describes risk as a function of hazard, exposure, and vulnerability. The model produced quasi-empirical risk trajectories for 51 coastal counties from Maine to South Florida between 1970 – 2016.

Our main findings were that:

- Risk trajectories rise over time (Figure 1.7).
- The rising risk trajectory is steepest when calculated using hazard derived from historical (pre-1960) rates of erosion, and shallowest when calculated with hazard derived from recent erosion rates (Figure 1.7).
- The values we use increase over time because property value in coastal counties, exposed to coastal hazards, increases each decade, in real terms.
- When we explore interactions between components, we find indications of similar mechanisms to those seen in Chapter 2 and Chapter 3:
    - Exposure is greater in counties that have high historical hazard, but low recent hazard, indicating that masked hazard may encourage development of exposed property (Chapter 2).
    - Exposure is also linked to a cumulative beach nourishment sub-component of vulnerability, indicating a feedback between development of exposed property and beach nourishment (Chapter 3).
- Feedbacks between components are inherent in the data used in our model, but we highlight the need to include feedbacks when developing any predictive model of coastal risk that is not informed by data.

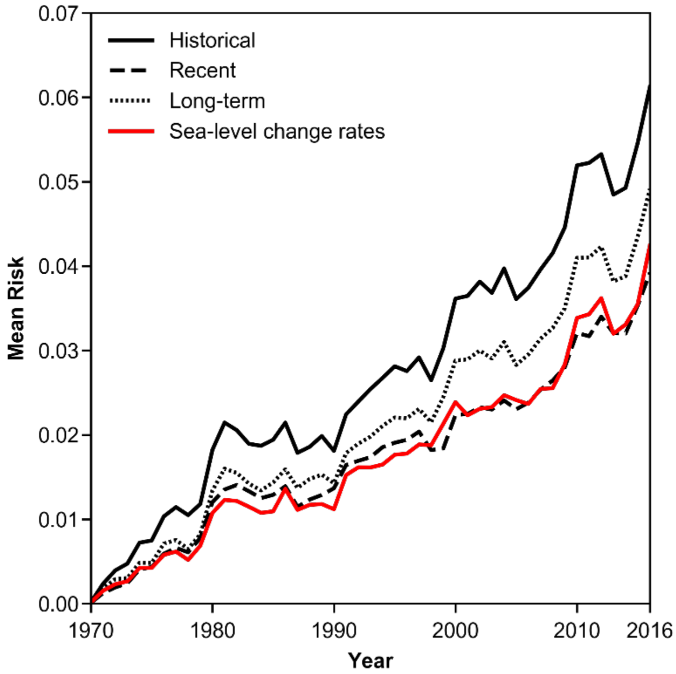

Figure 1.7 Comparison of evolution of mean US Atlantic Coast risk over time, with risk calculated using sea-level change rates (red), historical erosion rates (solid black), recent erosion rates (dashed black), and long-term erosion rates (dotted black). From (Armstrong and Lazarus, 2019b).

Chapter 2 Paper 1: Masked shoreline erosion at large spatial scales as a collective effect of beach nourishment

This paper is published as:

Armstrong, S. B., and Lazarus, E. D., 2019a. Masked Shoreline Erosion at Large Spatial Scales as a Collective Effect of Beach Nourishment. *Earth's Future*, **7**(2), 74–84. DOI: 10.1029/2018EF001070

This work has been presented as:

Oral Presentation: Armstrong, S.B and Lazarus, E.D. 2017, April. The U.S. Atlantic Coast is eroding – isn't it? In: *Young Coastal Scientists and Engineers Conference (YCSEC) 13*.

2.1 Abstract

Sea-level rise along the low-lying coasts of the world's passive continental margins should, on average, drive net shoreline retreat over large spatial scales (>10^2 km). A variety of natural physical factors can influence trends of shoreline erosion and accretion, but trends in recent rates of shoreline change along the U.S. Atlantic Coast reflect an especially puzzling increase in accretion, not erosion. A plausible explanation for the apparent disconnect between environmental forcing and shoreline response along the U.S. Atlantic Coast is the application, since the 1960s, of beach nourishment as the predominant form of mitigation against chronic coastal erosion. Using U.S. Geological Survey shoreline records from 1830–2007 spanning more than 2500 km of the U.S. Atlantic Coast, we calculate a mean rate of shoreline change, prior to 1960, of -55 cm/yr (a negative rate denotes erosion). After 1960, the mean rate reverses to approximately +5 cm/yr, indicating widespread apparent accretion despite steady (and, in some places, accelerated) sea-level rise over the same period. Cumulative sediment input from decades of beach nourishment projects may have sufficiently altered shoreline position to mask "true" rates of shoreline change. Our analysis suggests that long-term rates of shoreline change typically used to assess coastal hazard may be systematically underestimated. We also suggest that the overall effect of beach nourishment along of the U.S. Atlantic Coast is extensive enough to constitute a quantitative signature of coastal geoengineering, and may serve as a bellwether for nourishment-dominated shorelines elsewhere in the world.

2.2 Introduction

Along low-lying coasts at passive tectonic margins around the world, sea-level rise should, on average, drive net long-term shoreline erosion over large spatial scales (>10^2 km) (FitzGerald et al., 2008; Passeri et al., 2015). Coastal erosion is not necessarily an inevitable consequence of sea-level rise: a variety of natural, dynamic physical factors can influence positive and negative changes in shoreline position over decades to centuries (Cooper and Pilkey, 2004; FitzGerald et al., 2008; Kench et al., 2018; Komar and Holman, 1986; Nicholls and Cazenave, 2010; Passeri et al., 2015; Wong et al., 2014; Zhang et al., 2004). For example, isostacy (regional flexure of the Earth's crust) can exacerbate relative sea-level rise, such as through sediment loading at a major river delta (Syvitski et al., 2009), or effect relative sea-level fall, through long-term rebound after an ice sheet (Dyke et al., 1991; Lambeck and Chappell, 2001; Shennan et al., 2000). Nearshore geology can interact with wave forcing to drive cycles of erosion and accretion at specific reaches, both local (Houser et al., 2008; Lazarus and Murray, 2011) and regional (Valvo et al., 2006). Sediment supply, type, and whether littoral sediment comes from one or a combination of fluvial, offshore, or local (e.g., soft cliff) sources, can differentially affect shoreline position (FitzGerald et al., 2008), even within the same littoral cell (Willis and Griggs, 2003). Ecological feedbacks by which coastal vegetation (e.g., marshes, mangroves) or coral systems trap, retain, and create sediment may use relative sea-level rise to drive shoreline advance (Kench et al., 2018; Kirwan and Megonigal, 2013). Regional wave climates (multi-annual to multi-decadal distributions of deep-water wave height and direction of travel) reshape coastal planforms by setting up gradients in wave-driven alongshore sediment flux that drive transient spatial patterns of erosion and accretion over large spatial scales (~10^1–10^2 km) (Ashton and Murray, 2006b, 2006a; Lazarus et al., 2012; Lazarus, Ashton, et al., 2011). Over time, those spatial patterns of shoreline change may shift with prevailing weather patterns (Thomas et al., 2016; Valvo et al., 2006).

Even in this global context of varied and variable potential responses to environmental forcing, recent trends in shoreline change along the U.S. Atlantic Coast are enigmatic (Hapke et al., 2013). Tide-gauge records show that rates of relative sea-level rise along the U.S. Atlantic Coast vary over time but are increasing (Church and White, 2011; Gutierrez et al., 2011; Hapke et al., 2010; Morton and Miller, 2005). In the northern Mid-Atlantic region, rates of relative sea-level rise have been markedly accelerating (Ezer and Atkinson, 2014; Sallenger et al., 2012). In addition to sea-level rise, observations and modelled hindcasts of deep-water wave conditions in the Atlantic Ocean show a trend of increasing significant wave height over recent decades (Komar and Allan, 2008) and into the past century (Bertin et al., 2013). Greater wave heights will tend to drive larger fluxes of littoral sediment transport (Ashton and Murray, 2006b, 2006a). However, rather than reflecting widespread and intensified erosion, mean rates of recent shoreline change along the

U.S. Atlantic Coast show a predominant increase in accretion (Hapke et al., 2010, 2013; Himmelstoss et al., 2010; Miller et al., 2005; Morton and Miller, 2005). What makes the U.S. Atlantic Coast such an exceptional example of this apparent disconnect between environmental forcing and shoreline response is spatial scale. The trends in rates of shoreline change over recent decades are so distorted across such extended length scales (on the order of 10^2–10^3 km) that they appear systemic and indicative of dynamics distinct from natural conditions (Hapke et al., 2013; Johnson et al., 2015; Lazarus et al., 2016; Nordstrom, 2000).

The U.S. Geological Survey (USGS) has previously reported a marked, positive shift (toward accretion) between long-term and short-term rates of shoreline change along much of the U.S. Atlantic Coast north of North Carolina (Hapke et al., 2013). National estimates of U.S. shoreline change are based on composites of shoreline surveys dating back to 1830; these data represent the best available and most comprehensive coverage for such extended spatial and temporal scales (Hapke et al., 2010; Himmelstoss et al., 2010; Miller et al., 2005; Morton and Miller, 2005). National assessments by the USGS include two categorical rates of shoreline change: "long-term" and "short-term" (Hapke et al., 2010, 2013; Himmelstoss et al., 2010; Miller et al., 2005; Morton and Miller, 2005). In a recent analysis, the USGS offer that "a reduction in the percentage of eroding coast in the past two to three decades suggests that human alteration of the coastline is having a measureable impact over large spatial scales," and "even moderate amounts of development are associated with reduced erosion indicating that activities associated with protecting and preserving human infrastructure have a substantial and long-lasting impact" (Hapke et al., 2013).

Natural supply of sandy sediment to much of the U.S. Atlantic Coast is limited to what wave action can rework from patchy, relict deposits on the continental shelf (Meade, 1982; Milliman et al., 1972; Thieler et al., 2014). A possible explanation, then, for the apparent disconnect between sea-level rise and shoreline response along so much of the U.S. Atlantic Coast is the application, since the 1960s, of beach nourishment as the predominant form of mitigation against chronic coastal erosion (NRC, 1995, 2014) (Figure 2.1). Beach nourishment involves importing and redistributing large volumes of sand – typically 10^6–10^7 m^3 (PSDS, 2017) – to widen an eroding beach. From Maine to South Florida, 1341 nourishment projects have occurred since 1923, and 91% of them after 1960 (PSDS, 2017). An analysis of shoreline change at Cape Fear, North Carolina, suggests that recurrent beach nourishment projects may have cumulatively altered the response of the cape shoreline to natural physical drivers (e.g., wave climate and gradients in alongshore sediment flux) enough to "compensate for – and therefore to mask – natural responses to wave climate change that might otherwise be discernible in patterns of shoreline change alone" (Johnson et al., 2015). Beyond the U.S. Atlantic Coast, beach nourishment is prevalent in every U.S coastal state, including the Great Lakes (Trembanis et al., 1999), and is widely applied in Europe (Hanson et al., 2002), Australia (Cooke et al., 2012), and elsewhere in the world (Nordstrom, 2000; Walker and Finkl, 2002).

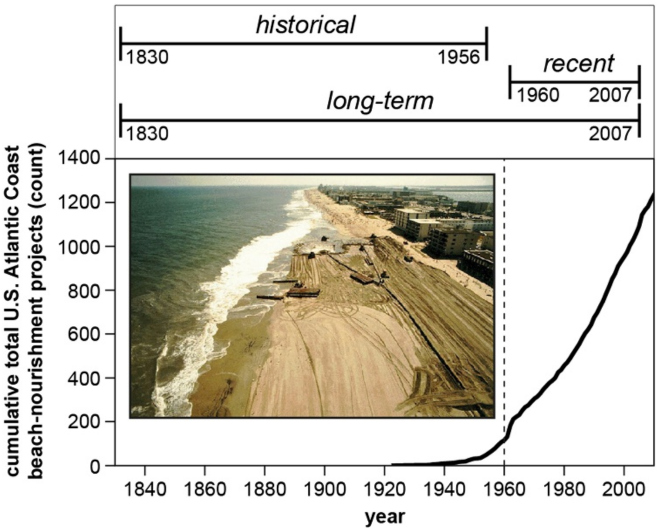

Figure 2.1 Ranges of survey dates used to calculate historical, recent, and long-term rates of shoreline change (see also Figure A.1), with the cumulative number of nourishment projects along the U.S. Atlantic Coast plotted over time. Dashed vertical line marks 1960. Inset photo shows an oblique aerial view of a beach-nourishment project (courtesy of NOAA).

To examine the potential influence of beach nourishment, specifically, on rates of shoreline change along ~2500 km of the U.S. Atlantic Coast from Massachusetts to South Florida (Figure 2.2; Figure A.1; Figure A.2), we use the USGS repository of composite shorelines from 1830–2007 (Himmelstoss et al., 2010; Miller et al., 2005) and the comprehensive dataset of beach nourishment projects maintained by the Program for the Study of Developed Shorelines (PSDS, 2017). We treat 1960 as the benchmark year for the onset of beach nourishment as the predominant mitigation response to coastal erosion (Figure 2.1) (NRC, 2014). To distinguish our categorical rates of shoreline change from those reported by the USGS, we define them here as "historical" (pre-1960) and "recent" (post-1960). We make this distinction because the method by which the USGS calculates their "long-term" rate involves taking a linear regression through all available shoreline surveys at a given location (Hapke et al., 2010, 2013; Himmelstoss et al., 2010; Miller et al., 2005; Morton and Miller, 2005), thus including any effects of nourishment in the result. The historical rate that we calculate still does not represent "natural" shoreline change: human interventions (direct and indirect) in shoreline position along the U.S. Atlantic Coast predate the 1830 shoreline survey (e.g., Kirwan et al., 2011). However, estimating rates of shoreline change prior to the onset of extensive inputs from beach nourishment may yield a more representative assessment of chronic erosion hazard as a component of coastal vulnerability (Thieler and Hammar-Klose, 1999; USGS, 2018).

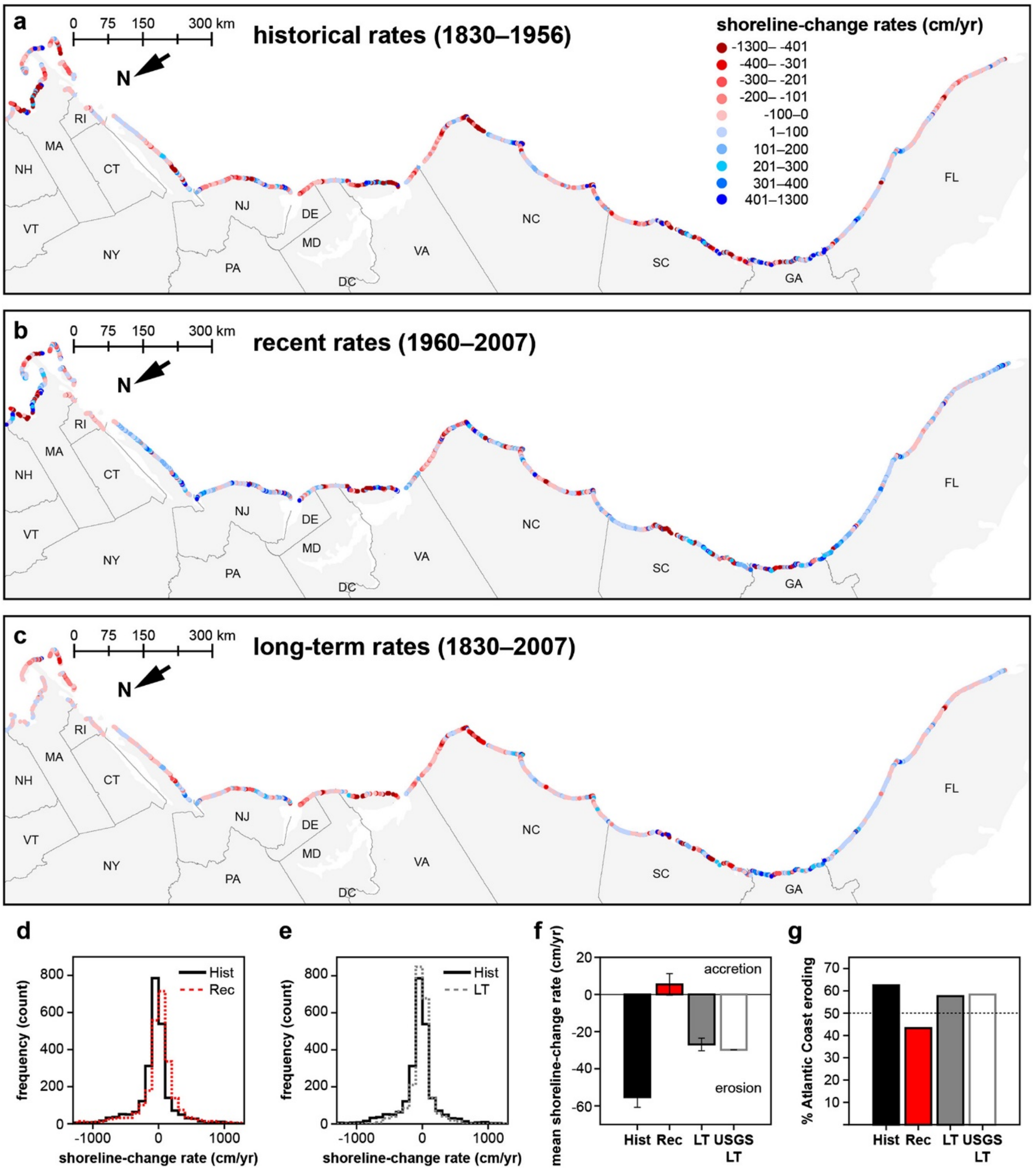

Figure 2.2 (a) Historical, (b) recent, and (c) long-term rates of shoreline change along the U.S. Atlantic Coast. Color represents the rate (cm/yr) at each 1 km alongshore. (Rates are also detailed in Figure A.2.) Histograms show the relative distributions of (d) historical (black, solid) versus recent (red, dotted) rates, and (e) historical (black, solid) versus long-term rates (gray, dotted). Bar charts compare historical, recent, long-term, and USGS long-term rates, for (f) mean erosion rate (cm/yr; whiskers ±1 standard error of the mean), and (g) the percentage of the U.S. Atlantic Coast that is eroding. (Descriptive statistics are listed in Table A.2.)

Three aspects of our analysis differentiate this work from related efforts by the USGS (Hapke et al., 2013). First, where the USGS compared long-term and recent shoreline change for the coastline from southern Maine to Virginia, our investigation extends from Massachusetts to the terminus of South Florida – nearly double the total distance. Second, by setting 1960 as a reference date for the onset of beach nourishment as a ubiquitous form of mitigation, we isolate a mean "historical" shoreline-change rate that is significantly higher than USGS calculations of "long-term" shoreline-change rates that are inevitably moderated by beach nourishment (Figure 2.1; Figure 2.2). Third, we spatially correlate rates of historical and recent shoreline change with records of beach nourishment to isolate and estimate the mean alongshore influence of nourishment inputs, specifically.

Our results suggest that mean rates of shoreline change over the past century (and longer) may be more erosional than previously reported "long-term" rates would convey. We also estimate that enough sand has been delivered to the U.S. Atlantic Coast since 1960 to likely account for the net positive change in shoreline position overall. Furthermore, we find that a majority of places along the U.S. Atlantic Coast are close enough to beach-nourishment sites to register significant reductions in their local erosion rates.

2.3 Methods

We calculated rates of shoreline change along the U.S. Atlantic Coast using publicly available shape files of shoreline surveys compiled by the USGS from T-sheets, aerial photography, and lidar (Himmelstoss et al., 2010; Miller et al., 2005). Because the USGS composite shorelines are stitched together from discontinuous surveys taken in various years, the range of available surveys varies alongshore (Figure A.1).

Along the USGS shoreline surveys we cast shore-normal transects at 1 km spacing (from a 50 m smoothed baseline cast) using the Digital Shoreline Analysis System (DSAS) tool in ESRI ArcGIS (Thieler et al., 2008). At each transect, we found the end-point rate of change in shoreline position for three categories of "end-point rate": "historical" (pre-1960), "recent" (post-1960), and "long-term" (full span). Start and end dates used to calculate the "historical" rates of shoreline change range from 1830–1956; "recent" rates from 1960–2007; and "long-term" rates from 1830–2007 (for direct comparison to USGS time frames) (Figure 2.1; Figure A.1; Table A.1). We calculated historical rates of shoreline change from the difference in shoreline position between the survey nearest but prior to 1960 and the earliest available survey, divided by the time between surveys (mean time frame ~73 years). We calculated recent rates from the difference in shoreline position between the most recent survey available and the first survey after 1960 (mean time frame ~27 years). We also calculated a long-term rate of change between 1830–2007 to match the temporal comparisons by the USGS (Hapke et al., 2010; Himmelstoss et al., 2010; Miller et al., 2005; Morton and Miller, 2005); those long-term rates only include start dates prior to 1899 (i.e., 1830–1899) and end dates after 1997 (i.e., 1997–2007). To address especially dynamic sections of shoreline that may have migrated out of (or into) fixed transect positions, resulting in extreme apparent rates of change (Hapke et al., 2010), we included only transects with rates that fall within the 99% distribution (+/- 2.58 σ around the mean) of the total dataset.

The method we used to calculate end-point rates differs in minor but notable ways from the method used by the USGS. The short-term rates from the USGS are the end-point rate between the two most recent surveys at a given location; their long-term rates are calculated as the linear regression through shoreline position in all available surveys at a given location (Hapke et al., 2010, 2013; Himmelstoss et al., 2010; Miller et al., 2005; Morton and Miller, 2005). The USGS also use a higher sampling frequency, casting a transect every 50 m alongshore to our 1 km.

Despite these methodological differences (including the coarser spacing between transects), the mean long-term rates that we calculate (-27 cm/yr) are comparable to those based on the USGS reports (-30 cm/yr) (Figure 2.2 f; Table A.2; Table A.3), and the mean percentage of eroding U.S. Atlantic Coast that we calculate is within 1% of the corresponding USGS mean (Figure 2.2 g; Table A.3). The mean shoreline-change rate and percentage of eroding coastline that we ascribe to the USGS measurements are summary metrics that we derived from the original USGS reports (Hapke et al., 2010; Himmelstoss et al., 2010; Miller et al., 2005; Morton and Miller, 2005), which list mean rates of shoreline change by state, along with the number of transects used to calculate those means. We weighted those state-by-state means by their number of constituent transects to find what we call the overall "USGS mean" of the U.S. Atlantic Coast.

The USGS national assessments of shoreline change split the U.S. Atlantic Coast into two main regions (Northeast and Southeast); error reporting differs slightly between the respective reports. The report for the Northeast cites an average uncertainty, for lidar surveys, of 2.3 m (Hapke et al., 2010; Himmelstoss et al., 2010). By contrast, the report for the Southeast cites maximum error, which includes large excursions (>20 m) attributed to localized offsets between shoreline records (Miller et al., 2005; Morton and Miller, 2005). We include those error maxima here (Figure A.3; Table A.2) because they are the only error metric published for the Southeast Atlantic surveys.

We related spatial patterns of shoreline change to corresponding data for population density (Figure 2.3 a–e) and beach nourishment projects (Figure 2.3 f–j). Using population density at the ZIP Code level from 2010 U.S. Census statistics (ESRI, 2012), we spatially joined those data to the shoreline transects. A ZIP Code is an index of local-scale spatial zones (for postal delivery) across the USA. ZIP Code areas are not necessarily the same as municipal boundaries: one or more municipalities may overlap with a given ZIP Code, and vice versa. Where publically available digitized maps of local municipal boundaries vary widely in their completeness, ZIP Codes offer complete and continuous spatial coverage of the entire U.S. Atlantic Coast (Armstrong et al., 2016), making them amenable to merging with other spatial data. Locations and counts of beach nourishment projects along the U.S. Atlantic Coast came from the database maintained by the Program for the Study of Developed Shorelines (PSDS, 2017). We excluded any record of beach nourishment prior to 1960 or that post-dates the final shoreline survey at a given location. To calculate the proximity of each transect to the nearest beach nourishment project, we used a GIS "near table" and binned the results into bands of 1 km "buffers."

To estimate the approximate total volume of sediment accreted along the U.S. Atlantic Coast since 1960, we used empirical scaling factors relating horizontal shoreline change to beach volume (Farris and List, 2007). We then compared that derived volume to the reported estimated volume of sand delivered from beach nourishment (PSDS, 2017) (Table A.4).

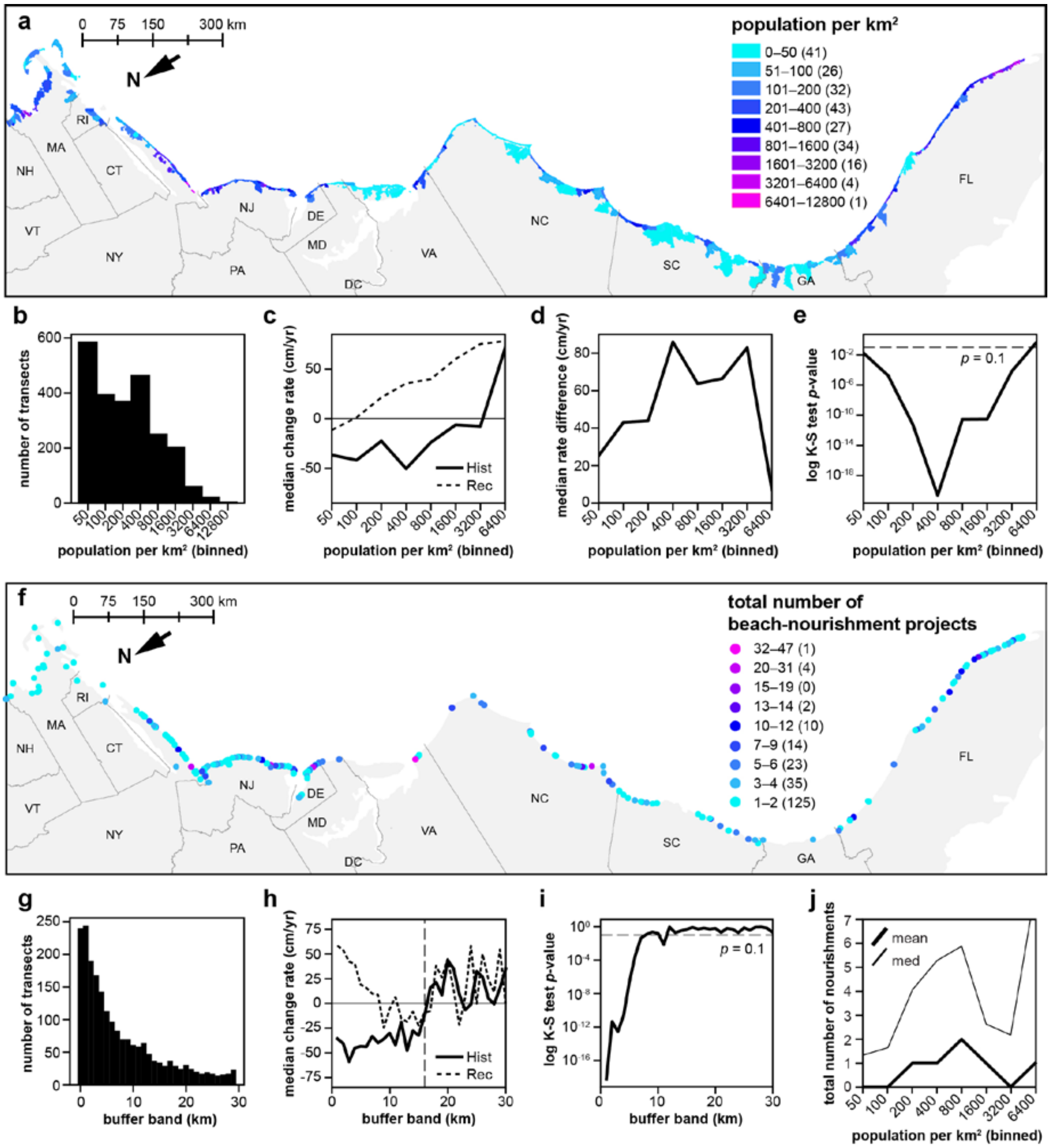

Figure 2.3 (a) Map of population density (population per km^2) for coastal ZIP Code zones along the U.S. Atlantic Coast. (b) Histogram showing the distribution of transects versus population density (binned). (c) Median historical and recent erosion rates (cm/yr) and (d) the difference between them versus population density. (e) Plot of p-values from a Kolmogorov-Smirnov test of historical versus recent erosion rates for transects within each population density; values below the dotted line are significant (the relative distributions are quantifiably different from each other) at $p < 0.1$. (f) Map of total number of beach-nourishment projects since 1960 at sites along the U.S. Atlantic Coast. (g) Histogram showing distribution of transects within each 1 km buffer distance from the nearest beach-nourishment site. (h) Median recent and historical erosion rates (cm/yr) versus buffer distance (see also Table A.5). (i) Plot of

p-values from a Kolmogorov-Smirnov test of historical versus recent erosion rates for transects within distance buffer bands; values below the dotted line are significant (the relative distributions are quantifiably different from each other) at $p < 0.1$. (j) Mean (thick line) and median (thin line) number of nourishment projects relative to population density, showing a pattern similar to the overall positive differences between recent and historical rates versus population density in panel (e).

2.4 Results

Historical, recent, and long-term shoreline change rates vary spatially along the U.S. Atlantic Coast (Figure 2.2 a–c; Figure A.2). However, comparing the distributions of the categorical rates (Figure 2.2 d, e) shows that historical rates of shoreline change are significantly more negative (indicating erosion) than recent (Mann-Whitney W = 5145138.5, $p < 0.01$) and long-term rates (Mann-Whitney W = 5356632.0, $p < 0.01$). We find the mean historical rate of shoreline change for the entire U.S. Atlantic Coast is -55 cm/yr. This rate is 60 cm/yr more negative than the mean recent rate of shoreline change (+5 cm/yr), and 28 cm/yr more negative than the mean long-term rate of shoreline change (-27 cm/yr) (Figure 2.2 f). Although our method for calculating rates of shoreline change differs from the one used by the USGS, the mean long-term rate of shoreline change that we determine (-27 cm/yr) is comparable to the equivalent rate in USGS reports (-30 cm/yr) (Hapke et al., 2010; Himmelstoss et al., 2010; Miller et al., 2005; Morton and Miller, 2005) (Figure 2.2 f). The proportion of transects at which rates of shoreline change are negative reflects the percentage of the U.S. Atlantic Coast that is eroding: more of the coast appears erosional in the historical rates (63%) than in the recent (43%) and long-term rates (58%) (Figure 2.2 g; Table A.3).

To test potential spatial relationships between rates of shoreline change and coastal population pressure (as a proxy for development intensity) (NOAA, 2013), we assigned to each transect the population density (people per km2) in the coastal ZIP Code from which it extends (Figure 2.3 a, b). We find a positive correlation between the rate of shoreline change (historical and recent) and population density (Figure 2.3 c). Comparing the historical and recent rates relative to population density shows the difference between their trends is greatest (and statistically significant) over the middle range of population density (Figure 2.3 d, e). This quantitative result aligns with a classification-based assessment of coastal-development intensity in the Northeast region and the relationship of those class types to rates of shoreline change (Hapke et al., 2013). Assuming that sparsely populated and/or undeveloped shorelines are free to change "naturally" in the absence of direct human intervention, we might expect that their historical and recent trends would, on average, show relatively little difference. That is, the mean historical and recent shoreline-change rates might not be the same, but we would not expect to see an overall reversal from erosion to accretion. Indeed, consistent with Hapke et al. (2013), we find that where population density is low, recent rates are generally less erosional than the historical rates, but erosional nonetheless (Figure 2.3 c,d). There is a similarly negligible difference between historical and recent shoreline-change rates where population density is highest (Figure 2.3 d), perhaps indicating the sustained maintenance of local shoreline position.

To explore potential spatial effects of beach nourishment (Figure 2.3 f) on proximal rates of shoreline change, at each shore-normal transect we measured the distance alongshore to the nearest beach-nourishment site. (We consider sites regardless of the number of nourishment projects recorded there or when the site was last active). We refer to these alongshore distances as "buffers", and binned them into bands 1 km long. We estimate that nearly 74% of the coastline is within ~16 km of a nourishment site (Figure 2.3 g). At the nourishment sites themselves (where buffer = 1 km), historical rates of shoreline change are negative (Figure 2.3 h), consistent with the expectation that beach nourishment after 1960 would occur in zones of chronic erosion. Up to ~16 km alongshore from a nourishment site, historical rates of shoreline change are generally negative – but recent rates (post-1960) are mostly positive, indicating accretion, with the largest positive differences between historical and recent rates at nourishment sites (Figure 2.3 h). With increasing buffer length, the historical and recent rates converge (at least up to ~30 km; Table A.5), and >16 km their respective distributions become statistically indistinguishable (Figure 2.3 i). Tellingly, the number of nourishment events relative to population density peaks over the same middle range of population densities (Figure 2.3 j) where the differences between historical and recent rates of shoreline change are greatest (Figure 2.3 d).

We do not ascribe particular mechanistic importance to the alongshore distance of 16 km, but the empirical result is not without physical basis. Beach nourishment projects are typically scrutinized in the cross-shore dimension, for the characteristic way in which wave action will relax a nourishment profile across the local shoreface (Dean and Dalrymple, 2001). But numerical modelling of long-term, non-local physical responses to shoreline interventions suggests that alongshore gradients in wave-driven net sediment flux are capable of affecting shoreline changes over several tens of kms alongshore (Ells and Murray, 2012; Williams et al., 2013).

Finally, we estimate that the summed total of estimated nourishment volumes since 1960 could account for the 60 cm/yr reversal from negative historical to positive recent rates of shoreline change (Table A.4). Approximately 95% of nourishment projects between 1960–2007 in the PSDS database (as of 2017) include an estimated or reported volume. Since 1960, an estimated ~285 million m^3 of nourishment sand has been deposited along the U.S. Atlantic Coast (PSDS, 2017) – the equivalent of ~114 m^3/m, were it distributed evenly along the coast. Meanwhile, the summed total of shoreline change, positive and negative, between 1960–2007 along the entire U.S. Atlantic Coast is net +54,702 m. Using an empirical scaling factor (c, where c = 1–3) relating horizontal to volumetric change for a sandy shoreline (Farris and List, 2007), +54,702 m of shoreline change distributed over 2339 transects for which there is a historical and recent rate (and assuming the rate per transect is the same as the rate per m alongshore) equates to between 23 m^3/m (c = 1) and 70 m^3/m (c = 3). This simplified balance suggests that the total volume of beach nourishment since 1960 could be at least twice (for c = 3) the estimated volume necessary to account for net shoreline change in the same period. Even using a large scaling factor (c = 5) to generate a deliberately conservative estimate of shoreline-change volume yields 117 m^3/m, within ~3% of the estimated volume from beach nourishment. Of the estimated total 285 million m^3 in nourishment, approximately 52 million m^3 (~18%) is attributed to navigational works, such as inlet maintenance (PSDS, 2017). Removing that navigational volume from consideration leaves 232 million m^3 of sand applied since 1960, or 93 m^3/m – still ~33% more than the estimated volume of net shoreline change (for c = 3; increasing the scaling factor to a more conservative value of c = 4 results in near equivalency). An alternative calculation of this volumetric comparison, based on shoreline-change rate rather than absolute shoreline change, yields lower but still sufficient nourishment volumes per m alongshore to account for positive shoreline change since 1960 (Table A.4).

2.5 Discussion and Implications

Our results provide an empirical indication that recent rates of shoreline change along the U.S. Atlantic Coast are, on average, less erosional than historical rates. This shift has occurred despite evidence of intensified environmental forcing, including acceleration in rates of relative sea-level rise and increased significant wave height in offshore wave climates. We suggest that the use, since the 1960s, of beach nourishment as the predominant form of mitigation against chronic coastal erosion in the U.S. (NRC, 1995, 2014) could explain the unexpected reversal in shoreline-change trends.

Although our analysis uses 1960 as a benchmark date to differentiate historical from recent rates of shoreline change, comparison to previous work (Hapke et al., 2013) suggests that our results are relatively insensitive to the choice of date (Table A.3). In the Southeast (North Carolina to Florida), for example, there is a stark gap in surveys between the late 1940s and mid-1960s, leaving no substantively different alternatives for our selection of dates. In the Northeast, the USGS has reported recent rates from the 1970s (Hapke et al., 2013). Scaling those mean recent rates by the lengths of their respective coastal segments yields an overall mean recent rate of +8 cm/yr, which the mean recent rate of +5 cm/yr that we calculate nearly matches (Table A.3).

However, the historical rate of shoreline change that we calculate is, on average, 25 cm/yr more erosional than the equivalent mean long-term rate from the USGS (Figure 2.2 f). Because the USGS long-term rates include the potential influence of beach nourishment, they may systematically underestimate the magnitude of "true" coastal erosion as a chronic hazard and component of coastal risk (Thieler and Hammar-Klose, 1999; USGS, 2018). We cannot explicitly disentangle the relative contributions of natural shoreline change, beach nourishment, and other human interventions (e.g., inlet dredging, sea walls, groyne fields, breakwaters) in the shoreline changes that we examine here. Nevertheless, we know that any effects of beach nourishment on rates of shoreline change would have to influence recent rates more than historical rates (Figure 2.1), and that no other single form of shoreline-change intervention along the U.S. Atlantic Coast is both so widely used and uniquely capable of the same reversing effect on erosion rates. It is reasonable to infer that the cumulative sediment input from decades of beach nourishment at sites along the U.S. Atlantic Coast could account for a significant proportion of the +60 cm/yr difference between recent and historical rates of shoreline change (Figure 2.2; Table A.4).

We also find that along the full span of the U.S. Atlantic Coast, rates of shoreline erosion may be significantly reduced up to ~16 km from beach-nourishment sites. Even on a segment of coastline where alongshore sediment transport travels in a predominant (net) direction, the effect of a regional wave climate, however asymmetrical, is to move sand laterally in both directions, with non-local effects on shoreline position (Ashton and Murray, 2006b, 2006a; Ells and Murray, 2012). This suggests that, in addition to getting redistributed across the shoreface, if some nourishment sand is redistributed laterally by wave-driven gradients in alongshore sediment transport, neighbouring coastal communities may benefit from each other's nourishment investments (Lazarus, McNamara, et al., 2011). A community that does not invest in beach nourishment may still benefit from the beach nourishment projects of its neighbours – in resource economics, a dynamic related to the prisoner's dilemma known as "free-riders" and "suckers" (Gopalakrishnan, McNamara, et al., 2016; Williams et al., 2013).

More broadly, if the quantity of beach nourishment in recent decades has been sufficient to mask "true" rates of shoreline erosion along the U.S. Atlantic Coast and "override the geomorphological signal of shoreline behavior" (Hapke et al., 2013), then our results point to the emergence of a system trap (Lazarus, 2017; Meadows and Wright, 2008). An "addiction" system trap may develop when an intervention to a problem obscures the true system state without addressing the underlying cause (Meadows and Wright, 2008). For example, the prospect of geoengineering the climate through solar radiation management – reducing global temperatures without reducing the amount of carbon dioxide in the atmosphere – would represent a system trap (Royal Society, 2009). Here, beach nourishment might reduce apparent erosion rates, but it does not change the climate systems that drive sea-level rise and long-term wave conditions. Moreover, by reducing apparent coastal hazard, beach nourishment may ultimately increase coastal risk by indirectly encouraging more coastal development in hazard-prone settings (Armstrong et al., 2016) – a phenomenon known in land-use planning as the "safe development paradox" (Burby, 2006; Mileti, 1999). By creating a reliance on hazard protection, a safe development paradox may reinforce an addiction trap.

This is not an argument against coastal management: coastal adaptation is predicted to cost less than doing nothing in response to climate-driven change (Hinkel et al., 2014). Nor do we imply a preference for hard over soft engineering – for seawalls instead of beach nourishment. But our findings do suggest that hazard from shoreline erosion might be stronger than it otherwise appears, placing diffuse but increased pressure on hazard mitigation. We propose that the cumulative, collective effect of beach nourishment on rates of shoreline change constitutes a quantitative signature of coastal geoengineering (Haff, 2003; Lazarus, 2017; Smith et al., 2015). An inclusive definition of geoengineering – one that extends beyond its typical reference to climate – is "the direct, large-scale, purposeful intervention in or manipulation of the natural environments of this planet, e.g., land, lakes, rivers, atmosphere, seas, ocean, and/or its physical, chemical, or biological processes" (Verlaan, 2009). The London Protocol defines "marine geoengineering" as

> "a deliberate intervention in the marine environment to manipulate natural processes, including to counteract anthropogenic climate change and/or its impacts, and that has the potential to result in deleterious effects, especially where those effects may be widespread, long-lasting or severe."
>
> **(Ginzky and Frost, 2014)**

A complex aspect of beach nourishment, at least as it manifests in the USA, is that local mitigation actions are deliberate but their collective consequences are not (Lazarus, McNamara, et al., 2011; Smith et al., 2015). Much like related implications for "termination effects" in climate geoengineering (Royal Society, 2009), were beach nourishment along the U.S. Atlantic Coast to suddenly stop – unmasking "true" rates of coastal erosion – then the economic effects on the coastal communities that have come to depend on its protection (Gopalakrishnan, Landry, et al., 2016; NRC, 2014) would indeed be deleterious, widespread, long-lasting, and severe. Beach nourishment as a form of geoengineering thus prompts the same question that arises in debates about solar radiation management, regarding how long it can be sustained once underway (Royal Society, 2009). For beach nourishment, however, the question is not hypothetical.

2.6 Acknowledgements

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Chapter 3 Paper 2: Indications of a positive feedback between coastal development and beach nourishment

This paper is published as:

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This work has been presented as:

Oral Presentation: Armstrong, S., Lazarus, E., Limber, P., Goldstein, E., Thorpe, C. and Ballinger, R., 2016, April. Intensified coastal development behind nourished beaches. In: *EGU General Assembly Conference Abstracts* (Vol. 18).

Poster: Armstrong, S., Lazarus, E., Limber, P., Goldstein, E., Thorpe, C. and Ballinger, R., 2016, April. Intensified coastal development behind nourished beaches in Florida. In: *Cardiff University School of Earth and Ocean Sciences Postgraduate Poster Showcase.*

Poster: Lazarus, E., Armstrong, S., Limber, P.W., Goldstein, E.B. and Ballinger, R., 2016, December. Intensified coastal development in beach-nourishment zones. In: *AGU Fall Meeting Abstracts*.

3.1 Abstract

Beach nourishment, a method for mitigating coastal storm damage or chronic erosion by deliberately replacing sand on an eroded beach, has been the leading form of coastal protection in the United States for four decades. However, investment in hazard protection can have the unintended consequence of encouraging development in places especially vulnerable to damage. In a comprehensive, parcel-scale analysis of all shorefront single-family homes in the state of Florida, we find that houses in nourishing zones are significantly larger and more numerous than in non-nourishing zones. The predominance of larger homes in nourishing zones suggests a positive feedback between nourishment and development that is compounding coastal risk in zones already characterized by high vulnerability.

3.2 Context

Population density, housing development, and property values in coastal communities along the U.S. Atlantic and Gulf Coasts continue to increase (Carter et al., 2014; NOAA, 2013; NRC, 2014) despite increasing hazard from storm impacts, chronic shoreline erosion, and sea-level rise (Moser et al., 2014; Wong et al., 2014). Since the 1970s, beach nourishment, which involves importing sand to widen an eroding beach, has been the main strategy in the United States for protecting coastal properties from hazard damage (NRC, 2014). However, research into dynamics linking natural hazards, socio-economic development, and associated risk points to a paradox: investment in hazard protection can have the unintended consequence of encouraging more development in places already vulnerable to damage (Cooper and McKenna, 2009; McNamara et al., 2015; Mileti, 1999; Nordstrom, 2000; Turner, 2000; Werner and McNamara, 2007). This is a positive feedback, whereby hazard protection drives development and vice versa (Werner and McNamara, 2007). Initial development may prompt protection, but once the feedback is established, both parts of the system drive—and respond to—each other. Versions of this dynamic have been described for leveed river systems with developed floodplains (Di Baldassarre et al., 2013; Werner and McNamara, 2007); for wildland–urban interfaces, where wildfire suppression protects development in fire-prone areas (Gude et al., 2008); and for developed high-relief landscapes, where basins are engineered to receive debris flows on mountain flanks (Johnson et al., 1991; McPhee, 1989). Research into developed coastlines likewise suggests that nourishment protection for high-value shorefront properties may in turn attract further development (Gopalakrishnan et al., 2011; McNamara et al., 2015; Nordstrom, 2000).

To explore this proposed relationship empirically, we use a large integrated data set: property-scale data from over 12,000 single-family shorefront homes fronting more than 1400 km of coastline around the U.S. state of Florida, combined with locations of historical and recent beach nourishment projects (Figure 3.1 a). We find that houses in nourishing zones are significantly larger and more numerous than in non-nourishing zones, and that the largest houses in nourishing zones are among the most recently built. While this spatial correlation does not establish the initial conditions of, or causality in, a relationship between coastal protection and development, it does reveal the signature of a positive feedback.

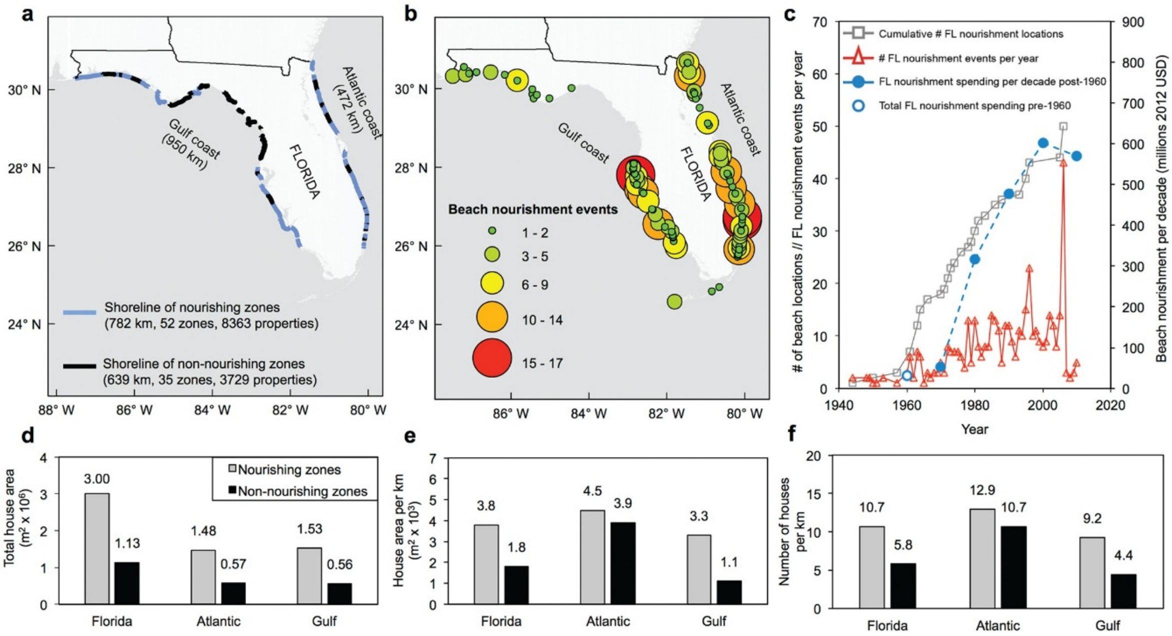

Figure 3.1 Beach nourishment and coastal development in Florida. (a) Shoreline segments of nourishing (light line) and non-nourishing zones (dark line) with shorefront single-family homes. (b) Map of recorded Florida nourishment events between 1940 and 2010. (c) Cumulative number of nourishing locations in Florida between 1940 and 2010; number of nourishment events per year in Florida between 1940 and 2010; and spending (in 2012 USD) on nourishment per decade in Florida since 1960 (open circle indicates total spending on nourishment prior to 1960). (d–f) Total house area (in m^2) (d), total house area per shoreline km (e), and total number of houses per km (f) in nourishing versus non-nourishing zones for all of Florida and the state's Atlantic and Gulf coasts.

There is more than one plausible route to intensified development in nourished zones. Nourishment may occur in higher-income zones, and faster income growth in nourishment zones may manifest in larger houses. Here, house size may be interpreted as a proxy for relative wealth, but is an indirect metric; matching fine-grained data capturing income and property value (Bin and Landry, 2013) would have been ideal, but were unavailable for this study. We do not suggest that coastal development is uniform prior to initial nourishment, or that nourishment projects are randomly allocated along the coast—antecedent conditions of coastal development surely play a role in where nourishment occurs. However, the range of spatial scales over which the nourishment–development relationship persists (from $\sim10^1$ to 10^3 km) suggests that the pattern of intensified development in nourishment zones is insensitive to specific, local-scale differences in building codes, permitting, and planning.

We focus our analysis on Florida because it is both an archetypal developed sandy coastline and an internationally relevant hotspot of coastal risk (Carter et al., 2014; Finkl, 1996; McNamara et al., 2015; Mileti, 1999; Moser et al., 2014; Nordstrom, 2000; NRC, 2014; Peacock et al., 2005; Wong et al., 2014). Florida has over three times the open-ocean coastline of other U.S. Atlantic or Gulf states (NOAA, 1975). Of 284 hurricane landfalls on the U.S. mainland between 1851 and 2010, 114 (40%) were in Florida, including 37 of 96 (39%) major hurricanes (Category 3–5) (Blake et al., 2011). In South Florida, porous limestone bedrock, low topography, growing urban centres, and aging water-management infrastructure make the coast from West Palm Beach (on the Atlantic side) to Fort Myers (on the Gulf of Mexico) especially sensitive to sea-level rise and weather-driven events, such as storm surges, that sea-level rise exacerbates (Carter et al., 2014). Of an estimated total $1 trillion in U.S. property and structures at risk from a potential 2 ft (0.61 m) increase in sea level (Parris et al., 2012), approximately half of that property is in Florida (Moser et al., 2014). Tourism and tax revenue from coastal development is fundamental to Florida's economy (Klein et al., 2004), and the state has a long history of coastal protection (Nordstrom, 2000). Of all recorded beach nourishment projects in U.S. Atlantic and Gulf states since the 1920s, the majority (27%) have occurred in Florida (Table 3.1). Although some places nourish more frequently than others (Figure 3.1 b), the cumulative number of beach locations in Florida that use or have used beach nourishment to protect against coastal hazard has increased steadily since the 1960s (Figure 3.1 c). The same is true of nourishment practices nationwide (NRC, 2014; Trembanis et al., 1999), with comparable trends in Europe (Hanson et al., 2002).

Table 3.1 Summary of Florida Beach Nourishment Events and Coastal Town Statistics.

	States	Coast Length (km)	All Nourishment Events	Florida Nourishment Events	% of All Events Represented by Florida
US Atlantic Coast	15	3230[a]	1242	265	21.34
US Gulf Coast	5	2610[b]	385	182	47.27
US Atlantic and Gulf	19	5840[c]	1627	447	27.47

	Coast Length (km)	# of Zones	# of Properties	Total House Area ($m^2 \times 10^6$)	Coast Length Per Zone (km)	# of Properties Per Zone	Total House Area Per Zone ($m^2 \times 10^3$)	# of Properties Per km	Total House Area Per km ($m^2 \times 10^3$)
All Florida	1423	87	12, 092	4.130	16.4	139	47.5	8.5	2.9
All FL Atlantic	472	39	5750	2.049	12.1	147.4	52.5	12.2	4.3
All FL Gulf	950	48	6342	2.081	19.8	132.1	43.4	6.7	2.2
All FL nourishing	782	52	8363	3.000	15.0	160.8	57.7	10.7	3.8
All FL non-nourishing	639	35	3729	1.130	18.3	106.5	32.3	5.8	1.8
FL Atlantic nourishing	325	24	4180	1.475	13.5	174.2	61.5	12.9	4.5
FL Atlantic non-nourishing	146	15	1570	0.574	9.8	104.7	38.3	10.7	3.9
FL Gulf nourishing	457	28	4183	1.525	16.3	149.4	54.5	9.2	3.3
FL Gulf non-nourishing	492	20	2159	0.557	24.6	108	27.8	4.4	1.1

	Coast Length (Miles)	# of Zones	# of Properties	Total House Area ($ft^2 \times 10^6$)	Coast Length Per Zone (Miles)	# of Properties Per Zone	Total House Area Per Zone ($ft^2 \times 10^3$)	# of Properties Per Mile	Total House Area Per Mile ($ft^2 \times 10^3$)
All Florida	884	87	12,092	44.454	10.2	139.0	510.9	13.7	50.3
All FL Atlantic	293	39	5750	22.051	7.5	147.4	565.4	19.6	75.3
All FL Gulf	590	48	6342	22.403	12.3	132.1	466.7	10.7	38.0
All FL nourishing	486	52	8363	32.287	9.4	160.8	620.9	17.2	66.4
All FL non-nourishing	397	35	3729	12.167	11.3	106.5	347.6	9.4	30.6
FL Atlantic nourishing	202	24	4180	15.875	8.4	174.2	661.4	20.7	78.6
FL Atlantic non-nourishing	91	15	1570	6.176	6.1	104.7	411.6	17.3	67.9
FL Gulf nourishing	284	28	4183	16.412	10.2	149.4	586.1	14.7	57.8
FL Gulf non-nourishing	306	20	2159	5.991	15.3	108.0	299.6	7.0	19.6

Note that all coast length measurements listed in the second (and third) section(s) of the table refer to Florida coastline fronted by single-family homes. The official total length of Florida's coast is 2170 km (1350 mi) (NOAA, 1975). This analysis therefore examines 66% of Florida's coastline; nourishing zones with shorefront single-family homes comprise 36% of the state's coastline overall.

a (Hapke et al., 2010; Morton and Miller, 2005; Shalowitz, 1964).

b (Morton et al., 2004; Shalowitz, 1964).

c (Hapke et al., 2010; Morton et al., 2004; Morton and Miller, 2005; Shalowitz, 1964).

3.3 Methods

To distinguish "nourishing" from "non-nourishing" coastal zones in Florida (Figure 3.1 a), we use the database of recent and historical U.S. beach nourishment projects maintained by the Program for the Study of Developed Shorelines (PSDS) (Pilkey and Clayton, 1989; Trembanis et al., 1999; Trembanis and Pilkey, 1998; Valverde et al., 1999). Projects in the database—the best available resource of its kind—are identified by a named "beach location" (e.g., "Jupiter Island") associated with an approximate latitude and longitude. We divide the coastline into "zones" according to ZIP code boundaries, and differentiate nourishing from non-nourishing zones by the presence of one or more beach nourishment projects within a given coastal segment. ZIP code areas are not the same as municipal jurisdictional boundaries. However, publicly available spatial data for Florida municipal boundaries are incomplete, comprising a small fraction of the (full) statewide spatial coverage afforded by ZIP code data: every Florida nourishment location in the nourishment database can be related spatially to a ZIP code; few can be related spatially to a municipality in the current dataset. Although one or more municipalities may overlap with a given ZIP code, and vice versa, spatial and jurisdictional boundaries for nourishment projects are not strictly municipal. Nourishment projects may span multiple municipalities, projects may be an elective local decision or be part of a federal emergency response to a disaster event, and even multi-decadal nourishment programs are designed to transfer project responsibility and management from federal to local authorities (NRC, 1995; Pilkey and Dixon, 1996). Given that the spatial boundaries pertaining to nourishment actions shift over time, ZIP codes serve as a useful, representative spatial unit by which to delineate coastal zones at intermediate scales ($\sim 10^1$ km) relative to individual property parcels ($\sim 10^{-1}$ km) and extended lengths of coastline ($\sim 10^3$ km).

To identify shorefront single-family homes, we query a spatially explicit, parcel-scale database of Florida properties assessed in 2010, available from the Florida Department of Revenue and the Florida Geographic Data Library. Listed parcel attributes include the total living area of an existing house and the year it was built. (Local municipality was not an attribute included in the housing data.) The single-family house criterion aligns our calculations with standard housing-stock metrics tracked by the U.S. Census Bureau. (In Figure 3.1 a, note that the greater Miami metropolitan area, on the east side of the South Florida peninsula, does not include any shorefront properties listed single-family houses, nor does Everglades National Park, immediately to the west.) To align the nourishment and property databases, we only include in our analysis beach nourishment projects undertaken before the end of 2010. Two-sample Kolmogorov–Smirnov tests check the extent to which house-size distributions for nourishing versus non-nourishing zones (Figure 3.3) (and various subsets of those distributions) are statistically different (Table B.1 in Appendix B, Supporting Information). Unless otherwise noted, we report comparative sample distributions that are significantly different at a threshold of $\alpha = 1\%$. These methods are further discussed in Appendix B.2.

3.4 Results

We find that nourishing zones account for more than half of the approximately 1400 km of Florida's coastline fronted by single-family homes (Table 3.1). Nourishing zones exceed non-nourishing zones in total number by nearly 50% (Figure 3.1 a). Total house area and number are both greater in nourishing zones than in non-nourishing zones (Figure 3.1 a, d), and nourishing zones are more densely developed in terms of house area and number per kilometre shoreline (Figure 3.1 e, f).

Shorefront housing density is higher on Florida's Atlantic coast, but the difference between housing density in nourishing versus non-nourishing zones is greatest on the Gulf coast (Figure 3.1 e, f). There are nearly three times as many Atlantic shorefront single-family houses in nourishing zones as in non-nourishing zones (and a 157% difference in total house area), but nourishing zones also claim 122% more Atlantic shoreline frontage (Figure 3.1 d; Table 3.1). By comparison, houses in Gulf coast nourishing zones are not only significantly larger than those in non-nourishing zones, they are more numerous. Gulf nourishing zones have nearly three times the house area per kilometre (Figure 3.1 e) and twice as many houses per kilometre (Figure 3.1 f) as non-nourishing zones, despite nearly equal lengths of relative shoreline frontage (Table 3.1).

These aggregate statistics of comparative house size and number prompt a more detailed look at the underlying data distributions (Figure 3.2; Figure 3.3; Figure 3.4; Table B.2). Parsing house size into percentile bands, we find that for the state overall (Figure 3.2 a) the relative difference in mean house area increases with percentile group. Mean size of houses in the 76–90th percentile is more than 50% larger in nourishing zones than in non-nourishing zones, and the very largest houses (91–100th percentile) in nourishing zones are nearly double the size of those in non-nourishing zones. Mean size of the largest houses on the Atlantic coast is greater in nourishing zones by 20% (Figure 3.2 b). On the Gulf coast, although mean house size in nourishing towns is larger across all percentile groups, houses in the 76–90th and 91–100th percentiles are larger in nourishing zones by 129% and 273%, respectively (Figure 3.2 c).

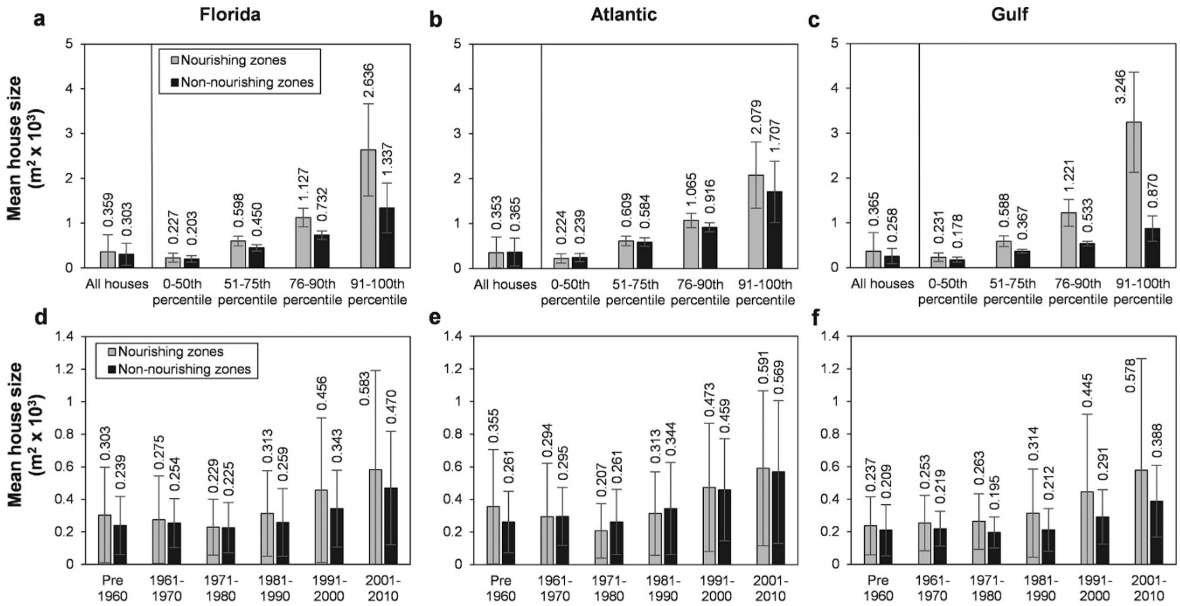

Figure 3.2 Mean house size by percentile for total living area and by decade built. (a–c) Mean size (m^2) of shorefront single-family houses ranked by percentile band for total living area in nourishing versus non-nourishing zones for all of Florida (a), and the state's Atlantic (b) and Gulf coasts (c). (d–f) Mean size of shorefront single-family houses sorted by decade built in nourishing versus non-nourishing zones for all of Florida (d), and the state's Atlantic (e) and Gulf coasts (f). Whiskers indicate ±1 standard deviation.

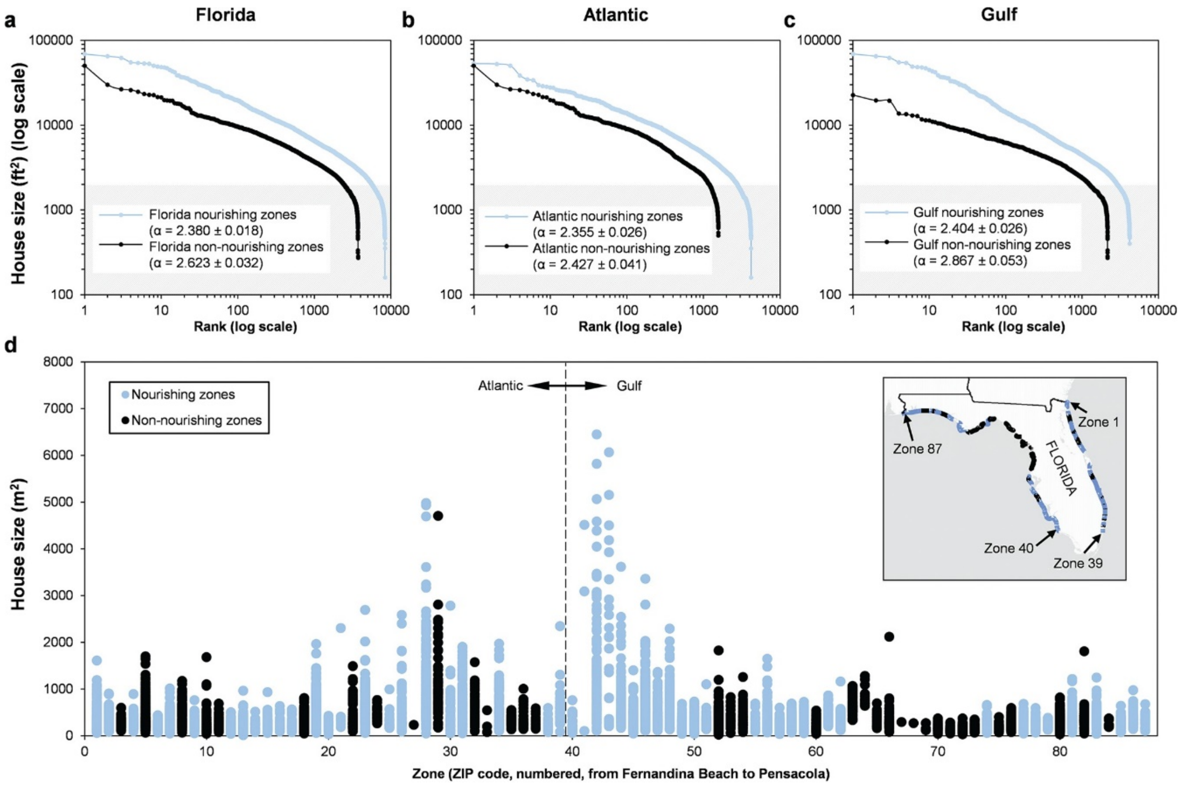

Figure 3.3 Size data for Florida shorefront single-family houses. (a–c) Log–log rank-order plots of house size (m^2) for all shorefront single-family homes in this study (n = 12,092), separated by nourishing (light line) and non-nourishing zones (dark line) for all of Florida (a), and the state's Atlantic (n = 8363) (b) and Gulf coasts (n = 3729) (c). Power law exponent (α) and expected statistical error (σ) are calculated according to Newman (2005), and apply to houses larger than ~186 m^2 (2000 ft^2); shaded region indicates houses smaller than that threshold. (d) Plot showing individual house sizes per coastal zone, where zones are numbered according to their sequence in real physical space (inset and Figure 3.1 a). Note that no single zone drives the disparity in house size between nourishing (blue) and non-nourishing zones (black). Even where zone types appear grouped (e.g., nourishing zones near other nourishing zones), the spatial scale of those groups is very large (>10^2 km), and may include municipalities of very different sizes and descriptions that locally manage their coastlines in different ways.

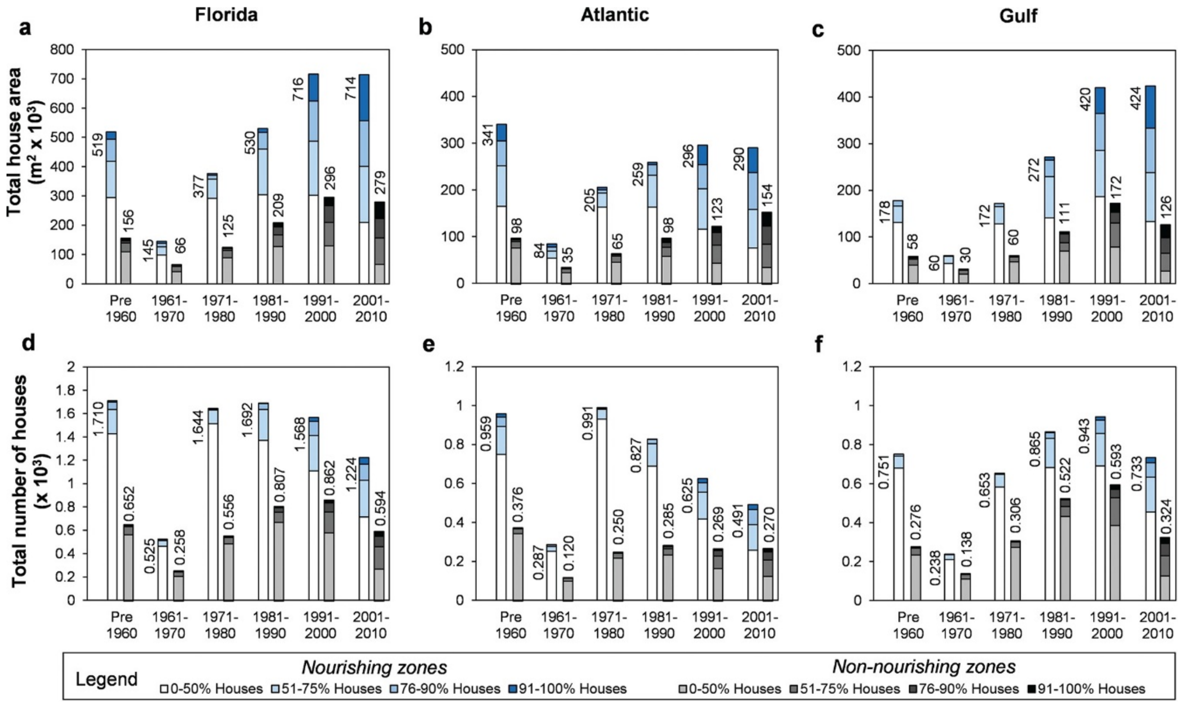

Figure 3.4 Total area and number of houses by decade built and percentile for size. (a–c) Total area (m^2) of shorefront single-family houses by decade built, with relative contributions from percentile bands for size, for all of Florida (a), and the state's Atlantic (b) and Gulf coasts (c). (d–f) Number of houses by decade built, with relative contributions from percentile bands for size, for all of Florida (d), and the state's Atlantic (e) and Gulf coasts (f). These data underpin the categorical means presented in Figure 3.2, and are provided in full in Table B.2.

Further subdividing the parcel data by year built lends insight into characteristics of Florida's shorefront single-family housing stock in the past. The data are for properties assessed in 2010, and do not represent a complete spatio-temporal record of previous houses that may have existed on a given parcel. Assuming some houses in the dataset replaced pre-existing structures, the data are likely skewed toward recent construction. However, assuming the absence of any temporal trend requires the unlikely condition that any houses formerly in the shorefront stock were at least as large as new houses that replaced them. Some legacy of development patterns from past decades (Desilver, 2015) is therefore embedded in the 2010 survey.

Figure 3.2 d shows the mean size of Florida shorefront single-family houses increases with each decade after the 1970s. In nourishing and non-nourishing zones alike, the average house built after 2001 is roughly twice the size of an existing house built in the 1960s. But the disparity between mean house size in nourishing and non-nourishing zones also increases with decade built (Figure 3.2 d; Table B.2). Mean size of houses built in the 1960s is only 8% larger in nourishing zones than in non-nourishing zones; for houses built after 1981, that relative difference in mean size increases to 21–33%. Development on the Gulf coast appears responsible for much of that increase (Figure 3.2 e, f). The mean size of Gulf houses built after 2001 is 250% larger in nourishing zones than in non-nourishing zones (Figure 3.2 f). The difference between total areas of houses built after 2001 in nourishing and non-nourishing towns is 5.5 times higher than the equivalent difference between houses built in the 1960s (∼3 times higher on the Atlantic coast; ∼10 times higher on the Gulf coast—see Table B.2).

3.5 Discussion and Implications

Recently built, large houses comprise a disproportionate quantity of the total house area in Florida's nourishing zones (Figure 3.4; Table B.2), and the size disparity relative to non-nourishing zones appears to be as large as it has ever been. According to a recent analysis of nationwide U.S. Census Bureau data (Desilver, 2015), the mean area of a single-family house built in 2014 is 57% larger than it was four decades ago (and the largest new homes have been built in the southeastern United States). We find that not only does the mean size of existing Florida shorefront single-family homes in 2010 exceed the 2014 new-build national average (Desilver, 2015) by 34%, but mean home size in nourishing zones in 2010 exceeds the 2014 new-build national average by 45%. The comparisons we calculate for coastal Florida demonstrate the extent to which development is concentrating in nourishing zones. While the details of building codes, permits, rules, and ordinances matter at the scale of individual properties and towns, our results show that intensified development in nourishment zones manifest across a range of much larger spatial scales (∼10^1–10^3 km), indicative of a feedback in coastal development apparently insensitive to specific differences in local management (Werner and McNamara, 2007).

We offer three possible, and not necessarily exclusive, explanations for how a positive feedback—or the signature of one—between coastal development and beach nourishment might arise. One possibility is that the spatial correlation we find is spurious; however, we consider spuriousness unlikely in this case, given that the disparity evident across the full scale of the data set is reproduced at subsampled, smaller spatial scales (Figure 3.3).

Another possibility we cannot rule out is that the overall feedback, rather than being insensitive to specific policies and management at local scales, is the cumulative effect of them. Perhaps various, contextually specific management practices, policies, and regulations around the state are driving local positive feedbacks between development and nourishment. With the exception of direct federal interventions for disaster relief, calls for beach nourishment projects originate locally, “sponsored” by a city, county, state, or regional authority, who request that the U.S. Army Corps of Engineers (USACE)—responsible for all U.S. navigable waterways—undertake a feasibility study (NRC, 1995). Over time, as project scope or maintenance requirements change for a given location, so might the sponsoring body. Notably, "only in the case of completely private ownership of a continuous strip of property with no public access is the federal government excluded from participation in shore protection projects" (NRC, 1995), and these circumstances are rare (Kelley et al., 2009). In terms of development, local governments in high-risk zones can require building codes for flood-proofing, for example, but such codes are not always implemented or enforced (Kunreuther, 1996; NRC, 2014). The pattern evident in our results therefore could reflect the combination of these local machinations, playing out independently of each other across the state.

A third possibility is that the positive feedback across the greater developed coastal system is the emergent consequence of a fundamental, common mechanism. We consider two such mechanisms. One is the economic concept of moral hazard: given access to nourishment protection and federal flood insurance, both subsidized, owners of shorefront property assume greater risk (build bigger houses) because they do not bear the full cost associated with that risk (Bagstad et al., 2007; Brody et al., 2016; Cutter and Emrich, 2006; McNamara et al., 2015; Petrolia et al., 2013). Federal subsidies for nourishment programs and flood insurance thus obscure the true cost of both mitigation actions and hazard impacts. In many cases (but not all), the federal government pays 65% of nourishment construction and some maintenance costs (NRC, 1995); 65–85% of U.S. nourishment projects include a federally funded component (Trembanis et al., 1999).

A second potential mechanism—more general than moral hazard, and not necessarily mutually exclusive from it—is that intensified development in nourishment zones could represent a variant of Jevons' paradox, a theoretical (and contested) argument from environmental economics in which more efficient use of a finite resource spurs an increase in its consumption (Alcott, 2005; Jevons, 1865; Sorrell, 2009). Jevons framed his original treatise in terms of coal. As steam-engine technology improved, engines became more efficient at converting coal into power. Even as better engines consumed less coal, industry—paradoxically, Jevons argued—was consuming coal in ever-increasing quantities. Here, we may consider coastal land the finite resource and coastal real-estate its "converted" form (or, land is to real-estate as coal is to power). Beach nourishment, then, functions as a kind of steam engine: by buffering against damage from hazards (e.g., storm impacts, chronic shoreline erosion) and preventing land loss over time, nourishment effectively "improves" the conversion of coastal land into viable real-estate. A reduction in coastal risk is thus equivalent to a gain in efficiency. Theoretically, if rates of development and hazard forcing remain constant, a nourishment program designed to optimize long-term economic net benefits should account for and counterbalance hazard effects, delivering a net gain in the overall economic benefit from the developed coastal zone (Landry, 2011; Landry and Hindsley, 2011; NRC, 1995, 2014; Smith et al., 2009).

However, we might infer from our results that intended reductions in coastal risk through hazard protection are ultimately offset, or even reversed, by increased coastal development. The trends we document appear to be evidence of large-scale, so-called “rebound” or “backfire” effects (Sorrell, 2009) in coastal risk. Rebound occurs when increased consumption offsets gains from increased resource efficiency. Returning to Jevons' coal system, total consumption is unchanged despite a better engine, in part because the system metabolizes the costs saved through efficiency into the production of so many more engines. Backfire is when increased consumption more than erases any gains. In the coastal system, if mitigating against hazard directly or indirectly encourages development and vice versa, such that investment in and “consumption” of coastal real-estate increases, then a positive feedback loop may lead to rebound, if not backfire. Beach nourishment may mask or reduce the apparent impact of coastal hazards without changing the natural processes driving them (Finkl, 1996; Landry and Jahan-Parvar, 2011; McNamara and Keeler, 2013; Petrolia et al., 2013; Wilde, 1998). Beach nourishment does not change the rate of sea-level rise, the prevailing wave climate, or where hurricanes make landfall. Masked risk, or the deceptive appearance of reduced risk—a wide, nourished beach is temporary, and eventually even a long-term beach-nourishment project may be discontinued—may lead to intensified development behind nourished beaches. (The lack of risk reduction, real or perceived, may inhibit development investment in non-nourishing zones.)

An appendix to the NRC landmark report on beach nourishment, published in 1995, includes a section—“Special features of the beach nourishment problem”—that describes a hypothetical scenario (NRC, 1995). If a beach nourishment project

> “increases amenity value of a given piece of privately owned property and reduces the risk of damage to or loss of the property from storms or erosion,” then “the land-use of the property may change. The USACE guidelines recognize this and suggest that, in forecasting the ‘with-plan conditions’, ‘any changes in population, land-use, affluence, or intensity of use expected as a result of implementation of a plan’ need to be included. In practice, however, these may be limited to gains from intensified or higher-valued uses of land owing to the reduction in risk. Thus, if a project provides risk reduction to private property, which subsequently stimulates private investment, the increase in net annualized income of the property (for example) may be counted as a benefit.”
>
> (NRC, 1995)

By raising the total value of infrastructure vulnerable to damage, intensified development makes its own case for intensified protection through continued or increased nourishment (McNamara et al., 2015; Mileti, 1999; Nordstrom, 2000; Turner, 2000).

We cannot state unequivocally that nourishment directly causes demand for large coastal houses to increase so much that all protection benefits from nourishment are lost. But if initial reductions in risk through beach nourishment are surpassed by rapid growth in coastal development, then the coastline becomes overdeveloped relative to the nourishment program intended to protect it, and risk continues to increase. The combination of federally subsidized nourishment and flood insurance (Bagstad et al., 2007; Landry and Jahan-Parvar, 2011) has possibly pushed developed coastlines past rebound and into backfire, with major ramifications for future coastal management and strategies for adaptation to climate change (McNamara et al., 2015).

Longevity and effectiveness of hazard interventions ultimately depend on the dynamics of natural physical conditions. Future climate-related coastal hazard impacts are expected only to intensify (Church et al., 2013). Development pressures related to growing coastal populations are increasing (Moser et al., 2014; NOAA, 2013; Wong et al., 2014). Meanwhile, the cost of nourishment projects is rising (Hoagland et al., 2012), and not all nourishing zones have equal likelihood of continued nourishment in the future, either because of differences in sand availability or financial resources or both (NRC, 1995, 2014). Given these realities, future spatial patterns of development disparity and relative coastal risk may be even more polarized if access to nourishment becomes an option for coastal adaptation only available to the wealthiest developed coastal zones (Lazarus et al., 2016; Lazarus, McNamara, et al., 2011; McNamara et al., 2011; Williams et al., 2013).

Resolving the dynamics driving the feedback (or feedbacks) between coastal development and hazard protection will require innovative research into short- and long-term decision-making among property owners and coastal managers (Paterson et al., 2014) that combines empirical and theoretical perspectives from psychology and economics (Brody et al., 2016; Busemeyer and Townsend, 1993; Gopalakrishnan, Landry, et al., 2016; Lazarus et al., 2016; Peacock et al., 2005; Slovic et al., 1977). The data and analysis we present here demonstrate the indication of a positive feedback between shorefront housing development and beach nourishment, but do not demonstrate causality. For that, more work is needed (e.g., improving historical temporal resolution across the same spatial coverage by reconstructing historical development patterns from decades of parcel-scale tax records). Indeed, once underway, most positive feedbacks blur into chicken-and-egg problems, especially if they turn out to have little dependence on specific initial conditions. That said, we contend that this feedback is systemic—a “special feature of the beach nourishment problem” that is exacerbating coastal risk.

3.6 Acknowledgements

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Chapter 4 Paper 3: Reconstructing patterns of coastal risk in space and time along the US Atlantic Coast, 1970–2016

This paper is submitted to Natural Hazards and Earth System Science, and is available as a discussion paper:

Armstrong, S. B., and Lazarus, E. D., 2019b. Reconstructing patterns of coastal risk in space and time along the US Atlantic Coast, 1970–2016. *Natural Hazards and Earth System Sciences Discussions*, **In review**. DOI: 10.5194/nhess-2019-159

Preliminary results from this chapter were presented as:

Poster: Armstrong, S.B., and Lazarus E.D., 2018, December. Unsafe at any speed? The velocity of coastal risk along the US Atlantic Coast. In: *AGU Fall Meeting Abstracts*.

4.1 Abstract

Despite interventions intended to reduce impacts of coastal hazards, the risk of damage along the US Atlantic Coast continues to rise. This reflects a long-standing paradox in disaster science: even as physical and social insights into disaster events improve, the economic costs of disasters keep growing. Risk can be expressed as a function of three components: hazard, exposure, and vulnerability. Risk may be driven up by coastal hazards intensifying with climate change, or by increased exposure of people and infrastructure in hazard zones. But risk may also increase because of interactions, or feedbacks, between hazard, exposure, and vulnerability. Here, we present a data-driven model that describes trajectories of risk at the county scale along the US Atlantic Coast over the past five decades. We also investigate indications of feedbacks between risk components that help explain these trajectories. Our findings suggest that spatially explicit modelling efforts to predict future coastal risk need to address feedbacks between hazard, exposure, and vulnerability to capture emergent patterns of risk in space and time.

4.2 Introduction

Risk reduction in developed coastal zones is a global challenge (Parris et al., 2012; Sallenger et al., 2012; Witze, 2018; Wong et al., 2014). In general terms, risk can be expressed as a function of hazard, exposure, and vulnerability (NRC, 2014; Samuels and Gouldby, 2009). Hazard is typically expressed as the likelihood that a natural hazard event will occur (e.g., a recurrence interval for a storm of a given magnitude) or as a chronic rate of environmental forcing (e.g., a rate of sea-level rise). Exposure tends to capture either the economic value of property and infrastructure that a hazard could negatively impact, or the number of people a hazard could affect. Vulnerability can reflect a wide variety of dimensions, but in physical terms (relative to social metrics) vulnerability generally represents the susceptibility of exposed property to potential damage by a hazard event (NRC, 2014). Although the reduction of disaster risk – across all environments, not only coastal settings – is an intergovernmental priority (UNISDR, 2015), a paradox has troubled disaster research for decades. Even as scientific insight into physical and societal dimensions of disaster events get clearer and more nuanced, the economic cost of disasters keeps rising (Blake et al., 2011; Mileti, 1999; Pielke Jr. et al., 2008; Union of Concerned Scientists, 2018).

There are a number of possible explanations for this trend. Economic costs could be rising because natural hazards, exacerbated by climate change, are getting worse (Estrada et al., 2015; Sallenger et al., 2012); because with migration and population growth more people are living in hazard zones (NOAA, 2013); or because more infrastructure of economic value, from highways to houses, now exists in hazard zones (AIR Worldwide, 2013; Desilver, 2015; Union of Concerned Scientists, 2018). These drivers are typically addressed separately – but they are not mutually exclusive.

An alternative explanation for the disaster paradox is that environmental, population, and infrastructural drivers are systemically intertwined, resulting in "disasters by design" (Mileti, 1999) – unintended consequences of coupled interactions, or feedbacks, between natural forcing and societal shaping of the built environment. An example of one such feedback is when infrastructure development in hazard zones destroys natural features that would otherwise buffer hazard impacts (e.g., the loss of coastal wetlands that would have absorbed storm surge) (Barbier et al., 2011; Temmerman et al., 2013). An example of another feedback is when hazard defences stimulate further infrastructure development behind them – a phenomenon called "safe development paradox" (Armstrong et al., 2016; Burby, 2006; Keeler et al., 2018; McNamara and Lazarus, 2018; Werner and McNamara, 2007). While both feedbacks can increase hazard impacts without any change in natural forcing, climate change accelerates them.

Investigations of coastal risk tend to focus on case studies of hazard, exposure, and/or vulnerability (Smallegan et al., 2016; Taylor et al., 2015), or on projections of future risk (e.g., Brown et al., 2016; Hinkel et al., 2010; Neumann et al., 2015). Few examine patterns of risk across large spatial scales (~10^2–10^3 km) or retrospectively over longer time scales (>10^1 yrs). Here, we develop a data-driven model to investigate how hazard, exposure, and vulnerability may describe trajectories of risk in space and time along the US Atlantic Coast, from Massachusetts to South Florida, at the county-level for the past 47 years (Figure 4.1). Our findings suggest that spatially explicit modelling efforts to predict future coastal risk need to address feedbacks between hazard, exposure, and vulnerability to capture emergent patterns of risk in space and time.

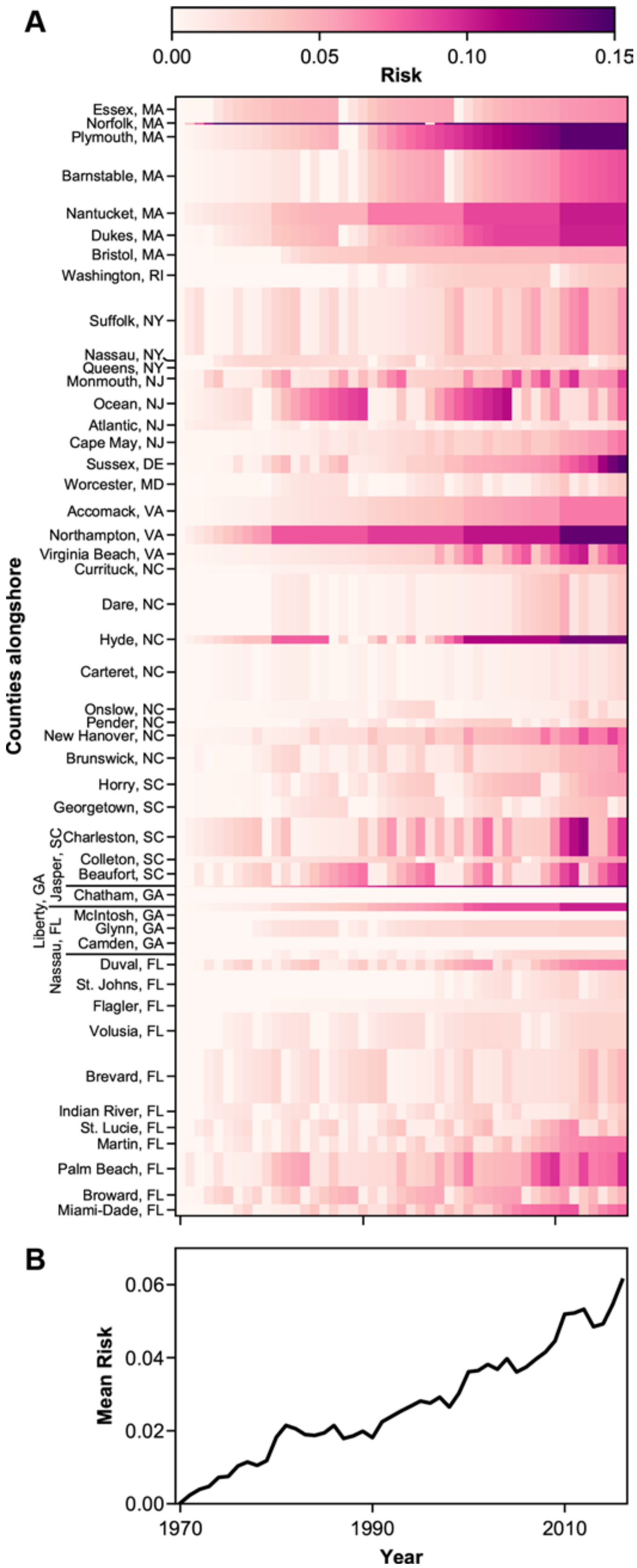

Figure 4.1 Evolution of risk (a function of hazard, exposure, and vulnerability) modelled at the (a) county scale along the US Atlantic Coast, from 1970–2016. Hazard in this simulation reflects historical erosion rates. County width is scaled by shoreline length. Panel (b) shows mean risk through time from (a). *Risk in Norfolk, Ma (a) exceeds the maximum scale bar value of 0.15 (2016 risk = 0.418; Table 4.1).

4.3 Methods

Using the components of risk broadly defined by the US National Research Council (NRC, 2014; Samuels and Gouldby, 2009), we represent coastal risk as a function of time (*t*) with the expression:

$$R(t) = H\,E\,V \qquad (1)$$

where *R* is coastal risk, *H* is natural hazard, *E* is exposure, and *V* is vulnerability. We define hazard (*H*) in terms of chronic shoreline erosion (as opposed to the likelihood of a hazard event). We define exposure (*E*) in terms of the total property value of owner-occupied housing units in US Atlantic coastal counties. We address vulnerability (*V*) as a function of beach width, modulated by beach nourishment – the active placement of sand on a beach to counteract erosion – which functions as a buffer between hazard and exposure (Armstrong et al., 2016; Armstrong and Lazarus, 2019a). For the purposes of this analysis, we limit our consideration to physical infrastructure; we do not address socio-economic or demographic vulnerability (Cutter et al., 2006, 2008; Cutter and Emrich, 2006; Cutter and Finch, 2008).

4.3.1 Hazard

We calculated rates of shoreline change in two different ways to compare their respective effects on risk over time.

4.3.1.1 Shoreline-change rates from shoreline surveys

First, we calculated "end-point" rates of change from surveys of shoreline position published by the US Geological Survey (USGS) (Himmelstoss et al., 2010; Miller et al., 2005). An end-point rate is the cross-shore distance between two surveyed shoreline positions, divided by the time interval between the surveys. Using the Digital Shoreline Analysis System (DSAS) tool for Arc GIS (Thieler et al., 2008), we cast cross-shore transects every 1 km alongshore to intersect the surveyed shorelines, and at each transect calculated the end-point rate for three time periods (Armstrong and Lazarus, 2019a): "historical", from the first survey to 1960; "recent", from 1960 to the most recent survey; and "long-term", from the first survey to most recent (Figure 4.2 a, e, i; Figure 4.3 a). We calculated the median historical, recent, and long-term rates of shoreline change for each county alongshore.

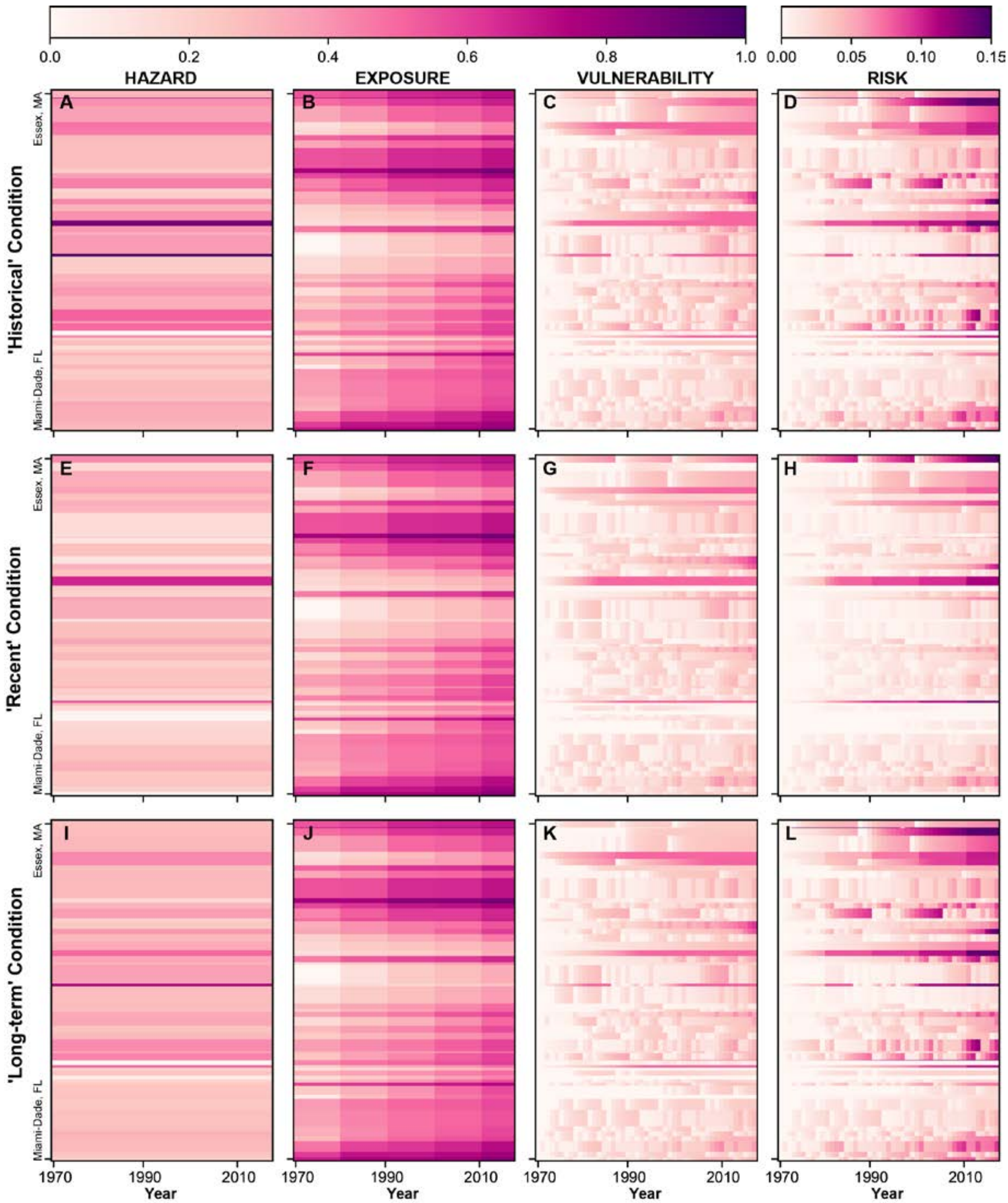

Figure 4.2 Columns show hazard, exposure, and vulnerability components and resulting risk. Each row of panels illustrates a different rate of shoreline change (i.e., hazard condition): (a–d) historical, (e–h) recent, and (i–l) long-term. *Risk in Norfolk, Ma (d) exceeds the maximum scale bar value of 0.15 (2016 risk = 0.418; Table 4.1).

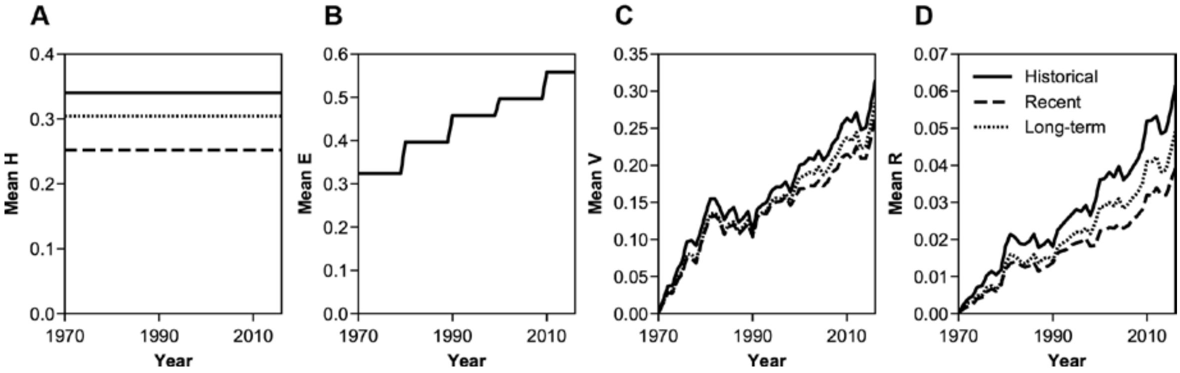

Figure 4.3 Evolution over time of alongshore mean risk components – (a) hazard, (b) exposure, and (c) vulnerability – and the resulting (d) mean risk, given historical (solid black), recent (dashed black), and long-term (dotted black) shoreline-change rates as hazard conditions.

We used 1960 to differentiate between historical and recent shoreline-change rates because during that decade, beach nourishment overtook shoreline hardening to become the predominant form of coastal protection in the United States (NRC, 1995, 2014). Cumulative, diffuse effects of nourishment are therefore embedded in recent and long-term rates of shoreline change (Hapke et al., 2013; Johnson et al., 2015). A historical rate calculated from shorelines surveyed prior to 1960 may better reflect environmental forcing in the effective absence of beach nourishment (Armstrong and Lazarus, 2019a). These historical rates are not "natural" rates: human alterations to the US Atlantic Coast began long before 1960, with engineered protection, including seawalls, groyne fields, and limited beach-nourishment projects (Hapke et al., 2013). Here, we consider them a pre-nourishment "background" rate of chronic forcing.

4.3.1.2 Shoreline-change rates from sea-level change rates

To test an independent measure of chronic shoreline-change hazard, we also derived rates of shoreline change (Figure 4.4 a, e) from recorded rates of sea-level change (Holgate et al., 2013; PSMSL, 2018) and a USGS dataset of cross-shore slope for the US Atlantic Coast (Doran et al., 2017). We calculated spatially distributed rates of sea-level rise from annual tide-gauge records maintained by the Permanent Service for Mean Sea Level (PSMSL) (Holgate et al., 2013; PSMSL, 2018). For each tide-gauge record, we linearly interpolated across gaps in the annual data. We smoothed the resulting continuous record with a 10-year moving average, and calculated the annual rate of sea-level change (Table C.1). Because the tide-gauge locations are not evenly distributed alongshore, to find rates of sea-level change for the full extent of the US Atlantic Coast we linearly interpolated rates of sea-level change between tide-gauge stations, and calculated the median annual rate of sea-level change at each coastal county. To convert a vertical change in sea level to a horizontal change in shoreline position, we shifted shoreline position at each transect up (or down) cross-shore slope from USGS coastal lidar surveys (Doran et al., 2017) (Table C.2). Linking the slope measurements to county shapefiles with a spatial join, we calculated median slope per county and then the horizontal distance that each annual vertical change in sea level moved the shoreline (Figure 4.4 a).

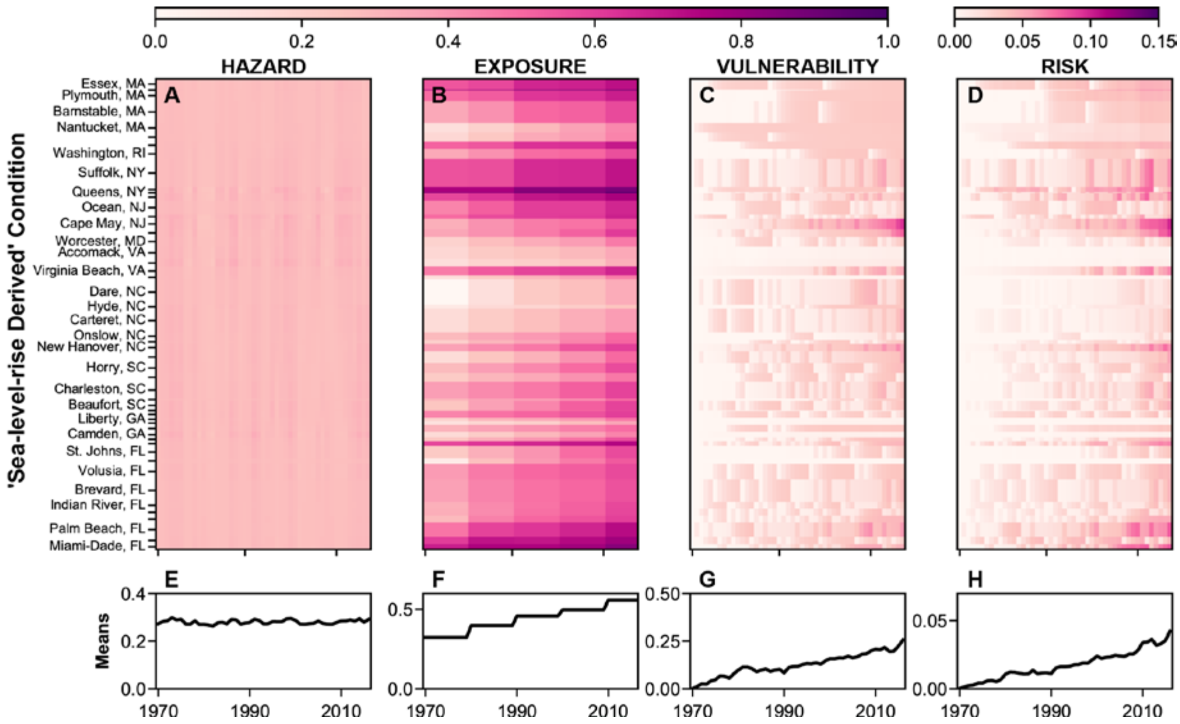

Figure 4.4 County-scale component (a) hazard, (b) exposure, (c) vulnerability and (d) overall risk evolution over time, and (e–h) corresponding means, using shoreline-change rates derived from sea-level change as the hazard condition.

The relationship between sea-level change and shoreline position is more complicated than the one abstracted in our deliberate simplification (Cooper and Pilkey, 2004; Lentz et al., 2016; Nicholls and Cazenave, 2010). Our estimation is effectively a "bathtub model" of change, controlled only by topography with no incorporation of wave-driven sediment transport or other shoreline dynamics. However, for this exercise, our method is useful for its simplicity – especially given the spatial scales under consideration – and for the independent estimation of shoreline change that it provides.

4.3.1.3 Sign convention

By the sign convention in our calculations, a negative rate of shoreline change denotes accretion (reducing hazard), and a positive rate denotes erosion (increasing hazard) (Figure 4.2 a, e, i). Hazard magnitudes are normalized by the minimum and maximum rates to range between 0–1.

4.3.2 Exposure

To represent exposure along the US Atlantic Coast, we used county-level Census data for the total value (adjusted to 2018 $USD) of owner-occupied housing units for each decade from 1970 (Table C.3) (Minnesota Population Center, 2011). Because property value data are sparse for the 2010 Census community survey (16 Atlantic coastal counties are missing), we instead used the 2009–2013 Census five-year survey. Several five-year Census surveys incorporate 2010, but we chose the 2009–2013 survey because it provides full overage of all the Atlantic coastal counties, and its mean of total values is closest to the 2010 Census community survey (for those Atlantic coastal counties surveyed in 2010). We adjusted the county-total values of owner-occupied housing units to 2018 $USD and divided by the number of transects in each county to yield a proxy for property value per alongshore kilometre. Because of the range of values along the coast, we took a log-transform and normalized the results to fall between 0–1 (Figure 4.2 b, f, j; Figure 4.3 b).

4.3.3 Vulnerability

We represented vulnerability (V) with a two-part relationship that tracks beach width (V_{bw}) and beach nourishment (V_{bn}) over time:

$$V = 0.5V_{bn} + 0.5V_{bw} \quad (2)$$

Because the value of exposed property is not included in V_{bw} or V_{bn}, this formulation disentangles vulnerability from exposure – a subtle but important conceptual departure from the definition used by the National Research Council (NRC, 2014; Samuels and Gouldby, 2009), which includes property values in vulnerability.

We made the beach-width component (V_{bw}) inversely related to vulnerability, such that vulnerability increases as beach width decreases. We express the beach-width component as:

$$V_{bw} = (x_0 + 1) - x \quad (3)$$

where x_0 is maximum beach width and x is beach width. We then normalized by the maximum and minimum V_{bw}. Because the real measurements are unavailable, we assumed that in 1970 all counties had the same beach width (x). From this baseline, the county-scale shoreline erodes or accretes according to the linear rate determined by the hazard condition (historical, recent, long-term, or sea-level derived). Because we used counties as the smallest spatial unit of comparison, our assumption implies that each county is fronted by beach. The physical geography of the real coastline is, of course, more spatially heterogeneous. Our analysis is too coarse to capture, for example, change at isolated pocket beaches in a predominantly rocky coastline, but counties with rocky coastlines will reflect very low or null rates of shoreline change.

For the beach-nourishment factor (V_{bn}), we collated beach-nourishment projects since 1970 by county from the beach-nourishment database maintained by the Program for the Study of Developed Shorelines (PSDS, 2017). We took V_{bn} as the running total number of nourishment projects per county over time (summed annually), and normalized V_{bn} by the maximum total number of projects across counties as of 2016 (i.e., the county that nourished the most has V_{bn} = 1 in 2016). Each county starts with V_{bn} = 0 in 1970, and V_{bn} increases incrementally with every nourishment project within the county boundary. We initiated V_{bn} in 1970 to match the Census data for exposure (*E*). Because 80% of beach nourishment projects on the US Atlantic Coast have occurred since 1970, we excluded a relatively small number of events. To test the sensitivity of our vulnerability and risk results to the 1970 start date, we examined the relative effects of (1) initiating V_{bn} from the first nourishment project in our record (in 1930), and (2) excluding the V_{bn} term altogether (Figure C.1). Although the risk patterns resulting from these sensitivity tests changed in detail, their general characteristics did not.

In our routine, until a county nourishes for the first time, beach width (*x*) changes according to the county median linear erosion rate (γ):

$$x(t) = x_{t-1} + \gamma_t \tag{4}$$

The linear erosion rate (γ) applied to each county is either the (pre-normalised) historical, recent, or long-term shoreline change rate, or the rate derived from sea-level change, depending on the hazard scenario. The sign convention for γ is negative for erosion, and positive for accretion.

Once a county has nourished – as determined by the empirical dataset of nourishment projects (PSDS, 2017) – beach width becomes a function of a linear erosion rate (γ), as in Eq. (4), and a nonlinear erosion rate (ϑ), which is applied to the nourished fraction of the total beach width (μ) to capture cross-shore and alongshore diffusion of nourishment deposition across and along the shoreface (Dean and Dalrymple, 2001; Lazarus, McNamara, et al., 2011; Smith et al., 2009):

$$x(t) = (1-\mu)x_0 + \mu e^{-\theta t}x_0 + \sum_1^t \gamma_t \tag{5}$$

where x_0 is maximum beach width, ϑ is nonlinear erosion rate, μ is the fraction of the total beach width that the nonlinear rate applies to, γ is linear erosion rate, and *t* is the number of years since the last nourishment project. If a county nourishes at least once in a given year, its beach is restored to a maximum width in that year before it begins to erode. (Our minimum temporal increment was 1 year, and we assumed that nourishment always occurs at the end of a given year.) Maximum beach width (x_0), nonlinear erosion rate (ϑ), and the fraction of beach width affected by the nonlinear rate (μ) are variables applied to the full spatial domain. Beach width (at the county scale) thus changes at a linear rate (γ), where a negative value is erosion and a positive value is accretion, with an additional nonlinear erosion rate (ϑ) over a fraction of the beach (μ) when nourishment occurs, until the beach is restored to maximum width by a subsequent nourishment project or reaches a specified minimum width (here, 10 m). The V_{bn} term is ultimately normalised by the maximum and minimum beach width.

Because vulnerability is normalised, the minimum beach width that we specify (10 m) affects the length of time it takes to reach maximum V_{bw}, but does not affect the overall magnitude of V. A wider minimum threshold means that V_{bw} reaches a maximum faster, and vice versa. We used a minimum width of 10 m to avoid the numerical instabilities in V_{bw} that arise with a minimum width equal to or less than 0 m. The minimum width threshold does not affect the cumulative beach-nourishment factor.

We test the effect of altering x_0, ϑ, and μ on both vulnerability and risk, under historical hazard and linear erosion rates (Figure C.1; Table C.4). Sensitivity testing shows that vulnerability over time is highest in the case of a narrow beach (x_0 = 25 m) with a high nonlinear erosion rate (ϑ = 0.75) affecting a large fraction of the beach (μ = 0.75). Vulnerability over time is lowest in the opposite case (x_0 = 100 m, ϑ = 0.05, μ = 0.25) (Fig S1). In calculating our results, we used a case in the middle of these extremes (x_0 = 50 m, ϑ = 0.5, μ = 0.33), applying a value of μ similar to the value (μ = 0.35) used by Smith et al. (2009) and Lazarus, McNamara, et al. (2011).

Like a ratchet, the cumulative beach-nourishment factor (V_{bn}) increases each time a county nourishes. The beach-width factor (V_{bw}) is comparatively more dynamic, reaching a minimum after a nourishment project (as the wide beach buffers property from hazard) but increasing as the nourished beach erodes and coastal properties become more susceptible to hazard.

4.4 Results

4.4.1 Risk trajectories

Our data-driven model generates a pattern of coastal risk that varies in space and time at county scale along the US Atlantic Coast (Figure 4.1). From 1970, each county generates its own risk trajectory that represents the interaction of hazard, exposure, and vulnerability in that county (Figure 4.1 a). For visualisation and analysis, we scaled each county by the number of 1 km transects they comprise (Figure 4.1 a). The result is a matrix of 2386 km over 47 years, in which each of the 2386 (1 km) rows is associated with a county. Alongshore mean values for the whole

US Atlantic Coast are taken from the full matrix so that they reflect the relative alongshore scale of each county (Figure 4.1 b).

We find that the collective trajectory of risk increases from 1970 to 2016 for all hazard scenarios – despite the occurrence of 998 beach-nourishment projects, ostensibly intended to reduce risk, during the same period (Figure 4.2; Figure 4.3). The influence of beach-nourishment projects on vulnerability means that county-scale risk varies over time even if hazard forcing remains constant. Because hazard based on measured shoreline change (historical, recent, and long-term) is spatially variable but temporally static (Figure 4.2; Figure 4.3), changes in risk over time under this model condition are driven by either exposure or vulnerability.

The overall risk trajectory also increases with the spatio-temporally variable hazard condition derived from rates of sea-level rise (Figure 4.4). The alongshore mean rate derived from sea-level rise shows close agreement with the mean "recent" shoreline-change rate, suggesting that our simplified "bathtub" representation of hazard is reasonable on a multi-decadal time scale (Figure 4.5).

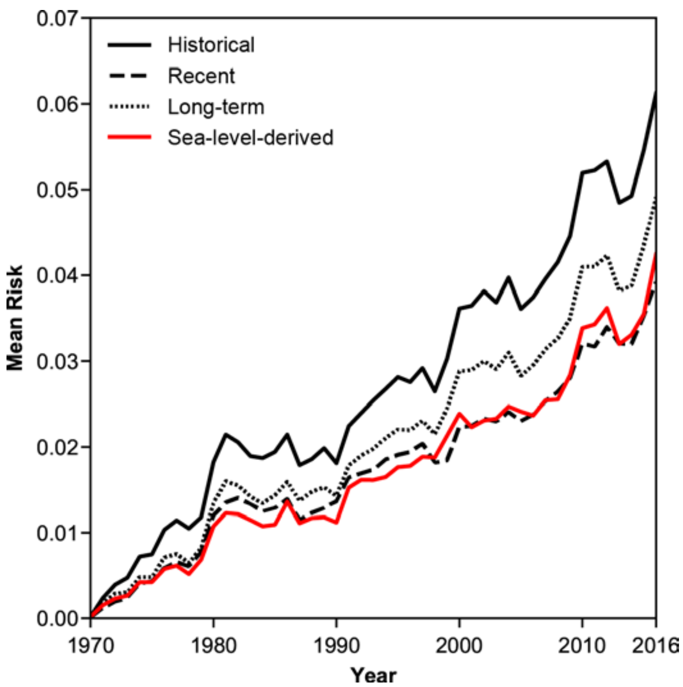

Figure 4.5 Comparative evolution of mean risk over time under different representations of shoreline-change rate (hazard condition): historical (solid black), recent (dashed black), long-term (dotted black), and sea-level-derived (red).

Individually, not all counties register rising risk trajectories over time. To compare how individual counties contribute to mean risk, we ranked each county ranked by its risk index in 2016 (Table 4.1). We also examined in detail two examples of how individual counties responded to different hazards and beach-nourishment cycles (Figure 4.6). Plymouth County, Massachusetts, demonstrates how vulnerability may respond to linear erosion rates (γ) that vary from eroding (negative, under the "historical" condition), to static (under the "long-term" and sea-level derived conditions), to accreting (positive, under the "recent" condition) (Figure 4.6 a-d). Ocean County, New Jersey, demonstrates how the cumulative beach-nourishment factor (V_{bn}) can drive up risk (Figure 4.6 e-h). There, V_{bn} causes the local maxima and minima in vulnerability to increase over time (Figure 4.6 g), such that even when beaches are at full width, exposed property is still subject to vulnerability $V > 0$. Ocean County highlights how the cumulative beach-nourishment factor functions as a ratchet, forcing vulnerability to only increase over time. Because not every county practices beach nourishment, it is possible for a county to have $V = 0$ if its shoreline is accreting (e.g., Camden and McIntosh Counties, Georgia). A county that never nourishes will have a $V_{bn} = 0$, and if a county nourishes only once or twice then their V_{bn} will remain negligible (but not negative). However, mean vulnerability is greater – and therefore mean risk is greater – when V_{bn} is left out ($V = V_{bw}$) (Figure C.1 c, d), because its inclusion makes vulnerability less sensitive to changes in beach width. For example, a county that does not nourish could have a narrow beach but a low V_{bn}, and therefore a lower vulnerability score than if its vulnerability were only a function of beach width.

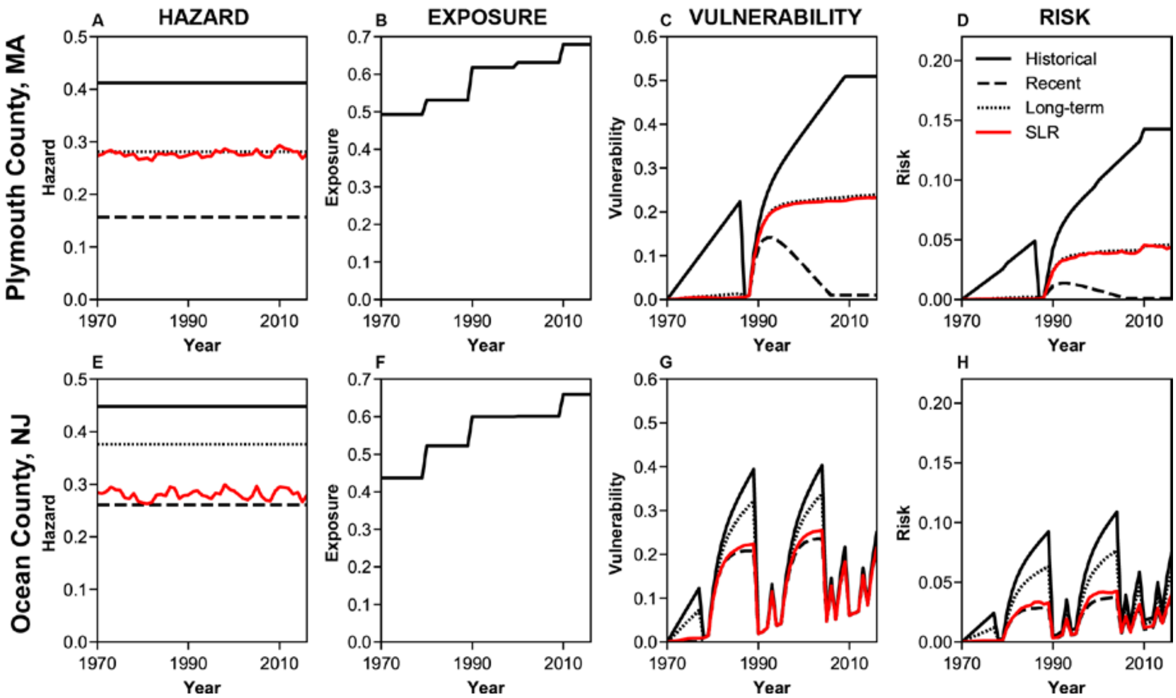

Figure 4.6 Evolution of (a–c) mean components and (d) risk for Plymouth County, Massachusetts, and (e–h) Ocean County, New Jersey. Line type indicates results under a given hazard condition. Note that the vulnerability time series for Ocean County (panel g) shows the "ratchet effect" of cumulative vulnerability from repeated beach nourishment episodes.

Table 4.1 Counties ranked by risk in 2016, calculated with historic, long-term, recent, and sea-level-derived shoreline-change rates.

	Historical			*Long-term*			*Recent*			*Sea-level-derived*		
Rank	*County*	*State*	*2016 Risk*	*County*	*State*	*2016 Risk*	*County*	*State*	*2016 Risk*	*County*	*State*	*2016 Risk*
1	Norfolk	MA	0.4176	Sussex	DE	0.1303	Essex	MA	0.1451	Cape May	NJ	0.0995
2	Sussex	DE	0.1456	Jasper	SC	0.1176	Liberty	GA	0.1304	Sussex	DE	0.0899
3	Plymouth	MA	0.1427	Liberty	GA	0.1171	Accomack	VA	0.1130	Miami-Dade	FL	0.0809
4	Northampton	VA	0.1400	Hyde	NC	0.0999	Sussex	DE	0.1010	Palm Beach	FL	0.0807
5	Jasper	SC	0.1382	Dukes	MA	0.0946	Bristol	MA	0.0867	Queens	NY	0.0763
6	Hyde	NC	0.1328	Nantucket	MA	0.0924	Nantucket	MA	0.0790	Duval	FL	0.0661
7	Nantucket	MA	0.1026	Beaufort	SC	0.0828	Palm Beach	FL	0.0696	Monmouth	NJ	0.0647
8	Liberty	GA	0.1009	Virginia Beach	VA	0.0808	Currituck	NC	0.0682	Virginia Beach	VA	0.0640
9	Dukes	MA	0.1008	Palm Beach	FL	0.0806	Queens	NY	0.0642	Norfolk	MA	0.0637
10	Beaufort	SC	0.1002	Northampton	VA	0.0798	Barnstable	MA	0.0634	New Hanover	NC	0.0621
11	Charleston	SC	0.0953	Cape May	NJ	0.0787	Brunswick	NC	0.0497	Suffolk	NY	0.0613
12	Virginia Beach	VA	0.0949	Charleston	SC	0.0732	New Hanover	NC	0.0488	Brunswick	NC	0.0529
13	Palm Beach	FL	0.0940	Monmouth	NJ	0.0700	Atlantic	NJ	0.0435	Martin	FL	0.0512
14	Monmouth	NJ	0.0895	New Hanover	NC	0.0700	Brevard	FL	0.0420	Beaufort	SC	0.0495
15	Barnstable	MA	0.0841	Suffolk	NY	0.0618	Washington	RI	0.0419	Charleston	SC	0.0490
16	Miami-Dade	FL	0.0758	Brunswick	NC	0.0610	Indian River	FL	0.0412	Atlantic	NJ	0.0484
17	Ocean	NJ	0.0737	Ocean	NJ	0.0583	Virginia Beach	VA	0.0405	Horry	SC	0.0483
18	New Hanover	NC	0.0711	Martin	FL	0.0549	Colleton	SC	0.0403	Nassau	FL	0.0467
19	Cape May	NJ	0.0711	Norfolk	MA	0.0542	Charleston	SC	0.0389	Essex	MA	0.0463
20	Martin	FL	0.0708	Queens	NY	0.0514	Cape May	NJ	0.0366	Nassau	NY	0.0461
21	Accomack	VA	0.0694	Miami-Dade	FL	0.0497	Ocean	NJ	0.0365	Brevard	FL	0.0456
22	Duval	FL	0.0692	Colleton	SC	0.0481	St. Lucie	FL	0.0350	Broward	FL	0.0453
23	Brunswick	NC	0.0690	Barnstable	MA	0.0460	Pender	NC	0.0350	Bristol	MA	0.0444
24	Essex	MA	0.0639	Plymouth	MA	0.0457	Martin	FL	0.0330	Volusia	FL	0.0439
25	Suffolk	NY	0.0596	Duval	FL	0.0437	Carteret	NC	0.0328	Plymouth	MA	0.0438
26	Colleton	SC	0.0578	Essex	MA	0.0427	Suffolk	NY	0.0308	Ocean	NJ	0.0395
27	Horry	SC	0.0545	Brevard	FL	0.0419	Dare	NC	0.0302	Washington	RI	0.0382
28	Bristol	MA	0.0484	Washington	RI	0.0411	Norfolk	MA	0.0296	Barnstable	MA	0.0380
29	Broward	FL	0.0468	Bristol	MA	0.0397	Beaufort	SC	0.0287	St. Johns	FL	0.0376
30	Brevard	FL	0.0455	Horry	SC	0.0377	Broward	FL	0.0282	Indian River	FL	0.0372
31	Queens	NY	0.0415	Broward	FL	0.0377	Worcester	MD	0.0271	Glynn	GA	0.0371
32	Currituck	NC	0.0408	St. Lucie	FL	0.0354	Horry	SC	0.0252	Carteret	NC	0.0369
33	St. Lucie	FL	0.0402	Indian River	FL	0.0350	Monmouth	NJ	0.0225	Pender	NC	0.0360
34	Pender	NC	0.0370	Dare	NC	0.0348	Dukes	MA	0.0223	Colleton	SC	0.0321
35	Washington	RI	0.0364	Accomack	VA	0.0346	Volusia	FL	0.0190	Chatham	GA	0.0321
36	Dare	NC	0.0364	Carteret	NC	0.0333	Nassau	NY	0.0161	St. Lucie	FL	0.0318
37	Worcester	MD	0.0346	Worcester	MD	0.0323	Onslow	NC	0.0157	Worcester	MD	0.0312
38	Indian River	FL	0.0344	Pender	NC	0.0317	St. Johns	FL	0.0156	Dukes	MA	0.0275
39	Nassau	NY	0.0314	Currituck	NC	0.0315	Georgetown	SC	0.0155	Nantucket	MA	0.0274
40	Glynn	GA	0.0311	Atlantic	NJ	0.0303	Chatham	GA	0.0143	Dare	NC	0.0253
41	Nassau	FL	0.0276	Volusia	FL	0.0299	Miami-Dade	FL	0.0079	Hyde	NC	0.0190
42	Volusia	FL	0.0271	St. Johns	FL	0.0287	McIntosh	GA	0.0057	Georgetown	SC	0.0188

Rank	*Historical* County	State	2016 Risk	*Long-term* County	State	2016 Risk	*Recent* County	State	2016 Risk	*Sea-level-derived* County	State	2016 Risk
43	Atlantic	NJ	0.0268	Nassau	NY	0.0222	Glynn	GA	0.0011	Onslow	NC	0.0132
44	St. Johns	FL	0.0260	Glynn	GA	0.0184	Plymouth	MA	0.0010	Camden	GA	0.0083
45	Carteret	NC	0.0248	Georgetown	SC	0.0182	Nassau	FL	0.0008	Northampton	VA	0.0078
46	Flagler	FL	0.0223	Nassau	FL	0.0170	Hyde	NC	0.0006	Jasper	SC	0.0069
47	Georgetown	SC	0.0206	Onslow	NC	0.0128	Flagler	FL	0	Liberty	GA	0.0061
48	Onslow	NC	0.0136	Chatham	GA	0.0007	Duval	FL	0	Accomack	VA	0.0058
49	Chatham	GA	0.0005	Flagler	FL	0	Camden	GA	0	McIntosh	GA	0.0053
50	Camden	GA	0	Camden	GA	0	Jasper	SC	0	Currituck	NC	0.0050
51	McIntosh	GA	0	McIntosh	GA	0	Northampton	VA	0	Flagler	FL	0.0021

Alongshore mean risk in our model also increases because of a well-documented national trend in exposure (NOAA, 2013). Exposure in an individual county may increase or decrease from one decade to the next, but mean exposure along the full span of the coast increases over time (NOAA, 2013; Union of Concerned Scientists, 2018). The 51 coastal counties in this analysis represent 1.6% of all US counties, but since 1970 have constituted 6.9–9.25% of the total value of all owner-occupied housing units in the country (Figure C.2). Thus, while our data-driven model includes simplifying assumptions, we suggest that the increasing risk trends in our findings represent a real phenomenon, since exposure has risen at the coast decade on decade in real terms, and our cumulative beach-nourishment factor both dampens mean vulnerability and highlights the reality of long-term risk in counties that nourish continually.

4.4.2 Component relationships

Finally, we compared the statistical distributions of exposure in high- and low-hazard counties, and in high- and low-intensity nourishing counties (as an aspect of vulnerability), to examine whether the three components of risk, as we represent them, reflect temporal interrelationships.

To explore potential relationships between exposure and hazard, we sorted the exposure time series (Figure 4.2) into counties associated with "high hazard" (eroding shorelines) and "low hazard" (accreting shorelines) for historical and recent shoreline change (Figure 4.7; Figure 4.8). We find that exposure increases each decade in zones of high and low hazard, alike, for both historical and recent shoreline change (Figure 4.7; Figure 4.8). Under “historical” shoreline-change hazard, exposure of property value is greatest in zones of high hazard (Figure 4.7 a-h; Figure 4.8 a). Conversely, exposure to high hazard is relatively low for "recent" shoreline-change rates (Figure 4.7 i-p; Figure 4.8 d), in part because recent shoreline-change rates tend to be less erosional than their historical counterparts (Figure 4.3 a). The difference between relative distributions of exposure in high and low hazard zones for historical shoreline-change rates increases in significance decade on decade, with a decreasing Kolmogorov-Smirnov *p*-value that reflects the significance of their divergence (Figure 4.8 c). There is no such temporal divergence of exposure in high and low hazard zones for recent shoreline-change rates (Figure 4.8 f).

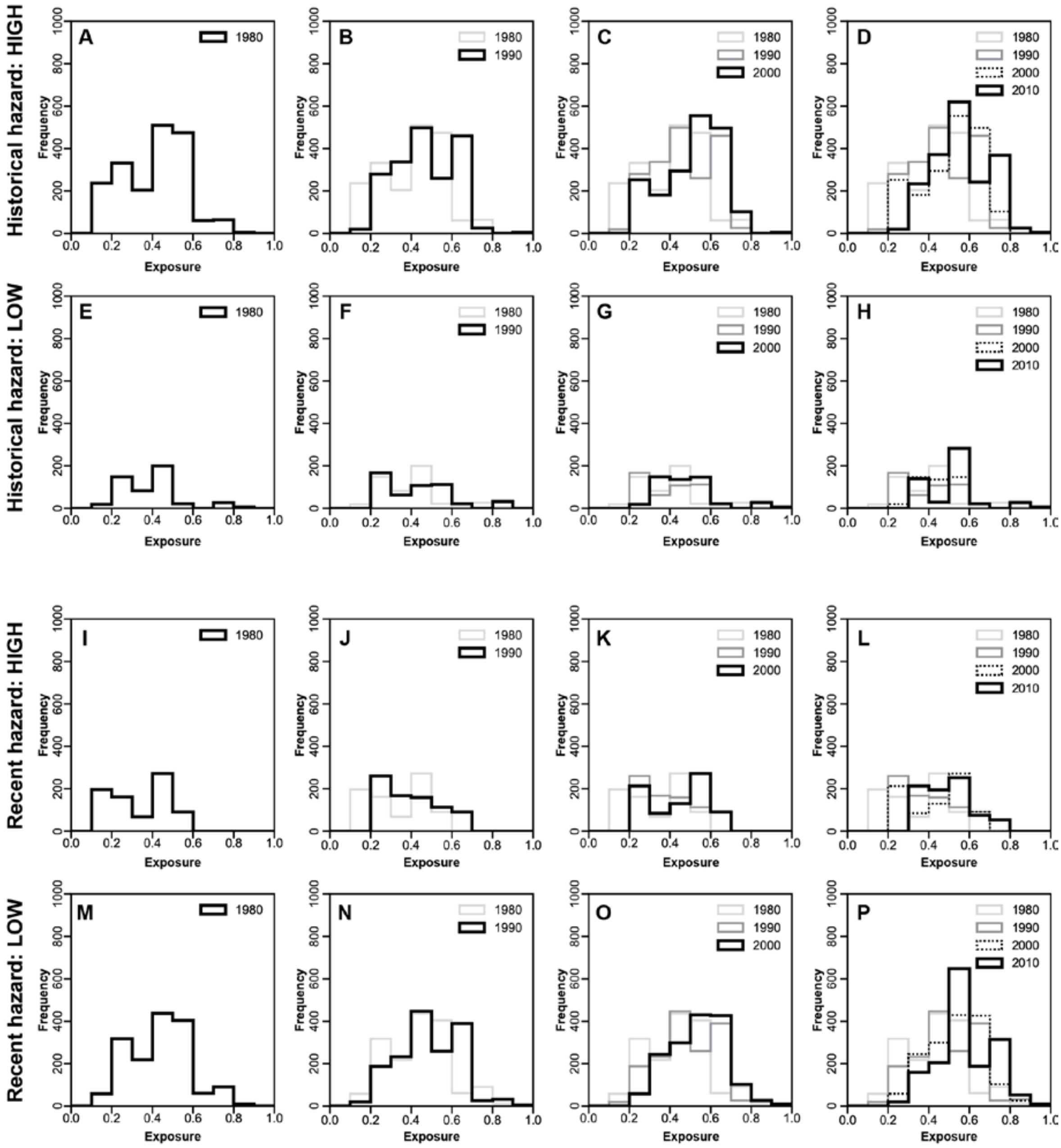

Figure 4.7 Distribution of exposed property, by decade, under (a¬–h) high and low historical and (i–p) high and low recent shoreline-change hazard. "High" hazard here is a value greater than 0.272 (the normalised value for a shoreline-change rate of zero); "low" hazard is a value greater than 0.272. High hazard therefore indicates erosion, and low hazard indicates accretion.

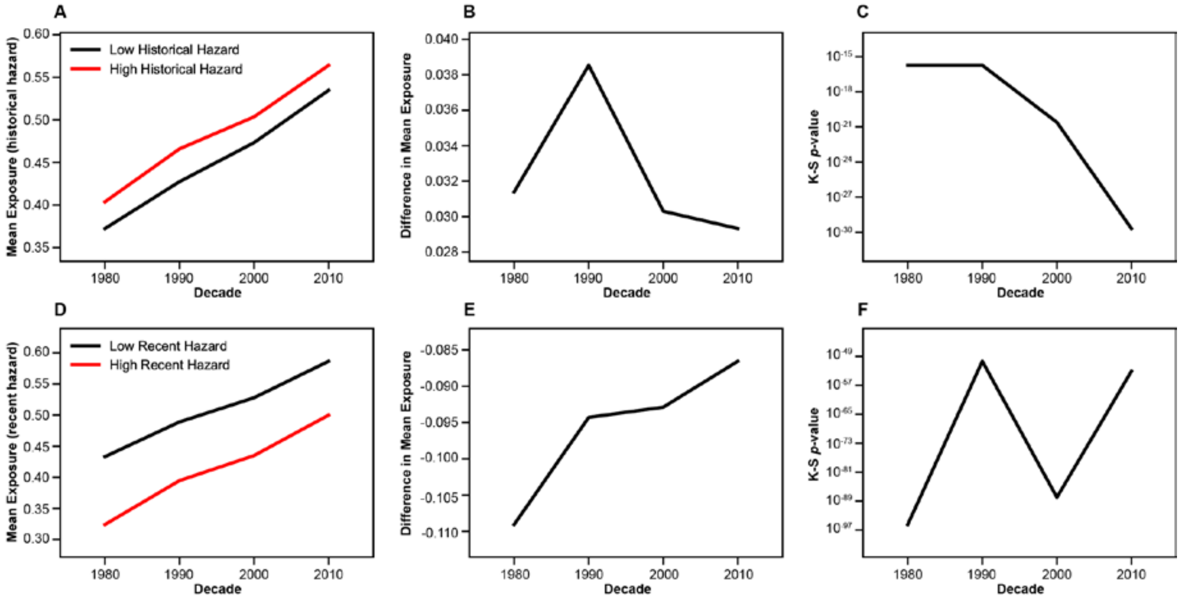

Figure 4.8 Comparisons of property exposed to high and low (a–c) historical and (d–f) recent shoreline-change hazard, from Figure 4.7. Columns show mean exposure each decade, the relative difference between mean exposure to high and low hazard each decade, and the Kolmogorov-Smirnov p-value for the difference in distributions each decade. All p-values indicate that the distributions are statistically distinct (i.e., a rejection of the null hypothesis that the distributions are sampled from the same parent distribution).

To explore, in parallel, potential relationships between exposure and vulnerability, we sorted the exposure time series into nourishing and non-nourishing counties, and then by the intensity of beach nourishment (high or low) according to whether counties fell above or below the 2016 median value of cumulative V_{bn} (Figure 4.9; Figure 4.10). We find that although exposure increases each decade in nourishing and non-nourishing counties, alike, more property is ultimately exposed in nourishing counties. Moreover, the mean value of that exposed property increases at a greater rate than in non-nourishing counties (Figure 4.9 a-h; Figure 4.10 a-c). Initially, all property is exposed in counties where nourishment intensity is present but low (their V_{bn} sits below the 2016 median) – which we expect, because for counties to accrue enough nourishment events to match the 2016 median cumulative-nourishment factor requires time (Figure 4.9 i, m). Exposure in intensively nourished counties (counties that accrue enough nourishment projects to have V_{bn} above the 2016 median) shows a marked increase in the 1980s (Figure 4.10 d). Total exposure in intensively nourished counties overtakes total exposure in sparsely nourished counties by the 2010s (Figure 4.10 e), such that more property ends up exposed in counties where nourishment intensity is high (Figure 4.9 i – p; Figure 4.10 d-f).

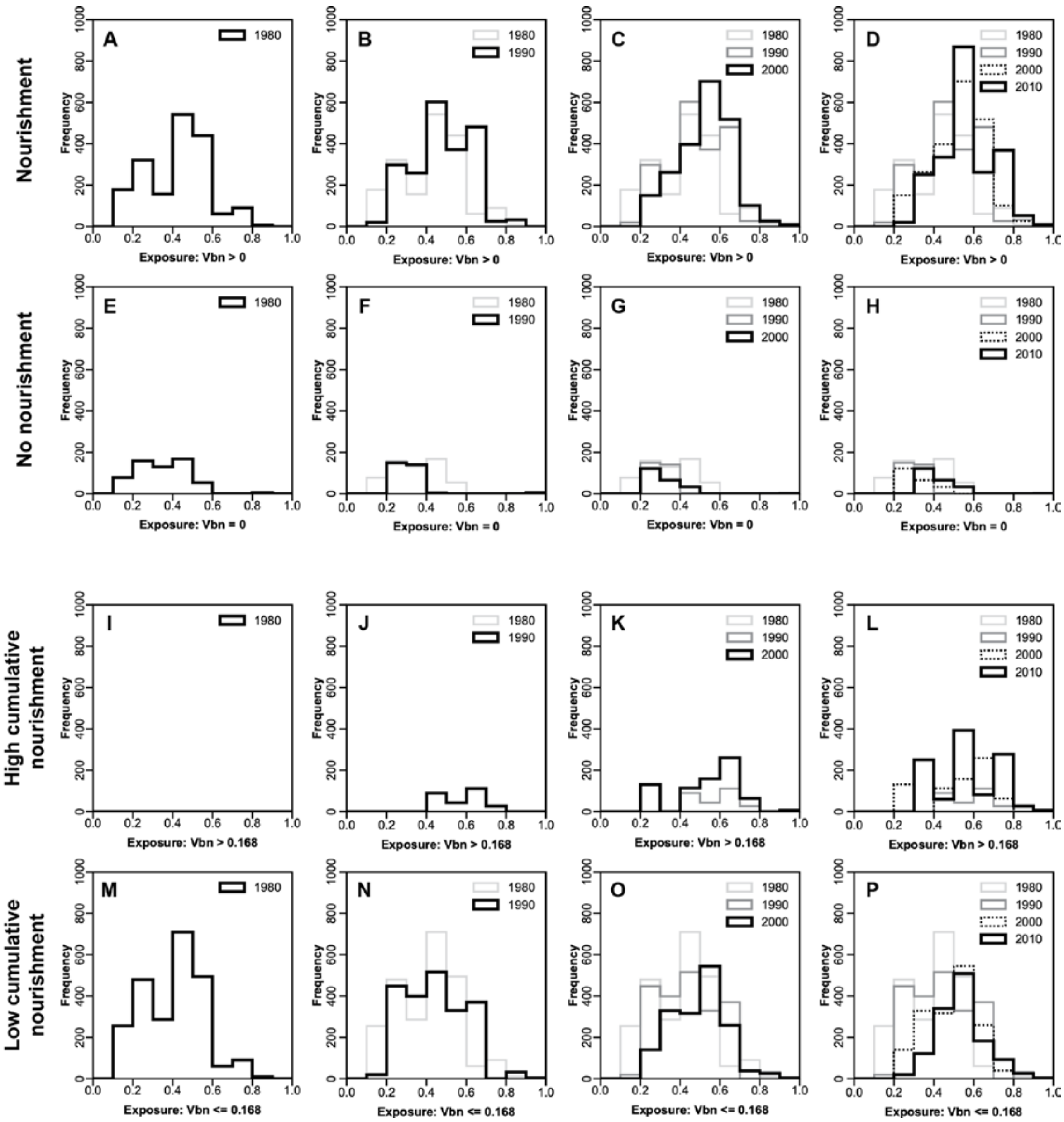

Figure 4.9 Distribution of exposed property, by decade, (a–h) in counties that have and have not nourished, and (i–p) in counties that have nourished above and below the 2016 median cumulative beach-nourishment index (V_{bn} = 0.168). The 2016 median V_{bn} denotes the normalised value of the overall median cumulative number of nourishments across the domain.

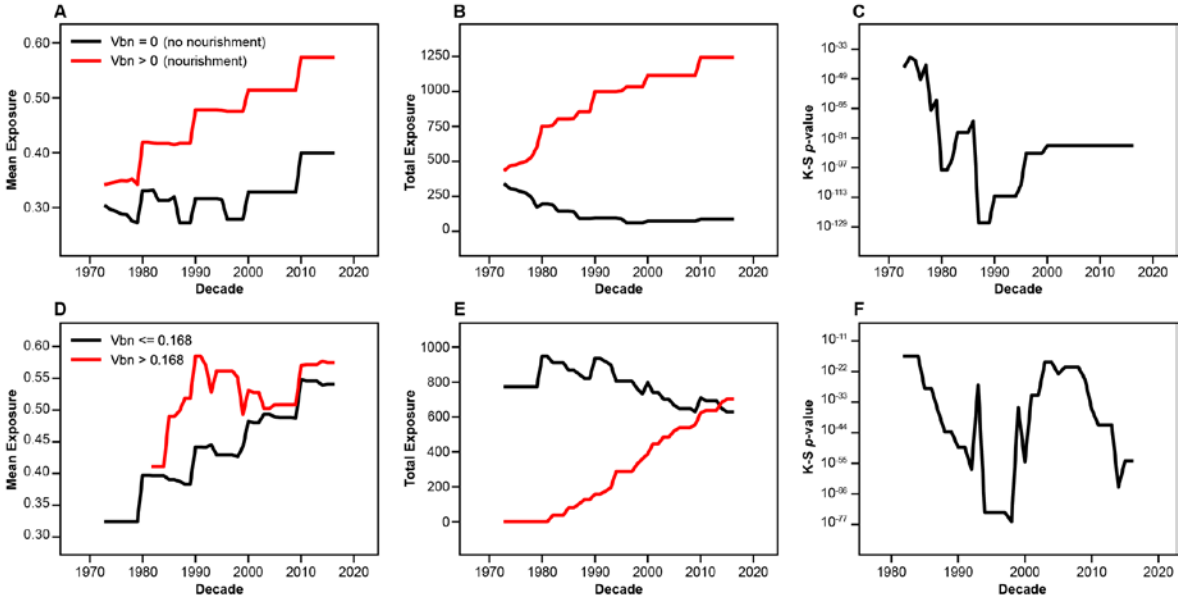

Figure 4.10 Comparisons of property exposed (a–c) in counties that have and have not nourished, and (d–f) counties that have nourished more or less than the 2016 median V_{bn}. Columns show mean exposure each decade, total exposure each decade, and the Kolmogorov-Smirnov *p*-value indicating the relative difference in exposure distributions each decade for each condition (nourished versus non-nourished; above versus below median V_{bn}). All *p*-values indicate that the distributions are statistically distinct (i.e., a rejection of the null hypothesis that the distributions are sampled from the same parent distribution).

Both of these temporal relationships in spatial patterns of exposure and hazard (Figure 4.7) and exposure and vulnerability (Figure 4.9) are likely two vantages of the same feedback, catalysed by beach nourishment. Higher property value is exposed where historical shoreline-change hazard was high (Figure 4.7 a–d) and recent shoreline-change hazard is low (Figure 4.7 m–p) because those places also practice relatively intensive use of beach nourishment (Figure 4.11). The cumulative effect of beach nourishment may be sufficiently strong to mask "true" rates of shoreline change (Armstrong and Lazarus, 2019a) – a defensive intervention that, by reducing apparent hazard, may spur further development (Figure 4.9), increasing exposure and creating demand for additional protection (Armstrong et al., 2016).

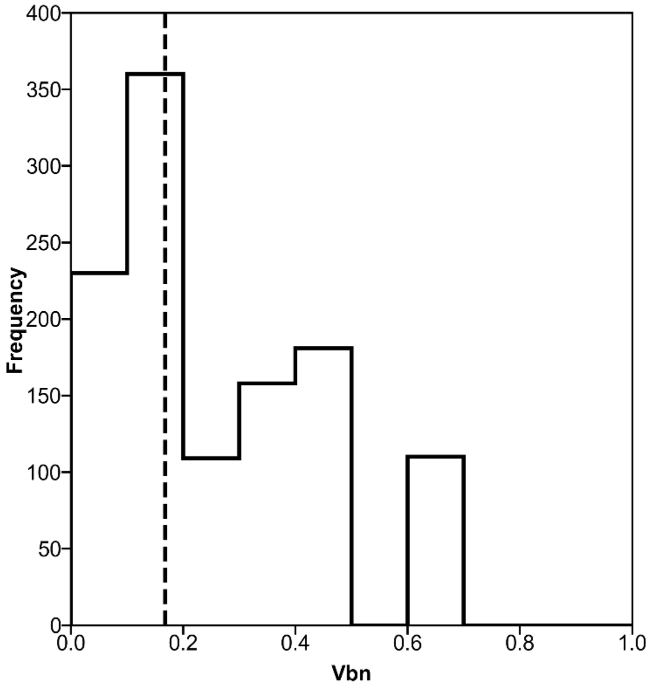

Figure 4.11 Cumulative beach-nourishment index (V_{bn}), as of 2016, at transects (across all counties) that express both high "historical" and low "recent" rates of shoreline erosion (see Figure 4.7, a–d and m–p). Dotted line indicates the overall median V_{bn} = 0.168 in 2016 for the full domain. For this component distribution, median V_{bn} = 0.178 (mean = 0.251). This spatial correspondence between a major reversal in shoreline-change trend (from erosion to accretion) and above-average nourishment intensity is an indication of a coupling between chronic erosion (hazard) and defensive intervention (vulnerability).

4.5 Discussion and implications

Our data-driven, spatio-temporal model of risk along the US Atlantic Coast produces trajectories that vary in space and, on average, rise over time for all four chronic hazard scenarios that we test (Figure 4.5). We know from the underlying data that real exposure increases over time, but we suggest that our modelled risk trajectories also reflect intrinsic feedbacks between hazard, exposure, and vulnerability (Mileti, 1999). We find more property is exposed in counties with "high hazard" historical shoreline-change rates and "low hazard" recent shoreline-change rates (Figure 4.7; Figure 4.8), and that exposure has increased more in places that have practiced beach nourishment intensively (Figure 4.9; Figure 4.10). The spatio-temporal relationships that we show between exposure and hazard (Figure 4.7; Figure 4.8) and exposure and vulnerability (Figure 4.9; Figure 4.10) may reflect a feedback between coastal development and beach nourishment (Figure 4.11) (Armstrong et al., 2016; Armstrong and Lazarus, 2019a) – a manifestation of the "safe development paradox" (Burby, 2006), in which hazard protections encourage further development in places prone to hazard impacts (Di Baldassarre et al., 2013; Lazarus et al., 2016; McNamara et al., 2015; Mileti, 1999; Smith et al., 2009; Werner and McNamara, 2007).

Our model is exploratory, and we reiterate its main caveats. Although there are many kinds of coastal hazard (e.g., storm impacts, flooding), we represented "chronic" hazard with shoreline-change rates that are spatially heterogeneous but temporally static. An alternative derivation of shoreline change, from sea-level rise rates and simplified shore slopes, varies in both space and time, and yielded overall results similar to those returned by the "recent" shoreline-change scenario. Exposure in our model only accounts for the monetary value of owner-occupied properties in coastal counties, as captured by the US Census, thus excluding other potential measures of exposure (e.g., Cutter et al., 2006, 2008; Neumann et al., 2015; NRC, 2014; Samuels and Gouldby, 2009; Strauss et al., 2012) and requiring that we spatially aggregate our analysis to county scales. Finally, our measure of vulnerability includes no method of shoreline protection other than beach nourishment, and its dynamics are underpinned by a set of broad assumptions: that beaches comprise shorelines at the county scale; that in 1970, all counties have the same initial beach width; that a beach-nourishment project always restores a beach to its full width; and that counties with intensive nourishment programmes may render themselves more vulnerable over time by masking a chronic erosion problem (Armstrong and Lazarus, 2019a; Pilkey and Cooper, 2014; Woodruff et al., 2018). We do not directly address alongshore spatial interactions within or between counties (Ells and Murray, 2012; Lazarus et al., 2016; Lazarus, McNamara, et al., 2011). Despite these assumptions, our model captures temporal interactions among the components of risk that ultimately yield large-scale spatial patterns similar to those identified in recent, fully empirical studies (Armstrong et al., 2016; Armstrong and Lazarus, 2019a).

We suggest that models intended to test different coastal management policies, interventions, and scenarios should aim to include feedbacks between hazard, exposure and vulnerability. In our data-driven model, traces of these feedbacks – and perhaps others – are likely embedded in the data we use. More detailed work at the intersection of theory and empiricism is necessary to resolve how feedbacks between hazard, exposure, and vulnerability dynamically affect each component of risk, and to explore how different management interventions may mitigate – or exacerbate – the “safe development paradox”.

4.6 Acknowledgements

The authors thank Evan Goldstein, Julian Leyland, and James Dyke for helpful discussions. This work was supported by the NERC BLUEcoast programme (NE/N015665/2).

Chapter 5 Synthesis and conclusions

5.1 Synthesis of this thesis into a conceptual framework

The three works presented in this thesis together form a contribution beyond their individual parts. Chapter 2 and Chapter 3 provide empirical evidence for phenomena explored further in Chapter 4, and all three works taken together inform a new understanding of interactions and feedbacks operating on the world's largest coastal coupled human-landscape system (Figure 1.1; Figure 1.3). In this synthesis section, I further develop the conceptual framing of a coupled human-landscape system driven by beach nourishment (Figure 1.3) (Lazarus et al., 2016) by redefining and amending the parts of the system (Figure 5.1) on the basis of my findings in Chapter 2, Chapter 3 and Chapter 4. I then use this re-imagined framing to consider further implications of interactions between the system components (Figure 5.2; Figure 5.3; Figure 5.4).

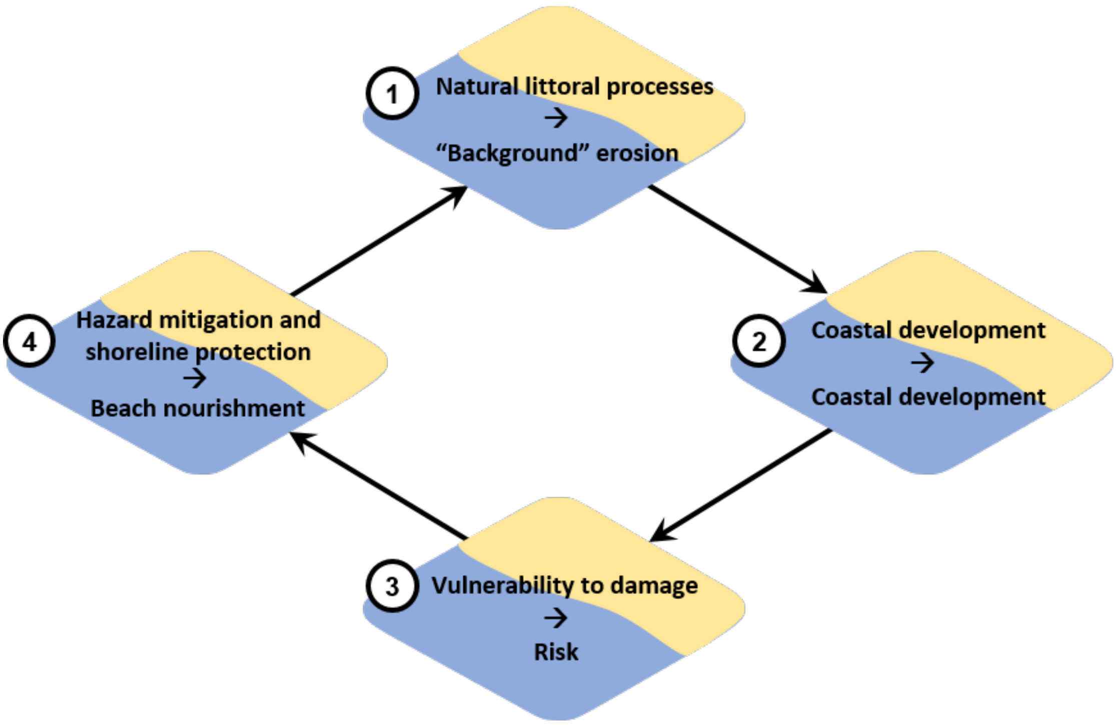

Figure 5.1 Terminology used to redefine Figure 1.3 (Lazarus et al., 2016). Here, (1) 'natural littoral processes' is redefined as 'natural erosion', (2) 'coastal development' remains unchanged, (3) 'vulnerability to damage' is redefined as 'risk', and (4) 'hazard mitigation and shoreline protection' is redefined as 'beach nourishment'. Note that in the explanation given in Lazarus et al. (2016), each part of this human landscape system links to the next, following in order between 1-4 and back to 1 in a loop.

First, how might the phenomenon of “masked erosion” (Chapter 2; Armstrong and Lazarus, 2019a) fit into the coupled human-landscape system described by Lazarus et al. (2016)? In this case, beach nourishment (part 4) alters “background” historical erosion rates (part 1), to create “altered” recent erosion rates (part 1a; Figure 5.2). Because “altered” erosion rates (part 1a) are currently observed, they appear to represent the background erosion, and effectively mask true “background” erosion rates (part 1) from developers and investors (part 2) (Figure 5.2). “Background” erosion rates (part 1), however, are always underlying, and therefore while “altered” erosion (part 1a) informs coastal development, underlying “background” erosion (part 1) affects risk (part 3) (Figure 5.2).

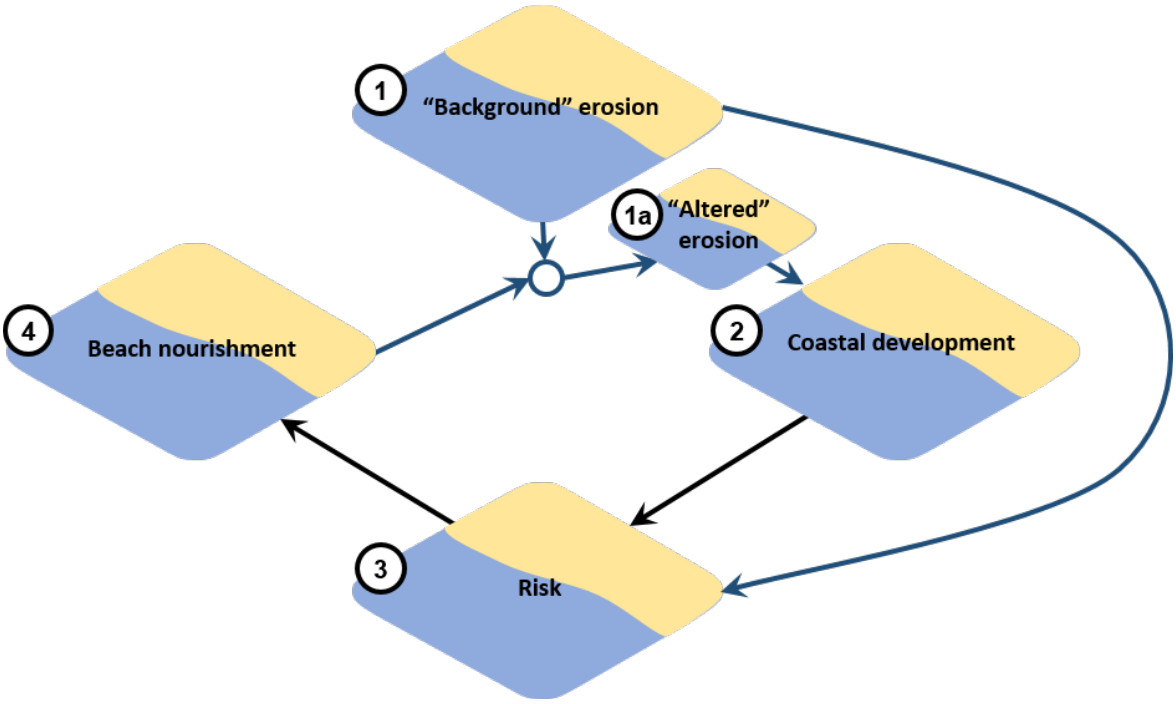

Figure 5.2 Schematic of the masking effect of beach nourishment, found in Chapter 2, on the coupled human-landscape system framework. Beach nourishment masking “background” erosion rates (blue), as an interaction between (1) “background” erosion and (4) beach nourishment that creates (1a) “altered” erosion, which masks (1) “background erosion from (2) coastal development, even though (1) “historical erosion” informs (3) risk. Adapted from (Lazarus et al., 2016).

Next, how might the feedback between coastal development and beach nourishment (Chapter 3; Armstrong et al., 2016), fit into the coupled human-landscape system described by Lazarus et al. (2016)? The interaction is a positive, or reinforcing, feedback loop between coastal development (part 2), and beach nourishment (part 4; Figure 5.3). While masked shoreline erosion (Figure 5.2) may influence the return leg of the feedback loop, between beach nourishment and coastal development (part 4 to part 2; Figure 5.3), I consider this feedback loop as a separate effect because beach nourishment does more than just protect property from erosion. By widening a beach, a beach nourishment project can increase the utility value of a coastal town, attracting investment in its own right. New development increases the value of property exposed to coastal hazard and makes a case for further nourishment under cost-benefit analysis (NRC, 1995, 2014). Following this logic, this feedback stands as its own feature driven by its own causes (Figure 5.3). The analysis in Chapter 3 does not determine which part of the system starts the feedback, but regardless of the trigger, once initiated, the feedback drives up both. By increasing the number of beach nourishment projects and the value of property exposed, this feedback impedes the effectiveness of beach nourishment as a means to risk reduction, and exemplifies the safe development paradox.

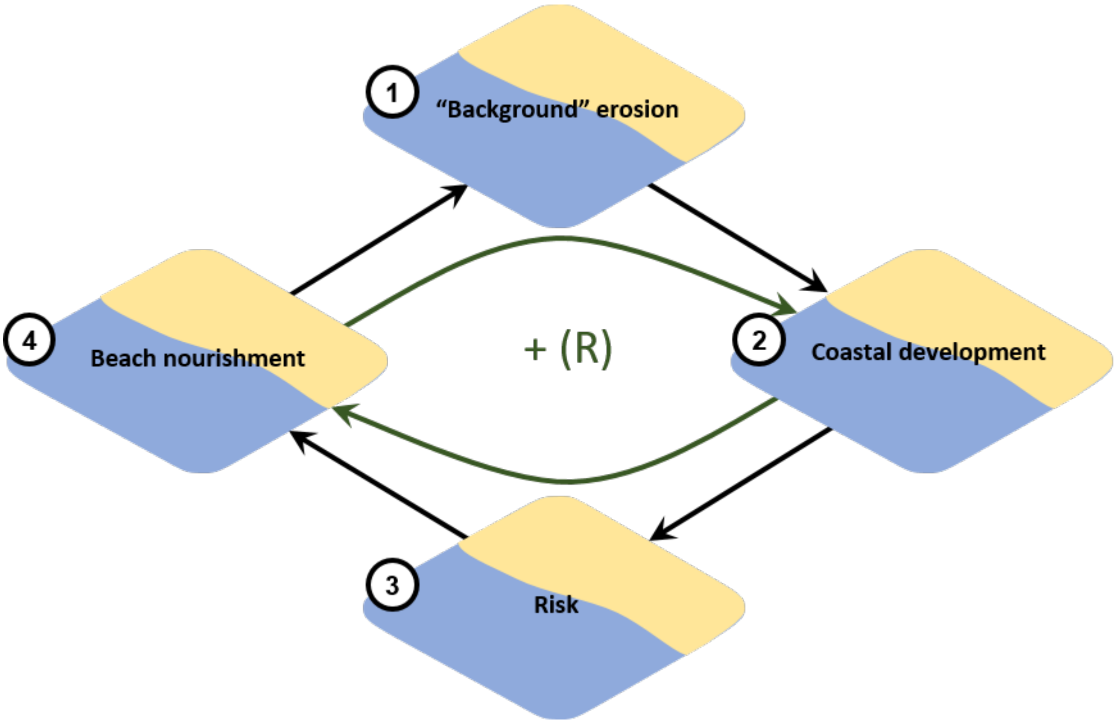

Figure 5.3 Schematic showing the feedback between coastal development and beach nourishment seen in Chapter 3 (green) on the coastal coupled human-landscape system framework. This feedback is a two-way interaction between (2) coastal development and (4) beach nourishment. Adapted from (Lazarus et al., 2016).

How do the components of a coastal risk equation (Chapter 4; Armstrong and Lazarus, 2019b) fit into a human-landscape system described by Lazarus et al. (2016)? Hazard is represented by coastal erosion (part 1), exposure is represented by coastal development (part 2), and vulnerability is represented by beach width, as altered by beach nourishment (part 4; Figure 5.4). Coastal risk (part 3) is calculated by multiplying the other three components together (Figure 5.4). Combining a human-landscape system conceptual framework with a risk calculation allows conceptual exploration of interactions between different system parts (Figure 5.2; Figure 5.3), explicitly in terms of risk (Figure 5.4). Because increased risk can be an unintended consequence of beach nourishment, exploring risk components over time is a way to start breaking down the problem of modelling the unintended consequences of beach nourishment. In Chapter 4, we explore the masking effect on exposure found in Chapter 2 by comparing hazard and exposure, and explore the feedback between beach nourishment and coastal development found in Chapter 3 by comparing exposure and vulnerability (Figure 5.4). We found that these effects are apparent in our model components, because they are present in the data we use. These interactions between risk components should be built in to any model that predicts future risk.

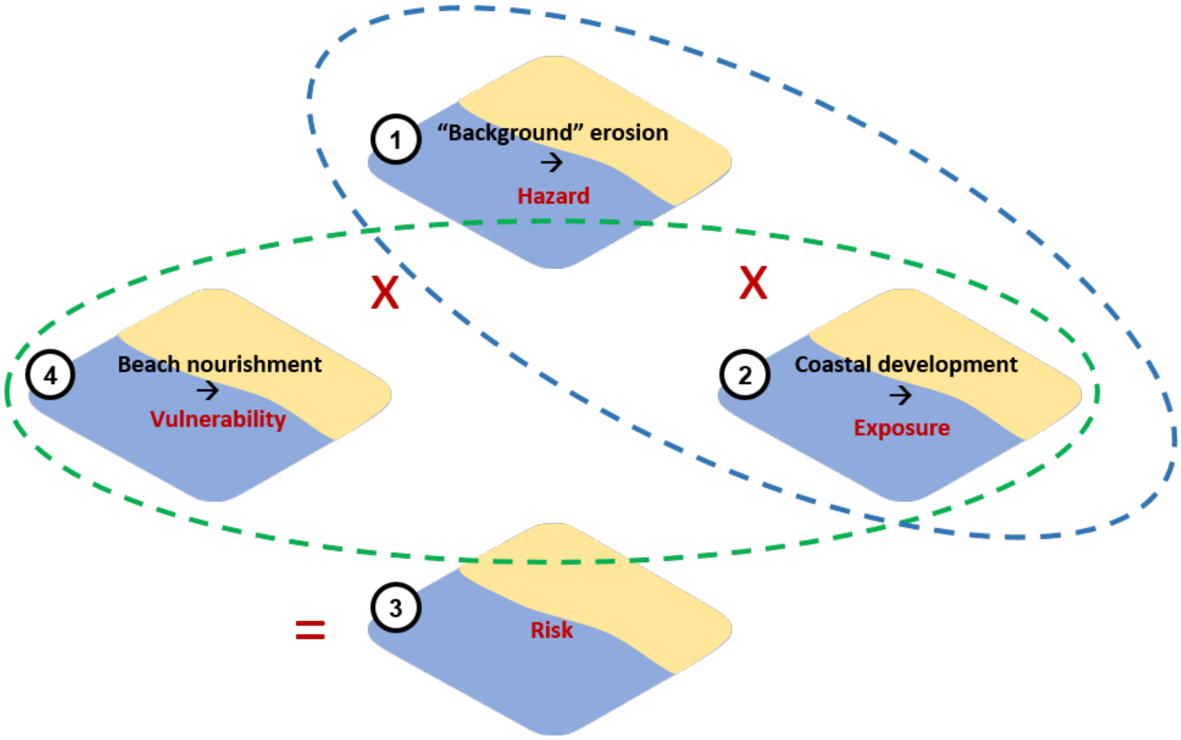

Figure 5.4 Schematic showing risk components expressed as parts in a coastal coupled human-landscape system in Chapter 4, where (1) 'historic erosion' is redefined as 'hazard', (2) 'coastal development' is redefined as 'exposure', and (4) 'beach nourishment' is redefined as 'vulnerability'. The blue dashed oval shows which components are compared to explore the masking found in Chapter 2, and the green dashed oval shows the components compared to explore the feedback found in Chapter 3. Adapted from (Lazarus et al., 2016).

A visual interpretation of the synthesis of all three works shows the interactions from Figure 5.2 and Figure 5.3 in the context of a coupled human-landscape system framework expressed as components of risk (Figure 5.5). This represents the framework of this thesis, which could become a starting point for modelling efforts into coastal risk that include the unintended feedbacks between hazard, exposure, and vulnerability found in this thesis. These feedbacks drive unintended consequences of beach nourishment, including unintended geoengineering leading to masked erosion, which in turn leads to the addiction system trap, and the feedback between exposed value and beach nourishment, exemplifying the safe development paradox that wipes out the risk reduction intended by beach nourishment by a backfire mechanism of Jevons' paradox. Such a model could test if policy interventions reduce or exacerbate the unintended consequences of beach nourishment.

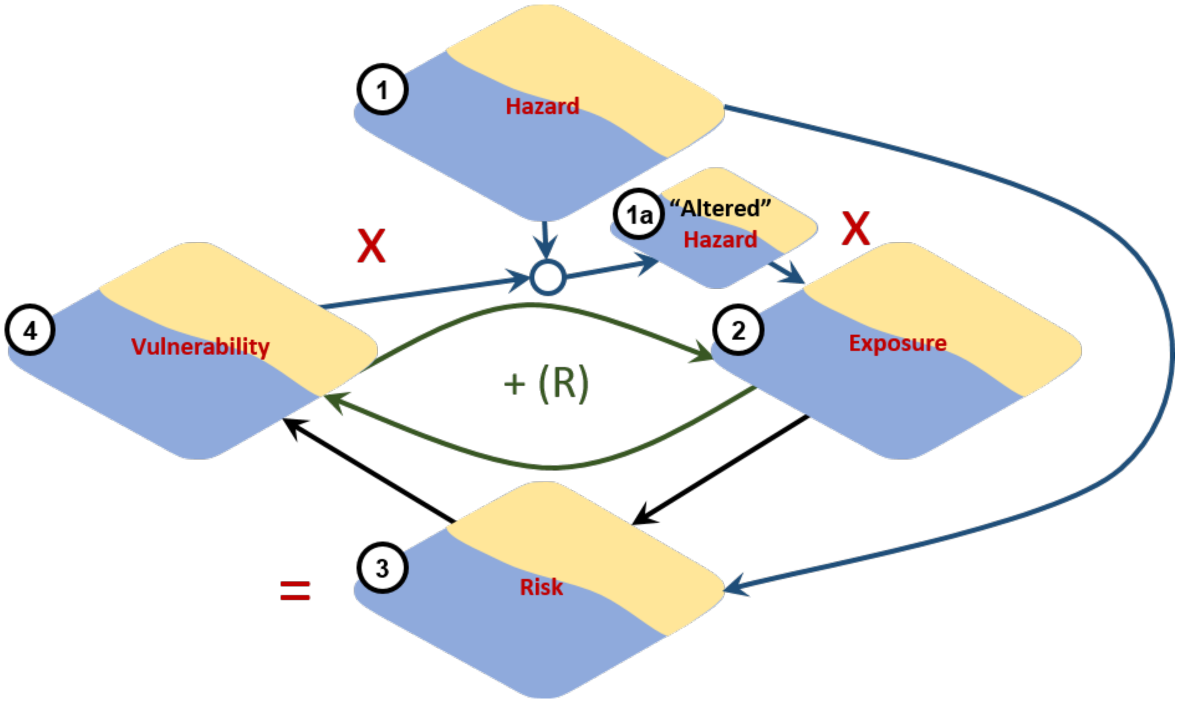

Figure 5.5 Schematic showing a visual synthesis of Chapter 2, Chapter 3, and Chapter 4. A coastal human-landscape system, with (4) beach nourishment masking (1) background shoreline erosion from (2) developers and investors, and a feedback between (2) coastal development and (4) beach nourishment. The parts in the coastal human-landscape system are re-interpreted as components of coastal risk, whereby (1) hazard is multiplied by (2) exposure and (4) vulnerability, resulting in (3) coastal risk.

5.2 Future research directions

Future research from this thesis could involve the study of other interactions between parts of the coastal coupled human-landscape system. For example, beach nourishment is often used as an unplanned emergency response to a disaster event. In the terms of the risk equation I use in Chapter 4, this would mean the presence of yet another feedback in which risk in one year would inform vulnerability in the next. In my formulation, risk is a consequence of hazard, exposure, and vulnerability, and does not feedback upon itself. Moreover, a new study has suggested the presence of another interaction, that of exposure increasing after disasters by rebuilding bigger houses than those lost or damaged by disasters (Lazarus et al., 2018). In the framework for coupled systems that I describe, addressing this interaction would link part 3 (risk) back to part 2 (exposure or development). Combining these parts to the overall coupled system interactions (Figure 5.5) could yield interesting further study into feedbacks in this coupled system. Furthermore, the coupled-system framework should be extended to settings beyond the predominant exemplar of sandy, low-lying, open coasts. Other developed coastal settings are described as coastal “anthromes” – anthropogenic equivalents of biomes (Lazarus, 2017).

Feedbacks between parts of coastal coupled systems could be approached through dynamical systems modelling (Meadows and Wright, 2008; Woodruff et al., 2018). This could be developed by taking Figure 5.5 as a basis, adding other interactions such as the positive effect disasters can have on value of exposed property (Lazarus et al., 2018), and converting into stocks, flows, feedbacks (reinforcing and balancing), and delays. The dynamics of the coupled system could then be modelled to further investigate the unintended consequences of beach nourishment on developed coasts. A further step to the systems approach to studying the coupled system could be to model the system as an agent based model, where decisions by individual agents affect the stocks and flows (Filatova et al., 2013; Karanci, 2017; de Koning et al., 2019).

My conceptualised framework (Figure 5.5) is informed by data describing beach nourishment along the US Atlantic Coast, on spatial scales of 10^1 – 10^3 km and temporal scales of years to decades. A model informed by this framework should be initially formed at these spatio-temporal scales. After initial development, however, if such a model were robust across multiple timescales, it would have potential to test for unintended feedbacks in other settings.

An altogether different line of inquiry for future research could result from incorporating social and physical datasets (new and historical) at higher spatio-temporal resolution, where available. I am currently involved in a project that will extend my Chapter 3 analysis of Florida (Armstrong et al., 2016) to New Jersey, using historical tax records to trace how property values may be influenced by beach nourishment over time. The tax records register the "sold price" of individual properties back to the late 1990s, delivering a time series of price far more detailed than Census data. Delineating by municipality aligns the spatial resolution with local governance, such that beach-nourishment projects match the administrative and management boundaries associated with individual nourishment decisions.

Another direction for future research that could overcome spatio-temporal limitations that arise in this thesis is to work more directly from patterns governed by physical processes – for example, finding the effect of beach nourishment on erosion rates within a given littoral cell, and/or deriving higher-resolution records of shoreline change from satellite data (Luijendijk et al., 2018; Vos et al., 2019).

5.3 Reflections

Why does risk still rise even though our understanding and constraint of hazards improves? And more specific to the setting of beach nourishment along developed coasts, why is coastal risk still rising despite ubiquitous use of beach nourishment?

In terms of existing policy, this thesis lends weight to the argument that beach nourishment is a sticking-plaster solution that masks the problem of increased exposure and vulnerability in coastal hazard zones (Armstrong et al., 2016; Armstrong and Lazarus, 2019a; Gopalakrishnan, McNamara, et al., 2016; Neal et al., 2018; Parkinson and Ogurcak, 2018). There is no silver bullet for policy to reduce risk, but if a model that includes the unintended consequences of beach nourishment could test policy solutions at different governance scales, perhaps solutions that cause further problems could be ruled out.

The novel contribution of this thesis is its empirical treatment of developed coasts as coupled human-landscape systems, functioning over large spatial scales and multi-decadal time scales. Previous work has tended to be theoretical (e.g., Mileti, 1999; Werner and McNamara, 2007; Smith et al., 2009), locally focussed (e.g., Paterson et al., 2014; Pilkey and Neal, 2009), or describe aspects of these systems qualitatively or anecdotally (e.g., Dash et al., 2007; Peacock et al., 2014; Platt et al., 2002). Here, I was able to combine "big data" datasets from diverse sources in new ways, and construct a formulation of coastal risk that could illustrate interactions between hazard, exposure, and vulnerability over time. My work is already informing literature and making an impact in terms of media coverage (Appendix D). By highlighting the extent of the "disaster by design" problem in developed coastal zones and providing a starting point for incorporating unintended consequences into risk modelling, my research may inform future tools for shaping and testing policy efforts to reduce coastal risk.

Appendix A Supporting Information: Paper 1

A.1 Introduction

Here we include four supplemental figures to augment those in the main text, and four supplemental tables with descriptive statistical data related to the figures.

A.2 Figures A.1 – A.3 and Tables A.1 – A.4

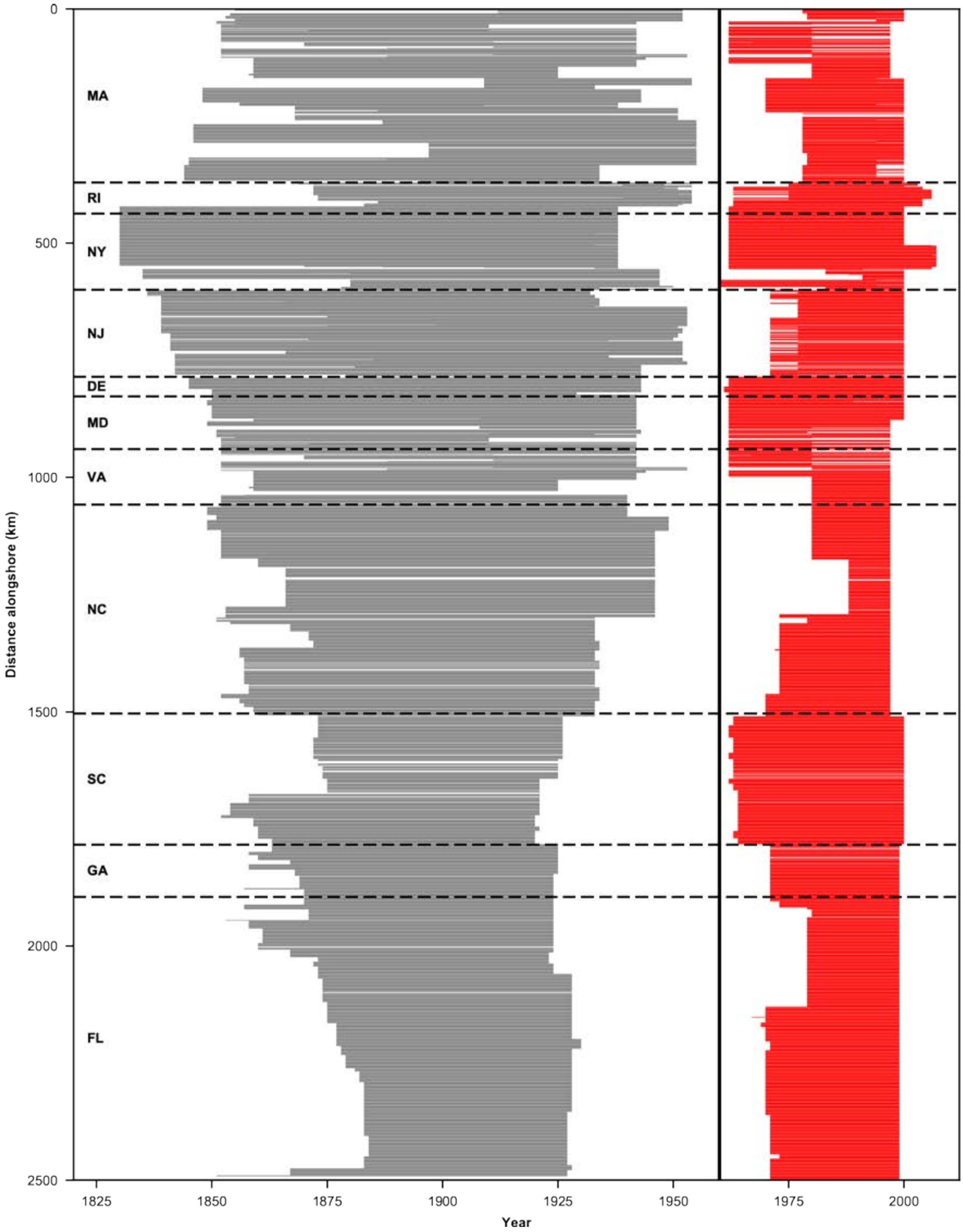

Figure A.1 Ranges of start and end dates used to calculate historical (left, gray) and recent (right, red) end-point rates of shoreline change at each transect alongshore. Dashed lines indicate state boundaries.

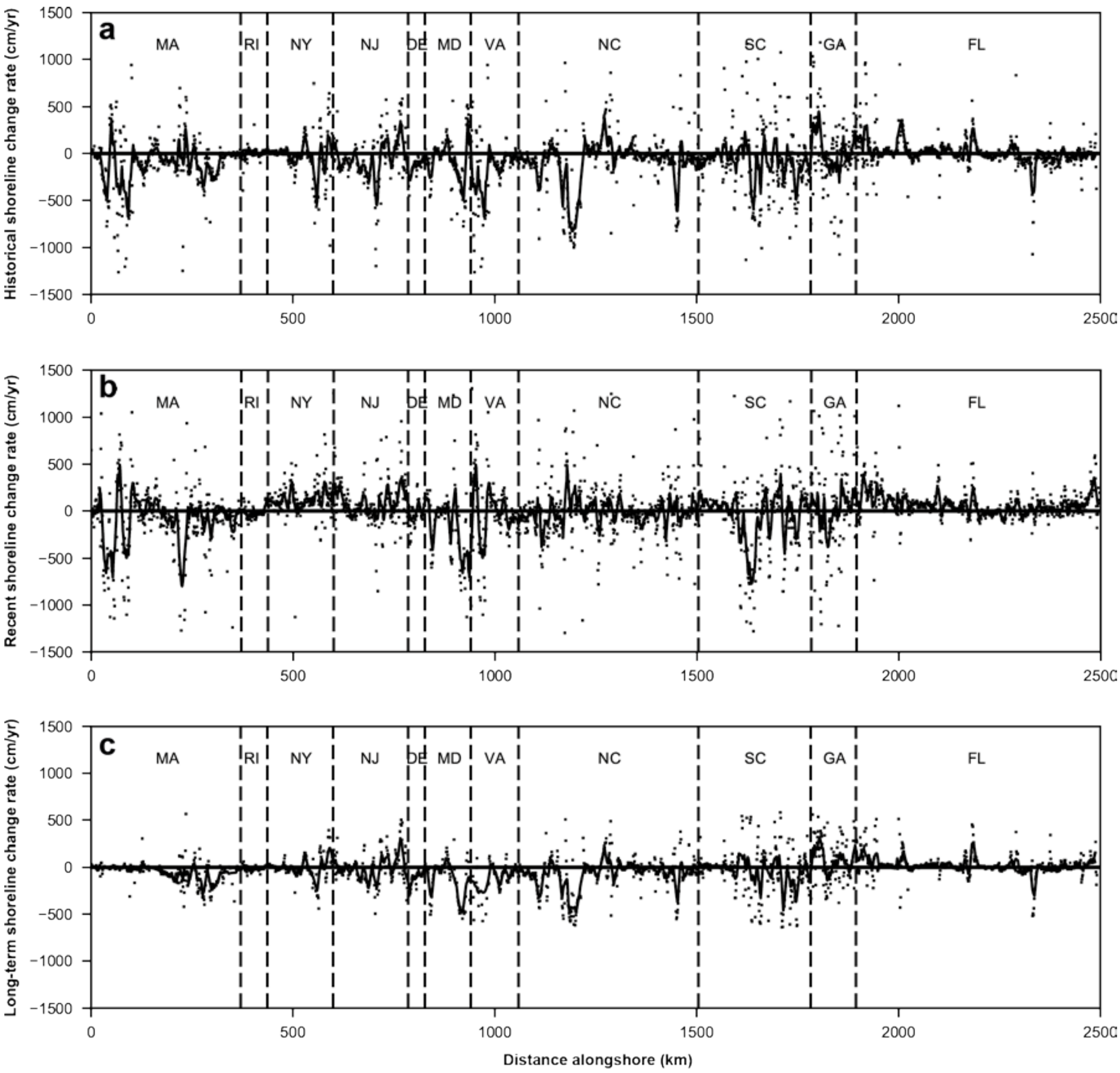

Figure A.2 (a) Historical, (b) recent, and (c) long-term rates of shoreline change plotted relative to distance alongshore (north to south). Dots represent rates at transects; solid lines are 10-km moving averages; dashed lines indicate state boundaries.

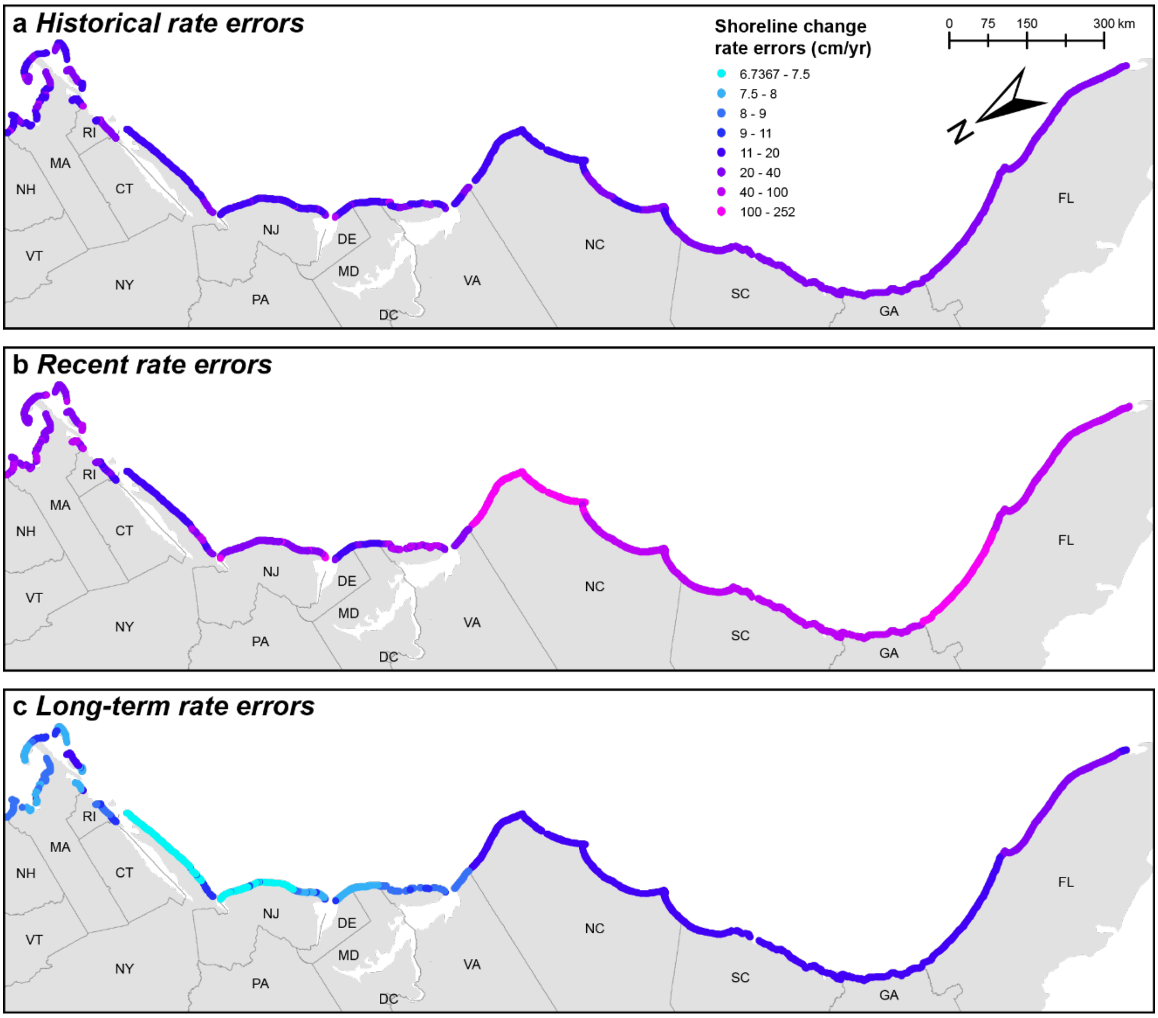

Figure A.3 Maps of (a) historical, (b) recent, and (c) long-term uncertainty in end-point erosion rate calculations (cm/yr) at each transect (see Table A.2).

Table A.1 Survey start and end dates used in each state (corresponding to Figure A.1).

State	historical start dates	historical end dates	recent start dates	recent end dates	long-term start dates	long-term end dates
NH	1855	1952	1994	2000	1855	2000
MA	1844, 1845, 1846, 1848, 1851, 1852, 1853, 1854, 1855, 1856, 1858, 1859, 1868, 1870, 1871, 1886, 1887, 1888, 1895, 1897, 1909, 1911, 1912, 1943	1909, 1910, 1911, 1925, 1933, 1934, 1938, 1942, 1943, 1944, 1951, 1952, 1953, 1954, 1955	1962, 1967, 1970, 1978, 1979, 1980, 1994	1980, 1994, 1997, 2000	1844, 1845, 1846, 1847, 1848, 1849, 1851, 1853, 1854, 1855, 1856, 1858, 1860, 1861, 1866, 1867, 1868, 1886, 1887, 1888, 1894, 1895, 1897	2000
RI	1869, 1872, 1873, 1883, 1886, 1939	1948, 1951, 1952, 1954, 1956	1963, 1975	2000, 2003, 2004, 2006	1869, 1872, 1873, 1883, 1886	2000, 2003, 2004, 2006
NY	1830, 1835, 1870, 1877, 1878, 1880, 1887, 1909, 1933	1933, 1934, 1938, 1947, 1950	1960, 1962, 1983, 1988, 1991	1991, 1994, 2000, 2006, 2007	1830, 1835, 1870, 1877, 1878, 1880, 1887	2000, 2006, 2007
NJ	1836, 1839, 1841, 1842, 1866, 1871, 1875, 1879, 1881, 1885, 1899, 1936	1932, 1933, 1934, 1936, 1943, 1950, 1951, 1952, 1953	1971, 1977	1977, 2000	1836, 1839, 1841, 1842, 1866, 1875, 1879, 1881, 1885, 1899	2000
DE	1845, 1850, 1882, 1903	1929, 1943	1961, 1962, 1970	2000	1845, 1850, 1882	2000
MD	1849, 1850	1942	1962	1989, 2000	1849, 1850	2000
VA	1849, 1850, 1851, 1852, 1855, 1858, 1859, 1870, 1871, 1888, 1908, 1910, 1911, 1943	1910, 1911, 1925, 1933, 1942, 1943, 1944, 1953	1962, 1967, 1980	1979, 1980, 1997, 2000	1849, 1850, 1851, 1852, 1855, 1858, 1859, 1870, 1871, 1888	1997, 2000
NC	1849, 1851, 1852, 1853, 1854, 1856, 1857, 1858, 1859, 1860, 1866, 1867, 1871, 1872, 1873	1925, 1933, 1934, 1940, 1946, 1949	1970, 1972, 1973, 1979, 1980, 1988	1997	1849, 1851, 1852, 1853, 1854, 1856, 1857, 1858, 1859, 1860, 1866, 1867, 1871, 1872, 1873	1997
SC	1852, 1854, 1858, 1859, 1860, 1863, 1872, 1873, 1874, 1875	1920, 1921, 1925, 1926	1962, 1963, 1964	2000	1852, 1854, 1858, 1859, 1860, 1863, 1872, 1873, 1874, 1875	2000
GA	1857, 1858, 1860, 1863, 1867, 1868, 1869, 1870	1924, 1925	1971, 1973	1999	1857, 1858, 1860, 1863, 1867, 1868, 1869, 1870	1999
FL	1851, 1853, 1857, 1858, 1860, 1861, 1867, 1871, 1872, 1873, 1874, 1875, 1877, 1878, 1879, 1881, 1882, 1883, 1884	1923, 1924, 1927, 1928, 1930	1967, 1969, 1970, 1971, 1973, 1979, 1980	1999	1851, 1853, 1857, 1858, 1860, 1861, 1867, 1871, 1872, 1873, 1874, 1875, 1877, 1878, 1879, 1881, 1882, 1883, 1884	1999

Table A.2 Statistics for rates of shoreline change (cm/yr) and rate errors.

Shoreline change rates	***Minimum***	***Maximum***	***Median***	***Mean***	***S.D.***	***Variance***
Historical (*n* = 2386 transects)	-1261	+1181	-30	-55	268	718
Recent (*n* = 2446)	-1297	+1304	+19	+5	288	828
Long-term (*n* = 2239)	-641	+581	-10	-27	160	256
Rate errors	***Minimum***	***Maximum***	***Median***	***Mean***	***S.D.***	***Variance***
Historical	15	331	23	24	13	2
Recent	16	252	63	72	53	28
Long-term	7	021	17	15	5	0

Table A.3 Comparison of mean shoreline-change rates (in cm/yr) and percent of eroding coastline from this study and from USGS rates and reports.

Timeframe	**Rate (cm/yr)**	**% eroding**
Historical	-55	62.5
Recent	+5	43.3
Long-term	-27	57.6
USGS long-term	-30	58.4
USGS short-term	+8	48.5

Table A.4 Comparison of total volumes of beach nourishment (reported) relative to shoreline change (derived).

PART A – Beach nourishment (BN) totals since 1960 (PSDS, 2017)[a]			
	All BN	**Nav BN[b]**	**Non-Nav BN[c]**
BN vol (m^3)	284,732,677	52,360,944	232,371,733
[d]BN vol per m (m^3/m)	**114**	**21**	**93**

[a] Includes beach nourishment projects between 1960 and the end-survey date in each state, respectively (Table A.1). Of 777 records, 739 (95%) have volumes attributed.

[b] Beach nourishment for navigation works, such as inlet maintenance.

[c] Beach nourishment excluding navigation works.

[d] Volume per meter alongshore, or total BN volume (m^3) x 2.5E-6 (m).

PART B – Volume comparisons (BN from Part A relative to volumes estimated from shoreline change)									
***Estimation method #1** (discussed in text) – total net volume estimated from net shoreline change (m) between 1960 and end-survey date in each state*									
[e]scaling factor (*c* = …)	1.0	1.5	2	2.5	3	3.5	4	4.5	5
total net difference (m)	54,702	54,702	54,702	54,702	54,702	54,702	54,702	54,702	54,702
estimated total vol. (m^3)	54,702	82,054	109,405	136,756	164,107	191,459	218,810	246,161	273,512
[f]estimated vol. per m (m^3/m)	**23**	**35**	**47**	**58**	**70**	**82**	**94**	**105**	**117**
ratio (All BN):(est. vol)	4.87	3.25	2.43	1.95	1.62	1.39	1.22	1.08	0.97
ratio (Non-Nav BN):(est. vol)	3.97	2.65	1.99	1.59	1.32	1.14	0.99	0.88	0.79
***Estimation method #2** – volume estimated from overall difference between historical and recent mean rates of shoreline change*									
[e]scaling factor (*c* = …)	1.0	1.5	2	2.5	3	3.5	4	4.5	5
diff. in mean rate (m/yr) per m	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
[g]diff. mean rate (m/yr)/m x 47 yrs	28.2	28.2	28.2	28.2	28.2	28.2	28.2	28.2	28.2
[h]estimated vol. per m (m^3/m)	**28**	**42**	**56**	**71**	**85**	**99**	**113**	**127**	**141**
ratio (All BN):(est. vol)	4.04	2.69	2.02	1.62	1.35	1.15	1.01	0.90	0.81
ratio (Non-Nav BN):(est. vol)	3.30	2.20	1.65	1.32	1.10	0.94	0.82	0.73	0.66

[e] Scaling factor *c* = 1–3 after Farris & List (2007).

[f] We divide estimated total volume by 2339 transects (1 km apart) that have both an associated "historical" and "recent" rate relative to 1960. We assume that the rate per transect rate is the same as the rate per m alongshore.

[g] Period of 47 years covers full date range in dataset, from 1960–2007.

[h] Here, volume per meter alongshore comes from: (difference in mean rate) x (47 years) x (scaling factor).

Table A.5 Comparative rates of mean and median historical and recent rates of shoreline change with distance from nearest beach-nourishment site. Note that for distances >16 km (below dashed horizontal line), the distributions of historical versus recent rates become statistically indistinguishable (Figure 2.3 i).

distance from nearest nourishment site (km)	**mean historical rate (cm/yr)**	**median historical rate (cm/yr)**	**mean recent rate (cm/yr)**	**median recent rate (cm/yr)**	***n* (samples)**
≤16 km	-65.0	-39.0	22.8	21.5	1720
>16 km	-23.0	-2.3	-39.6	10.6	619
16–30 km	31.6	20.0	20.6	26.5	316
>30 km	-80.1	-33.6	-102.3	-9.3	303

Appendix B Supporting Information: Paper 2

B.1 Introduction

This supporting information includes technical details regarding our data-acquisition method (Text B.2), a figure illustrating the method (Figure B.1), and tables (Table B.1; Table B.2; Table B.3) from which figures in the article derive.

B.2 Text B.2 – Extended Methods

Processing and analysis of spatial data was conducted using a GIS platform. Our data sources are publicly accessible (Table B.3).

To differentiate discrete zones of the Florida coast according to the presence or absence of beach nourishment activity, we spatially join nourishment project locations from the PSDS with a shapefile of ZIP code boundaries. Florida ZIP code data provide 100% state coverage, including coverage of its barrier islands, where many nourishment locations in the PSDS dataset are sited. Every Florida nourishment location in the PSDS nourishment database can be related spatially to a ZIP code. By comparison, the shapefile of Florida municipal boundaries available from the Florida Department of Revenue and Florida Geographic Data Library provides less than 10% state coverage. (The dataset for U.S. Census Places, another unit of area we considered using for spatial comparisons, provides 17% state coverage.) Although a ZIP code is not a unique identifier for a municipality, municipal boundaries do not necessarily define the explicit spatial limits of nourishment activities. ZIP codes serve a consistent, robust template by which to delineate zones of coastal development over large spatial scales.

The PSDS database includes representative spatial coordinates for beach nourishment projects. All projects associated with a given beach location share the same spatial coordinates. Where a beach nourishment coordinate falls within (or within 500 m of) a given ZIP code boundary, that ZIP code is denoted as a 'nourishing' zone. (For quality assurance, we checked this automated process against "beach location" descriptors in the PSDS database.) All remaining coastal segments are denoted as 'non-nourishing' zones.

Total coastline length of nourishing and non-nourishing zones, respectively, is the sum of ocean-facing edge lengths from the ZIP code boundaries. The PSDS database includes nourishment project "length" information where available (i.e., the approximate length of beach nourished in a given event), but those records are sparse, especially for historical projects. Note that the online

Appendix B

PSDS Beach Nourishment Viewer portal (http://beachnourishment.wcu.edu/), lists total nourishment length for a given state; that total is the sum of all project lengths on record, including multiple re-nourishments at a given location. We use ZIP code polygons to calculate nourishing and non-nourishing coastline lengths to avoid that redundancy.

From the state-wide database, we select parcels that fall within the boundaries of coastal ZIP codes. Of those parcels, we query the 'DESCRIPT' field in the data attribute table and select the parcels listed as 'SINGLE FAMILY'. To then select only the shorefront properties, we draw a continuous digitized line (polyline) through the parcels that comprise the seaward margin. In sections of crenulated coastline, we select only parcels fronting either the Atlantic or Gulf (Table B.1). Zones with no shorefront single-family homes are excluded from analysis. The most notable exclusion is Miami Beach (ZIP code 33154): Miami Beach has nourished 23 times since 1960, but all shorefront parcels are listed as either condominiums, hotels, or commercial buildings. Another notably blank section of South Florida coastline in our analysis (Figure 3.1 a) is Everglades National Park, which wraps from the Atlantic west of Miami into the Gulf. Because of ambiguities regarding 'shorefront' parcels on some islands, we exclude the Florida Keys. We differentiate between Florida's Atlantic and Gulf coasts (east and west of the Florida Keys, respectively) as other studies do (NRC, 2014) because the water bodies they face have markedly different hydrographic characteristics.

From each selected parcel, we extract two housing attributes: the total living area of an existing house on that parcel ('TOTLVGAREA'), and the year in which the house was built ('ACTYRBLT'). The house size data are not normally distributed (Figure 3.3). To resolve the salient contributions to total house area (Table B.2), we rank-order the house data by size, subdivide those rankings by percentile, split each percentile band by nourishment practice, and calculate the mean of each category. We present the 91–100th percentile separately because houses in that band are in many cases substantially larger than those in the band below. For the decadal analyses (Figure 3.2 d–f, Figure 3.4), houses within each percentile band are resorted by year built. Finally, we use a non-parametric, two-sample Kolmogorov-Smirnov test (which tests the null hypothesis that two sample distributions come from the same distribution) to compare various subsets of the house size data; comparative test results are listed in Table B.1.

B.3 Figure B.1 and Tables B.1 – B.3

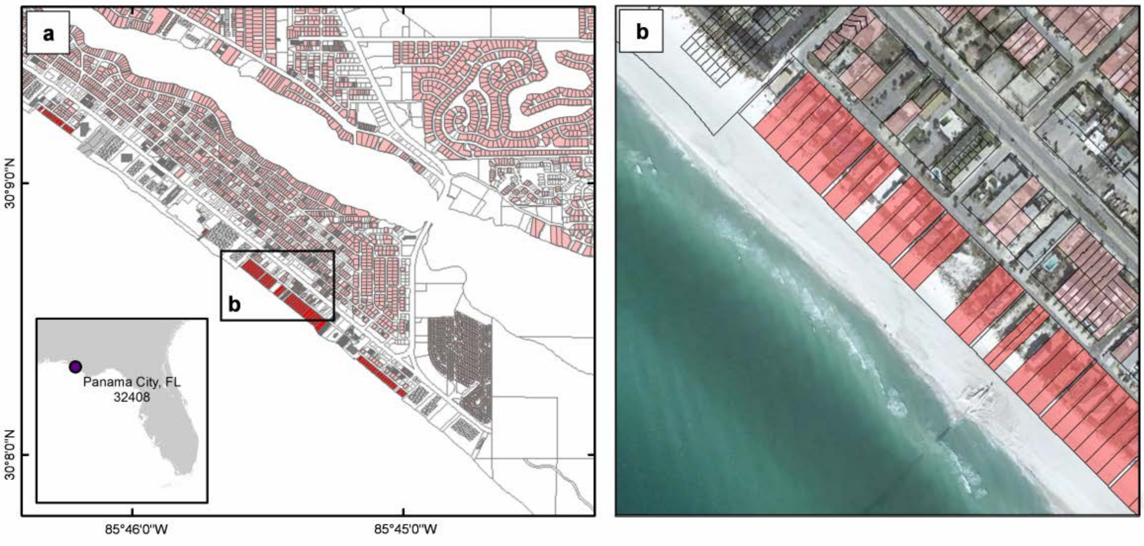

Figure B.1 Example showing parcel selection method. (a) Parcel-scale property data for Panama City, Florida. We select only shorefront parcels with single-family houses. (b) Zoomed in view of inset in (a), showing selected parcels (shaded).

Appendix B

Table B.1 Results of two-sample Kolmogorov–Smirnov tests for difference between combinations of data distributions and subdistributions. Alpha (α, shown as %) is the parameter for significance level. Comparisons indicate whether two sample distributions are different enough to reject (at the 1% or 5% significance level) or accept (-) the null hypothesis that they come from the same continuous distribution.

Two-sample Kolmogorov-Smirnov (K-S) tests for difference			
Distribution 1	**Distribution 2**	**Significance (α = %)**	**Corresponding figures**
All houses			
Florida nourishing zones	Florida non-nourishing zones	1	1d, 2a
Atlantic nourishing zones	Atlantic non-nourishing zones	1	1d, 2b
Gulf nourishing zones	Gulf non-nourishing zones	1	1d, 2c
Parsed by percentile band			
Florida nourishing zones:	*Florida non-nourishing zones:*		2a
0-50th percentile	0-50th percentile	1	
51-75th percentile	51-75th percentile	1	
76-90th percentile	76-90th percentile	1	
91-100th percentile	91-100th percentile	1	
Atlantic nourishing zones:	*Atlantic non-nourishing zones:*		2b
0-50th percentile	0-50th percentile	1	
51-75th percentile	51-75th percentile	5	
76-90th percentile	76-90th percentile	1	
91-100th percentile	91-100th percentile	1	
Gulf nourishing zones:	*Gulf non-nourishing zones:*		2c
0-50th percentile	0-50th percentile	1	
51-75th percentile	51-75th percentile	1	
76-90th percentile	76-90th percentile	1	
91-100th percentile	91-100th percentile	1	
Parsed by decade built			
Florida nourishing zones:	*Florida non-nourishing zones:*		2d
pre-1960	pre-1960	1	
1961-1970	1961-1970	-	
1971-1980	1971-1980	1	
1981-1990	1981-1990	1	
1991-2000	1991-2000	1	
2001-2010	2001-2010	5	
Atlantic nourishing zones:	*Atlantic non-nourishing zones:*		2e
pre-1960	pre-1960	1	
1961-1970	1961-1970	-	
1971-1980	1971-1980	1	
1981-1990	1981-1990	1	
1991-2000	1991-2000	-	
2001-2010	2001-2010	-	
Gulf nourishing zones:	*Gulf non-nourishing zones:*		2f
pre-1960	pre-1960	-	
1961-1970	1961-1970	-	
1971-1980	1971-1980	1	
1981-1990	1981-1990	1	
1991-2000	1991-2000	1	
2001-2010	2001-2010	1	

Table B.2 Total area and numbers of houses sorted by decade built and percentile band for size. Column headings: BN = nourishing zone; NN = non-nourishing zone; Diff = difference between nourishing and non-nourishing subtotal (BN–NN); Ratio = ratio of nourishing and non-nourishing subtotal (BN:NN).

Total house area ($m^2 \times 10^3$)		0-50%				51-75%				76-90%				91-100%				Total			
		BN	NN	Ratio	Diff	BN	NN	Ratio	Diff	BN	NN	Ratio	Diff	BN	NN	Ratio	Diff	BN	NN	Ratio	Diff
Florida	Pre 1960	294.941	109.065	2.704	185.877	123.264	30.382	4.057	92.882	75.384	7.449	10.119	67.935	25.029	8.879	2.819	16.151	518.618	155.774	3.329	362.844
	1961-1970	97.984	41.841	2.342	56.143	28.406	16.966	1.674	11.440	11.375	4.872	2.335	6.503	6.853	1.957	3.501	4.895	144.618	65.636	2.203	78.982
	1971-1980	291.331	89.464	3.256	201.867	66.102	25.134	2.630	40.967	13.655	7.223	1.891	6.432	5.714	3.330	1.716	2.383	376.801	125.151	3.011	251.650
	1981-1990	303.966	127.815	2.378	176.150	156.066	39.910	3.910	116.156	56.496	26.532	2.129	29.964	13.744	14.355	0.957	-0.611	530.271	208.612	2.542	321.659
	1991-2000	302.096	129.688	2.329	172.408	184.598	80.142	2.303	104.455	137.085	57.226	2.396	79.860	91.878	28.792	3.191	63.086	715.657	295.848	2.419	419.809
	2001-2010	209.157	66.990	3.122	142.166	191.307	90.068	2.124	101.239	155.859	65.903	2.365	89.956	157.293	56.372	2.790	100.921	713.616	279.333	2.555	434.283
	Total	**1499.47**	**564.86**	**2.65**	**934.61**	**749.74**	**282.60**	**2.65**	**467.14**	**449.85**	**169.20**	**2.66**	**280.65**	**300.51**	**113.69**	**2.64**	**186.83**	**2999.58**	**1130.35**	**2.65**	**1869.23**
Atlantic	Pre 1960	164.906	77.061	2.140	87.845	86.691	13.375	6.482	73.316	53.416	3.944	13.544	49.472	35.606	3.638	9.786	31.968	340.619	98.018	3.475	242.601
	1961-1970	54.105	23.732	2.280	30.372	15.119	8.806	1.717	6.313	8.287	2.888	2.869	5.399	6.853	0.000	-	6.853	84.364	35.427	2.381	48.938
	1971-1980	162.989	46.625	3.496	116.364	30.454	12.856	2.369	17.598	6.481	3.561	1.820	2.920	5.294	2.310	2.292	2.985	205.218	65.352	3.140	139.866
	1981-1990	163.323	58.850	2.775	104.473	67.954	19.767	3.438	48.187	22.462	10.154	2.212	12.308	4.936	9.280	0.532	-4.344	258.675	98.052	2.638	160.623
	1991-2000	115.583	44.568	2.593	71.015	86.763	38.984	2.226	47.779	51.491	26.525	1.941	24.966	42.042	13.303	3.160	28.740	295.879	123.380	2.398	172.499
	2001-2010	76.108	35.819	2.125	40.290	81.802	49.210	1.662	32.593	79.308	39.017	2.033	40.291	52.895	29.509	1.792	23.386	290.113	153.555	1.889	136.558
	Total	**737.01**	**286.66**	**2.57**	**450.36**	**368.78**	**143.00**	**2.58**	**225.79**	**221.45**	**86.09**	**2.57**	**135.36**	**147.63**	**58.04**	**2.54**	**89.59**	**1474.87**	**573.78**	**2.57**	**901.09**
Gulf	Pre 1960	131.026	39.127	3.349	91.899	35.593	12.419	2.866	23.174	11.380	3.441	3.307	7.939	0.000	2.769	0.000	-2.769	177.999	57.756	3.082	120.243
	1961-1970	43.438	19.706	2.204	23.732	14.607	8.229	1.775	6.378	2.209	1.630	1.356	0.580	0.000	0.645	0.000	-0.645	60.254	30.210	1.995	30.044
	1971-1980	127.941	46.487	2.752	81.454	36.932	9.886	3.736	27.046	6.709	2.673	2.510	4.036	0.000	0.752	0.000	-0.752	171.583	59.799	2.869	111.784
	1981-1990	140.712	69.107	2.036	71.605	88.971	17.894	4.972	71.076	34.840	19.162	1.818	15.678	7.074	4.397	1.609	2.677	271.596	110.560	2.457	161.036
	1991-2000	186.123	77.900	2.389	108.222	99.102	52.012	1.905	47.091	79.437	23.058	3.445	56.380	55.116	19.499	2.827	35.617	419.778	172.468	2.434	247.310
	2001-2010	133.105	25.950	5.129	107.156	105.113	38.441	2.734	66.672	94.904	33.782	2.809	61.122	90.381	27.606	3.274	62.775	423.503	125.778	3.367	297.725
	Total	**762.34**	**278.28**	**2.74**	**484.07**	**380.32**	**138.88**	**2.74**	**241.44**	**229.48**	**83.74**	**2.74**	**145.73**	**152.57**	**55.67**	**2.74**	**96.90**	**1524.71**	**556.57**	**2.74**	**968.14**

Number of houses ($\times 10^3$)		0-50%				51-75%				76-90%				91-100%				Total			
		BN	NN	Ratio	Diff	BN	NN	Ratio	Diff	BN	NN	Ratio	Diff	BN	NN	Ratio	Diff	BN	NN	Ratio	Diff
Florida	Pre 1960	1.427	0.564	2.530	0.863	0.207	0.071	2.915	0.136	0.065	0.011	5.909	0.054	0.011	0.006	1.833	0.005	1.71	0.652	2.623	1.058
	1961-1970	0.464	0.21	2.210	0.254	0.048	0.039	1.231	0.009	0.011	0.007	1.571	0.004	0.002	0.002	1.000	0	0.525	0.258	2.035	0.267
	1971-1980	1.513	0.487	3.107	1.026	0.116	0.057	2.035	0.059	0.012	0.01	1.200	0.002	0.003	0.002	1.500	0.001	1.644	0.556	2.957	1.088
	1981-1990	1.371	0.671	2.043	0.7	0.264	0.088	3.000	0.176	0.052	0.038	1.368	0.014	0.005	0.01	0.500	-0.005	1.692	0.807	2.097	0.885
	1991-2000	1.109	0.581	1.909	0.528	0.303	0.181	1.674	0.122	0.121	0.077	1.571	0.044	0.035	0.023	1.522	0.012	1.568	0.862	1.819	0.706
	2001-2010	0.713	0.272	2.621	0.441	0.315	0.192	1.641	0.123	0.138	0.088	1.568	0.05	0.058	0.042	1.381	0.016	1.224	0.594	2.061	0.63
	Total	**6.60**	**2.79**	**2.37**	**3.81**	**1.25**	**0.63**	**2.00**	**0.63**	**0.40**	**0.23**	**1.73**	**0.17**	**0.11**	**0.09**	**1.34**	**0.03**	**8.36**	**3.73**	**2.24**	**4.63**
Atlantic	Pre 1960	0.749	0.346	2.165	0.403	0.144	0.024	6.000	0.120	0.048	0.004	12.000	0.044	0.018	0.002	9.000	0.016	0.959	0.376	2.551	0.583
	1961-1970	0.252	0.101	2.495	0.151	0.025	0.016	1.563	0.009	0.008	0.003	2.667	0.005	0.002	0.000	-	0.002	0.287	0.120	2.392	0.167
	1971-1980	0.930	0.221	4.208	0.709	0.052	0.024	2.167	0.028	0.006	0.004	1.500	0.002	0.003	0.001	3.000	0.002	0.991	0.250	3.964	0.741
	1981-1990	0.689	0.236	2.919	0.453	0.115	0.033	3.485	0.082	0.022	0.011	2.000	0.011	0.001	0.005	0.200	-0.004	0.827	0.285	2.902	0.542
	1991-2000	0.417	0.167	2.497	0.250	0.139	0.064	2.172	0.075	0.048	0.029	1.655	0.019	0.021	0.009	2.333	0.012	0.625	0.269	2.323	0.356
	2001-2010	0.258	0.126	2.048	0.132	0.131	0.084	1.560	0.047	0.076	0.043	1.767	0.033	0.026	0.017	1.529	0.009	0.491	0.270	1.819	0.221
	Total	**3.30**	**1.20**	**2.75**	**2.10**	**0.61**	**0.25**	**2.47**	**0.36**	**0.21**	**0.09**	**2.21**	**0.11**	**0.07**	**0.03**	**2.09**	**0.04**	**4.18**	**1.57**	**2.66**	**2.61**
Gulf	Pre 1960	0.680	0.234	2.906	0.446	0.061	0.034	1.794	0.027	0.010	0.006	1.667	0.004	0.000	0.002	0.000	-0.002	0.751	0.276	2.721	0.475
	1961-1970	0.211	0.111	1.901	0.100	0.025	0.023	1.087	0.002	0.002	0.003	0.667	-0.001	0.000	0.001	0.000	-0.001	0.238	0.138	1.725	0.100
	1971-1980	0.582	0.273	2.132	0.309	0.066	0.027	2.444	0.039	0.005	0.005	1.000	0.000	0.000	0.001	0.000	-0.001	0.653	0.306	2.134	0.347
	1981-1990	0.682	0.431	1.582	0.251	0.150	0.050	3.000	0.100	0.030	0.035	0.857	-0.005	0.003	0.006	0.500	-0.003	0.865	0.522	1.657	0.343
	1991-2000	0.691	0.385	1.795	0.306	0.166	0.141	1.177	0.025	0.068	0.044	1.545	0.024	0.018	0.023	0.783	-0.005	0.943	0.593	1.590	0.350
	2001-2010	0.455	0.126	3.611	0.329	0.179	0.103	1.738	0.076	0.073	0.064	1.141	0.009	0.026	0.031	0.839	-0.005	0.733	0.324	2.262	0.409
	Total	**3.30**	**1.56**	**2.12**	**1.74**	**0.65**	**0.38**	**1.71**	**0.27**	**0.19**	**0.16**	**1.20**	**0.03**	**0.05**	**0.06**	**0.73**	**-0.02**	**4.18**	**2.16**	**1.94**	**2.02**

Table B.3 Digital data sources.

Organisation	Product	Dataset	Filename	Publisher/Source	Link	Accessed
Western Carolina University	PSDS	Beach nourishment database		PSDS	http://psds.wcu.edu/projects-research/beach-nourishment/	Oct-14
ESRI	ArcGIS	USA ZIP Code Areas	0000 USA ZIP Code Areas	Esri/TomTom	http://www.arcgis.com/home/item.html?id=8d2012a2016e484dafaac0451f9aea24	Dec-14
FGDL	Metadata Explorer	Florida Parcel data Statewide Parcels_2012		Florida Department of Revenue	http://www.fgdl.org/metadataexplorer/explorer.jsp	Nov-14

Appendix C Supporting Information: Paper 3

C.1 Introduction

Here we include two supplemental figures to augment those in the main text, and four supplemental tables, three with data sources and one with descriptive statistical data.

C.2 Figures C.1 – C.2 and Tables C.1 – C.4

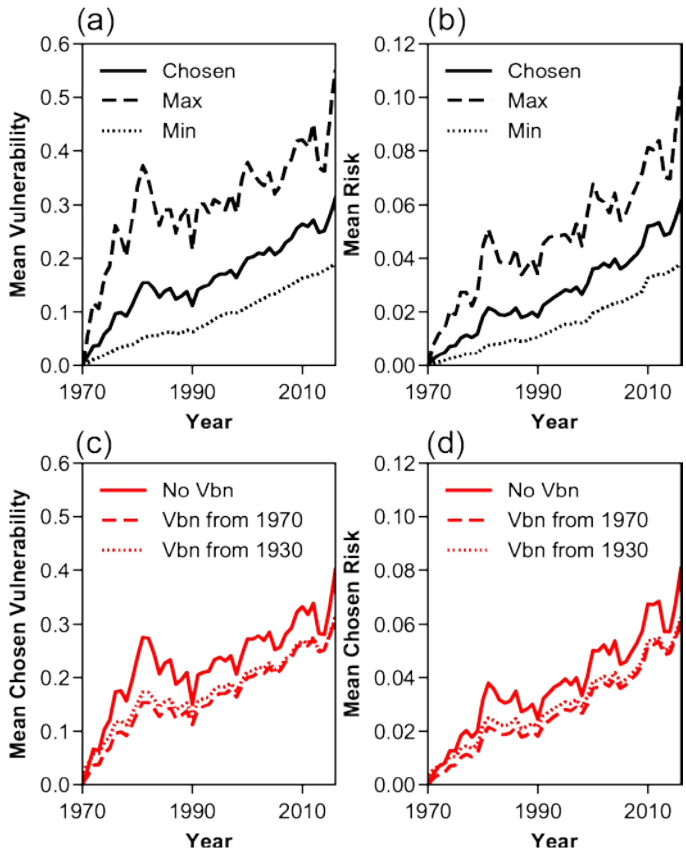

Figure C.1 Sensitivity analysis. Spread of mean vulnerability (a), and mean risk (b), for chosen vulnerability parameters (solid black), and parameters that create the maximum (dashed black) and minimum (dotted black) mean vulnerability. Spread of mean vulnerability (c), and mean risk (d), using chosen vulnerability parameters without V_{bn} (solid red), with V_{bn} calculated from 1970 (dashed red), and V_{bn} calculated from 1930 (dashed red).

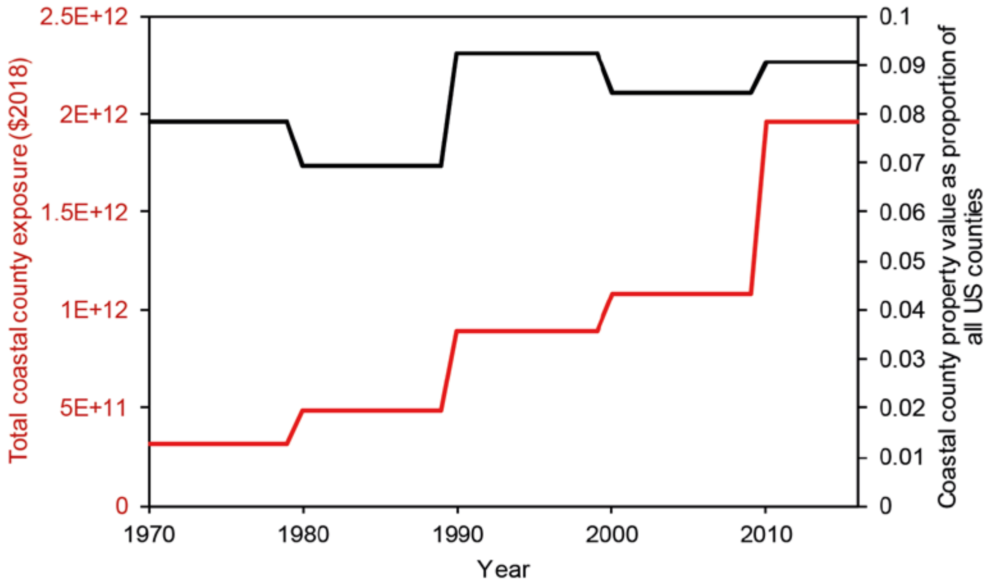

Figure C.2 Total exposure for 51 coastal counties in $2018 (red, left axis), as a proportion of all US counties (black dashed, right axis).

Table C.1 Tide gauges used to calculate sea-level change rates.

Tide Gauge	*Latitude*	*Longitude*
Bar Harbor, Frenchman Bay, ME	44.3917	-68.205
Boston, MA	42.3533	-71.0533
Woods Hole (Ocean. Inst.), MA	41.5233	-70.6717
Newport, RI	41.505	-71.3267
Montauk, NY	41.0483	-71.96
New York (The Battery), NY	40.7	-74.0133
Sandy Hook, NJ	40.4667	-74.0083
Atlantic City, NJ	39.355	-74.4183
Lewes (Breakwater Harbor), DE	38.7817	-75.12
Kiptopeke Beach, VA	37.165	-75.9883
Wilmington, NC	34.2267	-77.9533
Charleston I, SC	32.7817	-79.925
Fort Pulaski, GA	32.0333	-80.9017
Fernandina, FL	30.6717	-81.465
Key West, FL	24.555	-81.8067

All tide gauge data from Permanent Service for Mean Sea Level (PSMSL, 2018)

Table C.2 LiDAR files used to calculate beach slope.

Data files used	*USGS LiDAR files*
USGS LiDAR files	10CNT07_morphology (FL-NC)
	13CNT05_morphology (NY-NH)
	14CNT01_morphology (SC-NY)
	2016-368-DD_morphology (FL)

Lidar data from Doran et al., (2017)

Table C.3 Census data files used to calculate exposure.

Decade	*Data File*	*Source Code*	*NHGIS code*
1970	ds94_1970_county	NT14A	CBH
1980	ds104_1980_county	NT40 and NT42	C8K and C8M
1990	ds120_1990_county	NH24	ESV
2000	ds151_2000_county	NH078A	GB9
2010*	ds201_20135_2013_county	B25082	UMR

** use 2009-2013 5-year community survey in place of 2010 for coverage*

Data source: *Minnesota Population Center. 2011. National Historic Geographic Information System: Version 2.0. http://www.nhgis.org. Accessed 12/03/2019.*

Table C.4 Sensitivity testing of the effect of changing variables in Eq. (5) on the vulnerability due to beach width (V_{bw}). Factors are: maximum beach width (x_0), fraction of beach width affected by the nonlinear rate (µ), and the nonlinear rate (ϑ). Highlighted rows indicate the maximum and minimum mean V_{bw}, and the chosen set of variables, all of which are plotted on Figure C.1.

x_0	μ	ϑ	V_{bw} max mean	V_{bw} max median	V_{bw} max variance	Figure C.1
25	0.75	0.75	0.879921486	1	0.238276168	Max
25	0.66	0.75	0.837619876	0.973178273	0.228515365	
25	0.75	0.5	0.812977086	1	0.229546306	
25	0.66	0.5	0.764614503	0.896672321	0.219268978	
50	0.75	0.75	0.757426568	0.812667632	0.20000084	
25	0.5	0.75	0.724148105	0.766012983	0.195911534	
50	0.66	0.75	0.694330452	0.71098647	0.179730302	
50	0.75	0.5	0.684253691	0.689489093	0.191766161	
100	0.75	0.75	0.669695312	0.667161775	0.16489023	
25	0.75	0.25	0.663239488	0.741045746	0.200831919	
25	0.5	0.5	0.659276382	0.651402958	0.187095246	
50	0.66	0.5	0.62860932	0.61837553	0.174063671	
25	0.66	0.25	0.623883198	0.661900729	0.19273165	
100	0.66	0.75	0.604522644	0.600846261	0.141685799	
100	0.75	0.5	0.603277433	0.557908844	0.158263847	

Appendix C

x_0	μ	ϑ	V_{bw} max mean	V_{bw} max median	V_{bw} max variance	Figure C.1
50	0.5	0.75	0.572033801	0.5462328	0.144798312	
25	0.33	0.75	0.567529465	0.545899862	0.157351573	
50	0.75	0.25	0.551923387	0.465753575	0.176237297	
100	0.66	0.5	0.54607491	0.506611107	0.137084567	
25	0.5	0.25	0.54562914	0.495041802	0.177123537	
25	0.33	0.5	0.523770133	0.466287757	0.156396001	
50	0.5	0.5	0.522220392	0.472430072	0.142790918	
50	0.66	0.25	0.510965068	0.421488275	0.162509334	
25	0.75	0.1	0.490515605	0.405481161	0.178020267	
25	0.25	0.75	0.487472406	0.426503224	0.14579159	
100	0.5	0.75	0.486469537	0.474650386	0.105978907	
100	0.75	0.25	0.483897448	0.370947148	0.144004668	
25	0.66	0.1	0.466774318	0.366603894	0.174628282	
25	0.25	0.5	0.454519147	0.379043029	0.146138187	
25	0.33	0.25	0.446413944	0.335029587	0.154193301	
100	0.5	0.5	0.44219094	0.394234119	0.104064359	
100	0.66	0.25	0.441020523	0.331600214	0.127097143	
50	0.33	0.75	0.433541881	0.364941853	0.115762651	
50	0.5	0.25	0.432685403	0.342794407	0.138001607	
25	0.5	0.1	0.42061617	0.269679155	0.164919202	
50	0.75	0.1	0.40339037	0.266815988	0.154000228	
50	0.33	0.5	0.400665031	0.33625212	0.115907988	Chosen
25	0.75	0.05	0.400298363	0.237574677	0.167206633	
25	0.25	0.25	0.396462905	0.280872694	0.14662032	
25	0.66	0.05	0.38414404	0.22330029	0.162659349	
50	0.66	0.1	0.378487693	0.244388944	0.144360101	
50	0.25	0.75	0.368369213	0.287254869	0.107933547	
100	0.5	0.25	0.362592829	0.261650109	0.099731286	
25	0.33	0.1	0.360064439	0.198813102	0.150159303	
100	0.33	0.75	0.355942308	0.315993987	0.075004785	
25	0.5	0.05	0.35076797	0.171423949	0.154207676	
100	0.75	0.1	0.343996607	0.194113736	0.11732885	
50	0.25	0.5	0.343462508	0.244276109	0.108567792	
50	0.33	0.25	0.341571938	0.248212773	0.115807823	
25	0.25	0.1	0.331168061	0.16333967	0.146465666	
50	0.5	0.1	0.327759773	0.20353052	0.125771424	
100	0.33	0.5	0.32671843	0.274833569	0.074748399	
100	0.66	0.1	0.317907784	0.175986812	0.107855831	
50	0.75	0.05	0.317203403	0.164986448	0.130849361	
25	0.33	0.05	0.315338453	0.131957875	0.147441761	
25	0.25	0.05	0.301263407	0.113385606	0.144976684	
50	0.66	0.05	0.299083839	0.145479896	0.12448709	
50	0.25	0.25	0.298695014	0.185640676	0.109583098	
100	0.25	0.75	0.294285612	0.242770133	0.065338968	
100	0.33	0.25	0.27417866	0.187328122	0.07399774	
50	0.33	0.1	0.272757927	0.13747646	0.112796148	
100	0.25	0.5	0.272146311	0.209968921	0.065503813	

x_0	μ	ϑ	V_{bw} max mean	V_{bw} max median	V_{bw} max variance	Figure C.1
100	0.5	0.1	0.268476398	0.143761168	0.088324508	
50	0.5	0.05	0.266871281	0.117621491	0.115576825	
100	0.75	0.05	0.261384038	0.122358182	0.0960952	
50	0.25	0.1	0.246927408	0.101129683	0.109105535	
100	0.66	0.05	0.243437051	0.112841924	0.088826496	
50	0.33	0.05	0.232655666	0.083737609	0.109476288	
100	0.25	0.25	0.232343454	0.15235307	0.065687065	
50	0.25	0.05	0.216655523	0.064283981	0.106150414	
100	0.33	0.1	0.211741291	0.108617309	0.070288879	
100	0.5	0.05	0.209512152	0.095924132	0.075461562	
100	0.25	0.1	0.185042417	0.090458009	0.064239038	
100	0.33	0.05	0.17299541	0.064657731	0.064948939	
100	0.25	0.05	0.155851353	0.052276218	0.061316482	Min

Appendix D Other works, citations, and media generated

D.1 Other works

I have been co-author on two additional papers during my PhD period, (Lazarus et al., 2018) and (Lazarus and Armstrong, 2015):

> Lazarus, E. D., Limber, P. W., Goldstein, E. B., Dodd, R., and Armstrong, S. B., 2018. Building back bigger in hurricane strike zones. *Nature Sustainability*, **1**(12), 759–762. DOI: 10.1038/s41893-018-0185-y
>
> Lazarus, E. D., and Armstrong, S., 2015. Self-organized pattern formation in coastal barrier washover deposits. *Geology*, **43**(4), 363–366. DOI: 10.1130/G36329.1

D.2 Citations generated

At time of writing, only Chapter 3 (Armstrong et al., 2016) has generated citations, here is a brief review of the literature that cites it.

Armstrong et al. (2016) is mentioned in passing as a reference for increasing risk by promoting more development where hazard reductions are in place (Keeler et al., 2018; Lazarus, 2017; Lazarus et al., 2018; Limber et al., 2018). It has also been cited in PhD and Masters' dissertations (Karanci, 2017; Shahan, 2018; Thompson, 2018), hopefully informing future research from these early career researchers.

Woodruff et al. (2018) develop systems dynamics models of community adaptation to sea level rise, and cite Armstrong et al. (2016) in their argument for adding a reinforcing feedback loop between development and coastal hazard mitigation infrastructure.

In describing managed retreat for the Encyclopedia of Coastal Science, Neal et al. (2017) write:

> "…beach nourishment, has proven to be costly (PSDS, 2017) and has given the deceptive appearance of reduced risk actually encouraging development, and the cost is rising (Armstrong et al., 2016)."
>
> **(Neal et al., 2017)**

Vitousek et al. (2017b) consider if beaches can survive climate change, and write:

> "Increased coastal development on chronically eroding shorelines often causes the transition from natural to engineered systems, in order to preserve beaches and the benefits they provide (Armstrong et al., 2016)."
>
> **(Vitousek, Barnard, and Limber, 2017)**

In a book chapter on barrier islands as coupled human-landscape systems, McNamara and Lazarus (2018) write:

> "Paradoxically, investment in coastal defense then encourages further investment in development and infrastructure (Armstrong et al., 2016; Bagstad et al., 2007; Mileti, 1999; Nordstrom, 1994; Smith, 2013; Werner and McNamara, 2007). In Florida, single-family shorefront houses in nourishment zones are larger and more numerous than in non-nourishment zones, indicating intensified development in areas known to be at risk (Armstrong et al., 2016)."
>
> **(McNamara and Lazarus, 2018)**

D.3 Media generated

Chapter 2 (Armstrong and Lazarus, 2019a) was highlighted by the editor of Earth's Future for an AGU blog:

Beach building is keeping the Atlantic Coast from going under, *AGU GeoSpace Blog*, 31/01/2019, by Joshua Learn: https://blogs.agu.org/geospace/2019/01/31/beach-building-is-keeping-the-atlantic-coast-from-going-under/

This blog was picked up by Long Room, and Phys.org:

https://www.longroom.com/discussion/1351092/beach-building-is-keeping-the-atlantic-coast-from-going-under; https://phys.org/news/2019-01-beach-atlantic-coast.html

Chapter 3 (Armstrong et al., 2016) was an editor's highlight in Earth's Future:

> "This paper touches on an important but under-appreciated process in Earth sciences, which is the role played by the human regulatory environment. The authors describe a feature in coastal change that appears to be a positive feedback between housing development and beach nourishment schemes. This signature may reflect an emergent behavior of a human-natural system. This type of process is critical to understand in the context of Earth's future state."
>
> **https://agupubs.onlinelibrary.wiley.com/hub/article/10.1002/2016EF000425/editor-highlight/**

Armstrong et al. (2016) was also the subject of media stories:

Reinforce and Build, *Hakai Magazine*, by John R. Platt: https://www.hakaimagazine.com/news/reinforce-and-build/

The problem with beach nourishment, *Vox.com*, 10/12/2018, by Carlos Waters: https://www.vox.com/2018/12/10/18125945/beach-erosion-nourishment-coastal-engineering-rebuilding-beaches; this vox.com article features a video that has been viewed by over 1.25 million people to date on *YouTube*: https://www.youtube.com/watch?v=e3ZYaL0Q9os

Armstrong et al. (2016) was also mentioned in:

Beach replenishment is all that's standing between North Carolina and storms, *Think Progress*, 06/07/2017, by Mark Hand: https://thinkprogress.org/coastal-communities-prefer-short-term-fixes-b02bb1edac61/

List of References

Ahmed, H., Naik, G., Willoughby, H., and Edwards, A. G. K., 2012. Communicating risk. *British Medical Journal*, **344**. DOI: 10.1136/bmj.e3996

AIR Worldwide, 2005. *The Coastline at Risk : Estimated Insured Value of Coastal Properties*. Retrieved from http://www.air-worldwide.com/_public/NewsData/000797/The_Coastline_at_Risk-AIR_Worldwide.pdf

AIR Worldwide, 2013. *The Coastline at Risk : 2013 Update to the Estimated Insured Value*.

Alberti, M., Asbjornsen, H., Baker, L. A., Brozović, N., Drinkwater, L. E., Drzyzga, S. A., Jantz, C. A., et al., 2011. Research on Coupled Human and Natural Systems (CHANS): Approach, Challenges, and Strategies. *The Bulletin of the Ecological Society of America*, **92**(2), 218–228. DOI: 10.1890/0012-9623-92.2.218

Alcott, B., 2005. Jevons' paradox. *Ecological Economics*, **54**(1), 9–21. DOI: 10.1016/j.ecolecon.2005.03.020

An, L., Zvoleff, A., Liu, J., and Axinn, W., 2016. Agent-based modeling in coupled human and natural systems (CHANS): Lessons from a comparative analysis. *Handbook of Applied System Science*, **5608**, 267–296. DOI: 10.4324/9781315748771

Armstrong, S. B., and Lazarus, E. D., 2019a. Masked Shoreline Erosion at Large Spatial Scales as a Collective Effect of Beach Nourishment. *Earth's Future*, **7**(2), 74–84. DOI: 10.1029/2018EF001070

Armstrong, S. B., and Lazarus, E. D., 2019b. Reconstructing patterns of coastal risk in space and time along the US Atlantic Coast, 1970–2016. *Natural Hazards and Earth System Sciences Discussions*, **In review**. DOI: 10.5194/nhess-2019-159

Armstrong, S. B., Lazarus, E. D., Limber, P. W., Goldstein, E. B., Thorpe, C., and Ballinger, R. C., 2016. Indications of a positive feedback between coastal development and beach nourishment. *Earth's Future*, **4**(12), 626–635. DOI: 10.1002/2016EF000425

ASBPA, 2007. How Beach Nourishment Projects Work.

Ashton, A. D., and Lorenzo-Trueba, J., 2018. Morphodynamics of Barrier Response to Sea-Level Rise. In L. J. Moore and A. B. Murray (Eds.), *Barrier Dynamics and Response to Changing Climate* (pp. 277–304). Springer International Publishing. DOI: 10.1007/978-3-319-68086-6

Ashton, A. D., and Murray, A. B., 2006a. High-angle wave instability and emergent shoreline shapes: 2. Wave climate analysis and comparisons to nature. *Journal of Geophysical Research: Earth Surface*, **111**(4), 1–17. DOI: 10.1029/2005JF000423

Ashton, A. D., and Murray, A. B., 2006b. High-angle wave instability and emergent shoreline shapes: 1. Modeling of sand waves, flying spits, and capes. *Journal of Geophysical Research: Earth Surface*, **111**(4), 1–19. DOI: 10.1029/2005JF000422

Bagstad, K. J., Stapleton, K., and D'Agostino, J. R., 2007. Taxes, subsidies, and insurance as drivers of United States coastal development. *Ecological Economics*, **63**(2–3), 285–298. DOI: 10.1016/j.ecolecon.2006.09.019

Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Salinas, J. L., and Blöschl, G., 2013. Socio-hydrology: Conceptualising human-flood interactions. *Hydrology and Earth System Sciences*, **17**(8), 3295–3303. DOI: 10.5194/hess-17-3295-2013

Barbier, E. B., Hacker, S. D., Kennedy, C., Koch, E. W., Stier, A. C., and Silliman, B. R., 2011. The value of estuarine and coastal ecosystem services. *Ecological Monographs*, **81**(2), 169–193. DOI: 10.1890/10-1510.1

Bauch, C. T., Sigdel, R., Pharaon, J., and Anand, M., 2016. Early warning signals of regime shifts in coupled human-environment systems. *Proceedings of the National Academy of Sciences of the United States of America*, 201604978. DOI: 10.1073/pnas.1604978113

Berkes, F., Hughes, T. P., Steneck, R. S., Wilson, J. a, Bellwood, D. R., Crona, B., Folke, C., et al., 2006. Globalization, roving bandits, and marine resources. *Science*, **311**(March), 1557–1558. DOI: 10.1126/science.1122804

Bertin, X., Prouteau, E., and Letetrel, C., 2013. A significant increase in wave height in the North Atlantic Ocean over the 20th century. *Global and Planetary Change*, **106**, 77–83. Elsevier B.V. DOI: 10.1016/j.gloplacha.2013.03.009

Bin, O., and Landry, C. E., 2013. Changes in implicit flood risk premiums : Empirical evidence from the housing market. *Journal of Environmental Economics and Management*, **65**(3), 361–376. Elsevier. DOI: 10.1016/j.jeem.2012.12.002

Blake, E. S., Landsea, C. W., and Gibney, E. J., 2011. The deadliest, costliest, and most intense United States Tropical Cyclones from 1851 to 2010 (and other frequently requested Hurricane Facts). *NOAA Technical Memorandum NWS NHC-6*, **2010**(August).

Boonstra, W. J., and de Boer, F. W., 2014. The historical dynamics of social-ecological traps.

Ambio, **43**(3), 260–274. DOI: 10.1007/s13280-013-0419-1

Brody, S. D., Highfield, W. E., Wilson, M., Lindell, M. K., and Blessing, R., 2016. Understanding the motivations of coastal residents to voluntarily purchase federal flood insurance. *Journal of Risk Research*, 1–16. Routledge. DOI: 10.1080/13669877.2015.1119179

Brody, S. D., Zahran, S., Maghelal, P., Grover, H., and Highfield, W. E., 2007. The Rising Costs of Floods: Examining the Impact of Planning and Development Decisions on Property Damage in Florida. *Journal of the American Planning Association*, **73**(3), 330–345. DOI: 10.1080/01944360708977981

Brooks, N., 2003. *Vulnerability , Risk and Adaptation : A Conceptual Framework* (No. 38). Tyndall Centre Working Papers.

Brooks, S. M., Spencer, T., Mcivor, A., and Möller, I., 2016. Reconstructing and understanding the impacts of storms and surges, southern North Sea. *Earth Surface Processes and Landforms*, **864**(February), 855–864. DOI: 10.1002/esp.3905

Brown, A. G., Tooth, S., Bullard, J. E., Thomas, D. S. G., Chiverrell, R. C., Plater, A. J., Murton, J., et al., 2016. The Geomorphology of The Anthropocene: Emergence, Status and Implications. *Earth Surface Processes and Landforms*, n/a-n/a. DOI: 10.1002/esp.3943

Brown, S., Nicholls, R. J., Goodwin, P., Haigh, I. D., Lincke, D., Vafeidis, A. T., and Hinkel, J., 2018. Quantifying Land and People Exposed to Sea-Level Rise with No Mitigation and 1.5°C and 2.0°C Rise in Global Temperatures to Year 2300. *Earth's Future*, **6**(3), 583–600. DOI: 10.1002/2017EF000738

Brown, S., Nicholls, R. J., Hanson, S., Brundrit, G., Dearing, J. A., Dickson, M. E., Gallop, S. L., et al., 2014. Shifting perspectives on coastal impacts and adaptation. *Nature Climate Change*, **4**(9), 752–755. DOI: 10.1038/nclimate2344

Brown, S., Nicholls, R. J., Lowe, J. A., and Hinkel, J., 2016. Spatial variations of sea-level rise and impacts: An application of DIVA. *Climatic Change*, **134**(3), 403–416. DOI: 10.1007/s10584-013-0925-y

Burby, R. J., 2006. Hurricane Katrina and the Paradoxes of Government Disaster Policy: Bringing About Wise Governmental Decisions for Hazardous Areas. *The ANNALS of the American Academy of Political and Social Science*, **604**(1), 171–191. DOI: 10.1177/0002716205284676

Busemeyer, J. R., and Townsend, J. T., 1993. Decision Field Theory: A Dynamic-Cognitive Approach to Decision Making in an Uncertain Environment. *Psychological Review*, **100**(3), 432–459.

DOI: 10.1037/0033-295X.100.3.432

Carter, L. M., Jones, J. W., Berry, L., Burkett, V., Murley, J. F., Obeysekera, J., Schramm, P. J., et al., 2014. Southeast and the Caribbean. In J. M. Melillo, T. C. Richmond, and G. W. Yohe (Eds.), *Climate Change Impacts in the United States: The Third National Climate Assessment* (pp. 396–417). U.S. Global change Research Program. DOI: 10.7930/J0NP22CB

Cazenave, A., and Cozannet, G. Le, 2013. Sea level rise and its coastal impacts. *Earth's Future*, **2**, 15–34. DOI: 10.1002/2013EF000188

Church, J. A., Clark, P. U., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., Merrifield, M. a., et al., 2013. Sea level change. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, et al. (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1137–1216). Cambridge, UK and New York, NY, USA.

Church, J. A., and White, N. J., 2011. Sea-Level Rise from the Late 19th to the Early 21st Century. *Surveys in Geophysics*, **32**(4–5), 585–602. DOI: 10.1007/s10712-011-9119-1

Church, M., 2010. The trajectory of geomorphology. *Progress in Physical Geography*, **34**(3), 265–286. DOI: 10.1177/0309133310363992

Ciarletta, D. J., Lorenzo-Trueba, J., and Ashton, A. D., 2019. Mechanism for retreating barriers to autogenically form periodic deposits on continental shelves. *Geology*, **47**(3), 1–4. DOI: 10.1130/G45519.1

Cioffi-Revilla, C., and Rouleau, M., 2010. MASON RebeLand: An agent-based model of politics, environment, and insurgency. *International Studies Review*, **12**(1), 31–52. DOI: 10.1111/j.1468-2486.2009.00911.x

Cooke, B. C., Jones, A. R., Goodwin, I. D., and Bishop, M. J., 2012. Nourishment practices on Australian sandy beaches: A review. *Journal of Environmental Management*, **113**, 319–327. Elsevier Ltd. DOI: 10.1016/j.jenvman.2012.09.025

Cooper, J. A. G., and McKenna, J., 2009. Boom and Bust: The Influence of Macroscale Economics on the World's Coasts. *Journal of Coastal Research*, **253**, 533–538. DOI: 10.2112/09A-0001.1

Cooper, J. A. G., and Pilkey, O. H., 2004. Sea-level rise and shoreline retreat: Time to abandon the Bruun Rule. *Global and Planetary Change*, **43**(3–4), 157–171. DOI: 10.1016/j.gloplacha.2004.07.001

Crossett, K., Culliton, T., Wiley, P., and Goodspeed, T., 2004. *Population Trends Along the Coastal United States : 1980-2008*. *NOAA Coastal Trends Series Report*. Retrieved from http://oceanservice.noaa.gov/programs/mb/pdfs/coastal_pop_trends_complete.pdf

Cutter, S. L., Barnes, L., Berry, M., Burton, C., Evans, E., Tate, E., and Webb, J., 2008. A place-based model for understanding community resilience to natural disasters. *Global Environmental Change*, **18**(4), 598–606. DOI: 10.1016/j.gloenvcha.2008.07.013

Cutter, S. L., and Emrich, C. T., 2006. Moral Hazard, Social Catastrophe: The Changing Face of Vulnerability along the Hurricane Coasts. *The ANNALS of the American Academy of Political and Social Science*, **604**(1), 102–112. DOI: 10.1177/0002716205285515

Cutter, S. L., Emrich, C. T., Mitchell, J. T., Boruff, B. J., Gall, M., Schmidtlein, M. C., Burton, C. G., et al., 2006. The long road home: Race, class, and recovery from Hurricane Katrina. *Environment*, **48**(2), 8–20. DOI: 10.3200/ENVT.48.2.8-20

Cutter, S. L., and Finch, C., 2008. Temporal and spatial changes in social vulnerability to natural hazards. *Proceedings of the National Academy of Sciences*, **105**(7), 2301–2306. DOI: 10.1073/pnas.0710375105

Dash, N., Morrow, B. H., Mainster, J., and Cunningham, L., 2007. Lasting Effects of Hurricane Andrew on a Working-Class Community. *Natural Hazards Review*, **8**(1), 13–21. DOI: 10.1061/(asce)1527-6988(2007)8:1(13)

Davis, M., 2002. *Late Victorian Holocausts: El Nino Famines and the Making of the Third World*. London: Verso.

Day, I. N. M., and Wilson, D. I., 2001. Genetics and cardiovascular risk. *British Medical Journal*, **323**, 1409–1412. DOI: 10.1136/bmj.323.7326.1409

Dean, R. G., and Dalrymple, R. A., 2001. *Coastal Processes with Engineering Applications*. Cambridge: Cambridge University Press.

Desilver, D., 2015. As American homes get bigger, energy efficiency gains are wiped out. *Pew Res. Center*. Retrieved from http://www.pewresearch.org/fact-tank/2015/11/09/as-american-homes-get-bigger-energy-efficiency-gains-are-wiped-out/

Dionne, G., 2013. Risk management: History, definition, and critique. *Risk Management and Insurance Review*, **16**(2), 147–166. DOI: 10.1111/rmir.12016

Dolan, R., and Ferm, J. C., 1968. Crescentic Landforms along the Atlantic Coast of the United

States. *Science*, **159**(3815), 627–629. DOI: 10.1126/science.159.3815.627

Dolan, R., and Lins, H., 1986. *The Outer Banks of North Carolina (USGS Professional Paper 1177-B)*. Reston, Virginia. Retrieved from http://pubs.usgs.gov/pp/1177b/report.pdf

Dolan, R., Lins, H., and Smith, J. J., 2016. *The Outer Banks of North Carolina: USGS Professional Paper 1872*. DOI: 10.3133/pp1827

Doody, J. P., 2004. 'Coastal squeeze' – an historical perspective. *Journal of Coastal Conservation*, **10**(1), 129. Retrieved from https://link.springer.com/article/10.1652/1400-0350(2004)010[0129:CSAHP]2.0.CO;2

Doran, K. S., Long, J. W., Birchler, J. J., Brenner, O. T., Hardy, M. W., Morgan, K. L. M., Stockdon, H. F., et al., 2017. Lidar-derived beach morphology (dune crest, dune toe, and shoreline) for U.S. sandy coastlines (ver. 2.0 August 2018): U.S. Geological Survey data release. *Lidar-derived beach morphology (dune crest, dune toe, and shoreline) for U.S. sandy coastlines: U.S. Geological Survey data release*. DOI: 10.5066/F7GF0S0Z

Dumont, A., Mayor, B., and López-Gunn, E., 2013. Is the Rebound Effect or Jevons Paradox a Useful Concept for better Management of Water Resources? Insights from the Irrigation Modernisation Process in Spain. *Aquatic Procedia*, **1**, 64–76. DOI: 10.1016/j.aqpro.2013.07.006

Dyke, A. S., Morris, T. F., and Green, D. E. C., 1991. *Postglacial tectonic and sea level history of the central Canadian Arctic*. Geological Survey of Canada, Bulletin 397.

Elko, N., Brodie, K., Stockdon, H., Nordstrom, K., Houser, C., Mckenna, K., Moore, L., et al., 2016. Dune management challenges on developed coasts. *Shore & Beach*, **84**(1), 1–14.

Ells, K., and Murray, A. B., 2012. Long-term, non-local coastline responses to local shoreline stabilization. *Geophysical Research Letters*, **39**(19), L19401. DOI: 10.1029/2012GL052627

Elsayed, S. M., and Oumeraci, H., 2017. Effect of beach slope and grain-stabilization on coastal sediment transport: An attempt to overcome the erosion overestimation by XBeach. *Coastal Engineering*, **121**, 179–196. DOI: 10.1016/j.coastaleng.2016.12.009

ESRI, 2012. ArcGIS USA Zip Code Areas. Retrieved December 1, 2014, from http://www.arcgis.com/home/item.html?id=8d2012a2016e484dafaac0451f9aea24

Estrada, F., Botzen, W. J. W., and Tol, R. S. J., 2015. Economic losses from US hurricanes consistent with an influence from climate change. *Nature Geoscience*, **8**(November), 880–885. DOI:

10.1038/NGEO2560

Ezer, T., and Atkinson, L. P., 2014. Accelerated flooding along the U.S. East Coast: On the impact of sea-level rise, tides, storms, the Gulf Stream, and the North Atlantic Oscillations. *Earth's Future*, **2**(8), 362–382. DOI: 10.1002/2014EF000252

Fagan, B. M., 2004. *The Long Summer: How Climate Changed Civilization*. New York: Basic Books.

Farris, A. S., and List, J. H., 2007. Shoreline Change as a Proxy for Subaerial Beach Volume Change. *Journal of Coastal Research*, **233**, 740–748. DOI: 10.2112/05-0442.1

FEMA, 2018. Disaster Recovery Reform Act of 2018 Transforms Field of Emergency Management. *News release HQ-18-142*. Retrieved April 22, 2019, from https://www.fema.gov/news-release/2018/10/05/disaster-recovery-reform-act-2018-transforms-field-emergency-management

Fenster, M. S., Dolan, R., and Smith, J. J., 2016. Grain-size distributions and coastal morphodynamics along the southern Maryland and Virginia barrier islands. *Sedimentology*, **63**(4), 809–823. DOI: 10.1111/sed.12239

FGDL, 2014. FGDL Metadata Explorer. *Florida Geographic Data Library*. Retrieved November 1, 2014, from https://www.fgdl.org/metadataexplorer/explorer.jsp

Filatova, T., Mulder, J. P. M., and van der Veen, A., 2011. Coastal risk management: How to motivate individual economic decisions to lower flood risk? *Ocean and Coastal Management*, **54**(2), 164–172. DOI: 10.1016/j.ocecoaman.2010.10.028

Filatova, T., Verburg, P. H., Parker, D. C., and Stannard, C. A., 2013. Spatial agent-based models for socio-ecological systems: Challenges and prospects. *Environmental Modelling and Software*, **45**, 1–7. DOI: 10.1016/j.envsoft.2013.03.017

Finkl, C. W., 1996. What Might Happen to America's Shorelines if Artificial Beach Replenishment is Curtailed: A Prognosis for Southeastern Florida and Other Sandy Regions Along Regressive Coasts. *Journal of Coastal Research*, **12**(1), iii–ix.

Finkl, C. W., and Walker, H. J., 2006. Beach Nourishment. In M. Schwartz (Ed.), *Encyclopedia of Coastal Science* (pp. 147–161). Springer Science & Business Media.

FitzGerald, D. M., Fenster, M. S., Argow, B. a., and Buynevich, I. V., 2008. Coastal Impacts Due to Sea-Level Rise. *Annual Review of Earth and Planetary Sciences*, **36**(1), 601–647. DOI: 10.1146/annurev.earth.35.031306.140139

Galgano, F. A., 1998. *Geomorphic analysis of modes of shoreline behavior and the influence of tidal inlets on coastal configuration*. University of Maryland.

Galgano, F. A., and Leatherman, S. P., 2006. Modes and patterns of shoreline change. In M. L. Schwartz (Ed.), *Encyclopedia of Coastal Science* (pp. 651–656). Springer Netherlands.

Ginzky, H., and Frost, R., 2014. Marine geo-engineering : Legally binding regulation under the London Protocol. *Carbon and Climate Law Review*, **1**(2), 82–96.

Gopalakrishnan, S., Landry, C. E., Smith, M. D., and Whitehead, J. C., 2016. Economics of Coastal Erosion and Adaptation to Sea Level Rise. *Annual Review of Resource Economics*, **8**(1), 119–139. DOI: 10.1146/annurev-resource-100815-095416

Gopalakrishnan, S., McNamara, D., Murray, B., and Smith, M., 2010, July 29. Adapting to climate change: Combining economics and geomorphology in coastal policy. Retrieved from http://aquaticcommons.org/3906/1/Gopalakrishnan_papers.pdf

Gopalakrishnan, S., McNamara, D., Smith, M. D., and Murray, A. B., 2016. Decentralized Management Hinders Coastal Climate Adaptation: The Spatial-dynamics of Beach Nourishment. *Environmental and Resource Economics*. Springer Netherlands. DOI: 10.1007/s10640-016-0004-8

Gopalakrishnan, S., Smith, M. D., Slott, J. M., and Murray, a. B., 2011. The value of disappearing beaches: A hedonic pricing model with endogenous beach width. *Journal of Environmental Economics and Management*, **61**(3), 297–310. Elsevier. DOI: 10.1016/j.jeem.2010.09.003

Gude, P., Rasker, R., and Noort, J. Van Den, 2008. Potential for future development on fire-prone lands. *Journal of Forestry*, **106**(4), 198–205. Retrieved from https://academic.oup.com/jof/article/106/4/198/4599286

Gutierrez, B. T., Plant, N. G., and Thieler, E. R., 2011. A Bayesian network to predict coastal vulnerability to sea level rise. *Journal of Geophysical Research: Earth Surface*, **116**(2), 1–15. DOI: 10.1029/2010JF001891

Haff, P., 2003. Neogeomorphology, prediction, and the anthropic landscape. In P. R. Wilcock and R. M. Iverson (Eds.), *Prediction in geomorphology* (pp. 15–26). Washington, DC: American Geophysical Union. DOI: 10.1029/135GM02

Haff, P. K., 2010. Hillslopes, rivers, plows, and trucks: mass transport on Earth's surface by natural and technological processes. *Earth Surface Processes and Landforms*, **35**(10), 1157–1166. DOI: 10.1002/esp.1902

Haff, P. K., 2012. Technology and human purpose: the problem of solids transport on the Earth's surface. *Earth System Dynamics*, **3**(2), 149–156. Copernicus GmbH. DOI: 10.5194/esd-3-149-2012

Haimes, Y. Y., 2009. On the complex definition of risk: A systems-based approach. *Risk Analysis*, **29**(12), 1647–1654. DOI: 10.1111/j.1539-6924.2009.01310.x

Hanson, H., Brampton, A., Capobianco, M., Dette, H. H., Hamm, L., Laustrup, C., Lechuga, A., et al., 2002. Beach nourishment projects , practices , and objectives — a European overview. *Coastal Engineering*, **47**, 81–111. DOI: 10.1016/S0378-3839(02)00122-9

Hapke, C. J., Himmelstoss, E. A., Kratzmann, M. G., List, J. H., and Thieler, E. R., 2010. USGS Open-File Report 2010-1118: National Assessment of Shoreline Change: Historical Shoreline Change along the New England and Mid-Atlantic Coasts. Retrieved October 27, 2014, from http://pubs.usgs.gov/of/2010/1118/

Hapke, C. J., Kratzmann, M. G., and Himmelstoss, E. A., 2013. Geomorphic and human influence on large-scale coastal change. *Geomorphology*, **199**, 160–170. DOI: 10.1016/j.geomorph.2012.11.025

Hartman, R., 1976. The harvesting decision when a standing forest has value. *Economic Inquiry*, **14**(1), 52–58. DOI: 10.1111/j.1465-7295.1976.tb00377.x

Hewitt, G. M., 2000. The genetic legacy of the Quaternary ice ages. *Nature*, **405**, 907–913. DOI: 10.1038/35016000

Himmelstoss, E. A., Kratzmann, M., Hapke, C., Thieler, E. R., and List, J., 2010. *USGS Open-File Report 2010-1119: National Assessment of Shoreline Change: A GIS Compilation of Vector Shorelines and Associated Shoreline Change Data for the New England and Mid-Atlantic Coasts*. Retrieved from https://pubs.usgs.gov/of/2010/1119/

Hinkel, J., Lincke, D., Vafeidis, A. T., Perrette, M., Nicholls, R. J., Tol, R. S. J., Marzeion, B., et al., 2014. Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proceedings of the National Academy of Sciences of the United States of America*, **111**(9), 3292–7. DOI: 10.1073/pnas.1222469111

Hinkel, J., Nicholls, R. J., Vafeidis, A. T., Tol, R. S. J., and Avagianou, T., 2010. Assessing risk of and adaptation to sea-level rise in the European Union: An application of DIVA. *Mitigation and Adaptation Strategies for Global Change*, **15**(7), 703–719. DOI: 10.1007/s11027-010-9237-y

Hoagland, P., Jin, D., and Kite-Powell, H. L., 2012. The Costs of Beach Replenishment along the

U.S. Atlantic Coast. *Journal of Coastal Research*, **278**, 199–204. DOI: 10.2112/JCOASTRES-D-11-00066.1

Holgate, S. J., Matthews, A., Woodworth, P. L., Rickards, L. J., Tamisiea, M. E., Bradshaw, E., Foden, P. R., et al., 2013. New Data Systems and Products at the Permanent Service for Mean Sea Level. *Journal of Coastal Research*, **288**, 493–504. DOI: 10.2112/JCOASTRES-D-12-00175.1

Holladay, S., and Schwartz, J., 2010. Flooding the Market: The Distributional Consequences of the NFIP. *New York: Institute for Policy Integrity, …*. Retrieved from http://policyintegrity.org/publications/detail/flooding-the-market/

Hooke, R. L., 1994. On the Efficacy of Humans as Geomorphic Agents. *GSA Today*, **4**(9), 223–225.

Hooke, R. L., 2000. On the history of humans as geomorphic agents. *Geology*, **28**(9), 843–846. DOI: 10.1130/0091-7613(2000)28

Houser, C., Barrineau, P., Hammond, B., Saari, B., Rentschler, E., Trimble, S., Wernette, P., et al., 2018. Role of the Foredune in Controlling Barrier Island Response to Sea Level Rise. In L. J. Moore and A. B. Murray (Eds.), *Barrier Dynamics and Response to Changing Climate* (pp. 175–207). Springer International Publishing. DOI: 10.1007/978-3-319-68086-6

Houser, C., Hapke, C., and Hamilton, S., 2008. Controls on coastal dune morphology, shoreline erosion and barrier island response to extreme storms. *Geomorphology*, **100**(3–4), 223–240. DOI: 10.1016/j.geomorph.2007.12.007

IMO, 2015. Proceedings of the 2015 Science Day Symposium on Marine geoengineering, (April). Retrieved from http://www.imo.org/en/OurWork/Environment/LCLP/EmergingIssues/geoengineering/Pages/default.aspx

Jackson, N. L., and Nordstrom, K. F., 2019. Trends in research on beaches and dunes on sandy shores, 1969–2019. *Geomorphology*, 1969–2019. Elsevier B.V. DOI: 10.1016/j.geomorph.2019.04.009

Jevons, W. S., 1865. The coal question: Can Britain survive? In A. W. Flux (Ed.), *The Coal Question: An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of Our Coal-mines*. New York: Augustus M. Kelley.

Johnson, J. M., Moore, L. J., Ells, K., Murray, a. B., Adams, P. N., MacKenzie, R. a., and Jaeger, J. M., 2015. Recent shifts in coastline change and shoreline stabilization linked to storm climate change. *Earth Surface Processes and Landforms*, **40**(5), 569–585. DOI: 10.1002/esp.3650

Johnson, P. A., McCuen, R. H., and Hromadka, T. V, 1991. Debris basin policy and design. *Journal of Hydrology*, **123**(1–2), 83–95. DOI: 10.1016/0022-1694(91)90070-X

Kaplan, S., and Garrick, B. J., 1981. On the Quantitative Definition of Risk. *Risk Analysis*, **1**(1), 11–27. DOI: 10.1111/j.1539-6924.1981.tb01350.x

Karanci, A., 2017. *Agent-based Model to Evaluate Housing Dynamics and Beach Management Practices of Coastal Resort Communities Facing Storms and Sea Level Rise*. North Carolina State University. Retrieved from https://repository.lib.ncsu.edu/bitstream/handle/1840.20/34890/etd.pdf?sequence=1

Keeler, A. G., McNamara, D. E., and Irish, J. L., 2018. Responding to Sea Level Rise : Does Short-Term Risk Reduction Inhibit Successful Long-Term Adaptation? *Earth's Future*, **6**, 1–4. DOI: 10.1002/2018EF000828

Kelley, J. T., Pilkey, O. H., and Cooper, J. A. G., 2009. *America's Most Vulnerable Coastal Communities*. Boulder, Colorado: Geological Society of America.

Kench, P. S., Ford, M. R., and Owen, S. D., 2018. Patterns of island change and persistence offer alternate adaptation pathways for atoll nations. *Nature Communications*, **9**(1), 605. DOI: 10.1038/s41467-018-02954-1

King, R. O., 2013. *The National Flood Insurance Program : Status and Remaining Issues for Congress*. *Congressional Research Service*. Retrieved from https://digital.library.unt.edu/ark:/67531/metadc462628/m1/1/high_res_d/R42850_2013Feb06.pdf

Kirwan, M. L., and Megonigal, J. P., 2013. Tidal wetland stability in the face of human impacts and sea-level rise. *Nature*, **504**(7478), 53–60. DOI: 10.1038/nature12856

Kirwan, M. L., Murray, A. B., Donnelly, J. P., and Corbett, D. R., 2011. Rapid wetland expansion during European settlement and its implication for marsh survival under modern sediment delivery rates. *Geology*, **39**(5), 507–510. DOI: 10.1130/G31789.1

Klein, Y. L., Osleeb, J. P., and Viola, M. R., 2004. Tourism-Generated Earnings in the Coastal Zone: A Regional Analysis. *Journal of Coastal Research*, **204**(204), 1080–1088. DOI: 10.2112/003-0018.1

Komar, P. D., and Allan, J. C., 2008. Increasing Hurricane-Generated Wave Heights along the U.S. East Coast and Their Climate Controls. *Journal of Coastal Research*, **24**(2), 479–488. DOI: 10.2112/07-0894.1

Komar, P. D., and Holman, R. a., 1986. Coastal Processes and the Development of Shoreline Erosion. *Annual Review of Earth and Planetary Sciences*, **14**(1), 237–265. DOI: 10.1146/annurev.ea.14.050186.001321

Kondolf, G. M., and Podolak, K., 2014. Space and time scales in human-landscape systems. *Environmental Management*, **53**(1), 76–87. DOI: 10.1007/s00267-013-0078-9

de Koning, K., Filatova, T., and Bin, O., 2019. Capitalization of Flood Insurance and Risk Perceptions in Housing Prices: An Empirical Agent-Based Model Approach. *Southern Economic Journal*, **85**(4), 1159–1179. DOI: 10.1002/soej.12328

Kraus, N. C., and Galgano, F. A., 2001. *Beach Erosional Hot Spots: Types, Causes and Solutions* (No. ERDC/CHL CHETN-II-44). U.S. Army Corps of Engineers. Retrieved from https://apps.dtic.mil/dtic/tr/fulltext/u2/a588792.pdf

Kriesel, W., and Landry, C., 2004. Participation in the National Flood Insurance Program: An Empirical Analysis for Coastal Properties. *The Journal of Risk and Insurance*, **71**(3), 405–420. DOI: 10.1111/j.0022-4367.2004.00096.x

Kunreuther, H., 1996. Mitigating Disaster Losses through Insurance. *Journal of Risk and Uncertainty*, **12**, 171–187. DOI: 10.1007/BF00055792

Lambeck, K., and Chappell, J., 2001. Sea Level Change Through the Last Glacial Cycle. *Science*, **292**, 679–686. DOI: 10.1126/science.1059549

Landry, C. E., 2011. Coastal Erosion as a Natural Resource Management Problem : An Economic Perspective. *Coastal Management*, **39**(3), 259–281. DOI: 10.1080/08920753.2011.566121

Landry, C. E., and Hindsley, P., 2011. Valuing Beach Quality with Hedonic Property Models. *Land Economics*, **87**(1), 92–108. DOI: 10.3368/le.87.1.92

Landry, C. E., and Jahan-Parvar, M. R., 2011. Flood insurance coverage in the coastal zone. *Journal of Risk and Insurance*, **78**(2), 361–388. DOI: 10.1111/j.1539-6975.2010.01380.x

Lazarus, E. D., 2014. Threshold effects of hazard mitigation in coastal human–environmental systems. *Earth Surface Dynamics*, **2**(1), 35–45. DOI: 10.5194/esurf-2-35-2014

Lazarus, E. D., 2016. Scaling laws for coastal overwash morphology. *Geophysical Research Letters*,

43(23), 12,113-12,119. DOI: 10.1002/2016GL071213

Lazarus, E. D., 2017. Toward a Global Classification of Coastal Anthromes. *Land 2017, Vol. 6, Page 13*, **6**(1), 13. DOI: 10.3390/LAND6010013

Lazarus, E. D., and Armstrong, S., 2015. Self-organized pattern formation in coastal barrier washover deposits. *Geology*, **43**(4), 363–366. DOI: 10.1130/G36329.1

Lazarus, E. D., Ashton, A. D., and Murray, A. B., 2012. Large-scale patterns in hurricane-driven shoreline change. In A. S. Sharma, A. Bunde, V. P. Dimri, and D. N. Baker (Eds.), *Extreme events and natural hazards: The complexity perspective, Geophysical Monograph Series 196* (Vol. 196, pp. 127–138). Washingto, DC: American Geophysical Union. Retrieved from https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2011GM001074

Lazarus, E. D., Ashton, A., Murray, A. B., Tebbens, S., and Burroughs, S., 2011. Cumulative versus transient shoreline change: Dependencies on temporal and spatial scale. *Journal of Geophysical Research: Earth Surface*, **116**(F2), 1–10. DOI: 10.1029/2010JF001835

Lazarus, E. D., Ellis, M. A., Brad Murray, A., and Hall, D. M., 2016. An evolving research agenda for human-coastal systems. *Geomorphology*, **256**, 81–90. DOI: 10.1016/j.geomorph.2015.07.043

Lazarus, E. D., Harley, M. D., Blenkinsopp, C. E., and Turner, I. L., 2019. Environmental signal shredding on sandy coastlines. *Earth Surface Dynamics*, **7**, 77–86. DOI: 10.5194/esurf-7-77-2019

Lazarus, E. D., Limber, P. W., Goldstein, E. B., Dodd, R., and Armstrong, S. B., 2018. Building back bigger in hurricane strike zones. *Nature Sustainability*, **1**(12), 759–762. DOI: 10.1038/s41893-018-0185-y

Lazarus, E. D., McNamara, D. E., Smith, M. D., Gopalakrishnan, S., and Murray, a. B., 2011. Emergent behavior in a coupled economic and coastline model for beach nourishment. *Nonlinear Processes in Geophysics*, **18**(6), 989–999. DOI: 10.5194/npg-18-989-2011

Lazarus, E. D., and Murray, A. B., 2011. An integrated hypothesis for regional patterns of shoreline change along the Northern North Carolina Outer Banks, USA. *Marine Geology*, **281**(1–4), 85–90. DOI: 10.1016/j.margeo.2011.02.002

Lentz, E. E., Thieler, E. R., Plant, N. G., Stippa, S. R., Horton, R. M., and Gesch, D. B., 2016. Evaluation of dynamic coastal response to sea-level rise modifies inundation likelihood. *Nature Climate Change*, **6**, 696–700. DOI: 10.1038/nclimate2957

Leonard, L., Clayton, T. D., and Pilkey, O. H., 1990. An Analysis of Replenished Beach Design Parameters on U.S. East Coast Barrier Islands. *Journal of Coastal Research*, **6**(1), 15–36. Retrieved from https://www.jstor.org/stable/4297640

Limber, P. W., Barnard, P. L., Vitousek, S., and Erikson, L. H., 2018. A Model Ensemble for Projecting Multidecadal Coastal Cliff Retreat During the 21st Century. *Journal of Geophysical Research: Earth Surface*, **123**(7), 1566–1589. DOI: 10.1029/2017JF004401

Limber, P. W., List, J. H., Warren, J. D., Farris, A. S., and Weber, K. M., 2007. Using topographic lidar data to delineate the North Carolina shoreline. *Coastal Sediments '07*, 14. DOI: 10.1061/40926(239)144

Lins, H. F., 1980. Patterns and Trends of Land Use and Land Cover on Atlantic and Gulf Coast Barrier Islands. *Geological Survey Professional Paper 1156*.

Luijendijk, A., Hagenaars, G., Ranasinghe, R., Baart, F., Donchyts, G., and Aarninkhof, S., 2018. The State of the World's Beaches. *Scientific Reports*, **8**, 6641. DOI: 10.1038/s41598-018-24630-6

Marsh, G. P., 1869. *Man and Nature, or Physical Geography as Modified by Human Action*. New York: C. Scribner.

Masselink, G., and Van Heteren, S., 2014. Response of wave-dominated and mixed-energy barriers to storms. *Marine Geology*, **352**, 321–347. DOI: 10.1016/j.margeo.2013.11.004

McGranahan, G., Balk, D., and Anderson, B., 2007. The rising tide: Assessing the risks of climate change and human settlements in low elevation coastal zones. *Environment and Urbanization*, **19**(1), 17–37. DOI: 10.1177/0956247807076960

McNamara, D. E., Gopalakrishnan, S., Smith, M. D., and Murray, a B., 2015. Climate adaptation and policy-induced inflation of coastal property value. *PloS one*, **10**(3), e0121278. DOI: 10.1371/journal.pone.0121278

McNamara, D. E., and Keeler, A., 2013. A coupled physical and economic model of the response of coastal real estate to climate risk. *Nature Climate Change*, **3**(6), 559–562. DOI: 10.1038/nclimate1826

McNamara, D. E., and Lazarus, E. D., 2018. Barrier Islands as Coupled Human-Landscape Systems. In L. J. Moore and A. B. Murray (Eds.), *Barrier Dynamics and Response to Changing Climate* (pp. 363–383). Springer International Publishing. DOI: 10.1007/978-3-319-68086-6

McNamara, D. E., Murray, a. B., and Smith, M. D., 2011. Coastal sustainability depends on how economic and coastline responses to climate change affect each other. *Geophysical Research Letters*, **38**(7), L07401. DOI: 10.1029/2011GL047207

McNamara, D. E., and Werner, B. T., 2008a. Coupled barrier island–resort model: 1. Emergent instabilities induced by strong human-landscape interactions. *Journal of Geophysical Research*, **113**(F1), F01016. DOI: 10.1029/2007JF000840

McNamara, D. E., and Werner, B. T., 2008b. Coupled barrier island–resort model: 2. Tests and predictions along Ocean City and Assateague Island National Seashore, Maryland. *Journal of Geophysical Research*, **113**(F1), F01017. DOI: 10.1029/2007JF000841

McPhee, J., 1989. *The Control of Nature*. New York: Farrar, Straus and Giroux.

Meade, R. H., 1982. Sources, Sinks, and Storage of River Sediment in the Atlantic Drainage of the United States. *The Journal of Geology*, **90**(3), 235–252. DOI: 10.1086/628677

Meadows, D. H., and Wright, D., 2008. *Thinking in Systems: A Primer*. White River Junction, VT: Chelsea Green Publishing.

Michel-Kerjan, E. O., 2010. Catastrophe Economies : The National Flood Insurance Program. *The Journal of Economic Perspectives*, **24**(4), 165–186. DOI: 10.1257/jep.24.4.165

Mileti, D., 1999. *Disasters by Design: A Reassessment of Natural Hazards in the United States*. Washingto, DC: Joseph Henry Press.

Mileti, D. S., and Gailus, J. L., 2005. Sustainable development and hazards mitigation in the United States: Disasters by design revisited. *Mitigation and Adaptation Strategies for Global …*, **10**(3), 491–504. DOI: 10.1007/s11027-005-0057-4

Miller, T. L., Morton, R. A., and Sallenger, A. H., 2005. *USGS Open File Report 2005-1326: The National Assessment of Shoreline Change: A GIS Compilation of Vector Shorelines and Associated Shoreline Change Data for the U.S. Southeast Atlantic Coast*. Retrieved from https://pubs.usgs.gov/of/2005/1326/

Milliman, J. D., Pilkey, O. H., and Ross, D. A., 1972. Sediments of the Continental Margin off the Eastern United States. *Geological Society of America Bulletin*, **83**(May), 1315–1334. Retrieved from https://pubs.geoscienceworld.org/gsa/gsabulletin/article/83/5/1315/7538/sediments-of-the-continental-margin-off-the

Minnesota Population Center, 2011. National Historical Geographic Information System: Version

2.0. Minneapolis, MN: University of Minnesota. Retrieved from http://www.nhgis.org

Miselis, J. L., and Lorenzo-Trueba, J., 2017. Natural and Human-Induced Variability in Barrier-Island Response to Sea Level Rise. *Geophysical Research Letters*, **44**(23), 11,922-11,931. DOI: 10.1002/2017GL074811

Morton, R. A., and Miller, T. L., 2005. National Assessment Of Shoreline Change: Part 2 Historical Shoreline Changes And Associated Coastal Land Loss Along The US Southeast Atlantic Coast. *Open-File Report 2005-1401*, 35. DOI: 10.3133/ofr20051401

Morton, R. A., Miller, T. L., and Moore, L. J., 2004. National assessment of shoreline change: Part 1: Historical shoreline changes and associated coastal land loss along the US Gulf of Mexico, 45. DOI: 10.3133/ofr20041043

Moser, S. C., Davidson, M., Kirshen, P., Mulvaney, P., Murley, J., Neumann, J., Petes, L., et al., 2014. Coastal Zone Development and Ecosystems. *Climate Change Impacts in the United States: The Third National Climate Assessment*, 579–618. DOI: 10.7930/J0MS3QNW

Murray, A. B., Gopalakrishnan, S., McNamara, D. E., and Smith, M. D., 2013. Progress in coupling models of human and coastal landscape change. *Computers & Geosciences*, **53**, 30–38. Elsevier. DOI: 10.1016/j.cageo.2011.10.010

Murray, A. B., Lazarus, E. D., Ashton, A., Baas, A., Coco, G., Coulthard, T., Fonstad, M., et al., 2009. Geomorphology, complexity, and the emerging science of the Earth's surface. *Geomorphology*, **103**(3), 496–505. DOI: 10.1016/j.geomorph.2008.08.013

National Academy of Sciences Engineering and Medicine, 2018. *Understanding the Long-term Evolution of the Coupled Natural-Human Coastal System: The Future of the U. S. Gulf Coast*. Washington, DC: The National Acadamies Press. DOI: 10.17226/25108

Neal, W. J., Bush, D. M., and Pilkey, O. H., 2017. Managed Retreat. In C. W. Finkl and C. Makowski (Eds.), *Encyclopedia of Coastal Science* (pp. 866–866). Cham: Springer. DOI: 10.1007/978-3-319-48657-4_201-2

Neal, W. J., Pilkey, O. H., Cooper, J. A. G., and Longo, N. J., 2018. Why coastal regulations fail. *Ocean and Coastal Management*, **156**, 21–34. DOI: 10.1016/j.ocecoaman.2017.05.003

Neumann, B., Vafeidis, A. T., Zimmermann, J., and Nicholls, R. J., 2015. Future coastal population growth and exposure to sea-level rise and coastal flooding - A global assessment. *PLoS ONE*, **10**(3). DOI: 10.1371/journal.pone.0118571

Newman, M. E. J., 2005. Power laws, Pareto distributions and Zipf's law. *Contemporary Physics*, **46**(5), 323–351. DOI: 10.1080/00107510500052444

Nicholls, R. J., Brown, S., Goodwin, P., Wahl, T., Lowe, J. A., Solan, M., Godbold, J. A., et al., 2018. Stabilization of global temperature at 1.5°C and 2.0°C: implications for coastal areas. *Philosophical Transactions of the Royal Society A*, **376**(2119). DOI: 10.1098/rsta.2016.0448

Nicholls, R. J., and Cazenave, A., 2010. Sea-level rise and its impact on coastal zones. *Science*, **328**(5985), 1517–1520. DOI: 10.1126/science.1185782

NOAA, 1975. *The coastline of the United States*. Retrieved from https://shoreline.noaa.gov/_pdf/Coastline_of_the_US_1975.pdf

NOAA, 2006. Beach Nourishment: A Guide for Local Government Officials. Retrieved from http://coast.noaa.gov/archived/beachnourishment/index.htm

NOAA, 2012a. *The Southeast Coastal Region Fact Sheet*.

NOAA, 2012b. *The Gulf of Mexico at a Glance: A Second Glance*.

NOAA, 2013. *National Coastal Population Report*. *NOAA's State of the Coast*. Retrieved from https://aamboceanservice.blob.core.windows.net/oceanservice-prod/facts/coastal-population-report.pdf

Nordstrom, K. F., 1994. Beaches and dunes of human-altered coasts. *Progress in Physical Geography*, **18**(4), 497–516. DOI: 10.1177/030913339401800402

Nordstrom, K. F., 2000. *Beaches and Dunes of Developed Coasts*. Cambridge, UK: Cambridge University Press.

NRC, 1995. *Beach Nourishment and Protection*. Washington, DC: National Acadamy Press. DOI: 10.17226/4984

NRC, 2014. *Reducing Coastal Risks on the East and Gulf Coasts*. Washington, DC: National Acadamy Press. DOI: 10.17226/18811

Parkinson, R. W., and Ogurcak, D. E., 2018. Beach nourishment is not a sustainable strategy to mitigate climate change. *Estuarine, Coastal and Shelf Science*, **212**, 203–209. DOI: 10.1016/j.ecss.2018.07.011

Parris, A., Bromirski, P., Burkett, V., Cayan, D., Culver, M., Hall, J., Horton, R., et al., 2012. Global Sea Level Rise Scenarios for the US National Climate Assessment. *NOAA Tech Memo OAR*

CPO, 1–37. Retrieved from http://cpo.noaa.gov/sites/cpo/Reports/2012/NOAA_SLR_r3.pdf

Passeri, D. L., Hagen, S. C., Medeiros, S. C., Bilskie, M. V, Alizad, K., and Wang, D., 2015. The dynamic effects of sea level rise on low-gradient coastal landscapes : A review. *Earth's Future*, **3**, 159–181. DOI: 10.1002/2015EF000298

Paterson, S. K., Loomis, D. K., and Young, S. E., 2014. The Human Dimension of Changing Shorelines Along the U.S. North Atlantic Coast. *Coastal Management*, **42**(1), 17–35. DOI: 10.1080/08920753.2013.863724

Peacock, W. G., Brody, S. D., and Highfield, W., 2005. Hurricane risk perceptions among Florida's single family homeowners. *Landscape and Urban Planning*, **73**, 120–135. DOI: 10.1016/j.landurbplan.2004.11.004

Peacock, W. G., Van Zandt, S., Zhang, Y., and Highfield, W. E., 2014. Inequities in long-term housing recovery after disasters. *Journal of the American Planning Association*, **80**(4), 356–371. DOI: 10.1080/01944363.2014.980440

Peek, K. M., Young, R. S., Beavers, R. L., Hoffman, C. H., Diethorn, B. T., and Norton, S., 2015. *Adapting To Climate Change in Coastal Parks: Estimating the Exposure of Park Assets to 1 m of Sea-Level Rise. Natural Resource Report NPS/NRSS/GRD/NRR—2015/961*. Fort Collins, Colorado. Retrieved from https://irma.nps.gov/DataStore/DownloadFile/522630

Petrolia, D. R., Landry, C. E., and Coble, K. H., 2013. Risk Preferences, Risk Perceptions, and Flood Insurance. *Land Economics*, **89**(2), 227–245. DOI: 10.3368/le.89.2.227

Pielke Jr., R. a., Gratz, J., Landsea, C. W., Collins, D., Saunders, M. A., and Musulin, R., 2008. Normalized Hurricane Damage in the United States: 1900–2005. *Natural Hazards Review*, **9**(1), 29–42. DOI: 10.1061/(ASCE)1527-6988(2008)9:1(29)

Pilkey, O. H., and Clayton, T. D., 1989. Summary of beach replenishment experience on US East Coast barrier islands. *Journal of Coastal Research*, **5**(1), 147–159. Retrieved from https://www.jstor.org/stable/4297507

Pilkey, O. H., and Cooper, J. A. G., 2014. Are natural beaches facing extinction? *Journal of Coastal Research*, **70**(sp1), 431–436. DOI: 10.2112/SI70-073.1

Pilkey, O. H., and Dixon, K. L., 1996. *The Corps and the Shore*. Washington, DC: Island Press.

Pilkey, O. H., and Neal, W. J., 2009. North Topsail Beach, North Carolina: A model for maximizing coastal hazard vulnerability. In J. T. Kelley, O. H. Pilkey, and J. A. G. Cooper (Eds.), *America's*

Most Vulnerable Coastal Communities, Geological Society of America Special Papers (Vol. 460, pp. 73–90). Boulder, Colorado: Geological Society of America. DOI: 10.1130/2009.2460(05)

Pilkey, O. H., and Thieler, E. R., 1992. Erosion of the United States Shoreline. *Quaternary Coasts of the United States: Marine and Lacustrine Systems, SEPM Special Publication No. 48* (pp. 3–7). Society for Sedimentary Geology. DOI: 10.2110/pec.92.48.0003

Platt, R. H., Salvesen, D., and Baldwin II, G. H., 2002. Rebuilding the North Carolina Coast after Hurricane Fran: Did Public Regulations Matter? *Coastal Management*, **30**(February), 249–269. DOI: 10.1080/08920750290042192

Polimeni, J. M., Mayumi, K., Giampietro, M., and Alcott, B., 2008. *The Jevons Paradox and the Myth of Resource Efficiency Improvements*. London: Earthscan.

Pontee, N., 2013. Defining coastal squeeze: A discussion. *Ocean and Coastal Management*, **84**, 1–4. DOI: 10.1016/j.ocecoaman.2013.07.010

PSDS, 2014. PSDS: Beach nourishment database, Program for the Study of Developed Shorelines. Retrieved April 20, 2014, from http://beachnourishment.wcu.edu/glossary#downloads

PSDS, 2017. PSDS: Beach nourishment database, Program for the Study of Developed Shorelines. Retrieved July 20, 2017, from http://beachnourishment.wcu.edu/glossary#downloads

PSMSL, P. S. for M. S. L., 2018. Tide Gauge Data. Retrieved September 17, 2018, from http://www.psmsl.org/data/obtaining/

Royal Society, 2009. *Geoengineering the climate: science, governance and uncertainty*. *RS Policy Document 10/09*. Retrieved from https://royalsociety.org/~/media/royal_society_content/policy/publications/2009/8693.pdf

Sallenger, A. H., Doran, K. S., and Howd, P. a., 2012. Hotspot of accelerated sea-level rise on the Atlantic coast of North America. *Nature Climate Change*, **2**(12), 884–888. DOI: 10.1038/nclimate1597

Samuels, P., and Gouldby, B., 2009. *Language of Risk: Project Definitions (Second Edition)*. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.453.7855&rep=rep1&type=pdf

Schwartz, J., 2018, August. Surrendering to Rising Seas. *Scientific American*. Retrieved from https://www.scientificamerican.com/article/surrendering-to-rising-seas/

Senge, P. M., 2006. *The fifth discipline: The art and practice of the learning organization* (2nd ed.). London: Random House.

Shahan, T. A., 2018. *Morphologic Evolution and Alongshore Variability of Two Beach Nourishment Projects in Southeast Fl, USA*. Florida Atlantic University. Retrieved from https://search.proquest.com/docview/2051437653?pq-origsite=gscholar

Shalowitz, A. L., 1964. *Shore and Sea Boundaries* (No. 10–1). U.S. Dept. of Commerce Publ.

Shennan, I., Lambeck, K., Horton, B., Innes, J., Lloyd, J., McArthur, J., Purcell, T., et al., 2000. Late Devensian and Holocene records of relative sea-level changes in northwest Scotland and their implications for glacio-hydro-isostatic modelling. *Quaternary Science Reviews*, **19**(11), 1103–1135. DOI: 10.1016/S0277-3791(99)00089-X

Slovic, P., Fischhoff, B., and Lichtenstein, S., 1977. Behavioral Decision Theory. *Annual Review of Psychology*, **28**, 1–39. DOI: 10.1146/annurev.ps.28.020177.000245

Smallegan, S. M., Irish, J. L., Van Dongeren, A. R., and Den Bieman, J. P., 2016. Morphological response of a sandy barrier island with a buried seawall during Hurricane Sandy. *Coastal Engineering*, **110**, 102–110. DOI: 10.1016/j.coastaleng.2016.01.005

Smith, K., 2013. *Environmental hazards: assessing risk and reducing disaster* (6th Editio.). London: Routledge.

Smith, M. D., Murray, A. B., Gopalakrishnan, S., Keeler, A. G., Landry, C. E., McNamara, D., and Moore, L. J., 2015. *Geoengineering Coastlines? From Accidental to Intentional*. *Coastal Zones*. DOI: 10.1016/B978-0-12-802748-6.00007-3

Smith, M. D., Slott, J. M., McNamara, D., and Brad Murray, A., 2009. Beach nourishment as a dynamic capital accumulation problem. *Journal of Environmental Economics and Management*, **58**(1), 58–71. DOI: 10.1016/j.jeem.2008.07.011

Sorrell, S., 2009. Jevons' Paradox revisited: The evidence for backfire from improved energy efficiency. *Energy Policy*, **37**(4), 1456–1469. DOI: 10.1016/j.enpol.2008.12.003

Steneck, R. S., Hughes, T. P., Cinner, J. E., Adger, W. N., Arnold, S. N., Berkes, F., Boudreau, S. A., et al., 2011. Creation of a Gilded Trap by the High Economic Value of the Maine Lobster Fishery. *Conservation Biology*, **25**(5), 904–912. DOI: 10.1111/j.1523-1739.2011.01717.x

Stockdon, H. F., Sallenger, A. H., Holman, R. a., and Howd, P. a., 2007. A simple model for the spatially-variable coastal response to hurricanes. *Marine Geology*, **238**(1–4), 1–20. DOI:

10.1016/j.margeo.2006.11.004

Stockdon, H. F., Sallenger Jr., A. H., List, J. H., and Holman, R. A., 2002. Estimation of Shoreline Position and Change Using Airborne Topographic Lidar Data. *Journal of Coastal Research*, **18**(3), 502–513. Retrieved from http://www.jstor.org/stable/4299097

Strauss, B. H., Ziemlinski, R., Weiss, J. L., and Overpeck, J. T., 2012. Tidally adjusted estimates of topographic vulnerability to sea level rise and flooding for the contiguous United States. *Environmental Research Letters*, **7**(1), 014033. DOI: 10.1088/1748-9326/7/1/014033

Strauss, B., Tebaldi, C., and Kulp, S., 2014. *Florida and the Surging Sea*. Climate Central. Retrieved from http://sealevel.climatecentral.org/research/reports/florida-and-the-surging-sea

Strauss, D., Tomlinson, R., and Hunt, S., 2009. Profile Response and Dispersion of Beach Nourishment : Gold Coast , Australia. *Journal of Coastal Research*, **56**(56), 133–137. Retrieved from https://www.jstor.org/stable/25737552

Syvitski, J. P. M., Kettner, A. J., Overeem, I., Hutton, E. W. H., Hannon, M. T., Brakenridge, G. R., Day, J., et al., 2009. Sinking deltas due to human activities. *Nature Geoscience*, **2**(10), 681–686. DOI: 10.1038/ngeo629

Taylor, N. R., Irish, J. L., Udoh, I. E., Bilskie, M. V., and Hagen, S. C., 2015. Development and uncertainty quantification of hurricane surge response functions for hazard assessment in coastal bays. *Natural Hazards*, **77**(2), 1103–1123. DOI: 10.1007/s11069-015-1646-5

Tebaldi, C., Strauss, B. H., and Zervas, C. E., 2012. Modelling sea level rise impacts on storm surges along US coasts. *Environmental Research Letters*, **7**(1), 014032. DOI: 10.1088/1748-9326/7/1/014032

Temmerman, S., Meire, P., Bouma, T. J., Herman, P. M. J., Ysebaert, T., and De Vriend, H. J., 2013. Ecosystem-based coastal defence in the face of global change. *Nature*, **504**(7478), 79–83. DOI: 10.1038/nature12859

Thieler, E. R., Foster, D. S., Himmelstoss, E. A., and Mallinson, D. J., 2014. Geologic framework of the northern North Carolina, USA inner continental shelf and its influence on coastal evolution. *Marine Geology*, **348**, 113–130. DOI: 10.1016/j.margeo.2013.11.011

Thieler, E. R., and Hammar-Klose, E. S., 1999. *National assessment of coastal vulnerability to sea-level rise: Preliminary results for the U.S. Atlantic Coast*. DOI: 10.3133/ofr99593

Thieler, E. R., Himmelstoss, E. A., Zichichi, J. L., and Ergul, A., 2008. Digital Shoreline Analysis

System (DSAS) version 4.0—An ArcGIS extension for calculating shoreline change. *U.S. Geological Survey Open-File Report 2008-1278*. Reston, Virginia. Retrieved from https://woodshole.er.usgs.gov/project-pages/DSAS/version4/

Thomas, C. W., Murray, A. B., Ashton, A. D., Hurst, M. D., Barkwith, A. K. A. P., and Ellis, M. A., 2016. Complex coastlines responding to climate change: Do shoreline shapes reflect present forcing or "remember" the distant past? *Earth Surface Dynamics*, **4**(4), 871–884. DOI: 10.5194/esurf-4-871-2016

Thompson, A., 2018. *Rising Seas;Falling Funds: An Analysis of Beach Nourishment Finance in Dare County, NC*. Duke University. Retrieved from https://dukespace.lib.duke.edu/dspace/bitstream/handle/10161/16537/MP_AustinThompson_4_27.pdf?sequence=1

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

Trembanis, A. C., and Pilkey, O. H., 1998. Summary of Beach Nourishment along the U.S. Gulf of Mexico Shoreline. *Journal of Coastal Research*, **14**(2), 407–417. Retrieved from https://www.jstor.org/stable/4298795

Trembanis, A. C., Pilkey, O. H., and Valverde, H. R., 1999. Comparison of Beach Nourishment along the U.S. Atlantic, Great Lakes, Gulf of Mexico, and New England Shorelines. *Coastal Management*, **27**, 329–340. DOI: 10.1080/089207599263730

Turner, R. K., 2000. Integrating natural and socio-economic science in coastal management. *Journal of Marine Systems*, **25**(3–4), 447–460. DOI: 10.1016/S0924-7963(00)00033-6

Union of Concerned Scientists, 2018. *Underwater: Rising Seas, Chronic Floods, and the Implications for US Coastal Real Estate*. Retrieved from https://www.ucsusa.org/sites/default/files/attach/2018/06/underwater-analysis-full-report.pdf

UNISDR, 2015. *Sendai Framework for Disaster Risk Reduction 2015 - 2030*. *Proceedings of the 3rd United Nations World Conference on DRR, Sendai, Japan*. Retrieved from https://www.unisdr.org/files/43291_sendaiframeworkfordrren.pdf

USACE, 2000. *Planning Guidance Notebook*. *ER 1105-2-100* (Vol. EM 200-1-1). Retrieved from https://www.publications.usace.army.mil/Portals/76/Publications/EngineerRegulations/ER_1105-2-100.pdf

USACE, 2015. *North Atlantic Coast Comprehensive Study: Resilient Adaptation to Increasing Risk - Final Report*. Retrieved from http://www.nad.usace.army.mil/Portals/40/docs/NACCS/NACCS_main_report.pdf

USGS, 2018. Coastal Change Hazards Portal. Retrieved July 1, 2018, from https://marine.usgs.gov/coastalchangehazardsportal/

Valverde, H. R., Trembanis, A. C., and Pilkey, O. H., 1999. Summary of Beach Nourishment episodes on the US East Coast Barrier Islands. *Journal of Coastal Research*, **15**(4), 1100–1118. Retrieved from https://www.jstor.org/stable/4299028

Valvo, L. M., Murray, A. B., and Ashton, A., 2006. How does underlying geology affect coastline change? An initial modeling investigation. *Journal of Geophysical Research: Earth Surface*, **111**(F2), F02025. DOI: 10.1029/2005JF000340

Vecchi, G. A., and Villarini, G., 2012. Next Season's Hurricanes. *Science*, **343**, 618–619. DOI: 10.1126/science.1247759

Verburg, P. H., Dearing, J. A., Dyke, J. G., Leeuw, S. van der, Seitzinger, S., Steffen, W., and Syvitski, J., 2015. Methods and approaches to modelling the Anthropocene. *Global Environmental Change*, **39**, 328–340. DOI: 10.1016/j.gloenvcha.2015.08.007

Verlaan, P., 2009. Geo-engineering, the Law of the Sea, and Climate Change. *Carbon and Climate Law Review*, **4**(3), 446–458. Retrieved from https://heinonline.org/HOL/P?h=hein.journals/cclr3&i=468

Vitousek, S., Barnard, P. L., Fletcher, C. H., Frazer, N., Erikson, L., and Storlazzi, C. D., 2017. Doubling of coastal flooding frequency within decades due to sea-level rise. *Scientific Reports*, **7**, 1399. DOI: 10.1038/s41598-017-01362-7

Vitousek, S., Barnard, P. L., and Limber, P., 2017. Can beaches survive climate change? *Journal of Geophysical Research: Earth Surface*, **122**(4), 1060–1067. DOI: 10.1002/2017JF004308

Vitousek, S., Barnard, P. L., Limber, P., Erikson, L., and Cole, B., 2017. A model integrating longshore and cross-shore processes for predicting long-term shoreline response to climate change. *Journal of Geophysical Research: Earth Surface*, **122**(4), 782–806. DOI: 10.1002/2016JF004065

Vos, K., Harley, M. D., Splinter, K. D., Simmons, J. A., and Turner, I. L., 2019. Sub-annual to multi-decadal shoreline variability from publicly available satellite imagery. *Coastal Engineering*, **150**, 160–174. DOI: 10.1016/j.coastaleng.2019.04.004

Wahl, T., Jain, S., Bender, J., Meyers, S. D., and Luther, M. E., 2015. Increasing risk of compound flooding from storm surge and rainfall for major US cities. *Nature Climate Change*, **5**, 1093–1097. DOI: 10.1038/nclimate2736

Walker, H. J., and Finkl, C. W., 2002. Beach Nourishment: Case Studies. In J. Chen, D. Eisma, K. Hotta, and H. J. Walker (Eds.), *Engineered Coasts* (pp. 23–59). Dordrecht, Netherlands: Springer.

Welch, A. C., Nicholls, R. J., and Lázár, A. N., 2017. Evolving deltas: Coevolution with engineered interventions. *Elementa Science of the Anthropocene*, **5**(49). DOI: 10.1525/elementa.128

Werner, B. T., and McNamara, D. E., 2007. Dynamics of coupled human-landscape systems. *Geomorphology*, **91**(3–4), 393–407. DOI: 10.1016/j.geomorph.2007.04.020

Wernette, P., Houser, C., Weymer, B. A., Everett, M. E., Bishop, M. P., and Reece, B., 2018. Influence of a spatially complex framework geology on barrier island geomorphology. *Marine Geology*, **398**, 151–162. DOI: 10.1016/j.margeo.2018.01.011

Wilde, G. J. S., 1998. Risk homeostasis theory: an overview. *Injury Prevention*, **4**(2), 89–91. DOI: 10.1136/ip.4.2.89

Williams, Z. C., McNamara, D. E., Smith, M. D., Murray, a B., and Gopalakrishnan, S., 2013. Coupled economic-coastline modeling with suckers and free riders. *Journal of Geophysical Research: Earth Surface*, **118**(2), 887–899. DOI: 10.1002/jgrf.20066

Willis, C. M., and Griggs, G. B., 2003. Reductions in Fluvial Sediment Discharge by Coastal Dams in California and Implications for Beach Sustainability. *The Journal of Geology*, **111**(2), 167–182. DOI: 10.1086/345922

Wilson, J., 2006. Matching Social and Ecological Systems in Complex Ocean Fisheries. *Ecology and Society*, **11**(1), 9. Retrieved from http://www.ecologyandsociety.org/vol11/iss1/art9/

Witze, A., 2018. Attack of the extreme floods. *Nature*, **555**(7695), 156–158. DOI: 10.1038/d41586-018-02745-0

Wong, P. P., Losada, I. J., Gattuso, J.-P., Hinkel, J., Khattabi, A., McInnes, K. L., Saito, Y., et al., 2014. Coastal systems and low-lying areas. In C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M.

D. Mastrandrea, T. E. Bilir, M. Chatterjee, et al. (Eds.), *Climate Change 2014: Impacts, Adaption, and Vulnerability. Part a: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 361–409). Cambridge, UK and New York, NY, USA: Cambridge University Press.

Woodruff, J. D., Irish, J. L., and Camargo, S. J., 2013. Coastal flooding by tropical cyclones and sea-level rise. *Nature*, **504**(7478), 44–52. DOI: 10.1038/nature12855

Woodruff, S., BenDor, T. K., and Strong, A. L., 2018. Fighting the inevitable: infrastructure investment and coastal community adaptation to sea level rise. *System Dynamics Review*, **34**(1–2), 48–77. DOI: 10.1002/sdr.1597

Wu, S.-Y., Yarnal, B., and Fisher, A., 2002. Vulnerability of coastal communities to sea-level rise: a case study of Cape May County, New Jersey, USA. *Climate Research*, **22**, 255–270. DOI: 10.3354/cr022255

Zhang, K., Douglas, B. C., and Leatherman, S. P., 2004. Global warming and coastal erosion. *Climatic Change*, **64**, 41–58. DOI: 10.1023/B:CLIM.0000024690.32682.48