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Dredging the sand commons: the economic and geophysical drivers of beach nourishment

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Abstract
Beaches are natural capital stocks that provide value through localized storm protection, recreational amenities, and ecosystem services at regional and global scales. In response to increased storm risks and sea-level rise, coastal communities invest in shoreline stabilization by rebuilding eroding sections of the coast through periodic re-nourishment. While conceptual models of the coastal-economic system provide a capital-theoretic framework to study beach management, empirical analysis of the drivers of beach nourishment policy is limited. Using data from 21 coastal towns in North Carolina, we examine the geophysical and economic factors that reflect coastal vulnerability and influence the frequency of beach nourishment investments. We find that beach towns with access to periodically replenishable sand deposits from inlets and river channels nourish more frequently. Beaches that rely on offshore sand reserves are nourished less frequently. Our results provide new insights into the heterogeneous risks that local communities face with higher costs, limited sand reserves and the growing nourishment demand driven by climate change and increased vulnerability.

Keywords Coastal adaptation · Vulnerability · Beach nourishment · Storms

1 Introduction

Beaches are a form of natural capital that provide amenity flows and benefits at different spatial scales (Smith et al. 2009). These amenities range from localized storm protection to regional and global public goods in the form of recreational amenities, carbon sequestration, and habitats for marine biodiversity (Barbier 2012; Gopalakrishnan et al. 2018). Climate change places coastal communities at risk due to sea-level rise (IPCC 2014), changing wave climates, and increasing

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frequency and intensity of storms (Emanuel 2013). These changes in geophysical processes have a significant economic impact on coastal development, infrastructure, and tourism. To adapt to and mitigate climate risks, communities manage their shorelines in a number of ways. Management policies include the construction of hardened structures, such as seawalls and jetties; investments in rebuilding natural capital through the maintenance of vegetated dunes and beach nourishment by periodically rebuilding an eroding section of a beach with sand dredged from offshore or nearshore inlets; and sometimes abandoning nearshore development (Dean 2003; Leuttich et al. 2014).

Along the Atlantic and Gulf coasts in the United States, beach nourishment is currently the dominant climate adaptation policy and is widely recognized as an effective shoreline stabilization strategy (Leuttich et al. 2014). Despite its short-term effectiveness, there are concerns about the long-term implications of nourishment due to potential ecological impacts of dredging (Speybroeck et al. 2006), spatial feedbacks that affect erosion in neighboring communities (Gopalakrishnan et al. 2017), and the need for repeated periodic investment when sand resources and funding to support dredging over time are uncertain. In this paper, we provide the first empirical analysis of the decision to undertake beach nourishment, examining the factors that determine the frequency of investment and depletion of available sand resources. The frequency of beach nourishment has systematically increased over the past 50–70 years from less than five nourishment projects per year during the 1950s to more than twenty nourishment projects in the 2000s (PSDS 2015). Along the North Carolina coast, we observe a similar trend between 1990 and 2014 (Fig. 1). Correspondingly, the volume of sand dredged from offshore and inlet sand deposits to rebuild beaches has also steadily increased (Fig. 2). Nourishment costs, which include the fixed costs of infrastructure and variable costs of acquiring nourishment sand, are estimated between one and four million dollars per mile of shoreline (PSDS 2015; Gopalakrishnan et al. 2018).

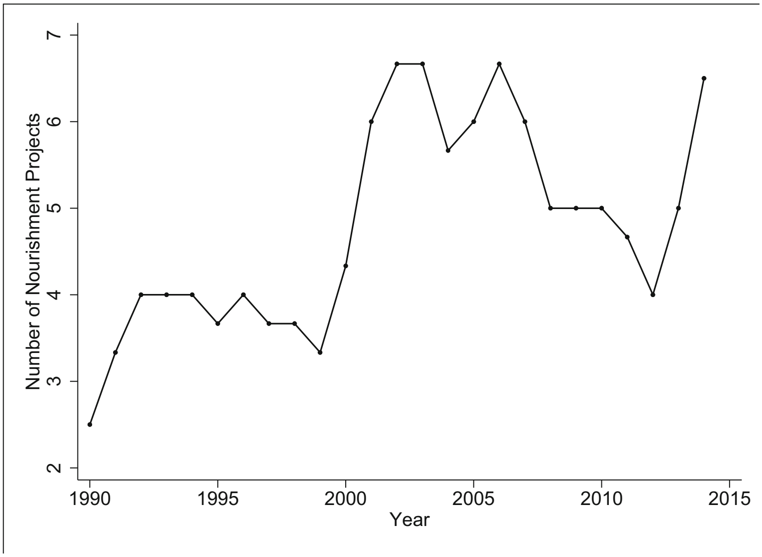

Fig. 1 Number of beach nourishment events (3-year average) in North Carolina over time. Source: Program for the Study of Developed Shorelines (PSDS), Western Carolina University

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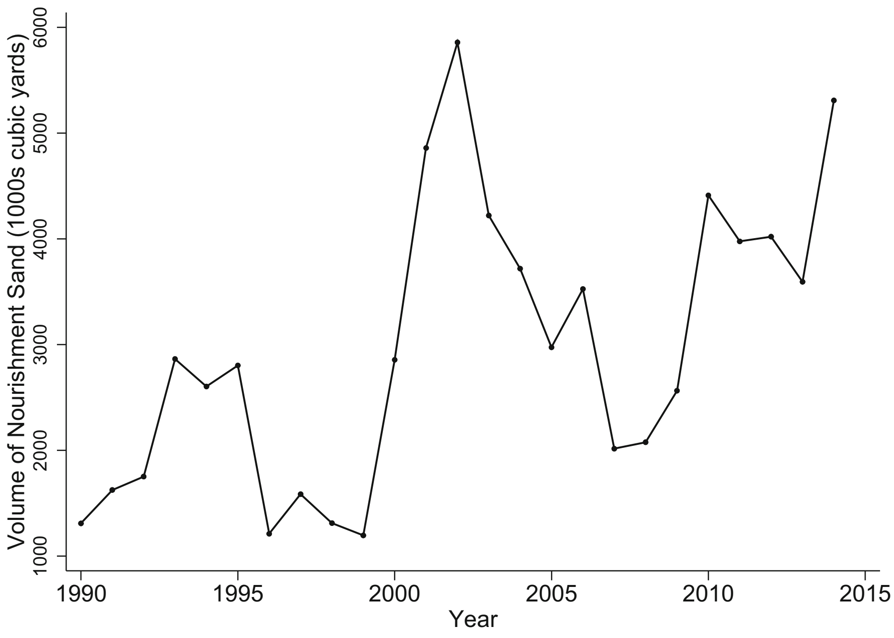

Fig. 2 Volume of sand used for beach nourishment in North Carolina (in millions of cubic yards, 3-year average). Source: Program for the Study of Developed Shorelines (PSDS), Western Carolina University

Beach nourishment projects in the United States have historically been funded through federal budget appropriations and implemented by the Army Corps of Engineers. Approximately, two-thirds of the costs of nourishment are supported by federal expenditures (McNamara et al. 2015; Trembanis et al. 1999) with cumulative expenditure exceeding \$7 billion (PSDS 2015). With potential cutbacks in federal contributions toward beach nourishment (Valverde et al. 1999; Coburn 2009; NC DEQ 2011), state and local governments face an increasing share in costs of nourishment to maintain wide beaches (Mullin et al. 2018; Qiu and Gopalakrishnan 2018). As local, decentralized decision-making is expected to increase for nourishment projects in the future, discussions over the appropriate frequency and scope of nourishment will increasingly focus on the costs and benefits occurring at local levels. To pay for nourishment, many towns along the US coast use specially designated property taxes to fund beach nourishment and assign higher rates of taxes to nearshore property owners who receive the largest benefits from shoreline protection (Mullin et al. 2018).

In undertaking beach nourishment, local beach managers aim to maintain wide beaches to support tourism and reduce storm damages to coastal property. Historic records of nourishment show that these decisions are heterogonous in the volume of sand placed, length of shoreline nourished, and nourishment costs across locations and over time (PSDS 2015). As the growing demand for shoreline stabilization continues to deplete available sand resources, a better understanding of the factors that determine the timing and rate at which nourishment sand resources are dredged is important in evaluating policy decisions at local and federal levels. Combining nourishment records from beach towns in North Carolina with geophysical beach characteristics and local amenities, we examine the factors that affect periodic

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investments in nourishment, focusing on town-level attributes that determine the demand for shoreline stabilization and the costs of nourishment as towns continue to extract common pool sand reserves. We find that towns with access to replenishable sand deposits near inlets nourish more frequently, whereas towns that rely on offshore dredging invest in less frequent, but potentially larger scale nourishment projects. These findings provide new insights into the heterogeneous risks that local communities face with increasing costs and declining sand reserves due to the growing nourishment demand driven by climate change and increased vulnerability.

1.1 Benefits and costs of coastal adaptation

Empirical work has largely focused on estimating the value (cost) of coastal amenities (risks) and evaluating the impact of coastal adaptation policies. This literature suggests that real estate markets can respond directly to changes in coastal resource stocks and capitalize the value of coastal amenities and risks. Empirical analyses consistently show that wider beaches, better beach views, lower flood risks, and proximity to waterfront increase coastal property values (Brown and Pollakowski 1977; Bin and Polasky 2004; Bin et al. 2008; Gopalakrishnan et al. 2011). Housing values may also capitalize storm risks, resulting in decreased prices after a hurricane for properties located in floodplains (Bin and Polasky 2004; Hallstrom and Smith 2005; Kousky 2010; Atreya and Ferreira 2015). However, the associated risk discount attenuates over time in the absence of additional natural hazard events (Atreya et al. 2013; Bin and Landry 2013).

Similarly, housing markets can reflect the value of risk mitigation measures such as increasing elevation of the structure, construction of seawalls, and windstorm resistance measures (Simmons et al. 2002; Rambaldi et al. 2013; Jin et al. 2015). Empirical analysis on the impact of federal expenditures on disaster management also shows that investment in ex ante mitigation projects provides larger benefits through risk reduction relative to ex post recovery spending (Davlasheridze et al. 2017). Because the construction of hardened structures generally exacerbates erosion in neighboring locations (Kraus and Pilkey 1988; Ells and Murray 2012), beach towns are prioritizing natural capital investments such as vegetated dunes and beach nourishment. Vegetated dunes provide amenities and storm risk reduction that increase coastal housing values but also generate ancillary costs due to reduced ocean views (Dundas 2017). The benefits from beach nourishment are also heterogeneous with a disproportionate share of benefits accruing to oceanfront property owners, suggesting that a differential tax policy could fund long-term nourishment projects (Mullin et al. 2018; Qiu and Gopalakrishnan 2018).

Ex-post evaluation of infrastructure and adaptation investments in reducing storm damage provides insight when evaluating alternative policies (Dundas 2017). However, the analysis of factors that affect the rate of extraction of sand reserves and the implications of these policies on the long-term viability of shoreline stabilization policies has received considerably less attention from researchers.

1.2 Dredging the sand commons

Economically viable deposits of nourishment sand are common pool resources that multiple towns extract to maintain beach amenities and provide storm protection (Stone and Kaufman 1985). These deposits also serve to supply inputs for industry (Höflinge 2014). The two

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primary sources of sand extracted by towns and industry are inlet sand and offshore sand. Because offshore reserves are typically harder to access and replenish slowly (decades), they can be considered common pool non-renewable resources (Finkl and Khalil 2005). Sand deposits from inlets and river channels are periodically replenished and are renewable on shorter time scales (months to years). Towns are likely to access sand reserves that are closest to the beach location to minimize costs. However, not all nearby sand reserves are suitable for beach nourishment. If the sediment placed on a beach is significantly finer or coarser than the natural sand on the beach, it will be ineffective for nourishment.[1] As the demand for shoreline management increases and sand resources become increasingly scarce, the cost of nourishment sand is expected to continue to increase (Fig. 3).

Early research on adaptation decisions along the coast explores interactions of complex physical processes and economic benefits and costs using capital-theoretic models, representing management decisions in a representative beach town that decides how often to nourish its beach (Smith et al. 2009; Landry 2011; McNamara et al. 2011). While conceptual models provide a framework to study beach management as a capital accumulation problem, empirical analysis to examine the timing of beach nourishment policy is very limited. Survival analyses are a commonly used method to examine the duration until the occurrence of an event, such as beach nourishment. Duration models have been used to analyze the adoption by firms of international standards of environmental management (Singer and Willett 1993; Nishitani 2009); land development (Irwin and Bockstael 2002; Irwin and Bockstael 2004; Towe et al. 2008; Wrenn et al. 2017); the ecological and political-economic determinants of deforestation (Vance and Geoghegan 2002); and the influence of invasive species on lakeshore housing development (Goodenberger and Klaiber 2016). In each of these studies, the econometric model of optimal timing is motivated by a reduced form representation of an underlying economic optimization problem. In the case of beach nourishment, we estimate a reduced form model of a local town managers' welfare optimization problem.

We build on this literature by adopting a duration modeling framework to examine factors that determine the frequency of beach nourishment along the coast of North Carolina. The unit of analysis is a beach town that must decide whether to nourish or not in any given year. Using data from coastal towns in North Carolina, we examine how beach nourishment decisions are affected by sand access and availability, which provide reduced form measures of the costs associated with nourishment.

1.3 Background on the nourishment process in North Carolina

Under the North Carolina Coastal Area Management Act (CAMA), towns need to acquire a major development permit with a cooperative agreement between local and state governments to establish a long-term coastal management plan for the town with minimal disturbance to the marine benthic environment before implementing a nourishment project (NC DEQ 2011). The Coastal Resources Commission (CRC) is a 13-member citizen board representing local governments, state agencies, and relevant areas of technical expertise, appointed by the North Carolina Governor that establishes the rules and policies for development within the 20 coastal counties. Before applying for a major permit, towns complete a sand borrow area survey and

[1] For example, Nags Head in the Outer Banks of North Carolina was unable to use the sand deposit in nearby Oregon Inlet for its nourishment project because the sediment texture was inappropriate (Nags Head 2011).

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compatibility analysis, to determine viability and access of sand reserves (Cooney et al. 2003; Finkl and Khalil 2005; USACE, PD 2014; USACE, Wilmington 2019).

Once an application is submitted to Division of Coastal Management (DCM) of the North Carolina Department of Environmental Quality (NC DEQ), the DCM field consultant visits the project site, examines the application file, and submits a field investigation report to the local DCM office, state agencies, and federal agencies including the Army Corps of Engineers for review. The reviewing process includes mandatory comment periods for local residents and homeowners to raise any concerns that they may have. Based on input from the state and federal review agencies and the public, the DCM director issues or denies the permit (NC DEQ 2016a).

The CAMA requires that a major permit is to be issued within 75 days from receipt of application, with a maximum extension of an additional 75 days under exceptional circumstances (NC DEQ 2018). A permit will expire in 3 years since issuance (NC DEQ 2016b). Because detailed data on the timing and approval rates are unavailable for our study period, and the time lag between permit application and project completion is short under normal circumstances, we use the observed time of project implementation rather than the permit application in our analysis.

Our analysis makes three important contributions to the literature. First, we empirically examine geophysical and economic factors that influence beach nourishment decisions along sandy beaches. Second, our paper begins to bridge a gap between empirical analyses of costs and benefits that influence coastal outcomes and conceptual models of dynamic decisions in the coastal zone to advance empirically grounded models for coastal management. Finally, we use the estimated model to predict observed patterns of nourishment and conduct counterfactual simulations to provide policy insight as coastal managers continue to grapple with rising sea levels and depleting sand resources.

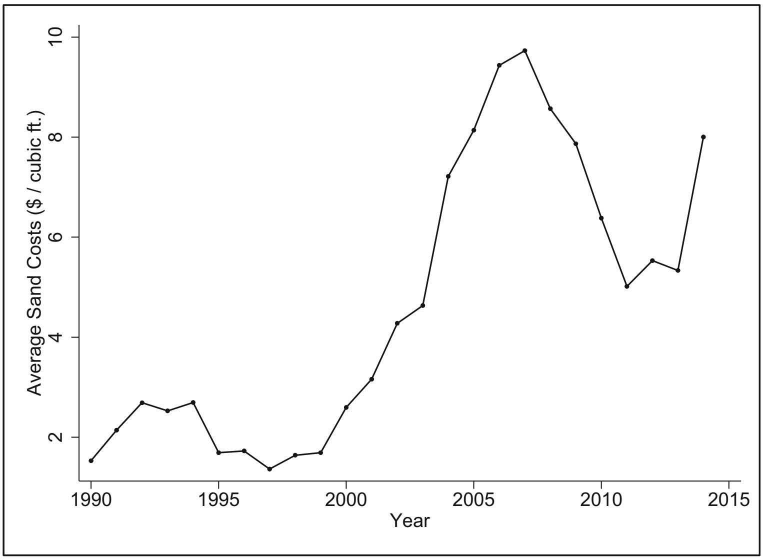

Fig. 3 Nourishment sand costs (in 2016$) over time

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2 Study area and data

Our empirical analysis uses data on beach re-nourishment projects from 21 beach communities along the North Carolina coast over the 25-year period between 1990 and 2014 (Fig. 4). These communities are largely tourism-dependent with significant coastal development and a long history of shoreline stabilization. Data are structured as a panel with annual time steps, allowing us to capture the repetitive pattern of beach nourishment decisions with multiple nourishment events occurring in a number of towns.

Beach nourishment patterns and access to sand reserves are heterogenous along the North Carolina coast (Fig. 4). The majority of sand resources are near inlets or intracoastal waterways. Four offshore sand reserves were accessed for nourishment during our study period—one near the Outer Banks, one near Kure Beach, and two along the Bogue Banks and Cape Fear. The geographic scope of this analysis is driven by the availability of data on the location of sand reserves and sand source information for beach nourishment. We acquired information on sand sources accessed for nourishment from the Army Corps of Engineers. We restrict the analysis to nourishment episodes that occurred beginning in 1990 for two reasons. First, sand access information and historic beach characteristics were unavailable for nourishment activity prior to 1990. Second, shoreline stabilization activity along the Atlantic coast systematically increased during the study period (Fig. 1). Records maintained by the Program for the Study of Developed Shoreline at West Carolina University (hereafter "PSDS") indicate that over 65% of the sand dredged for beach nourishment in the study region was placed from 1990 onwards.

The PSDS database provides information about the timing of nourishment projects, volume of sand placed, and nourishment costs. In the analysis, we include covariates that control for the cost of nourishment activity such as the distance to the closest sand resource and factors that reflect beach amenities and the potential demand for shoreline stabilization. We use beach

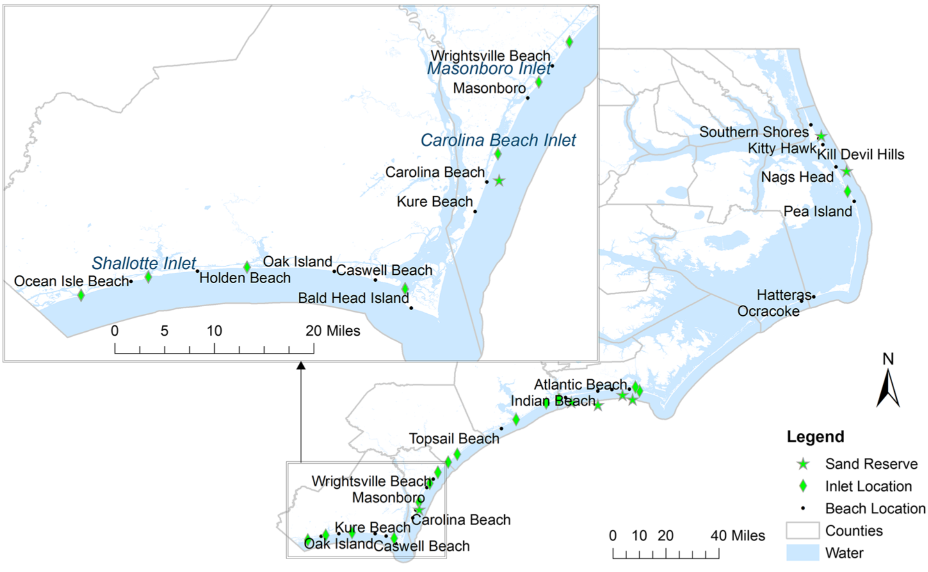

Fig. 4 Sand reserves in North Carolina

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nourishment records maintained by the North Carolina Department of Environment and Natural Resources (NC DENR) and Carteret County Shore Protection Office to identify the locations of sand reserves used for beach nourishment in North Carolina. For sand dredge sites along inlets, we identify the coordinates of inlets to geocode sand reserves and to calculate (using ArcGIS) the Euclidean distance from the centroid of each beach town to the closest sand reserves. Maps of offshore sand reserves in North Carolina are manually geocoded to measure the distance between a town and the nearest offshore sand reserve. Offshore reserves are considered non-renewable resources due to slow replenishment, while sand deposits from inlets and river channels are replenished over short time scales.[2]

We calculate the number of renewable sand reserves (e.g., inlets, coastal waterways) and the number of offshore sand reserves located within 2 miles, 5 miles, and 10 miles of every beach. As a measure of relative availability of nourishment sand, we also calculate the percentage of total renewable (inlets) and non-renewable (offshore) sand reserves located within these distance thresholds for each beach. We use an indicator variable to identify the type of sand source (as renewable or non-renewable) that is accessed for every beach nourishment event. We hypothesize that beaches with access to renewable sand deposits along inlets or river channels are likely to nourish more frequently because they rely on less costly, sustainable sand resources.

Demand for shoreline stabilization is driven by the coastal amenities that wide beaches provide, and are, at least partly, capitalized in housing markets (Pompe and Rinehart 1995; Landry et al. 2003; Gopalakrishnan et al. 2011; Landry and Hindsley 2011; Dundas 2017; Qiu and Gopalakrishnan 2018). We use geospatial information on beach attributes (NCDENR 2013; USGS 2014) and include covariates that represent beach characteristics, including shoreline length, and recreational amenities such as the number of public beach access points, the number of showers and restroom facilities, and the number of overlook points and dune walks on a beach. Long-term erosion rates are obtained from the North Carolina Department of Environmental Quality (NC DEQ), which provides geospatial information (GIS) on erosion rates at 50-m oceanfront transects calculated in 2009. We use the average erosion rate (in feet per year) for the length of the shoreline in each beach location. The maximum erosion rate corresponds to the 50-m transect that has the highest erosion in each beach location. We include both to control for the impact of the mean and extreme values.

To control for exposure to coastal risk, we develop a measure of the density of housing stock in each town that is potentially affected by nourishment decisions (Li et al. 2020). Data on the housing stock—the number of housing units in each town—were collected from the 2010 US census (US Census Bureau 2017). We also include county controls for time-invariant unobservable factors that influence nourishment decisions. Finally, to control for baseline housing values, we include quality-adjusted average housing values. We estimate these baseline values using property tax records for arms-length single-family residential transactions in the study area obtained from County tax assessor's offices and from CoreLogic, controlling for observable structural attributes, such as property age, acres, square footage, and number of bedrooms and bathrooms. This regression recovers location-specific housing value indices for each beach town.

[2] The classification of renewable and non-renewable is based on the rate of replenishment for future nourishment at economically relevant time scales (months/year to decades).

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Our panel data set is composed of yearly observations for 21 beach towns from 1990 to 2014. During our study period, we observe a total of 119 nourishment episodes of which 71 were inlet navigation projects and 48 were classified as shore protection or emergency nourishment projects. We dropped projects where either the volume of sand placed or the cost was zero. We also did not include one project that was undertaken for the purpose of "ecosystem restoration". Table 1 summarizes the beach nourishment frequency by town. The adoption of beach nourishment policy varies significantly across locations along the North Carolina coast; beach towns in the Outer Banks (Nags Head) did not begin nourishment until 2011 while other towns such as Carolina Beach have invested in shoreline stabilization since 1955. Average nourishment intervals (the duration between two consecutive projects) range from less than 2 years (Topsail Beach) to nearly 15 years (Caswell Beach).

In Table 2, we present summary statistics of the covariates included in the empirical analysis. On average, beach towns in North Carolina have 3146 housing units with an average baseline value of $108,810. There are 23 access points per town, on average, with nearly 5 restrooms. A representative town has 15 dune walks and 4 overlook points. The average shoreline length is 9.68 miles, but this varies greatly across locations ranging from 2.5 to over 40 miles. Sixty-seven percent of the beach towns in our study have access to nourishment quality sand within 5 miles, and beaches have at most two inlet sources and two offshore reserves within 2 miles. The average cumulative volume of sand dredged for nourishment is 2 million cubic yards. The average sand cost per cubic yard, calculated every year based on the reported nourishment costs for all locations that were nourished in a given year, over the study period is $4.73, with a maximum of over $11.

Table 1 Nourishment frequency by beach

Beach location	County	First nourishment	Number of nourishment episodes 1990–2014			Average nourishment interval
			Total	Inlet source	Offshore source	
Atlantic Beach	Carteret	1961	6	6	0	4.67
Bald Head Island	Brunswick	1992	10	10	0	3.30
Carolina Beach	New Hanover	1955	8	8	0	3.00
Caswell Beach	Brunswick	2001	2	0	2	14.50
Emerald Isle	Carteret	1984	15	11	4	1.80
Hatteras	Dare	1966	2	2	0	7.50
Holden Beach	Brunswick	1971	10	7	3	2.70
Indian Beach	Carteret	2002	3	0	3	9.00
Kill Devil Hills	Dare		0	0	0	-
Kitty Hawk	Dare		0	0	0	-
Kure Beach	New Hanover	1998	5	0	5	6.60
Masonboro	New Hanover	1986	2	2	0	12.00
Nags Head	Dare	2011	1	0	1	-
Oak Island	Brunswick		2	0	2	6.00
Ocean Isle Beach	Brunswick	1974	5	5	0	5.00
Ocracoke	Dare		2	2	0	3.00
Pea Island	Dare	1990	16	16	0	2.13
Pine Knoll Shores	Carteret	2002	4	0	4	8.25
Southern Shores	Dare		0	0	0	-
Topsail Beach	Pender	1982	18	18	0	1.39
Wrightsville Beach	New Hanover	1965	8	8	0	3.13

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Table 2 Summary statistics

Variable	Mean	Std. dev.	Min	Max
Number of housing units	3146.43	2060.38	374.00	8686.00
Baseline housing value (1000s $)	108.81	22.00	83.44	177.79
Shore length (miles)	9.68	8.75	2.53	42.17
Number of access points	23.33	22.47	0.00	68.00
Number of facilities (showers/restrooms)	4.90	7.39	0.00	34.00
Number of dune walks	15.14	16.36	0.00	59.00
Number of overlook points	4.38	6.26	0.00	29.00
Long-term erosion rate (ft/year)	− 0.54	2.28	− 6.91	3.53
Distance to nearest inlet (miles)	10.74	12.42	1.50	43.60
Dist. to nearest offshore sand source (miles)	13.97	14.41	1.03	50.89
Number of inlets within 2 miles	0.24	0.43	0.00	1.00
Number of inlets within 5 miles	0.67	0.78	0.00	2.00
Number of offshore reserves within 2 miles	0.10	0.29	0.00	1.00
Number of offshore reserves within 5 miles	0.43	0.58	0.00	2.00
Sand costs per cubic yard	4.73	3.58	0.00	11.40
Total sand placed on beach (mil. cubic yards)	2.07	3.07	0.00	13.49
Total number of navigation projects	4.86	5.24	0.00	19.00
Number of beach towns	21			

3 Econometric analysis of beach re-nourishment decisions

Duration models are used to analyze factors that affect the time, or duration, until an event occurs. In our model, a coastal town manager's problem is to determine when to invest in beach nourishment to mitigate coastal risk. Nourishment is done at discrete periods over time, rather than continuously, because it is characterized by high fixed costs—identifying sand borrow sites, mobilizing dredges, designing the project, and obtaining necessary permits. A beach manager then chooses optimal time intervals between periodic investments in nourishment events. Every realized nourishment is irreversible from the managers' perspective, although future nourishment is a periodic repeated process as the nourished beach continues to face erosion due to geomorphological factors, sea-level rise, and storms.

The unit of analysis in this model is an individual town stabilizing its shoreline with a beach manager deciding whether to invest in rebuilding beach capital at each time step. As we do not observe the actual town planners' benefits and costs, we collect beach-level data that approximate the benefits and costs facing this planner and specify a latent model of welfare maximization. Our welfare problem takes the following structure

$$W_{it}^{*} = X_i\beta + Q_{it}\alpha + \epsilon_{it} \tag{1}$$

where X is a vector of town specific attributes affecting town welfare, Q includes time-varying attributes associated with beach condition and nourishment costs, and ϵ_{it} is an idiosyncratic error term. Benefits from nourishment are affected by the recreational amenities provided on the beach and the exposure to coastal risk from housing development. To reflect beach amenities, we include the number of public beach access points, facilities such as showers and restrooms, and the number of overlook points and dune walks on the beach. We include the number of housing units and the baseline housing values in each location to control for risk exposure. Supply-side drivers of nourishment include distance to the closest sand reserve, which influence

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the costs of nourishment projects, the number of inlet sand reserves, and the number of offshore sand reserves, cumulative amount of sand placed on a beach, and the number of prior nourishment events. We also include geographic covariates, such as the length of shoreline and long-term erosion rate.

The duration model we estimate uses observations, or spells, over time at the town level. We characterize realizations of the decision to nourish using the following density function

$$f(t) = \Pr(t \leq T < t + dt) \tag{2}$$

with an associated cumulative density function given as

$$F(t) = \int_0^t f(s)ds = \Pr(T \leq t), \mathrm{t} \geq 0 \tag{3}$$

T denotes the random duration time of nourishment and t is a realization of that random variable.

While Eq. (5) specifies the cumulative probability of nourishment in a given time period, the probability of not nourishing prior to this time, the survival rate, is obtained by subtracting this term from one

$$S(t) = Prob(T > t) = 1 - F(t) \tag{4}$$

We can then specify the hazard function, which is the instantaneous probability of a nourishment event occurring in the time interval dt as

$$h(t) = \Pr(t \leq T < t + dt | \; T \geq t) = \frac{f(t)}{1 - F(t)} \tag{5}$$

Estimation of the model proceeds by specifying a proportional hazard function given by the following expression:

$$h(t) = h_0(t)h(X_{it}\beta + Q_{it}\alpha), \tag{6}$$

where $h_0(t)$ is the baseline hazard rate that is constant across all observations. As the vector of covariates changes, the baseline hazard is shifted proportionally, and the econometric model recovers the parameter estimates associated with these covariates. To empirically estimate the model, we make the commonly used assumption that the hazard function $h(t)$ is assumed to be proportional to a baseline hazard $h_0(t)$. An advantage of the resulting Cox proportional hazard specification is that it allows us to avoid assuming a parametric form for the baseline hazard.

To test the robustness of our results, we also estimate a parametric hazard model that assumes a Weibull distribution and find that results are consistent with the main model as discussed in Section 4. We use the estimated model to simulate potential changes in the pattern of nourishment under hypothetical climate and policy scenarios.

4 Results and discussion

We estimate four specifications of a Cox proportional hazard model to recover parameter estimates of covariates that influence the timing of nourishment events (Table 3). A positive coefficient indicates an increase in the probability of nourishment while a negative coefficient indicates a decrease in the probability of nourishment associated with the covariate. In models 1 and 2 (Table 3, columns 1–4), we do not control for beach amenities and housing stock that

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Table 3 Cox proportional hazard model

	Coeff.	Haz. ratio	Coeff.	Haz. ratio	Coeff.	Haz. ratio	Coeff.	Haz. ratio
Shore length (miles)	0.0665	1.069	0.0731 *	1.076	0.162	1.176	0.239 ***	1.270
	(0.0439)		(0.0434)		(0.126)		(0.0427)	
Average erosion rate (ft/year)	−0.171 *	0.842	−0.357 ***	0.700	−0.0823	0.921	−1.052 ***	0.349
	(0.0888)		(0.128)		(0.140)		(0.189)	
Maximum erosion rate (ft/year)	0.0344	1.035	0.0845 **	1.088	0.0773 **	1.080	0.371 ***	1.449
	(0.0266)		(0.0371)		(0.0321)		(0.0621)	
Distance to nearest inlet (miles)	−0.0796 ***	0.923	−0.147 ***	0.863	−0.111 **	0.895	−0.264 ***	0.768
	(0.0235)		(0.0402)		(0.0533)		(0.0442)	
Dist. to nearest offshore sand source (miles)	0.0104	1.010	0.0619 **	1.064	−0.0244	0.976	0.127 **	1.135
	(0.0252)		(0.0313)		(0.0695)		(0.0501)	
% Inlets within 5 miles	0.0361	1.037	0.0699	1.072	0.103	1.108	0.287 ***	1.332
	(0.0404)		(0.0619)		(0.0982)		(0.0510)	
% Offshore sand reserves within 5 miles	0.0272	1.028	0.000607	0.999	0.00296	1.003	−0.0433	0.958
	(0.0271)		(0.0294)		(0.0575)		(0.0373)	
Total sand placed on beach (mil. cubic yards)	−0.144 *	0.866	−0.162 **	0.850	−0.260 *	0.771	−0.268 ***	0.765
	(0.0739)		(0.0805)		(0.144)		(0.0956)	
Number of prior nourishment events	0.277 **	1.319	0.380 ***	0.380 ***	0.345 ***	1.412	0.439 **	1.551
	(0.115)		(0.115)	(0.115)	(0.119)		(0.196)	
Number of Prior navigation projects	−0.153	0.858	−0.304 ***	0.738	−0.226 *	0.798	−0.405 **	0.667
	(0.107)		(0.114)		(0.128)		(0.163)	
Amenity controls	No		No		Yes		Yes	
County controls	No		Yes		No		Yes	
Observations	525		525		525		525	
Number of beach towns	21		21		21		21	

Robust standard errors clustered by beach are in parentheses

*** $p < 0.01$

** $p < 0.05$

* $p < 0.1$

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influence the demand for nourishment. In models 1 and 3, we do not include county level controls to adjust for shifts in the baseline hazard rates. Results show that including additional controls improve the ability to explain patterns of nourishment. In our preferred model (Table 3, columns 7–8), we include all controls and find that the estimated coefficients are similar to other specifications, but the statistical significance of estimates improves. As model 4 is our preferred specification, we focus on Table 3, columns 7–8 in the discussion and interpretation of results.

Examining geophysical factors that affect nourishment decisions, we find that towns with longer coastlines are likely to nourish more frequently. An additional mile of coastline is associated with a 27% increase in the probability of nourishment in any given year. This is intuitive as towns with longer coastlines likely support larger populations of residents and beachgoers and have greater financial resources to support nourishment. Because erosion rates are reported as negative changes in shoreline position, the coefficient on average erosion rate is interpreted as the effect of a marginal decrease in erosion (or as marginal accretion). A 1-ft decrease in the average long-term erosion rate, attributable to sea-level rise and local wave climates, decreases the probability of nourishment by nearly 65%. A decrease in the maximum erosion rate, however, is associated with a decrease in the probability of nourishment.

We include several covariates that reflect access to nourishment sand and therefore the costs of nourishment. Proximity to sand reserves can reduce costs of access, transport, and infrastructure needed. An increase in the distance to the nearest inlet source by 1 mile lowers the probability of nourishment by 23%. When the closest offshore reserve is located farther away, we find that towns are likely to nourish more frequently. While this result appears counterintuitive, there could be two plausible explanations. First, it reflects an indirect effect that increases the rate at which inlet sand deposits are dredged when offshore reserves are located farther away. Alternatively, offshore sand deposits are common pool resources accessed by all beach towns, and a higher frequency of nourishment could indicate competition among beaches with limited access to nourishment sand. Because we do not have information on the specific location of offshore or inlet sand deposit dredged for every nourishment project, we are unable to further examine this effect.

Inlet sand deposits are effectively renewable resources, which can potentially make beach nourishment more sustainable. An increase in the proportion of inlet sources located within 5 miles from the beach increases the probability of nourishment by 33%, whereas the effect of offshore reserves located within 5 miles from the beach is statistically insignificant. These results support the hypothesis that access to renewable sand reserves makes beach nourishment a viable adaptation policy, whereas offshore sand sources are more likely a common pool resource with increasing costs as the available deposits continue to be depleted (Stone and Kaufman 1985; Lazarus et al. 2016). As the cumulative volume of sand placed on a beach increases (in millions of cubic yards), the likelihood of nourishment in a given year decreases by 24%. We also find a positive feedback with an increase in the likelihood of future nourishment with every prior nourishment event. However, as sand dredged from inlet navigation projects is placed on nearby beaches and provides nourishment benefits, towns with more navigation projects are less likely to nourish their beach in any given year.

In model 4, we control for county level baseline hazard shifters as well as a number of additional demand side controls. We label these controls as amenity controls, and they include a number of beach amenities, the housing stock, and baseline housing values that are expected to affect the demand for nourishment. We report the coefficients for these amenity controls in the appendix Table 7. While several amenities are statistically

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insignificant, overall, the signs and magnitudes of these estimates appear consistent with expectations; a larger housing stock and higher baseline housing values increase nourishment frequency.

Finally, we further examine the effect of navigation projects that are implemented to maintain navigable inlet channels rather than shoreline protection as they effectively act as nourishment for beaches receiving the dredged sand. During the study period, a total of 119 nourishment projects were undertaken, and 71 of them sourced sand from navigation projects. We repeat the analysis, but now do not treat navigation sourced projects as nourishment events. We control for the cumulative number of navigation projects in each location and the total sand placed on the beach through navigation projects. Results, shown in Table 4, are consistent with our intuition that navigation projects act as a substitute for nourishment in beaches that are located near inlets. We find that the likelihood of nourishment for shoreline management is significantly lower in locations that have received larger volumes of sand from navigation projects in the past. We also find that, while beaches located near inlets are more likely to nourish in any given year, the effect of the concentration of inlets within 5 miles from the beach is insignificant. We note that the outcome of interest in our empirical model is the frequency of sand placed on a beach, controlling for the source of sand and other economic and geophysical controls. Whereas the management process for inlet navigation projects is different from shoreline protection

Table 4 Proportional hazard model without navigation-driven nourishment

	Coeff.	Haz. ratio	Coeff.	Haz. ratio
Shore Length (miles)	−0.0264	0.974	0.0598	1.062
	(0.147)		(0.0771)	
Average erosion rate (ft/year)	−0.0298	0.971	−0.481 ***	0.618
	(0.247)		(0.179)	
Maximum erosion rate (ft/year)	0.0188	1.019	0.159 ***	1.172
	(0.0602)		(0.0466)	
Distance to nearest inlet (miles)	−0.0837	0.920	−0.174 ***	0.841
	(0.0782)		(0.0552)	
Dist. to nearest offshore sand source (miles)	−0.0181	0.982	0.098 **	1.103
	(0.0196)		(0.0391)	
% Inlets within 5 miles	0.0587	1.060	−0.0182	0.982
	(0.0591)		(0.0511)	
% Offshore sand reserves within 5 miles	0.0150	1.015	0.0313	1.032
	(0.0305)		(0.0236)	
Number of prior navigation projects	0.0574	1.059	0.211 **	1.234
	(0.149)		(0.0886)	
Total sand from navigation (mil. cubic yards)	−0.212	0.809	−0.226 **	0.798
	(0.129)		(0.111)	
Amenity controls	No		No	
County controls	No		Yes	
Observations	525		525	
Number of beach towns	21		21	

Robust standard errors clustered by beach are in parentheses

*** $p < 0.01$

** $p < 0.05$

* $p < 0.1$

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nourishment projects, our key outcome variable is the beach location and timing of sand placement. Ignoring inlet navigation projects will underpredict the frequency of beach widening outcomes that provide amenity and storm protection benefits.

4.1 Robustness checks and policy simulations

To examine the robustness of our results, we estimate a parametric Weibull model (Table 5). Comparing results from the Weibull specification with our main proportional hazards model (Table 3, model 4), we find that the magnitudes and statistical significance of estimated coefficients are similar. We find that beaches that are located close to inlet deposits are more likely to nourish and beaches located farther away from offshore reserves nourish more frequently. When the proportion of inlet sand deposits within 5 miles from the beach increases by a percentage-point, the probability of re-nourishment increases by 47%. A 1-ft decrease in the average long-term erosion rate decreases the probability of nourishment by over 70%. The estimated

Table 5 Weibull hazard model

	Coeff.
Shore Length (miles)	0.297***
	(0.0572
Average erosion rate (ft/year)	− 1.247***
	(0.370)
Maximum erosion rate (ft/year)	0.449***
	(0.106)
Distance to nearest inlet (miles)	− 0.282***
	(0.0645)
Dist. to nearest offshore sand source (miles)	0.0941*
	(0.0510)
% Inlets within 5 miles	0.387***
	(0.0674)
% Offshore sand reserves within 5 miles	− 0.0788**
	(0.0351)
Total sand placed on beach (mil. cubic yards)	− 0.360***
	(0.103)
Number of prior nourishment events	0.329***
	(0.124)
Number of prior navigation projects	− 0.349***
	(0.110)
Constant	0.480***
	(0.171)
ln(p)	− 11.00***
	(2.421)
Amenity controls	Yes
County controls	Yes
Observations	525
Number of beach towns	21

Robust standard errors clustered by beach are in parentheses

*** $p < 0.01$

** $p < 0.05$

* $p < 0.1$

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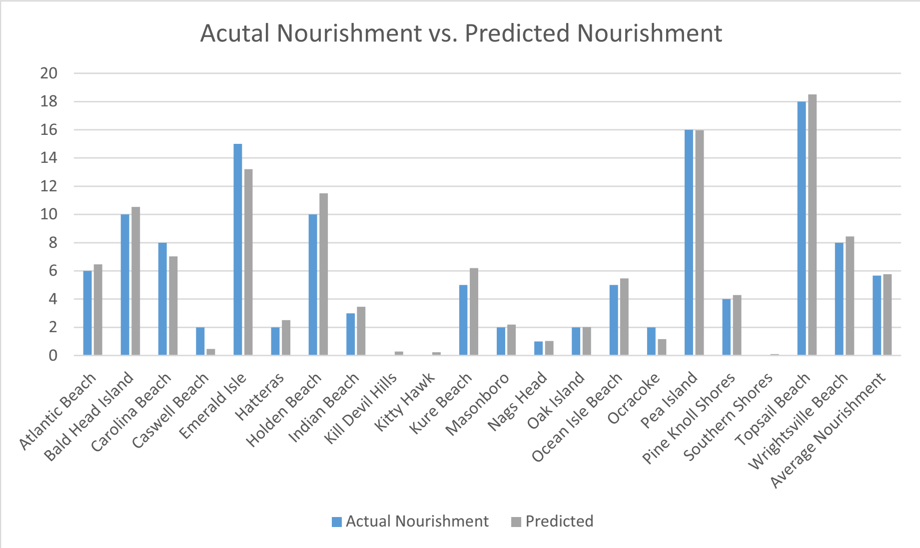

Fig. 5 Comparison of observed and predicted nourishment by location

shape parameter p is positive and significant, which implies that the hazard risk from coastal erosion increases over time. This is consistent with physical models of coastal processes, which show that nourishment accelerates local erosion as the nourished beach returns to its equilibrium profile (Ashton and Murray 2006; Smith et al. 2009), and subsequently increases the need for re-nourishment.

Using the Weibull model, which provides a parametric estimate of the baseline hazard rate that can support counterfactual simulation, we conduct policy counterfactuals to examine the potential impacts of changes in economic and geomorphological process on nourishment activity. To provide a baseline for comparison, we first use the Weibull model to predict nourishment patterns in the study area using the observed data. A comparison of the model predictions and actual number of nourishment events for each beach (Fig. 5) confirms that our model provides a good fit, providing us a reliable baseline for comparison with counterfactual simulations. For all simulations, including the baseline simulation, we assign nourishment outcomes for each beach using an accept-reject algorithm that compares the predicted probability of nourishment in each location with a random draw from a uniform distribution at each time step. A beach is assigned as having implemented a nourishment project if the predicted probability is larger than the draw from the uniform distribution. We repeat this process 500 times and report the average number of nourishment events. We use the baseline simulation to compare nourishment outcomes under two hypothetical scenarios (Table 6).

In the first scenario, we close three inlet channels and eliminate navigation-driven sand deposits in Carolina Beach Inlet, Masonboro Inlet, and Shallotte Inlet. The loss of accessible sand deposits from inlets systematically reduces the frequency of nourishment in neighboring locations, and the predicted total number of nourishment episodes in the study area decreases by 22%. In the second simulation, we consider

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Table 6 Policy scenarios

Beach location	Baseline simulation 1990–2014		Three inlet closures		Increased erosion 0.5 ft/year	
	Actual nourishment	Predicted nourishment	Predicted nourishment	Std. dev.	Predicted nourishment	Std. dev.
Atlantic Beach	6	6	9	2	11	2
Bald Head Island	10	10	13	2	18	2
Carolina Beach	8	7	0	0	13	2
Caswell Beach	2	0	1	1	1	1
Emerald Isle	15	13	15	2	20	2
Hatteras	2	3	3	2	5	2
Holden Beach	10	11	1	1	18	2
Indian Beach	3	4	3	2	6	2
Kill Devil Hills	0	0	0	1	1	1
Kitty Hawk	0	0	0	0	1	1
Kure Beach	5	6	2	1	11	2
Masonboro	2	2	0	0	4	2
Nags Head	1	1	1	1	2	1
Oak Island	2	2	2	1	4	2
Ocean Isle Beach	5	5	0	0	10	2
Ocracoke	2	1	1	1	2	1
Pea Island	16	16	18	2	20	2
Pine Knoll Shores	4	4	4	2	8	2
Southern Shores	0	0	0	0	0	0
Topsail Beach	18	19	19	2	24	1
Wrightsville Beach	8	8	1	1	16	2
Total nourishment	119	121	93		192	
Avg. nourishments	6	6	4		9	

the impact of climate forcing which uniformly increases long-term erosion rate by 0.5 ft per year. As erosion rates increase, due to rising sea levels, the need for shoreline stabilization also increases and we find that the total number of nourishment episodes in the study area would increase by 61%. Overall, our simulations underscore the need for better informed adaptation policies that consider geophysical and economic factors in coastal management decisions.

5 Conclusion

Beaches provide amenities and ecosystem services that appeal to residential development and tourism and have experienced significant growth in development over the past half century. This development has increased the number of households living in potentially vulnerable coastal locations with vulnerability likely to increase due to climate change, rising sea levels, and increasing frequency and severity of coastal storms. Coastal communities have responded to these risks by investing in shoreline stabilization, even though federal budgets are becoming tighter. As nourishment quality sand becomes scarce, the pressure to dredge common pool sand reserves will inevitably increase. To make beach nourishment policy more effective, projects must

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more effectively coordinate decisions regarding where to extract sand, when to extract sand, and ultimately where to place the extracted sand reserves.

Although patterns of shoreline stabilization are heterogeneous along the US Atlantic coast, there is an increasing trend in the number of beach nourishment projects (Fig. 1). However, the growing use of nourishment to reduce vulnerability and maintain critical ecosystem services raises concerns about the viability of this strategy over long periods. Viable sand deposits are a common pool resource that multiple towns access when they make localized shoreline management decisions (Lazarus et al. 2016). While existing geo-economic models of interactions between complex coastal processes and economic decisions provide a conceptual framework for modeling periodic nourishment decisions with a representative beach town (Smith et al. 2009), empirical analyses have not focused on the timing of nourishment decisions. This paper presents the first empirical economic analysis of the factors that affect beach stabilization decisions along sandy coastlines, including geophysical features of the coastal-economic system, economic indicators of coastal vulnerability, and proximity to sand reserves. Examining the drivers of beach nourishment decisions provides insights in understanding factors that affect coastal vulnerability in general and exploring other adaptation strategies.

Our analysis shows that beach towns with access to sand deposits from inlets and river channels, which are periodically replenished, nourish more frequently. Towns that rely on offshore reserves are nourished less frequently but these investments are likely to place a larger volume of sand on the beach due to higher fixed costs associated with accessing offshore reserves. In North Carolina, for example, the volume of sand placed during any single nourishment project is about three times larger when it is dredged from an offshore reserve relative to an inlet source (PSDS 2015). Our findings support earlier theoretical models of beach re-nourishment (Smith et al. 2009) and complements numerical models of coastline change that show that increasing the cost of sand can accelerate the depletion of a finite sand reservoir when towns that have high property values are located in regions that experience high erosion rates (McNamara et al. 2011).

Finally, the empirical estimates and counterfactual simulations further reveal that the policy decisions and patterns of extraction of common pool sand reserves are shaped by both economic considerations and geophysical coastline features, such as shoreline length, erosion rates, and proximity to inlets. As inlets are dynamic in nature, the formation of new inlets and inlet closures can affect the pathways for sediment deposits. Because inlets are important for navigation and recreational fishing, towns are purposefully managing development around inlets and inlet hazard areas where the rate of shoreline change is more rapid and variable than other locations along the coast. Our analysis shows that the management of inlets is critical not only to maintain navigation channels but also for the viability of beach nourishment and motivates future research to examine feedbacks between inlet management and the evolution of the coastline.

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Appendix

Table 7 Cox proportional hazards model

	Coeff.	Haz. ratio	Coeff.	Haz. ratio
Risk exposure				
Number of housing units (100 units)	0.0305	1.031	0.0646***	1.067
	(0.0279)		(0.0242)	
Average housing price (10,000s $)	0.215	1.240	0.336*	1.399
	(0.138)		(0.203)	
Beach amenitiestio				
Number of access points	− 0.0554	0.946	− 0.0859**	0.918
	(0.0391)		(0.0423)	
Number of facilities (showers/restrooms)	− 0.00364	0.996	− 0.00419	0.996
	(0.0247)		(0.124)	
Number of dune walks	0.0149	1.015	− 0.0472	0.954
	(0.0229)		(0.0672)	
Number of overlook points	0.0597	1.062	0.388**	1.475
	(0.0474)		(0.162)	
Amenity controls	Yes		Yes	
County controls	No		Yes	
Observations	525		525	
Number of beach towns	21		21	

Robust standard errors clustered by beach are in parentheses

*** $p < 0.01$

** $p < 0.05$

* $p < 0.1$

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