AGU PUBLICATIONS

Earth's Future

RESEARCH ARTICLE

10.1002/2016EF000425

Indications of a positive feedback between coastal development and beach nourishment

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Key Points:

- We examine property-scale data from over 12,000 single-family shorefront homes along more than 1400 km of coastline in Florida, USA
- Houses are significantly larger and more numerous in beach-nourishment zones
- This spatial correlation suggests the emergence of a positive feedback between coastal development and beach nourishment

Supporting Information:

- Supporting Information S1

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

Received 11 AUG 2016
Accepted 7 NOV 2016
Accepted article online 10 NOV 2016
Published online 21 DEC 2016

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.

1. Context

Population density, housing development, and property values in coastal communities along the U.S. Atlantic and Gulf Coasts continue to increase [*National Oceanic and Atmospheric Administration (NOAA)*, 2013; *Carter et al*., 2014; *National Research Council (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 [*Mileti*, 1999; *Nordstrom*, 2000; *Turner*, 2000; *Werner and McNamara*, 2007; *Cooper and McKenna*, 2009; *McNamara et al*., 2015]. 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 [*Werner and McNamara*, 2007; *Di Baldassarre et al*., 2013]; 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 [*McPhee*, 1989; *Johnson et al*., 1991]. Research into developed coastlines likewise suggests that nourishment protection for high-value shorefront properties may in turn attract further development [*Nordstrom*, 2000; *Gopalakrishnan et al*., 2011; *McNamara et al*., 2015].

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 1a). 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.

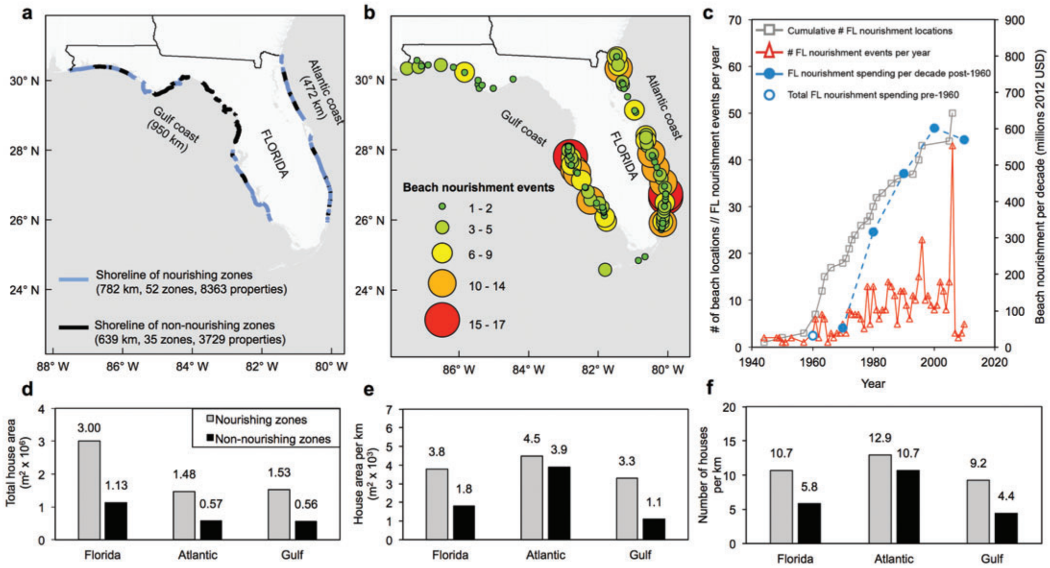

Figure 1. Beach nourishment and coastal development in Florida. (a) Shoreline segments of nourishing (light line) and non-nourishing zones (dark line) with shorefront single-family homes. (b) Map of recorded Florida nourishment events between 1940 and 2010. (c) Cumulative number of nourishing locations 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 ~10^1 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 [*Finkl*, 1996; *Mileti*, 1999; *Nordstrom*, 2000; *Peacock et al*., 2005; *Carter et al*., 2014; *Moser et al*., 2014; *NRC*, 2014; *Wong et al*., 2014; *McNamara et al*., 2015]. 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 and Gibney*, 2011]. In South Florida, porous limestone bedrock, low topography, growing urban centers, 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 1). Although some places nourish more frequently than others (Figure 1b), 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 1c). The same is true of nourishment practices nationwide [*Trembanis et al*., 1999; *NRC*, 2014], with comparable trends in Europe [*Hanson et al*., 2002].

Table 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] *Shalowitz* [1964]; *Morton and Miller* [2005]; *Hapke et al.* [2010].

[b] *Shalowitz* [1964]; *Morton et al.* [2004].

[c] *Shalowitz* [1964]; *Morton et al.* [2004]; *Morton and Miller* [2005]; *Hapke et al.* [2010].

2. Methods

To distinguish "nourishing" from "non-nourishing" coastal zones in Florida (Figure 1a), 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 and Pilkey*, 1998; *Trembanis et al.*, 1999; *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 1a, 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) (and various subsets of those distributions) are statistically different (Table S1 in Appendix S1, 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 Text S1.

3. 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 1). Nourishing zones exceed non-nourishing zones in total number by nearly 50% (Figure 1a). Total house area and number are both greater in nourishing zones than in non-nourishing zones (Figures 1a and 1d), and nourishing zones are more densely developed in terms of house area and number per kilometer shoreline (Figures 1e and 1f).

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 (Figures 1e and 1f). 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 1d; Table 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 kilometer (Figure 1e) and twice as many houses per kilometer (Figure 1f) as non-nourishing zones, despite nearly equal lengths of relative shoreline frontage (Table 1).

These aggregate statistics of comparative house size and number prompt a more detailed look at the underlying data distributions (Figures 2, 3, and 4; Table S2). Parsing house size into percentile bands, we find that for the state overall (Figure 2a) 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

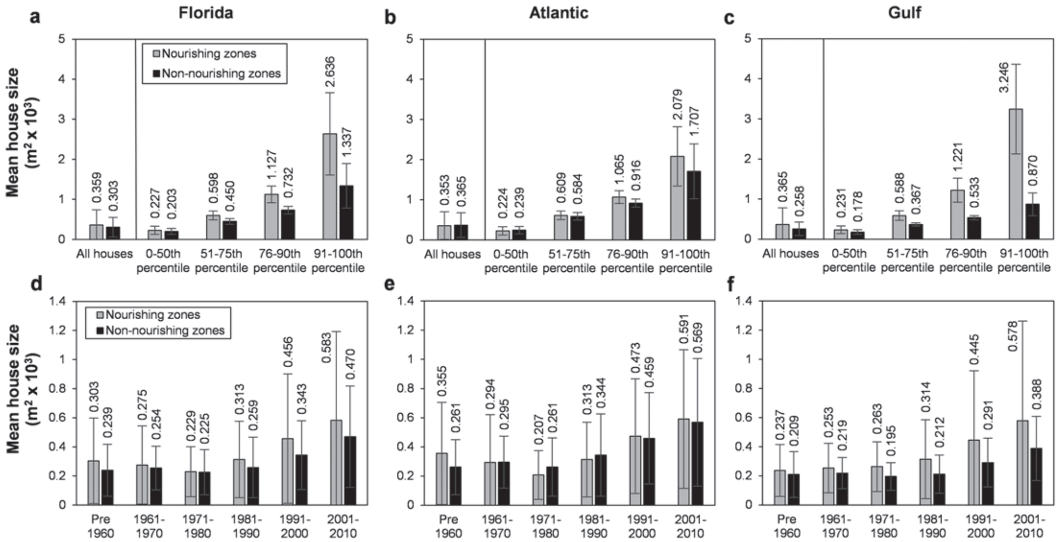

Figure 2. Mean house size by percentile for total living area and by decade built. (a–c) Mean size (m^2) of shorefront single-family houses ranked by percentile band for total living area in nourishing versus non-nourishing zones for all of Florida (a), and the state's Atlantic (b) and Gulf coasts (c).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

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 2b). 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 2c).

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 2d 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 2d; Table S2). 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 (Figures 2e and 2f). The mean size of Gulf houses built after 2001 is 250% larger in nourishing zones than in non-nourishing zones (Figure 2f). 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 S2).

4. Discussion and Implications

Recently built, large houses comprise a disproportionate quantity of the total house area in Florida's nourishing zones (Figure 4; Table S2), 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

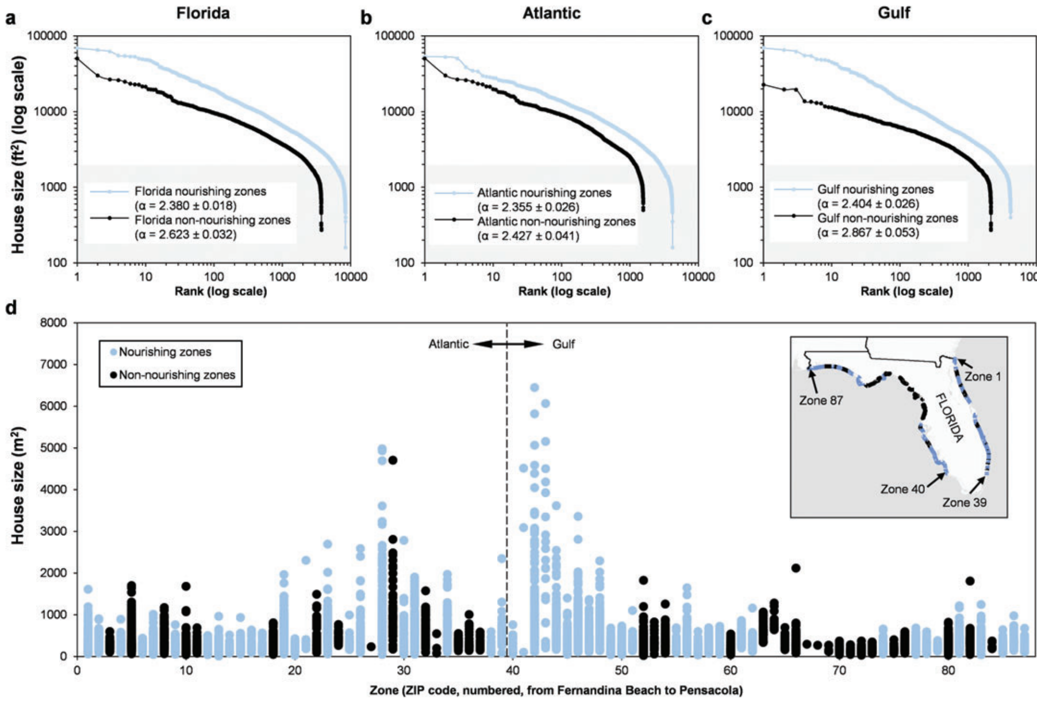

Figure 3. Size data for Florida shorefront single-family houses. (a–c) Log–log rank-order plots of house size (m^2) for all shorefront single-family homes in this study ($n = 12{,}092$), separated by nourishing (light line) and non-nourishing zones (dark line) for all of Florida (a), and the state's 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 1a). 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.

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).

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

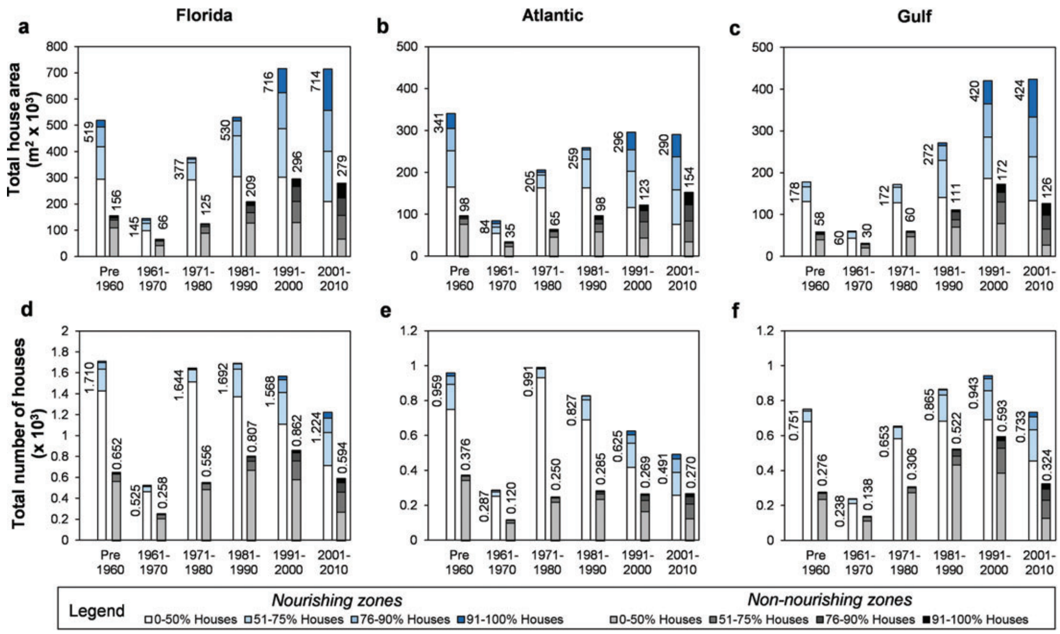

Figure 4. Total area and number of houses by decade built and percentile for size. (a–c) Total area (m^2) of shorefront single-family houses by decade built, with relative contributions from percentile bands for size, for all of Florida (a), and the state's Atlantic (b) and Gulf coasts (c). (d–f) Number 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 2, and are provided in full in Table S2.

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 [*Cutter and Emrich*, 2006; *Bagstad et al*., 2007; *Petrolia et al*., 2013; *McNamara et al*., 2015; *Brody et al.,* 2016]. 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 [*Jevons*, 1865; *Alcott*, 2005; *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 [*NRC*, 1995, 2014; *Smith et al*., 2009; *Landry*, 2011].

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; *Wilde*, 1998; *Landry and Jahan-Parvar*, 2011; *McNamara and Keeler*, 2013; *Petrolia et al*., 2013]. 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." By raising the total value of infrastructure vulnerable to damage, intensified development makes its own case for intensified protection through continued or increased nourishment [*Mileti*, 1999; *Nordstrom*, 2000; *Turner*, 2000; *McNamara et al*., 2015].

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 [*NOAA*, 2013; *Moser et al*., 2014; *Wong et al*., 2014]. Meanwhile, the cost of nourishment projects is rising [*Hoagland et al*., 2011], 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*., 2011; *McNamara et al*., 2011; *Williams et al*., 2013; *Lazarus et al*., 2016].

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 [*Slovic et al.,* 1977; *Busemeyer and Townsend*, 1993; *Peacock et al*., 2005;

Brody et al., 2016; Gopalakrishnan et al., 2016; Lazarus et al., 2016]. 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.

Acknowledgments
This work was supported in part by funding (to E.D.L. and R.C.B) from Welsh Government and HEFCW through the Sêr Cymru National Research Network for Low Carbon, Energy and the Environment RESILCOAST Project, by the Cardiff Undergraduate Research Opportunities Programme (CUROP; to E.D.L. and C.T.), and is a contribution (via E.D.L.) to the UK NERC BLUEcoast project (NE/N015665/2). The authors thank A. Coburn (PSDS) for data support, and thank reviewers and the journal editors for their constructive comments. Links to publicly accessible data sources used in this work are listed in Table S3.

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