Progress in Coupling Models of Human and Coastal Landscape Change

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ABSTRACT

Humans are increasingly altering the Earth's surface, and affecting processes that shape and reshape landscapes. In many cases, humans are reacting to landscape-change processes that represent natural hazards. Thus, the landscape is reacting to humans who are reacting to the landscape. When the timescales for landscape change are comparable to those of human dynamics, human and 'natural' components of developed environments are dynamically coupled—necessitating coupling models of human and physical/biological processes to study either environmental change or human responses. Here we focus on a case study coupling models of coastal economics and physical coastline change. In this modeling, coastline change results from patterns of wave-driven sediment transport and sea-level rise, and shoreline stabilization decisions are based on the benefits of wide beaches (capitalized into property values) balanced against the costs of stabilization. This interdisciplinary modeling highlights points that may apply to other coupled human/natural systems. First, climate change, by accelerating the rates of landscape change, tends to strengthen the coupling with human dynamics. In our case study, both increasing sea-level-rise rates and changing storm patterns tend to increase shoreline change rates, which can induce more vigorous shoreline stabilization efforts. However, property values can fall dramatically as erosion rates and stabilization costs rise, which can also lead to the abandonment of expensive stabilization methods as shoreline change rates increase. Second, socio-economic change can also strengthen the human/landscape coupling. Changing costs of shoreline stabilization can alter stabilization decisions, which in turn

alters patterns of coastline change. The coupled modeling illuminates the long-range effects of localized shoreline stabilization efforts; communities arrayed along a coastline are unwittingly affecting each other's erosion rates, and therefore each other's economies. Our coupled modeling experiments show that spatial distributions of property values and erosion rates can jointly affect economic outcomes, resource allocation between communities, and patterns of shoreline change. These findings raise questions about coastal management strategies, and efficient and equitable allocation of scarce resources among coastal communities.

I. Introduction

In the past, researchers studying the processes that shape the Earth's surface most often looked for pristine landscapes in nature—environments in which the physical and/or biological processes proceed without the complicating influence of human manipulations. However, human modifications of landscapes, and of the processes that change landscapes, have become so ubiquitous that opportunities for analyzing pristine landscapes are limited. To understand the evolution of much of the planet's surface, Earth-surface-process studies increasingly need to address the human component of the system (e.g. (Haff 2003; Werner and McNamara, 2007)). Addressing the human component often requires more than just superimposing a model of human effects on some representation of a 'natural' system. Human actions and landscape change do not necessarily act independently but are often coupled in feedback loops. Feedbacks occur because: 1) many human actions are explicit reactions to landscape changes or to the processes that shape landscapes in the long term (e.g. arresting river bank or shoreline erosion, or trying to affect the course of debris flows that threaten alpine infrastructure and lives); and 2) human manipulations often affect future landscape changes. Humans react to landscape-change processes that are in part functions of human actions.

Such couplings range from being local in time and space—flood control levees on a river lead to increased flooding and increased need for flood control immediately downstream (Criss and Shock, 2001)—to less local and less obvious—a dam constructed at one point along a river course will ultimately cause a wave of erosion to propagate downstream. The longer the timescale considered the longer the distance over which the local human manipulation will affect riverine environments, human habitation, and use of these environments. Similarly, land use changes in mountainous environments that affect vegetation will ultimately change the shape of the landscape on the mountain-range scale (Collins *et al.*, 2004; Istanbulluoglu and Bras, 2005). When thinking about large-scale landscape features such as mountain ranges and major river systems, the timescales of landscape change are often very long compared to those of human dynamics. In such cases, human actions might come and go so quickly that the landscape reactions to each one are insignificant—they are dynamically uncoupled from the human disturbances.

On the other hand, when the timescales for human dynamics and landscape change are closer together, the coupling between the two can be strong (Werner and McNamara, 2007). In such cases, the recursive adjustments of humans to landscapes and vice versa can lead to the emergence of phenomena that would be impossible to anticipate by studying either the physical landscape or human components in isolation (e.g.(McNamara and Werner, 2008; Magliocca *et al.*, **in** press)).

On sandy coastlines, large-scale changes can occur relatively rapidly. Shorelines and barrier islands can shift as much as a kilometer in the cross-shore direction over decades (e.g. (Dean and

Perlin, 1977)), and the plan-view shape of a coastline can adjust over human timescales even on spatial scales of a hundred kilometers (Slott *et al.*, 2006). McNamara and Werner (2008) coupled a numerical model of barrier island evolution to resort community development and found the emergence of temporal and spatial cycles of island stability and economic expansion alternating with periods of rapid island migration and property loss. The cycles arose neither from the patterns of forcing (sea level rise and storm statistics were constant) nor from the dynamics of either human or landscape components alone, but from the feedbacks between them.

Here we present a case study involving shoreline erosion and the plan-view evolution of a sandy coastline which further illustrates that in a tightly coupled human/landscape system, we cannot understand either the human dynamics or the physical/biological system separately. This model-coupling endeavor also illustrates the synergistic benefits to multiple disciplines that result from thoroughly interdisciplinary interactions between researchers who ordinarily study the component parts separately. Rather than pasting together models developed independently within the respective disciplines, a deliberate melding of human and landscape processes in numerical models generates new insights about coupled human and coastal landscape change.

In a numerical model addressing how patterns of wave-driven alongshore sediment transport shape coastlines, experiments have shown that even one localized shoreline-stabilization project, when maintained for decades, can affect coastline evolution over surprisingly long distances. Erosion rates change up to 100 kilometers away. Those early experiments, described briefly in section 2 below, lacked human dynamics; the shoreline stabilization was assumed to occur perpetually at one location in the form of beach nourishment, which adds sand to the nearshore system at a long-term rate sufficient to counteract erosion locally. However, beach nourishment is an expensive endeavor. Not all coastal communities choose to spend resources in this way, and communities that employ nourishment at one time may not maintain the practice forever as the costs and/or perceived benefits change. Thus, addressing how a developed coastline evolves requires a model of human dynamics. In section 3, we outline economic models that characterize the costs and benefits of beach nourishment and the resulting decision calculus of individual communities. The costs of nourishment depend in part on erosion rates that might change over time and are tied to the physical system. The benefits reflect increased property values (or avoided property losses) from wider (narrower) beaches. These economic models, in combination with the coastline change models, suggest that coastal property values depend strongly on how the coastline evolves. Section 4 illustrates how coastline evolution in turn depends on the distribution of coastal property values. Thus, fully coupled modeling is required to investigate the behaviors of either the human or landscape components of the system in this case.

Our case study illustrates two other points that are also likely to apply more broadly. Climate change, by accelerating landscape change, accentuates the coupling between humans and the environments they inhabit. In our case, the intensified coupling arises because both increased rates of sea-level rise and changing storm climates tend to increase shoreline erosion rates. These increases tighten the connections between shoreline changes in different locations even when they are far apart in space. Similarly, changes in socio-economic conditions can accentuate human/landscape coupling by accelerating changes in the patterns of land use and landscape manipulations. In our case, changes in the cost of nourishment (possibly related to dwindling resources of suitable sand for nourishment) precipitate abrupt changes in coastal economies and therefore patterns of coastline change.

Our coupled coastline/economic modeling endeavor includes many facets, ranging from projects involving a little bit of economics integrated into landscape change models, to those involving a little bit of geomorphology woven into economics models, to more complete coupling involving increasingly complex economic and coastline-change components. We will outline examples of each after some of the background motivating this work.

II. Background: Large-Scale Coastline Morphodynamics

Gradients in wave-driven alongshore sediment transport play a key role in shaping sandy coastlines, especially on spatial scales of kilometers and greater (e.g. Komar, 1998; Lazarus and Murray, 2007; Lazarus *et al.*, in press). Where net alongshore transport (averaged over timescales of years or longer) brings more sediment into a stretch of coast than it takes out, the convergence of sediment transport tends to produce a seaward progradation of the shoreline. On the other hand, a divergence of transport tends to drive shoreline erosion. This conservation of nearshore sediment is expressed by:

(1) $$\frac{\partial \eta(x,t)}{\partial t} = -\frac{1}{D}\frac{\partial Q_s(x,t)}{\partial x},$$

where η is the cross-shore shoreline position, x is the alongshore coordinate (Figure 1), Q_s is the alongshore sediment flux (m^3/day), and D is the water depth (m) to which cross-shore wave-driven transport processes redistribute sediment over the seabed (plus the height of the beach, or dunes if any are present).

Alongshore sediment transport results from the combined action of breaking waves, which entrain sandy sediment, and a subtle alongshore current that advects the suspended sediment. Breaking waves deliver momentum into the nearshore water, and the alongshore component of that momentum flux drives the alongshore current. The strength of the current is related to the rate at which waves deliver alongshore momentum into the surf zone (Longuet-Higgins, 1972). Picturing waves approaching shore in relatively deep water (before shoaling and refracting over the nearshore seabed) (Longuet-Higgins, 1972; Ashton *et al.*, 2001; Ashton and Murray, 2006a), the flux of momentum toward shore is greatest when the waves are propagating most directly toward shore—when the wave crests are closest to parallel to the shore. However, the alongshore component of the wave momentum vanishes as wave crests become parallel to the shore. The alongshore component of the wave momentum is greatest when waves approach shore most obliquely. However, as the angle between wave crests and the shoreline approaches 90°, the flux of momentum (and energy) toward shore vanishes. The competition between these two influences on the alongshore current leads to a maximum in alongshore sediment flux for intermediate wave-approach angles—roughly 45° between wave crests and shoreline orientation (Ashton *et al.*, 2001) (Figure 1). Several different formulae relate alongshore sediment flux to wave characteristics, all showing this flux maximizing angle when expressed in terms of relatively deep-water waves (outside the 'shoreface' zone of approximately shore-parallel bed contours) (Ashton and Murray, 2006a), including one based on the commonly used CERC equation:

$$Q_s = K_2 H_0^{12/5} \sin(\phi_0 - \theta) \cos^{6/5}(\phi_0 - \theta), \quad (2)$$

where H_o is the deep-water wave height, ϕ_o is the relatively deep-water wave approach angle, and K_2 is an empirical constant (Komar, 1998) (set to 0.32 $m^{3/5}s^{-6/5}$). (The assumption of shore-parallel contours that is essential to transforming sediment transport formulae that are typically expressed in terms of breaking wave height and angle into a relationship involving deeper-water wave characteristics is an approximation that improves as the alongshore scales considered increase, because more complicated shoreface bathymetry on scales commensurate with the cross-shore extent of the shoreface will cause alongshore variations in breaking waves on those scales not captured by (2). In addition, this approximation fails in the vicinity of cape-associated shoals, which involve contours in shallow water that are not even approximately shore parallel.) For a given wave approach angle, on alongshore scales of kilometers or more, alongshore changes in shoreline orientation cause gradients in alongshore sediment flux. When the waves in relatively deep water approach from an angle smaller than the one that maximizes alongshore sediment flux ('low-angle' waves), these gradients tend to smooth a coastline shape. However, when the waves approach from more oblique directions ('high-angle' waves), alongshore transport tends to exaggerate any subtle undulations in the coastline shape (Ashton *et al.*, 2001; Ashton and Murray, 2006a; Ashton and Murray, 2006b) (Figure 1). Along a given stretch of coastline, whether coastline undulations grow over time or not depends on whether high-angle or low-angle waves dominate the time-averaged distribution of wave influences on alongshore transport (the 'wave climate').

Previous work using a numerical model based on equations (1) and (2) (Ashton *et al.*, 2001; Ashton and Murray, 2006a) has shown that when high-angle waves dominate a regional wave climate, the way multiple growing bumps along a coastline interact with each other can lead to the emergence of interesting coastline shapes, including a cuspate coastline such as the Carolina Capes, USA (Figure 2). The shape the coastline takes on depends sensitively on both the ratio of influences from high- and low-angle waves, and on the ratio of waves approaching from the left and right, looking off shore (Ashton and Murray, 2006a).

The shapes that emerge from these relatively simple interactions can be complex, and pose numerical challenges; with a highly asymmetric wave climate (more influence from left or right), asymmetric capes or even 'flying spits' form. A numerical algorithm relying on a global reference frame would fail, because at a given alongshore location in the global reference frame, multiple shorelines can exist, facing very different directions on either side of a spit (Figure 3). In addition, protruding shoreline features can effectively block waves from some directions from affecting some segments of the shoreline (Figure 3). Exploring the range of coastline behaviors arising from the simple interactions between sediment flux and shoreline orientation motivated the development of an algorithm that defines local coordinate systems based on the locations of the shoreline in adjacent model cells, and which delineates wave 'shadow' zones, as described in detail in Ashton and Murray (2006a).

Experiments using this model showed that shifting storm behaviors—changes in either the frequency or strength of tropical or extra tropical cyclones—change the distribution of wave-approach angles affecting coastlines. Such changes will tend to reshape coastlines, accelerating shoreline change rates greatly in some areas (Slott *et al.*, 2006). The spatial pattern of accelerated shoreline change depends on how the storm climate changes.

Slott *et al.* (2010) showed that as the shape of a cuspate coastline tends to adjust to a changing wave climate, even localized shoreline stabilization—which prevents the adjustment in one place—could affect shoreline change rates over surprisingly long distances, up to 100 km. These effects can rival the shoreline-erosion rates expected from sea level, on the order of meters per year, within tens of kilometers of the localized shoreline stabilization (Figure 4).

In these model experiments, Slott *et al.* (2010) analyzed the long-term effects of beach nourishment, which is the prevalent form of shoreline stabilization on many developed coastlines. However, they did not include any human dynamics, treating beach nourishment as a static, perpetual policy at a single location. On actual developed coastlines, the decisions about whether to employ beach nourishment involve ongoing debates and evaluation of the benefits and considerable costs. In addition, these decisions and the resulting shoreline stabilizations occur in multiple locations. Given that the highly simplified modeling from (Slott *et al.*, 2010) suggests that communities that choose to stabilize their beach are affecting the erosion rates at many other locations, multiple towns existing along a coastline are likely to be affecting each other's physical environments, and therefore each other's decision making processes. Addressing how actual developed coastlines evolve clearly requires including some representation of human dynamics in the modeling endeavor.

III Geomorphology embedded in Economic Modeling

Beaches are important natural resources that provide value to humans through storm protection and a whole suite of recreational amenities (Pendleton et al. 2011), including sunning, viewing the ocean and wildlife, and access to surfing, swimming, boating, and fishing. These values are not static (involving stocks of value at a point in time) but are dynamic (involving flows of value over time), as beaches erode or accrete and the surrounding economic environment changes. Although beach values can diminish due to erosion, humans can rebuild beaches through beach nourishment, a costly engineering solution. Thus, an economic view of what communities do when they decide whether and when to nourish beaches is that they choose an optimal strategy based on maximizing benefits minus costs. Because the state of the system (the width of the beach) changes over time and nourishment is done on a periodic basis, this problem is fundamentally one of dynamic optimization (a modeling approach that maximizes the total flow of value over time). In this approach, beach managers choose a nourishment interval (how often to nourish the beach) and the extent of nourishment (how far out to build the beach) in order to maximize a stream of net benefits over time.

The benefits of nourishment at least partly reflect the coastal real estate market. Previous studies have consistently found that beach width contributes positively to coastal property values (Edwards and Gable, 1991; Pompe and Rinehart, 1995; Kreisel *et al.*, 2005; Landry and Hindsley, 2010). The value of coastal property is decomposed into individual attributes including property characteristics (such as number of rooms, area, age of the property), neighborhood characteristics (such as school district, crime rates) and environmental attributes (such as beach width), and the marginal value of the beach is then the value added to the property with an increment in the width. Shoreline stabilization policies are based on economic studies that show that there are significant benefits from maintaining beach quality and preventing the shoreline from shifting landward (Yohe *et al.*, 1995; Landry *et al.*, 2003). However, until recently, these benefit-cost analyses did not consider the feedbacks between economic decisions (beach nourishment) and shoreline dynamics. When nourishment feedbacks are incorporated in the estimation, coastal property values are far more sensitive to beach width (Gopalakrishnan *et al.*, 2011). In an empirical study using data from ten beach towns in North Carolina, Gopalakrishnan *et al.* (2011) found that a one percent increase in beach width results in 0.5% increase in the value of oceanfront property when nourishment feedbacks are incorporated compared to only 0.08% increase in the value of oceanfront property if beach width is exogenous (no nourishment feedback).

Smith *et al.* (2009) developed one of the first dynamic models of beach nourishment, in which a single representative community chooses how often to nourish the beach incorporating beach dynamics in determining the benefits flow, nourishment costs (cost of sand needed to replenish the beach to an initial width) and the state of the natural resource (beach width) at any given time (Smith *et al.*, 2009). The model characterizes benefits from wide beaches as a continuous flow that is capitalized in property values and the costs include fixed infrastructure costs and variable costs of nourishment sand that are in proportion to the extent of beach build out. Drawing on the literature in forest economics (Faustmann, 1849; Hartman, 1976), nourishment is modeled as a periodic process and the community chooses an optimal interval (T* years) between nourishment events that maximizes net benefits over an infinite time horizon. The benefits over a nourishment interval of length T years are:

(3) $$B(T) = \int_0^T e^{-\delta t} \delta\alpha (x(t)^{\beta}) dt$$

where $x(t)$ is the beach width at time t, α is the base property value, which includes the value of all other attributes, β is the marginal value of beach width, and δ is the discount factor. The costs of nourishment are the sum of fixed costs (c) and variable costs (φ) proportional to the extent of beach build-out to return to an initial width (x_0):

(4) $$C(T) = c + \varphi(x_0 - x(T))$$

Nourishment affects short run morphodynamics of the beach (changes to the shoreline on timescales equal to or less than the nourishment interval) and this effect is modeled by including a background linear erosion rate and an exponential decay rate to capture alongshore sediment transport and the cross-shore effect as the shoreface profile returns to equilibrium. The beach width at time t is:

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

where γ (m/year) is the background erosion (e.g. attributable to sea level rise), θ is the exponential decay rate of nourished portions of the beach (μ). Each time a community nourishes, it re-sets the beach at the initial width x_0.

The model assumes a background erosion rate of 0.6 m/year and an exponential retreat rate of 0.1 for the nourished portion of the beach ($m = 0.35$).

Results show that the optimal nourishment interval decreases when the value of beach width increases, when the baseline property value increases and when the background erosion rate increases. The coupling of human-natural systems is clear in the result that the optimal nourishment interval is one that balances the difference in marginal benefits and costs in a single interval (T) with the cost of delaying all future nourishments. The choice of nourishment interval implicitly determines the rate at which the beach resource is allowed to decay and simultaneously determines the state of the resource at all future time periods. An unexpected result that emerges from the model is that the optimal nourishment interval and the amount of nourishment sand used can decrease or increase with an increase in the variable costs of nourishment sand (Figures 5a, 5b). Economic intuition in a non-coupled system suggests that as costs rise, the demand for nourishment will fall leading to less frequent nourishment. But here the optimal response to an increase in the cost of nourishment sand depends on economic and physical parameters, which illustrates that a coupled model is required to understand feedbacks in the economic and physical system. The difference between the economic discount rate and the exponential decay rate of nourished sand is a key determinant of whether optimal nourishment frequency increases or decreases as a result of increased variable costs of sand. When the exponential decay rate of nourished beach is higher than the discount rate, nourishment interval can decrease with higher sand costs. This result suggests that, as coastal communities face increased demand for nourishment due to sea-level rise and changes in storm patterns, we are likely to observe more frequent nourishments for some time into future.

The physical-economic coupling is also supported by empirical analysis in North Carolina. Gopalakrishnan *et al.* (2011) used estimates of beach value from the empirical study to parameterize the dynamic model of optimal nourishment (Smith *et al.*, 2009) and found that the predicted optimal nourishment intervals using beach values incorporating nourishment feedbacks are closer to observed nourishment intervals in five out of six town that have periodically nourished their beach (Figure 6). (In the case of Atlantic Beach alone, the predicted optimal nourishment interval without feedback is closer to the observed interval. However, this likely reflects the fact that Atlantic Beach has received sand as part of the dredge fill disposal scheme from the nearby regions. Dredge fill disposal is effectively beach nourishment but does not get recorded as a nourishment project in the data (Limber and Warren, 2006). If we account for this effect, the observed nourishment interval would be lower and closer to the predicted interval incorporating feedbacks.)

IV. Coastal Morphodynamics Meet Coastal Economics

In more recent economic-coastline modeling, we have coupled an economics-based decision model with the large-scale coastline model described above (Background) (Ashton *et al.*, 2001; Ashton and Murray, 2006b). The economic decision model chooses whether to nourish a given location along a coastline by considering the net benefits (benefits minus cost) to property value that result from nourishment. As in Smith *et al.* (2009) and Gopalakrishnan *et al.* (2011), the benefits function in the model captures the multiplicative benefits to a baseline property value from increased width, and the cost function incorporates the cost of sand (a variable cost as it depends on the amount of sand used in a nourishment project) and the fixed cost of nourishment associated with mobilizing nourishment equipment. However, this decision making model is simpler than the one developed by Smith *et al.* (2009); it does not involve optimization over an infinite time horizon, and allows for repeated decision making over time, as physical and economic conditions change. The large-scale coastline model simulates the impact of wave-driven alongshore sediment transport and erosion due to sea level rise on plan-view coastlines. The coupling between these economic and coastline models was initially used to investigate the impact of nourishment decisions on neighbor towns along a straight coastline (Slott *et al.*, 2008), one with no large-scale shape features such as cuspates or spits. Results from that initial study found that the amount of money spent on nourishing the beach was a strong function of distance between towns, and whether adjacent towns nourished in unison.

Extending this work, the coupled model was applied to a coastal setting similar to the Carolina cuspate coast (Figure 2) (McNamara *et al.*, in press) to probe the response of that coastline to an observed increase in hurricane waves (Komar and Allan, 2008). The coupled economic and coastline model was run for four configurations. In all configurations the initial condition coastline was one that results from forcing the large-scale coastline model with a wave climate similar to that found off the case study North Carolina coastline. The wave climate used was statistically similar to WIS hindcast station 509 with respect to the influence of yearly wave conditions on alongshore sediment transport. The coastline that resulted from this wave climate is similar to that found along the Carolina coast. The approximate aspect ratio (measured as cross-shore to alongshore cusp extent) of this initial shoreline is 0.11 while the aspect ratio of the Carolina capes varies between 0.13 and 0.23.

As a baseline for later comparison, the first configuration simulated the natural evolution (no shoreline stabilization) of the initial coastline in response to rising sea level and to a continuation of the WIS station 509 wave climate for 100 years. The next configuration simulated natural coastal evolution in response to rising sea level and an observed increase in hurricane waves (Komar and Allan, 2008) in the region. A 100-year synthetic wave record used to force the model was generated by increasing the size of hurricane waves according to the observed trend for 50 years, after which the wave climate remained at the new, elevated hurricane wave levels for 50 years. In the remaining two simulations, towns making dynamic nourishment decisions were positioned 10km to the north and south of cape locations (Slott *et al.*, 2010) and a finite reservoir of nourishment sand (Cleary et al., 2004) was defined at the start of the simulations. As nourishment occurs and reduces the reservoir during model runs, the cost of sand increases linearly. For the third configuration the towns to the north of the cape tips had higher baseline property value than towns to the south, and vice versa for the fourth configuration.

Results show that there are large variations in coastal evolution for the various configurations (Figure 7). The response of a coastline without nourishment to increased hurricane waves is to enhance erosion along coastline sections to the north of cape tips. This increase in erosion is larger than the overall signal of erosion from sea level rise. For the two configurations with towns extending to the north and south of cape locations, the coastal response varies depending on whether high property value towns are located to the north or south. In both simulations the higher property value towns utilize more of the nourishment reservoir than lower property value towns (Figure 8). This causes the shoreline locations where higher property value towns are located to be less eroded compared to the contrary simulations when a lower property value town is in the given location. The reason that the higher property value towns extract more of the nourishment reservoir is due to their increased economic incentive (via higher benefits) to nourish relative to lower property value towns. As nourishment costs rise, lower property value towns eventually cannot justify nourishment, leaving the remainder of the reservoir to higher property value towns. For simulations when higher property value towns are located in the more erosive northern segments, the nourishment reservoir is depleted more rapidly than when lower property value towns are north of cape tips. As costs rise in both simulations and the lower property value towns are prevented from nourishing, the high property value town depletes the reservoir more rapidly when it is in the more erosive northern segment.

These results show wide variation in the physical and economic coastal responses to wave climate change for varying patterns of property value. Long-time-scale characteristics of the coupled system, such as sustainability and resource equity of coastal defense against changing environmental conditions, depend strongly on the coupling between large-scale economic and coastal change patterns.

V. Discussion

The case study for coupled human and natural systems we focus on here involves coupling economic models of property value with physical models of sediment transport dynamics. An overarching finding of each modeling endeavor is that in developed coastal environments, the evolution of the economic or coastal system cannot be considered in isolation. The long-term evolution of developed coastal environments can only be understood by exploring the coupled dynamics between economic and coastal processes. Furthermore, in order to understand how the system responds to changes in economic or climate forcing one must consider the impact of these forcing changes on the strength of coupling within the system. These findings are not exclusive to coupled economic and sediment transport models and could also arise from coupling different aspects of the human or natural systems. For example, models representing political or cultural dynamics at the coastline might be used to extend the human side of the coupled modeling and explore the impact of changes to government institutions or cultural norms (Parker *et al.*, 2003; Werner and McNamara, 2007). Additional natural system dynamics might include ecological models for species interactions along a coastline or hydrodynamic models for pollution transport.

The next step in extending the coupled model involves integrating the large-scale coastline evolution model with an economic model for optimal beach replenishment in a spatial-dynamic framework. An interesting question is whether large scale patterns can emerge when we consider a coupled spatial-dynamic model of optimal shoreline nourishment, in which the coastal manager simultaneously chooses where to nourish and how much to nourish a beach at any given time. In our past modeling and in the current policy climate in North Carolina, individual communities make decisions along a complex coastline in a decentralized manner without necessarily any regard for upsteam or downstream effects. But our research suggests that there might be potential benefits of coordination across communities making coastal management decisions. Does a coordinated management strategy, which maximizes the total net benefits to all communities, lead to long-run shoreline patterns that are qualitatively different from individual communities making localized nourishment decisions?

If local wave climates are dominated by low-angle waves that tend to smooth bumps caused by nourishment, the dynamics of nourishment sand can be modeled as a diffusion of coastline shape (FalquÈs and Calvete, 2005; Ashton and Murray, 2006a; Ashton and Murray, 2006b). When alongshore dynamics are modeled as a diffusive process, with nourishment sand moving from regions of high concentration to low concentration (smoothing bumps) the conditions for optimal control of the spatial-dynamic system are a system of partial differential equations that can be solved to determine the optimal steady state of the resource in space (Brock and Xepapadeas, 2008).

Another direction in which the coupled model can be developed is incorporating the ecological impact of nourishment on the coastal environment. For instance, how does nourishment affect sea turtle nesting habitats, beach habitat for seabirds, or marine ecosystems more broadly when dredging disturbs the benthos? Including ecological costs in the economic analysis could increase the fixed costs of nourishment (better technology) or change the benefits flow. The optimal outcome will depend on the specific form in which these impacts enter the model.

While characterizing the nature of an optimal coastline in a coupled morpho-economic system is an important objective for this research, ultimately policy makers will need to know how policies are likely to interact with the coupled system and achieve desired outcomes. What policies will allocate scarce sand resources efficiently over time as sea level rises? One possibility is to draw on the large literature in environmental economics on cap and trade programs for pollution control (e.g. tradable emissions allowances for sulfur dioxide) and for managing common-pool resources (e.g. individually transferable quotas for fisheries). We might imagine individual communities trading sand allowances, such that a community that experiences only mild erosion sells its sand allowance to a community experiencing more severe erosion.

Assuming a simple, straight coastline enhances the analytical tractability of testing the effects of different policy scenarios. What policies will facilitate coordination across communities arrayed along a complex-shaped coast? Here the prospects are less clear. One can at least conjecture that because the problem is spatial-dynamic in nature, policies to address coast-wide coordination will likely need to be delineated in space and time. Again, one might consider the possibility of sand trading, but the allowances would have to be time- and space-specific. The need to delineate in this manner stems from a similar concern to pollution hot spots under the sulfur dioxide allowance trading.

The ability to describe our physical and economic systems with equations that are smooth in time is useful for generating insights about coupled models, but it has limitations. For instance, our modeling does not describe community responses to sudden, catastrophic events such as a tsunami, the breach of a levy, or a major hurricane strike. If shoreline retreat in any location is more influenced by an individual event rather than the wave climate operating continuously on the location, our modeling approach is not ideal. A related limitation of our modeling framework is that it does not incorporate wind and flood damage to property from periodic storm events such as hurricanes and the associated impacts on insurance premiums. Wider beaches may provide some protective value, but they cannot protect communities from all of these impacts. As a first step toward understanding this broader coastal management issue, in ongoing work we are developing an economic extension of our beach nourishment model that incorporates stochastic storms. We anticipate that the conceptual insights from this modeling will help to inform the next generation of coupled models that begins to tackle a more comprehensive suite of coastal risks.

The coupled modeling in our case study involved researchers with diverse backgrounds in physical science (geomorphology) and social science (economics). Beginning to build coupled models required significant investments of time, not just in modeling itself, but also in learning each other's disciplines. Naturally, common languages of mathematics, statistical methods, and computer programming facilitate that learning. Nevertheless, there were barriers to overcome including jargon, typical assumptions, scale, and what each discipline considers first principles. With significant investments in learning, modeling decisions at every step still involved some disciplinary compromises, ones that would permit tractability in the coupled model but that would preserve the main insight of each discipline.

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FIGURES

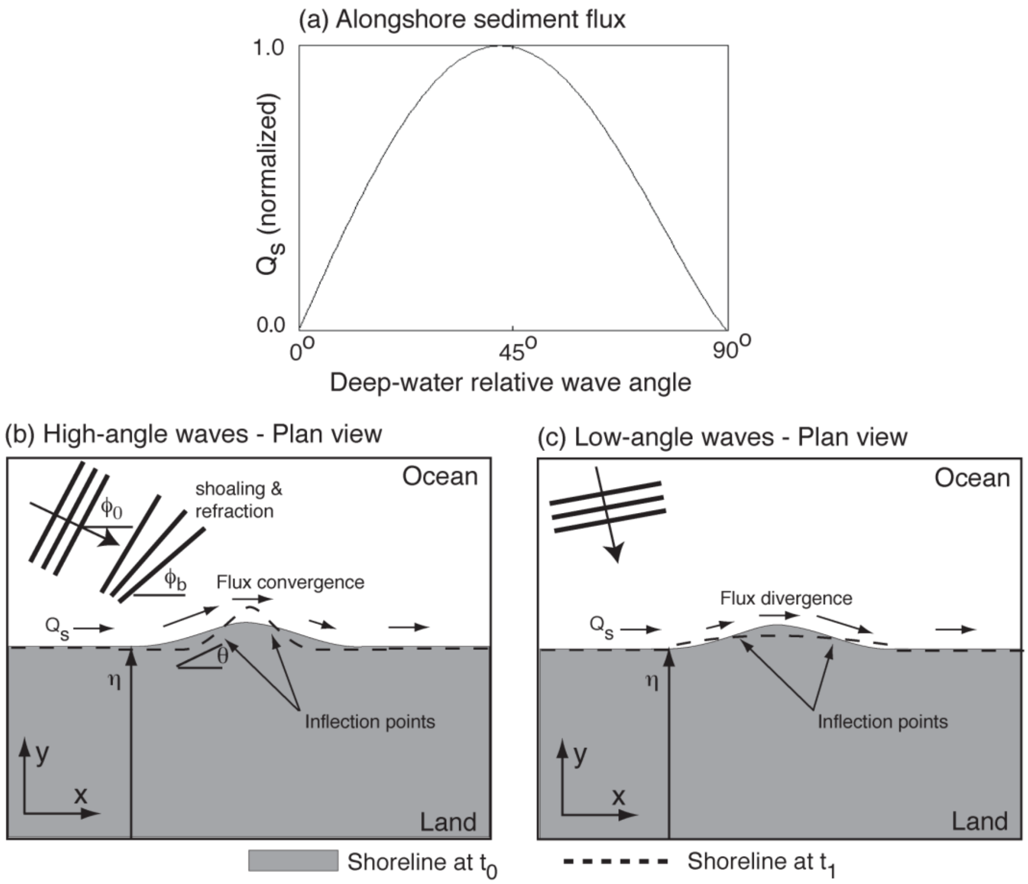

Figure 1: Schematic illustration of zones of shoreline recession and accretion caused by gradients in the alongshore sediment flux, *Q_s*. a. Plot of alongshore sediment flux, *Q_s*, as a function of the relative angle between deep-water wave crests and the shoreline. Alongshore sediment transport is maximized for relative deep-water wave angles of ~45°. b. Growth of a shoreline bump caused by a convergence in *Q_s* along the bump crest (magnitudes depicted by varying-length arrows) when subjected to high-angle waves. ϕ_o is the wave-approach angle in relatively deep water (seaward of the approximately shore-parallel nearshore bed contours), ϕ_b is the breaking-wave angle, and θ is the shoreline angle. c. Smoothing caused by a divergence of alongshore sediment transport on the crest of a shoreline bump when subjected to low-angle waves. From *Slott et al.* (2010).

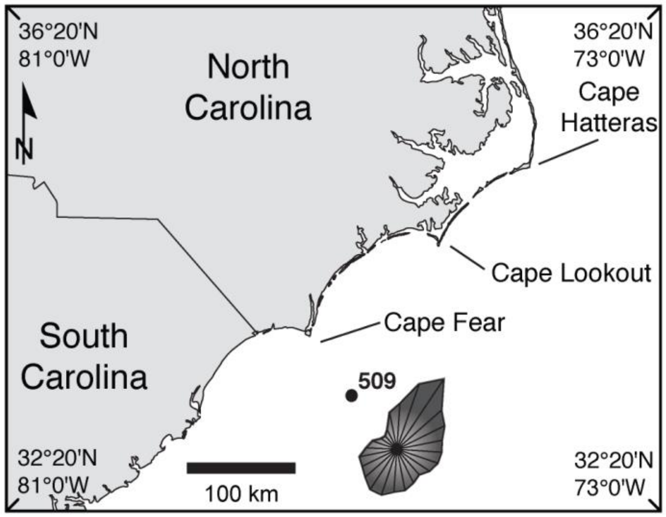

Figure 2: The coastline of North Carolina and South Carolina, from Cape Hatteras, NC to Cape Fear, SC, USA along the US Atlantic coastline. From *Ashton and Murray* (2006b).

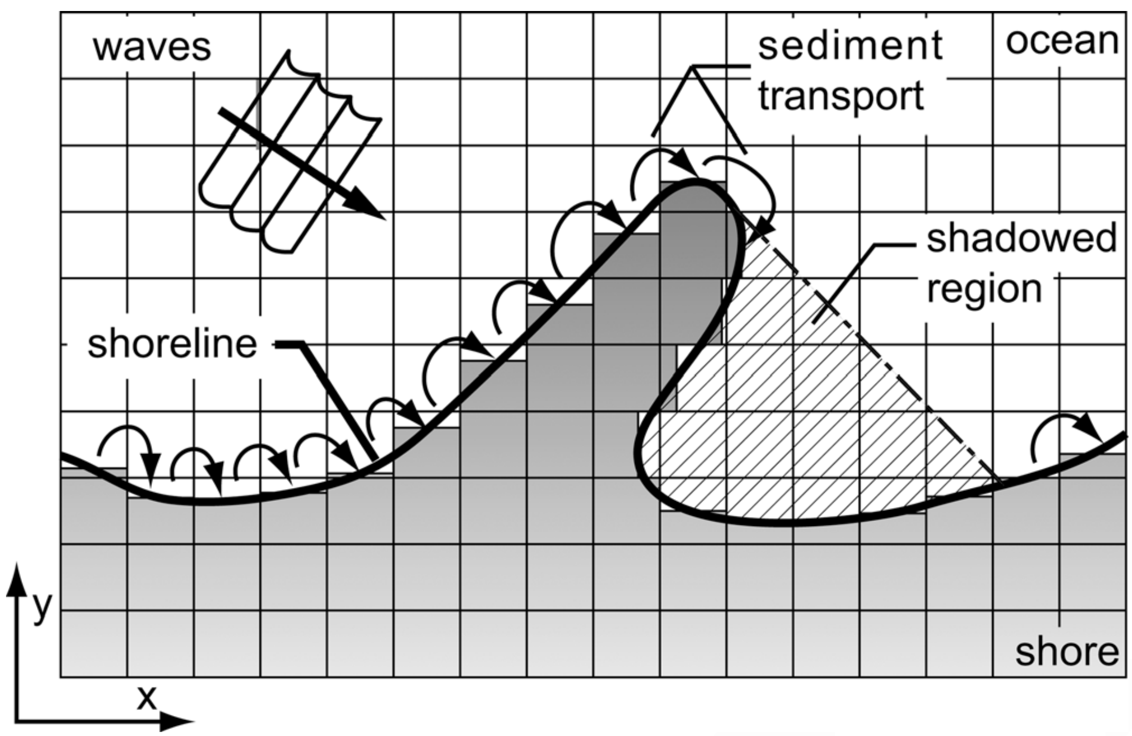

Figure 3: Plan view schematic of the model domain demonstrating the interpreted shoreline configuration, the directions of sediment fluxes for a given wave approach angle, and the region shadowed from incoming waves. From Ashton and Murray (2006a).

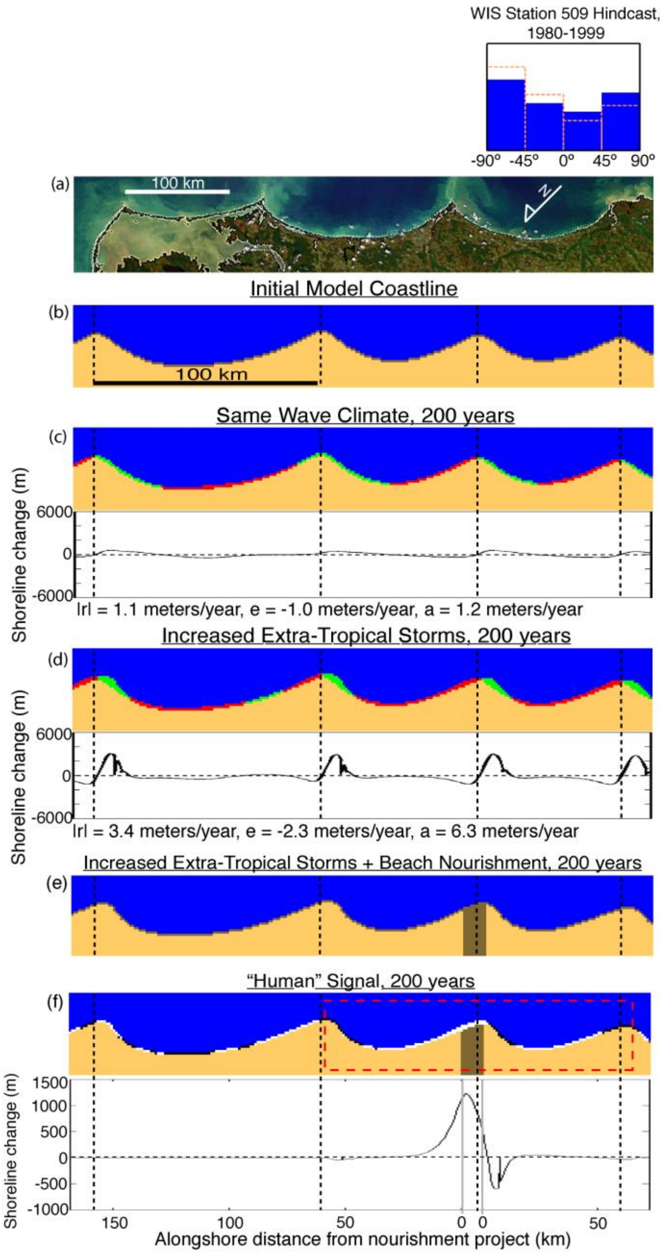

Figure 4: Shoreline response to increased extra-tropical storm influence and a 10 km beach nourishment. a. The cuspate-cape shoreline of the Carolinas, rotated 150° counterclockwise so that the normal to the regional shoreline trend points up. Satellite image courtesy of the SeaWiFS Project NASA/GSFC and ORBIMAGE. b. An initial model condition, generated using the approximation to the WIS wave-climate data (blue in inset), resembling the Carolina capes. c. The cuspate-cape initial model condition subjected to 200 years of waves drawn from a PDF of wave hindcasts based on WIS Station 509 (*WIS*) (*A* = 0.55, *U* = 0.60, blue in inset). Shoreline change over 200 years is depicted graphically, and summarized by |*r*|, the alongshore average of the magnitude of shoreline change, by *e*, the alongshore average of recession in receeding areas, and by *a*, the alongshore average of accretion in accreting areas. d. The cuspate-cape shoreline subjected to 200 years of waves drawn from a wave climate featuring a greater portion of waves approaching from the left (*A* = 0.65; dotted rectangles in inset). Green shoreline segments represent zones of accretion, red segments represent zones of recession. Shoreline change over

200 years is depicted graphically. e. An altered cuspate-cape shoreline subjected to 200 years of waves drawn from a wave climate featuring a greater portion of waves approaching from the left (*A* = 0.65, *U* = 0.60, inset), and a 10 km beach nourishment located near the tip of one cape. f. The change in shoreline position between d. and e. attributable to the 10 km beach nourishment. Black (white) shows where the final shoreline is farther landward (seaward) than in the equivalent model run without the localized shoreline stabilization (also shown graphically). From *Slott et al*. (2010).

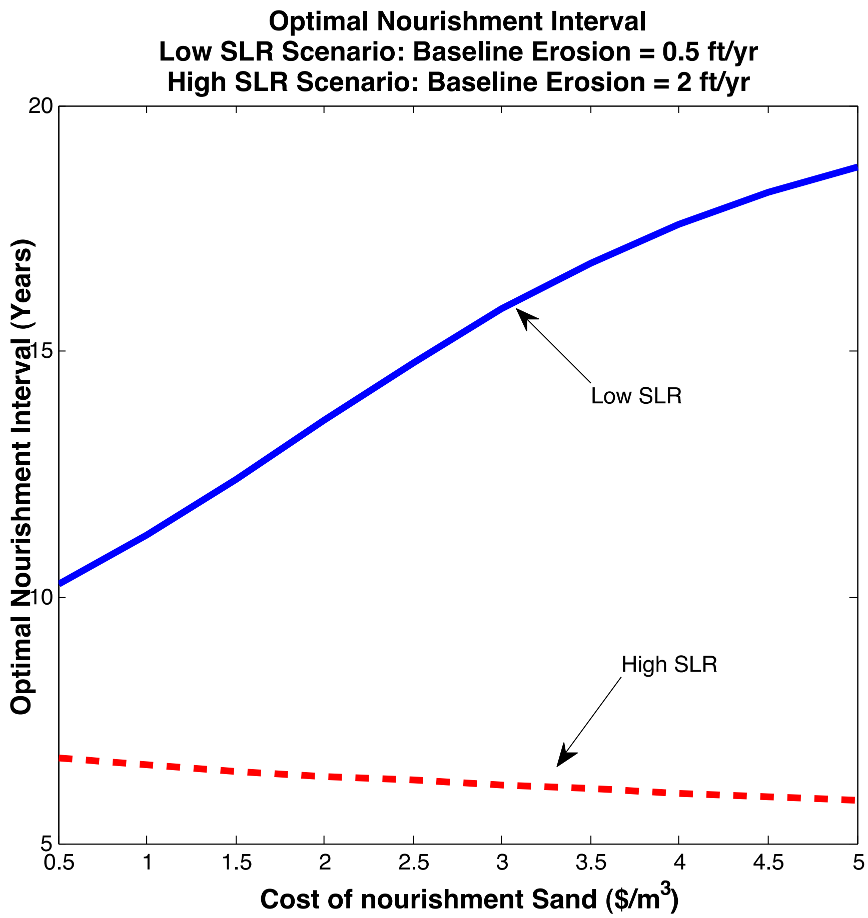

Figure 5a: Optimal Nourishment Interval as a function of sand costs. In the low SLR scenario (blue), optimal nourishment interval increases as the cost of nourishment sand (per m^3) increases but in the high SLR scenario (red) it is optimal to nourish more frequently (nourishment interval decreases) as the cost of nourishment sand increases.

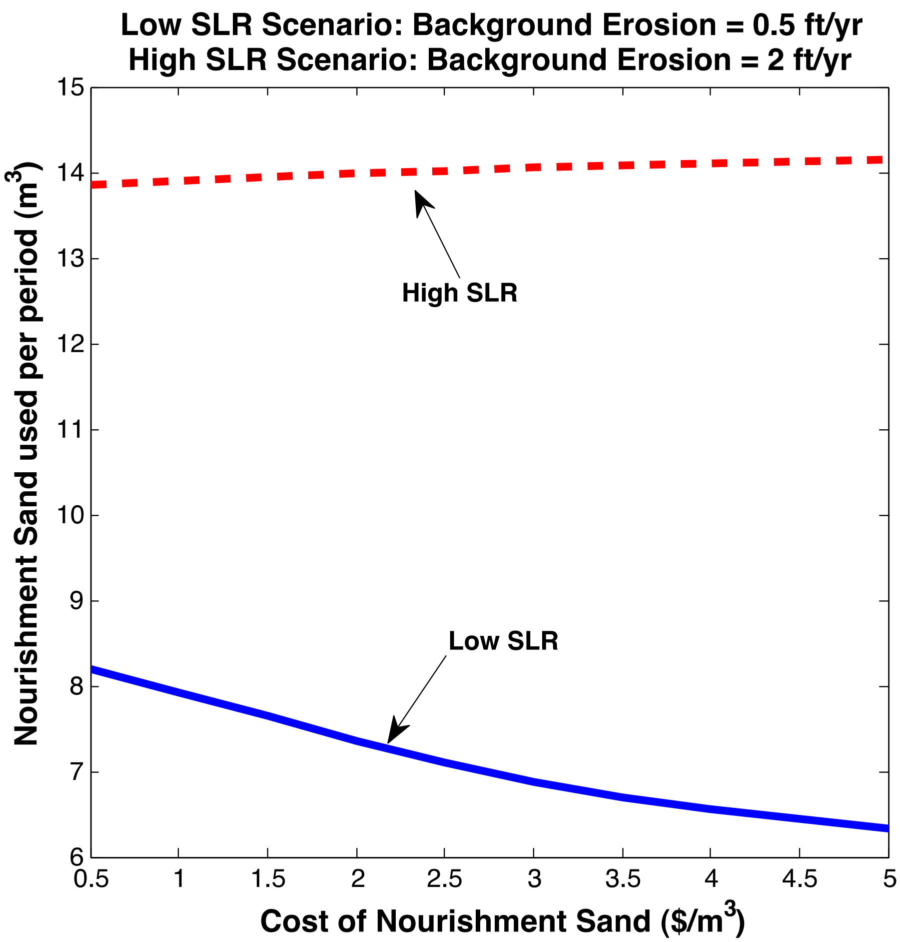

Figure 5b: Sand use as a function of the cost of nourishment sand. In the low SLR scenario (blue), demand for nourishment decreases as the cost of nourishment sand increases. In the high SLR scenario (red) the demand for nourishment increases as the cost of nourishment sand increases.

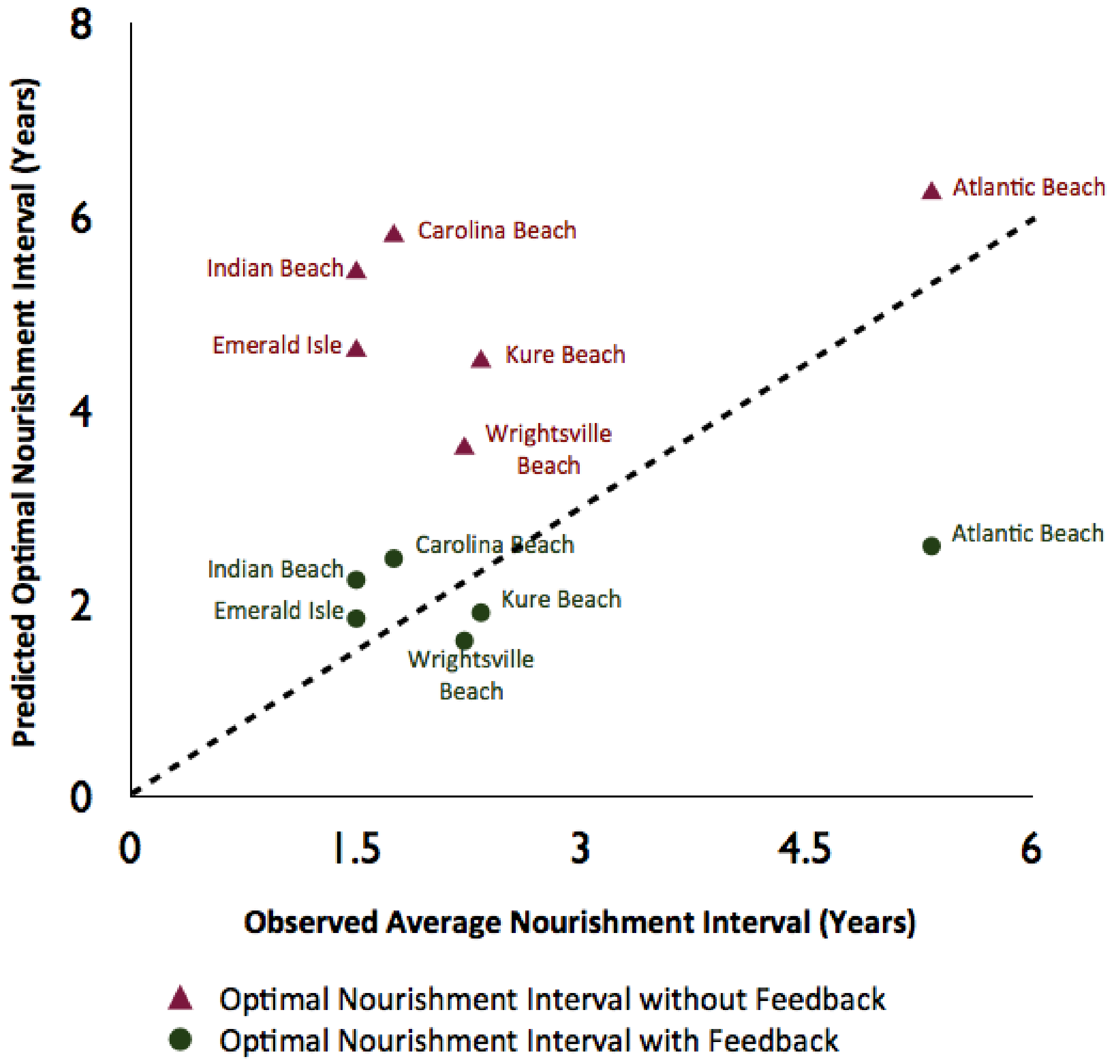

Figure 6: Comparison of observed nourishment intervals and predicted optimal nourishment interval with and without incorporating nourishment feedbacks. Predicted optimal intervals with nourishment feedback (green) are closer than the predicted intervals without feedback (brown) to the 1:1 (dashed) line where observed and predicted nourishment intervals are equal.

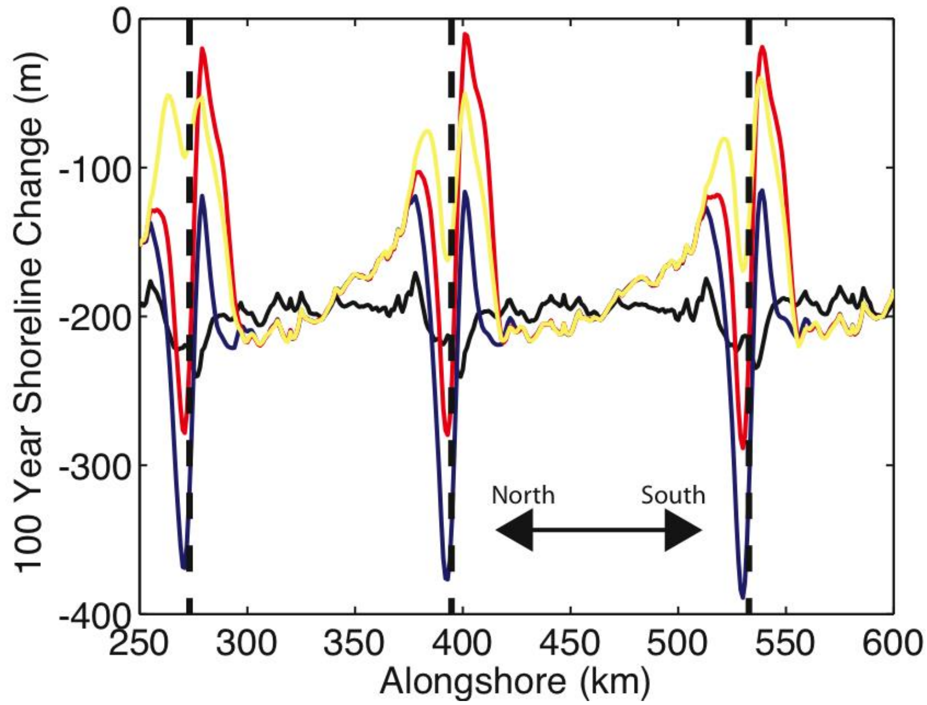

Figure 7: The total change in shoreline position after 100 years versus alongshore position for the four simulated configurations: no towns and no wave climate change (black), no towns and a change in wave climate to increased hurricane waves (blue), high property value towns north of cape tips and low property value towns south of cape tips with a change in wave climate (yellow), and low property value towns north of cape tips and high property value towns south of cape tips with a change in wave climate (red). Cape tip locations are indicated by dashed vertical black line.

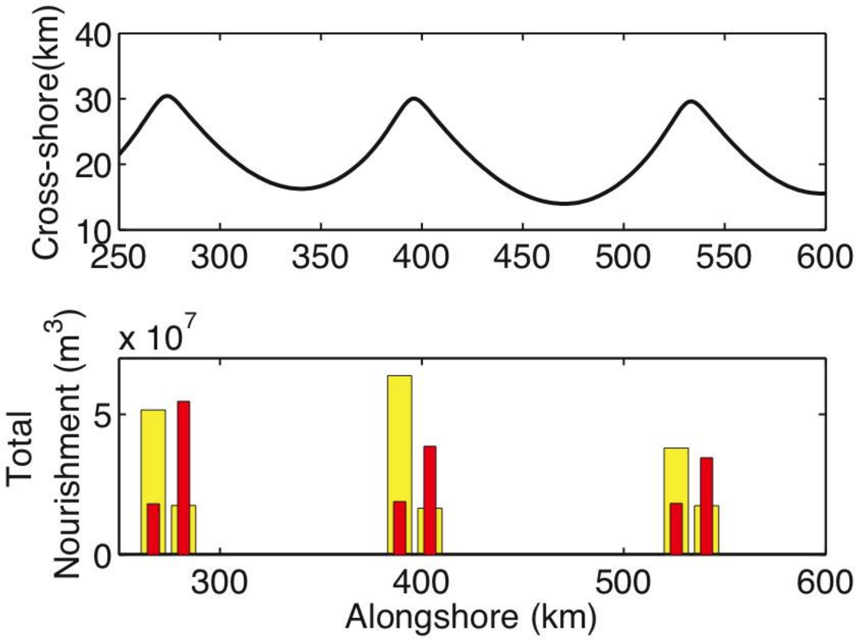

Figure 8: Top panel shows the position of the coastline. The bottom panel shows total nourishment volume for the simulation with high property value towns located north of cape tips (magenta) and the simulation with low property value towns located north of cape tips (red).