From Coastal Retreat to Seaward Growth: Emergent Behaviors from Paired Community Beach Nourishment Choices

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Abstract

Coastal communities facing shoreline erosion preserve their beaches both for recreation and for property protection. One approach is nourishment, the placement of externally-sourced sand to increase the beach's width, forming an ephemeral protrusion that requires periodic re-nourishment. Nourishments add value to beachfront properties, thereby affecting re-nourishment choices for an individual community. However, the shoreline represents an alongshore-connected system, such that morphodynamics in one community are influenced by actions in neighboring communities. Prior research suggests coordinated nourishment decisions between neighbors were economically optimal, though many real-world communities have failed to coordinate, and the geomorphic consequences of which are unknown. Toward understanding this geomorphic-economic relationship, we develop a coupled model representing two neighboring communities and an adjacent non-managed shoreline. Within this framework, we examine scenarios where communities coordinate nourishment choices to maximize their joint net benefit versus scenarios where decision-making is uncoordinated such that communities aim to maximize their independent net benefits. We examine how community-scale property values affect choices produced by each management scheme and the economic importance of coordinating. The geo-economic model produces four behaviors based on nourishment frequency: seaward growth, hold the line, slow retreat, and full retreat. Under current conditions, coordination is strongly beneficial for wealth-asymmetric systems, where less wealthy communities acting alone risk nourishing more than necessary relative to their optimal frequency under coordination. For a future scenario, with increased material costs and background erosion due to sea-level rise, less wealthy communities might be unable to afford nourishing their beach independently and thus lose their beachfront properties.

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Key Points:

- Property value disparities and the level of coastal management coordination are key to understanding past shoreline changes
- Less wealthy communities might be nourishing more than necessary relative to their optimal scheme under coordination
- A coordinated approach will preserve beachfront properties farther into the future under higher erosion rates and sand material costs

Abstract

Coastal communities facing shoreline erosion preserve their beaches both for recreation and for property protection. One approach is nourishment, the placement of externally-sourced sand to increase the beach's width, forming an ephemeral protrusion that requires periodic re-nourishment. Nourishments add value to beachfront properties, thereby affecting re-nourishment choices for an individual community. However, the shoreline represents an alongshore-connected system, such that morphodynamics in one community are influenced by actions in neighboring communities. Prior research suggests coordinated nourishment decisions between neighbors were economically optimal, though many real-world communities have failed to coordinate, and the geomorphic consequences of which are unknown. Toward understanding this geomorphic-economic relationship, we develop a coupled model representing two neighboring communities and an adjacent non-managed shoreline. Within this framework, we examine scenarios where communities coordinate nourishment choices to maximize their joint net benefit versus scenarios where decision-making is uncoordinated such that communities aim to maximize their independent net benefits. We examine how community-scale property values affect choices produced by each management scheme and the economic importance of coordinating. The geo-economic model produces four behaviors based on nourishment frequency: seaward growth, hold the line, slow retreat, and full retreat. Under current conditions, coordination is strongly beneficial for wealth-asymmetric systems, where less wealthy communities acting alone risk nourishing more than necessary relative to their optimal frequency under coordination. For a future scenario, with increased material costs and background erosion due to sea-level rise, less wealthy communities might be unable to afford nourishing their beach independently and thus lose their beachfront properties.

Plain Language Summary

In response to coastal erosion, communities defend their homes by widening beaches via sand dredging and placement (i.e., beach nourishment). Past research has found that, at regional scales, the net effect of nourishment has in many cases not only counteracted erosion, but has reversed erosional trends, on average shifting shorelines seaward. Using a model that couples natural coastal dynamics with the economics of human intervention through nourishment, we compare different management schemes to determine their economic consequences. We find that coordinating beach nourishment between communities is most important economically for both when they have different property values because the less wealthy town tends to nourish more than necessary if they preserve their beach alone. However, in a scenario where climate change causes shorelines to retreat more rapidly and the overexploitation of sand resources dramatically increases its cost, less wealthy communities may be unable to keep pace with the changing conditions and instead abandon their properties altogether, leaving only the wealthiest homeowners along the coast. Such divergent outcomes based upon wealth disparity should be considered in future policy development at the state and federal levels.

1 Introduction

Beach nourishment involves dredging sediment from external sources to deposit locally in order to widen beaches (Hoagland et al., 2012; Lazarus et al., 2011; Smith et al., 2009). As the predominant form of beach maintenance along the U.S. east coast since the 1960's, this practice has not only masked regional historical trends in coastal erosion but also led to net shoreline accretion in developed areas along the U.S. East and Gulf coasts, e.g. New York and New Jersey (Armstrong & Lazarus, 2019; Hapke et al., 2013). While communities or groups of communities often nourish on a local scale, these sudden increases in beach width are subject to heightened erosion due to alongshore and cross-shore sediment transport, thereby diminishing the volume of sand placed by these communities over time and thus, the efficiency (sand lost relative to the sand added) of the nourishment project as well. When combined with neighboring actions, regional nourishment comprises a dynamical system (Ells & Murray, 2012).

Aggregate shoreline trends do not always explain community-scale nourishment choices, however. While many communities have widened their beaches since initiating maintenance activities, some have held their shoreline position (Hapke et al., 2013). In extreme cases, communities have lost individual properties or have abandoned entire municipalities (Kobell, 2014; Tischler, 2006). This range of outcomes highlights the location-specific variability of beach nourishment decisions, potentially influenced by underlying differences in geology and socioeconomics that affect the efficiency or feasibility of nourishment projects, and necessitates a deeper analysis of the dynamic processes by which communities and coastlines interact, accounting for both human and natural components.

Previous work found a positive feedback between coastal development and nourishment effort, whereby widened beaches add value to adjacent properties and compel future beach nourishments (Armstrong et al., 2016; McNamara et al., 2015). There is limited knowledge on what initially triggers this geomorphic-economic feedback, and what role, if any, the distribution of alongshore wealth might play in this feedback. Recent work has suggested that the level of coordination among coastal neighbors could partially explain these emergent outcomes (Gopalakrishnan et al., 2016; Smith et al., 2015).

Many studies have explored the economic effects of coordinated vs. independent behavior (Brandts & Schram, 2001; Cason & Gangadharan, 2015; Gachter et al., 2017; Metzner et al., 2006), but research on its application to coastal dynamics is still in its infancy. Empirical studies in behavioral economics use rule-based games to explore how humans interact (Bohnet & Frey, 1999; Hoffman et al., 1996). In one such example, a public goods game, two players contribute toward a shared good, and enjoy that good regardless of their contribution levels. Each player may choose not to contribute but still enjoy the good, thus benefiting from the other player's effort and maximizing self-utility. Contributors who compare their payoff to the "free-rider" often react by giving less out of spite, resulting in an economically suboptimal outcome in subsequent rounds of the game (Cason et al., 2004).

Beach nourishment interactions among coastal neighboring communities follow these economic dynamics, including feedbacks between human "players" and their natural environment. In response to geomorphic processes and background erosion, coastal communities actively maintain their beaches to protect nearby properties and infrastructure (Johnston et al., 2014), for recreational activities such as surfing, swimming, or sunbathing (Lazarow, 2007; Wagner et al., 2011), for providing ecosystem services including dune and intertidal habitats (Landry & Whitehead, 2015; Pompe & Rinehart, 1995), and for supporting local tourism economies (King, 1999).

Properties adjacent to the beach capitalize these services into their value. A small but growing literature on hedonic pricing has shown that property owners benefit economically from local beach widening due to human intervention (Gopalakrishnan et al., 2011; Landry & Hindsley, 2011; Pompe & Rinehart, 1995). Ocean currents driven by waves redistribute this sand along the coast between neighboring communities, implying that beach nourishment is a quasi-public good where down flow communities cannot be excluded. Where communities border natural coast, tidal inlets, or other sinks for nourishment sand, these currents might also reduce the physical efficiency of nourishment projects by removing sand from the active beach system. Using a simplified game-theoretic framework, we explored how socioeconomic relationships drive nourishment decisions and how these management outcomes and their corresponding nourishment efficiencies might differ if communities coordinate their beach maintenance programs or choose strategies independently.

Historically, coastal communities have not coordinated their nourishment plans (Gopalakrishnan et al., 2016; Lazarus et al., 2011). Records of past beach maintenance projects indicate that local governments and private sponsors fund many such projects, most of which have occurred in New Jersey and Florida (Pilkey & Clayton, 1989; PSDS, 2019). One example is Ocean City, NJ, which pumped sand onto its beaches more than 30 times between 1952 and 1982 using city funds and a city-owned dredge (Pilkey & Clayton, 1987). Similarly, Captiva Island, FL states on their Erosion Prevention District website, "(the) residents and businesses on Captiva Island have successfully managed their beaches for over 50 years" (Captiva Erosion Prevention District, 2020).

This decentralized behavior often has both local and non-local effects (Beasley & Dundas, 2018; Ells & Murray, 2012; Goodrow & Procopio, 2018; Hillyer, 1996), and Gopalakrishnan et al. (2016) suggest this has resulted in narrower beaches due to the effort-reducing feedback described earlier, leading to an economically suboptimal outcome to alongshore coordination. In other words, cooperation amongst communities represents their economically optimal solution. Further, there is no incentive for communities acting alone to increase their nourishment effort because doing so would mean they would lose more sand from their beach due to the higher angle formed by their seaward protrusion, effectively reducing their nourishment project's physical efficiency as well. These historically uncoordinated beach nourishments may have caused accidental geoengineering of the coastal system that differs from the natural dynamics resulting in narrower beaches (Smith et al., 2015). Indeed, Armstrong et al. (2019) and Hapke et al. (2013) detected this anthropogenic signature, finding that beaches along the US east coast have accreted seaward since beach nourishment began in earnest in the 1960s.

While anecdotal evidence indicates that communities have exhibited uncoordinated behavior, intuition from game theory and past research would suggest that this behavior results in narrower beaches. Yet, the outcome of widened beaches is both observable and quantifiable; which suggests the question: is uncoordinated or coordinated beach nourishment the cause of this coastal-anthropic signature? Perhaps it is not mutually exclusive but depends on certain conditions. If so, what are the underlying conditions that drive cooperation?

In this paper, we construct an idealized modeling framework that couples cross-shore and alongshore geodynamics with changes in coastal property values, and we explore how community-scale economic characteristics control beach nourishment decisions. We speculate that the property value distribution between coastal neighbors determines the importance of coordinating nourishment plans, and that alongshore wealth asymmetry could control the emergent system behaviors. These differences could explain the broad array of outcomes along the U.S. East and Gulf coasts, ranging from seaward growth to retreating shorelines, and they could provide insight into the key drivers of past coastal behavior.

It will be especially important to understand the future evolution of these heavily developed coasts under different coordination schemes when faced with more extreme conditions, including more rapid sea-level-rise rates and higher sand resource costs for completing beach nourishment projects. Exploring how these future changes might affect community- and regional-scale behaviors using our geo-economic framework could help address these knowledge gaps, and inform coastal policymakers and managers dealing with unique challenges associated with global climate change.

2 Mathematical Framework

We explore beach nourishment decisions for two alongshore-neighboring communities with an idealized geometry as depicted in Figure 1. The model domain includes neighboring communities $i=1,2$ that can nourish and an alongshore-adjacent boundary region $i=3$ that cannot nourish, each with alongshore length s_i. Each community has an average shoreline location $x_{S,i}$ and shoreface toe location $x_{T,i}$. The geometric relationship comprising these boundaries along with the depth of closure (shoreface depth) D form the shoreface slope θ_i:

$$\theta_i(t) = \frac{D}{x_{T,i}(t) - x_{S,i}(t)}. \quad (1)$$

The property setback $x_{H,i}$ delineates the community's seaward limit, and along with its shoreline, bounds the community's beach width w_i, i.e., $w_i = x_{S,i} - x_{H,i}$. Given this idealized geometry, we can describe the system with two state variables per alongshore community: the location of the shoreline $x_{S,i}$ and the shoreface toe $x_{T,i}$.

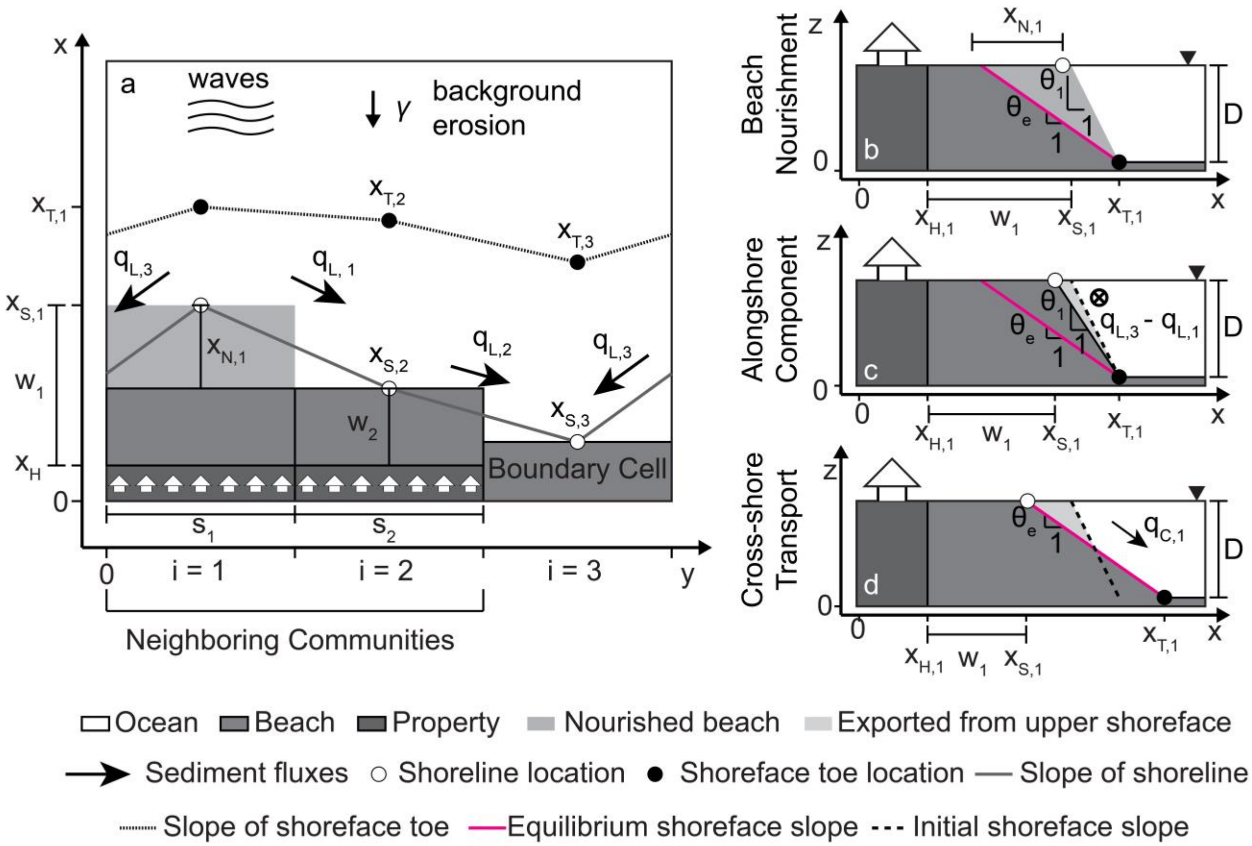

Figure 1. (a) Model setup planview, (b) cross-section illustrating beach nourishment, and (c) the alongshore and (d) the cross-shore transport that occurs due to this seaward protrusion.

To describe the dynamics of this system, we account for both natural processes, including cross-shore and alongshore sediment transport, and human processes, including beach nourishment practices. Communities respond to a background erosion rate γ by nourishing their beaches with a fixed nourishment width $x_{N,i}$, with the human intervention thus forming a shoreline protrusion. A low-angle wave climate flattens these beach nourishments via natural processes. Alongshore sediment flux $q_{L,i}$ is directed from seaward-relative communities to landward-relative communities, with an alongshore distance between communities $(s_i + s_{i+1})/2$.

We highlight a representative example of the flux direction between communities in Figure 1, but in theory the alongshore transport can occur in either direction depending on the shoreline's configuration.

The boundary cell represents a natural coastline in which no nourishment occurs. A periodic boundary condition at the edges of the system domain means that any sediment leaving the system at one boundary re-enters at the other boundary. When one or both communities nourish, sediment from these protrusions transports alongshore from the communities to the boundary cell, which therefore serves as a sediment sink for nourishment sand. Nourishment events at the shoreline also trigger cross-shore sediment flux $q_{C,i}$ due to the over-steepened shoreface slope, directing sand from the shoreline to the shoreface toe. The balance between the volume of nourishment sand and the sand lost alongshore to the boundary cell, cross-shore to the toe, or removed from the system due to background erosion determine the physical efficiency of the nourishment project.

A two-community system with a boundary cell is analyzed here. The governing equations are presented in general form allowing an extension to *n* communities. We characterize the geometry of each community (and the adjacent boundary coast) with the average shoreline location $x_{S,\mathrm{i}}$ and shoreface toe $x_{T,i}$, which allows us to describe the evolution of the system using six ordinary differential equations.

We present these geodynamics in the first section below, followed by the coupling between physical processes and community behaviors. We then discuss the control problem by which communities choose nourishment actions, and we propose a numerical solution to this problem.

2.1 Beach and Shoreface Morphodynamics

We compute the alongshore-averaged component of sediment flux $q_{L,i}$ using the difference in average shoreline locations $x_{s,i} - x_{s,i+1}$ between neighboring communities *i* and *i+1*:

$$q_{L,i}(t) = K_1 \cdot \frac{(x_{S,i}(t) - x_{S,i+1}(t))}{(s_i + s_{i+1})/2}, \quad (2)$$

where K_1 is the alongshore flux coefficient. This equation, which assumes the low-wave-angle case for a standard CERC formula (Coastal Engineering Research Center, 1984), represents an average alongshore flux between each community based on the angle formed by the two shoreline locations. This shoreline angle controls both the magnitude and the direction of alongshore sediment transport, given by equation 2.

Widening a beach via nourishment steepens the beach's slope (i.e., shoreface) relative to its equilibrium profile (Dean, 1977, 1991; Miselis & Lorenzo-Trueba, 2017), which triggers cross-shore sediment transport. The shoreface flux $q_{C,i}$ is the cross-shore component of sediment transport based on its slope θ_i relative to its equilibrium profile θ_{eq}:

$$q_{C,i}(t) = K_2 \cdot \left(\theta_i(t) - \theta_{eq}\right), \quad (3)$$

where K_2 is the shoreface flux coefficient. When the shoreface is steeper than its equilibrium profile (i.e., $\theta_i > \theta_{eq}$), sand moves from the upper shoreface to the lower shoreface, whereas the opposite is true if the shoreface has a milder slope than its equilibrium profile (i.e., $\theta_i < \theta_{eq}$).

Changes in shoreline position $x_{S,i}$ are computed using the discretized ordinary differential equation $\Delta x_{s,i}/\Delta t$ for each cell:

$$\frac{\Delta x_{S,i}(t)}{\Delta t} = \frac{2 \cdot \left(q_{L,i-1}(t) - q_{L,i}(t)\right)}{s_i} - \frac{4 \cdot q_{C,i}(t)}{D} - \gamma + N_i\left(x_{N,i}, R\right), \quad (4)$$

where $q_{L,i}$ and $q_{C,i}$ are given by equations (2) and (3). The nourishment term N_i is a function representing intermittent nourishment with a fixed cross-shore width $x_{N,i}$ and rotation length R_i (time interval between periodic nourishment) (Smith et al., 2009).

We assume the nourishment function N_i to be discrete in order to capture the time-specific costs of each sand placement. Nourishment events occur when the time function equals a multiple j of the rotation length R_i with a subsequent cross-shore magnitude $x_{N,i}$:

$$N_i^*(t, R_i) = \begin{cases} x_{N,i}; & if\ t = R_i \cdot \sum_{j=1}^{h_i} j \\ 0; & else \end{cases}, \quad (5)$$

where h_i is the number of nourishment episodes per community. We only apply the nourishment term N_i in equat

A second discretized ordinary differential equation $\Delta x_{T,i}/\Delta t$ simulates the evolution of the shoreface toe location $x_{T,i}$ as a function of the cross-shore sediment flux $q_{C,i}$, the shoreface depth D, and the background erosion rate γ:

$$\frac{\Delta x_{T,i}(t)}{\Delta t} = \frac{4 \cdot q_{C,i}(t)}{D} - \gamma. \quad (6)$$

These geodynamics can then be used to describe the physical efficiency of the nourishment projects, or in other words, the volume of sand retained in the beach system relative to the volume of sand pumped onto the beach via nourishment activities. We track the volume of sediment lost from the nourishment projects q_{Loss} in both communities based on the cross-shore flux q_C, the alongshore flux q_L and the background erosion rate γ:

$$q_{Loss}(t) = (s_1 + s_2) \cdot D_T \cdot \gamma + 4 \cdot \left(s_1 \cdot q_{C,1}(t) + s_2 \cdot q_{C,2}(t)\right) + 2 \cdot D_T \cdot \left(q_{L,3}(t) - q_{L,2}(t)\right). \quad (7)$$

The total volume of sand lost over the course of a model run V_{Loss} is the integration of this q_{Loss} through time:

$$V_{Loss} = \int_0^{t_f} q_{Loss}(t) \cdot dt, \quad (8)$$

where *tf* is the planning time horizon.

The total volume of sand added by the nourishment projects $V_{Nourish}$ is the discrete sum of all nourishment volumes based on the cross-shore project widths $x_{N,1}$ and $x_{N,2}$, and the rotation lengths R_1 and R_2 in communities one and two:

$$V_{Nourish} = \frac{D_T}{2} \cdot \left(\frac{t_f \cdot x_{N,1} \cdot s_1}{R_1} + \frac{t_f \cdot x_{N,2} \cdot s_2}{R_2}\right). \quad (9)$$

The efficiency of the nourishment project E can then be determined by the balance between the volume nourished $V_{Nourish}$ and the volume lost V_{Loss}:

$$E = \frac{V_{Nourish}}{V_{Nourish} + V_{Loss}}. \quad (10)$$

2.2 Economic Model

The system's physical components feed into a socioeconomic framework used to compare the outcomes of different nourishment choices (i.e., rotation lengths). Toward this end, beaches are assumed to provide both protective and recreational benefits for coastal communities (Jin et al., 2015; Landry et al., 2003; McNamara & Keeler, 2013; McNamara et al., 2015; Pompe & Rinehart, 1995, Simmons et al., 2002). When analyzing the benefit for the whole community, we assume that an average beach width borders all beachfront homes in the community with an average property value. We assume that each community is the relevant decision-maker.

The value of beach width w_i is capitalized into the benefit function B_i for community *i* as:

$$B_i(t) = \alpha_i \cdot \rho \cdot \left(\frac{w_i(t)}{w_\alpha}\right)^\beta, \quad (11)$$

where α_i is the baseline property value that includes all of a home's amenities except for that of the beach's width (i.e., the number of bedrooms/bathrooms, square footage, lot acreage, etc.) as well as the number of alongshore properties per community, ρ is the discount rate that weights future vs. present values and can be interpreted here as the capitalization rate through time, and w_α is the baseline width beyond which the beach adds value to the front property.

Note that $\alpha_i \cdot \rho$ is the baseline rental value or capital added per unit time for the average home in community *i*. The positive parameter β describes the effects on B_i of unit changes in beach width. The sum of all property values in a community represents the community's total wealth. Assuming each community has the same number of homes, the difference in average property value reflects the difference in total wealth between neighboring communities. This relationship, therefore, captures how beach morphodynamic processes affect a community's level of wealth.

In addition to the benefits of widening a beach, communities incur a cost for their nourishment project C_i based on the fixed cost c_f (for permitting, equipment, labor, etc.) and the variable cost ϕ_N (i.e., volumetric price of sand resource):

$$C_i(t) = c_f + \phi_N \cdot \frac{1}{2} \cdot x_{N,i} \cdot D \cdot s_i \ , \tag{12}$$

where nourishment volume is a triangular prism formed by the cross-shore width $x_{N,i}$, the depth of closure D, and the alongshore project length s_i (Figure 1). Non-nourishing communities do not incur any costs, i.e., $C_i = 0$.

2.3 Optimization: Nourishment Rotation Length for Coordination and Non-Coordination

We define the net benefit NB_i as the sum of continuous benefits B_i (Equation 11) and discrete costs C_i (Equation 12) discounted by a representative rate ρ over a planning time horizon t_f:

$$NBi = \int_0^{t_f} B_i(t) \cdot e^{-\rho \cdot t} \cdot dt - \sum_{j=1}^{h_i} \frac{C_{i,j}(t)}{(1+\rho)^t} \ . \tag{13}$$

We simulate two levels of coordination: jointly optimized rotation lengths (coordination), and independently optimized rotation lengths (non-coordination). Under non-coordination, each community *i* independently maximizes its net benefits NB_i as follows:

$$\max_{R_i} NBi \ . \tag{14}$$

We explore two end-member assumptions and present one as a representative decentralized case. For one end member scenario, a community choosing its nourishment strategy independently assumes its neighbor will not nourish, which is a cautionary assumption. This might cause the community to nourish more frequently than necessary and may be suboptimal, but at least the community can avoid under-nourishing its beach and potentially losing beachfront properties. While this assumes that communities cannot observe what their neighbor is doing, which represents a limited setup that simplifies the problem of non-cooperation, we use this scenario as a baseline analysis because it is the most conservative assumption a community can make. For the other end member scenario, a community assumes its neighbor will nourish with high frequency, which is a risky assumption because it could lead to more instances of beachfront property loss. The risky end member is included in the appendix.

Under coordination, both communities share their management decision by choosing the optimal rotation lengths that maximize the sum of their net benefits:

$$\max_{R_1,R_2} \sum_{i=1}^{2} NBi \tag{15}$$

Coordination implies both communities have full information about their neighbor's behavior, and thus represents the socially optimal solution. There are cases in which communities might find it individually net beneficial to deviate from their socially optimal solution, however, unless a cost-sharing arrangement exists.

In all cases, communities commit to the nourishment rotation lengths yielded by equations (14) or (15) until the end of the model run, similar to a real-world community's contractual obligation to a dredge company for a fixed period (USACE, 1999). This represents a one-time decision in our framework. While this approach does not allow for dynamic feedbacks between communities through time, this simplifies a difficult problem into a basic decision framework, describing how communities might choose their nourishment strategies initially, and how these first moves might differ based on their coordination scheme.

2.4 Numerical Solution

In this section, we explain how we numerically solve the optimization problem described in equations (14) and (15). First, we compute the evolution of the shoreline location x_S and shoreface toe x_T in each community for a wide range of nourishment rotation lengths between 0-25 years with a spacing of 0.2 years. In particular, we obtain x_S and x_T from equations (4) and (6) respectively, which we solve numerically using the simplified forward Euler method. We then calculate the benefits and costs for each scenario using equations (11) and (12) respectively. The discounted difference between the benefits and costs yields the net benefit, which we compare between all options. The rotation lengths R_1* and R_2* provide the maximum net benefit under each scenario (i.e., non-coordination and coordination). All results presented below ensure that neither the resolution nor the boundary limits employed misrepresent the true optimal choice.

2.5 Parameter Estimation

Table 1

Economic Input Parameters for Model Simulations

Economic Parameters	Symbol	Feasible range of values	Units	Test value: figs. 2, 5-6, 8	Test value: figs. 9-10
Variable Nourishment Cost[a,b,e,i,m,p,t]	ϕ_N	5—30	$\$/m^3$	15	15—50
Fixed Nourishment Cost[d,j,p]	c_f	-	$1,000,000	1	1
Baseline Property Value[c,f,h,k,n,r,u]	α	-	$1,000	25—550	Community 1: $385 Community 2: $257
Discount Rate[g,q,s,t]	ρ	1—10	%/yr	6	6
Hedonic Parameter (Beach Width)[b,d,l,o,q]	β	0.05—0.8	-	0.4	0.4

Sources. [a]ASBPA (2020). [b]Gopalakrishnan (2010). [c]Gopalakrishnan et al. (2011). [d]Gopalakrishnan et al. (2016). [e]Hillyer (1996). [f]Jin et al. (2015). [g]Landry (2004). [h]Landry and Hindsley (2011). [i]Mcdowell Peek et al. (2016). [j]McNamara et al. (2011). [k]National Association of REALTORS (2020). [l]Pompe and Rinehart (1995). [m]PSDS (2019). [n]Redfin Inc. (2020). [o]Slott (2008). [p]Slott et al. (2010). [q]Smith et al. (2009). [r]Trulia LLC. (2020). [s]USACE (1999). [t]Williams et al. (2013). [u]Zillow Inc. (2020).

Table 2

Physical Input Parameters for Model Simulations

Physical Parameters	Symbol	Feasible range of Values	Units		Test value: figs. 2, 5-6, 8a	Test value: fig. 7	Test value: fig. 8b	Test value: figs. 9-10
Background Erosion Rate[a,i,k,r,v,w]	γ	0—10	m/yr		5	5	5	5—10
Nourishment Magnitude[b,t]	x_N	0—200	m		50	100	50	50
Rotation Length[b,o,t,u]	R	-	yr		0—25	(g) R_1=6.38 R_2=11.86 (h) R_1=6.92 R_2=7.55	0—25	0—25
Depth of Closure[f,g,j,m,n,s]	D	5—20	m		16	16	16	16
Alongshore Flux Coefficient[c,d,e,h]	K_1	10—1,000	1,000 m^2/yr		600	600	600	600
Cross-shore Flux Coefficient[p,q,s]	K_2	-	m^2/yr		2,000	2,000	2,000	2,000
Shoreface Equilibrium Slope[p,q,s]	θ_{eq}	-	m/m		0.02	0.02	0.02	0.02
Alongshore Community Length (Cell Length)[l]	s	-	m		1,500	(g) s_1=7090 s_2=3670 s_3=5380 (h) s_1=2720 s_2=7780 s_3=5250	10,000	1,500

Sources: [a]Armstrong and Lazarus (2019). [b]ASBPA (2020). [c]Ashton et al. (2001). [d]Ashton and Murray (2006a). [e]Ashton and Murray (2006b). [f]Birkemeier (1985). [g]Brutsché et al. (2014). [h]Falqués (2003). [i]Gopalakrishnan (2010). [j]Hallermeier (1981). [k]Hapke et al. (2013). [l]Inspired by field values observed in New Jersey. [m]Kraus and Batten (2007). [n]Kraus et al. (1994). [o]Lazarus et al. (2011). [p]Lorenzo-Trueba and Ashton (2014). [q]Miselis and Lorenzo-Trueba (2017). [r]Murray et al. (2013). [s]Ortiz and Ashton (2016). [t]PSDS (2019). [u]Smith et al. (2009). [v]Williams et al. (2013). [w]Zhang et al. (2004).

3 Community Behaviors

3.1 Single Community

The model produces four primary behaviors based on nourishment choices: seaward growth due to frequent beach nourishment (i.e., short rotation length); hold the line due to moderately frequent nourishment (i.e., medium rotation length); slow retreat due to infrequent nourishment (i.e., long rotation length) and resulting in property abandonment; and full retreat due to a lack of nourishment and resulting in property abandonment (Figure 2). We characterize seaward growth behavior as the maximum shoreline position in the final five years greater than the maximum seaward extent of the first nourishment event. Hold the line behavior falls between this threshold and the initial property setback. Whereas, slow retreat and full retreat result in shorelines landward of the initial property setback. The only difference between the latter two scenarios is that slow retreat includes nourishment effort on the part of the community and full retreat does not (Figure 2). When considering two communities, each behavioral category that includes beach nourishment can comprise a mix of two primary behaviors.

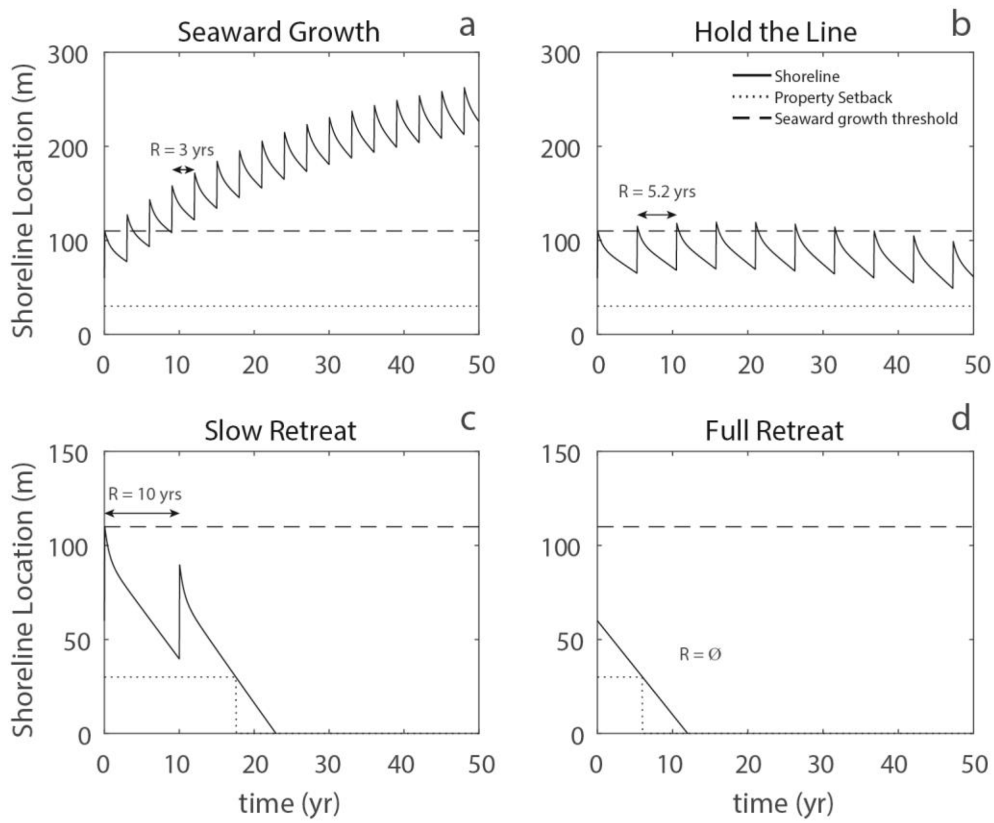

Figure 2. Mode behaviors resulting from different beach nourishment frequencies: a) R=3 years b) R=5.2 years c) R=10 years d) R=Ø (no nourishment).

We present an example of each mode behavior observed in the field. Using the beach nourishment databases from the Program for the Study of Developed Shorelines (PSDS) of Western Carolina University (2019) and the American Shore and Beach Preservation Association (ASBPA, 2020), we report the number of nourishment events and year of first/last nourishment event for each example below and show that these mode behaviors likely depend on nourishment decisions (Figure 3a-d).

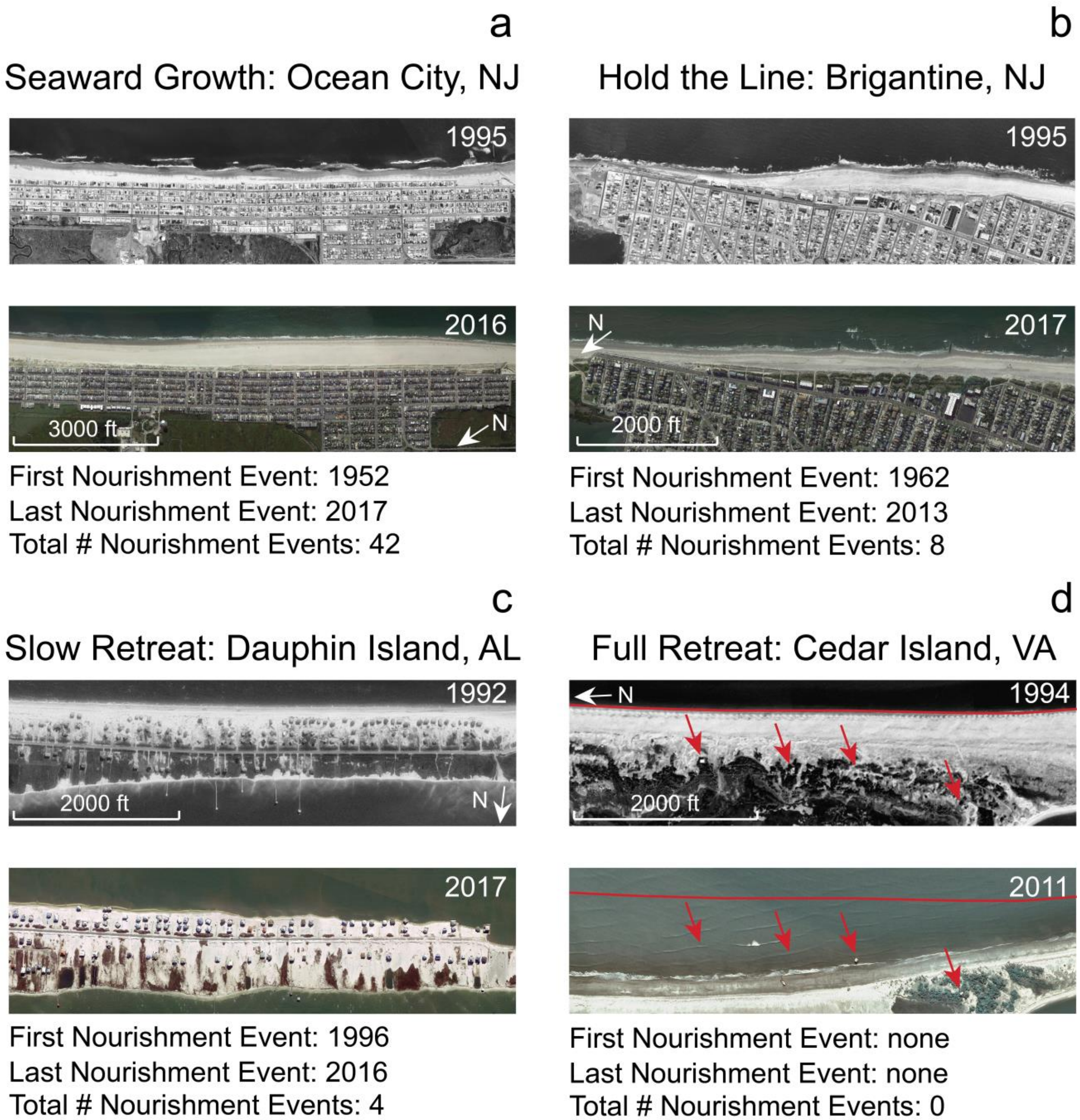

Figure 3. Emergent mode behaviors observed in the United States East and Gulf coasts: (a) seaward growth in Ocean City, NJ; (b) hold the line in Brigantine, NJ; (c) slow retreat in Dauphin Island, AL; and (d) full retreat in Cedar Island, VA.

Toward coupling these nourishment decisions and their emergent mode behaviors with community-scale socioeconomics, we present the rotation lengths for coastal New Jersey communities as a function of their property values (Figure 4). We determine a median property value estimate using four real estate search engines (National Association of REALTORS, 2020; Redfin Inc., 2020; Trulia LLC., 2020; Zillow Inc., 2020), and calculate the representative beachfront property value assuming a power law relationship between property value and inland distance from the ocean (Gopalakrishnan et al., 2011; Pompe & Rinehart, 1995). We gather data using spatial analyst tools on alongshore community lengths and representative property sizes. The total wealth of the community is defined here as the summed value of all alongshore properties in a community. We track the number of nourishment events by community, as reported in the PSDS (2019) and the ASBPA (2020) databases, and use the first (1936) and last (2020) completed nourishment event along the New Jersey coast to calculate a representative rotation length for each community.

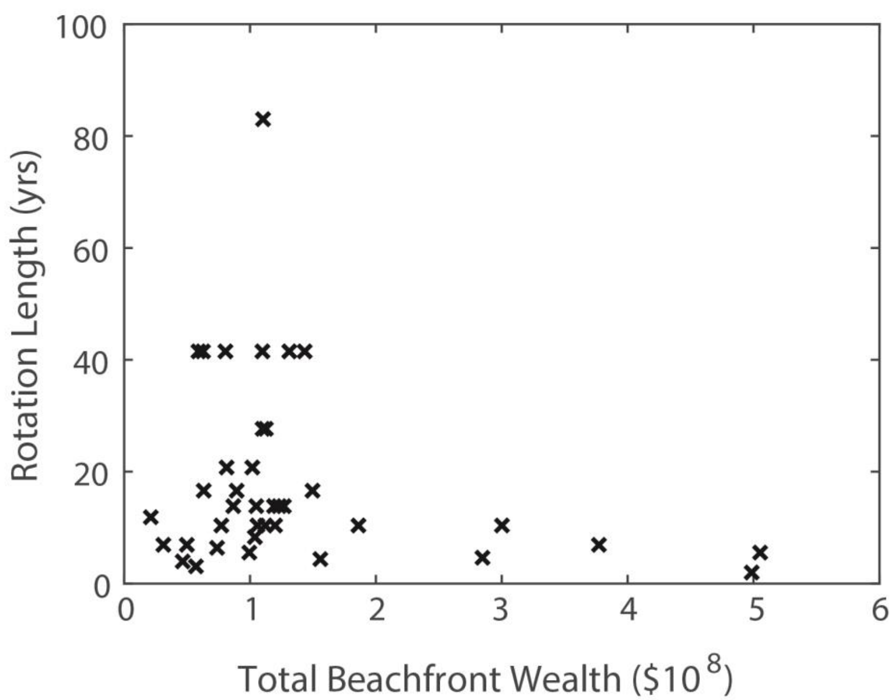

Figure 4. Rotation lengths for coastal communities in New Jersey as a function of their total beachfront wealth (alongshore sum of beachfront property values), exhibiting nourishment variability for low-wealth communities and frequent nourishment for high-wealth communities.

While in general, the rotation length decreases as total beachfront wealth increases, there is variability for low-wealth communities. This could be due to commercial real estate exerting control over nourishment frequency (e.g. Atlantic City, Ocean City, Asbury Park, Cape May, Wildwood, Long Branch, etc.), where beach tourism economies are often located in neighborhoods with lower property values (or there is a disamenity associated with proximity to tourism areas). Other variability, however, could be due to alongshore interactions between neighboring communities' nourishment decisions.

In many field cases, mode behaviors realized by a community depend at least in part on their neighbor's actions as well. We account for this alongshore coupling between neighboring nourishment choices in the subsequent section (3.2). However, these initial field insights do provide context for our beach nourishment game concerning the range of both property values and rotation lengths used for model explorations.

3.2 Two-community Interconnection

In order to capture the alongshore feedbacks between neighboring community nourishment decisions, a two-community model setup was implemented, allowing a comparison of the emergent behaviors produced by coordinated and uncoordinated schemes. The setup comprises a sample array of real-world scenarios in which neighboring communities can be wealth-symmetric or wealth-asymmetric (Figure 5). The sensitivity of community nourishment decisions to different baseline property values (Equation 7) in each community was explored.

Under coordination, community-specific rotation lengths depend on relative baseline property value balances, but under non-coordination, they depend only on each community's baseline property value (Figure 5a-b). This baseline property value regime space encompasses all key behaviors that emerge from the model (Figure 2) including instances of mixed behaviors (i.e., seaward growth/hold the line). The thresholds between these behaviors depend upon the level of coordination, and these thresholds demarcate regions in which communities that do not coordinate misallocate their distribution of nourishment effort (rotation length) compared to their economically optimal distribution of effort produced by coordination. This emerges, in particular, when there is a disparity in baseline property values between neighbors (Figure 5a-b).

Full retreat arises for the lowest wealth systems regardless of whether or not coordination occurs. Both coordinated and uncoordinated emergent behaviors are sensitive to minor changes in baseline property values for low and moderately wealthy systems, while they are less sensitive for high baseline property values. Neighboring communities with different baseline property values experience many instances of behavioral difference between coordinated and uncoordinated regimes, particularly for moderate baseline property values. By working independently, communities effectively treat all of their neighbors equally; thereby, ignoring the marginal importance of helping a neighbor based on the benefit they might provide the system. Accounting for the alongshore distribution of wealth under coordination represents the economically optimal allocation of nourishment effort, contrasting with the uncoordinated scenario in which communities might either under-nourish (i.e., longer rotation lengths) or over-nourish (i.e., shorter rotation lengths) compared to their rotation length choices under coordinated efforts (Figure 5a-b, e).

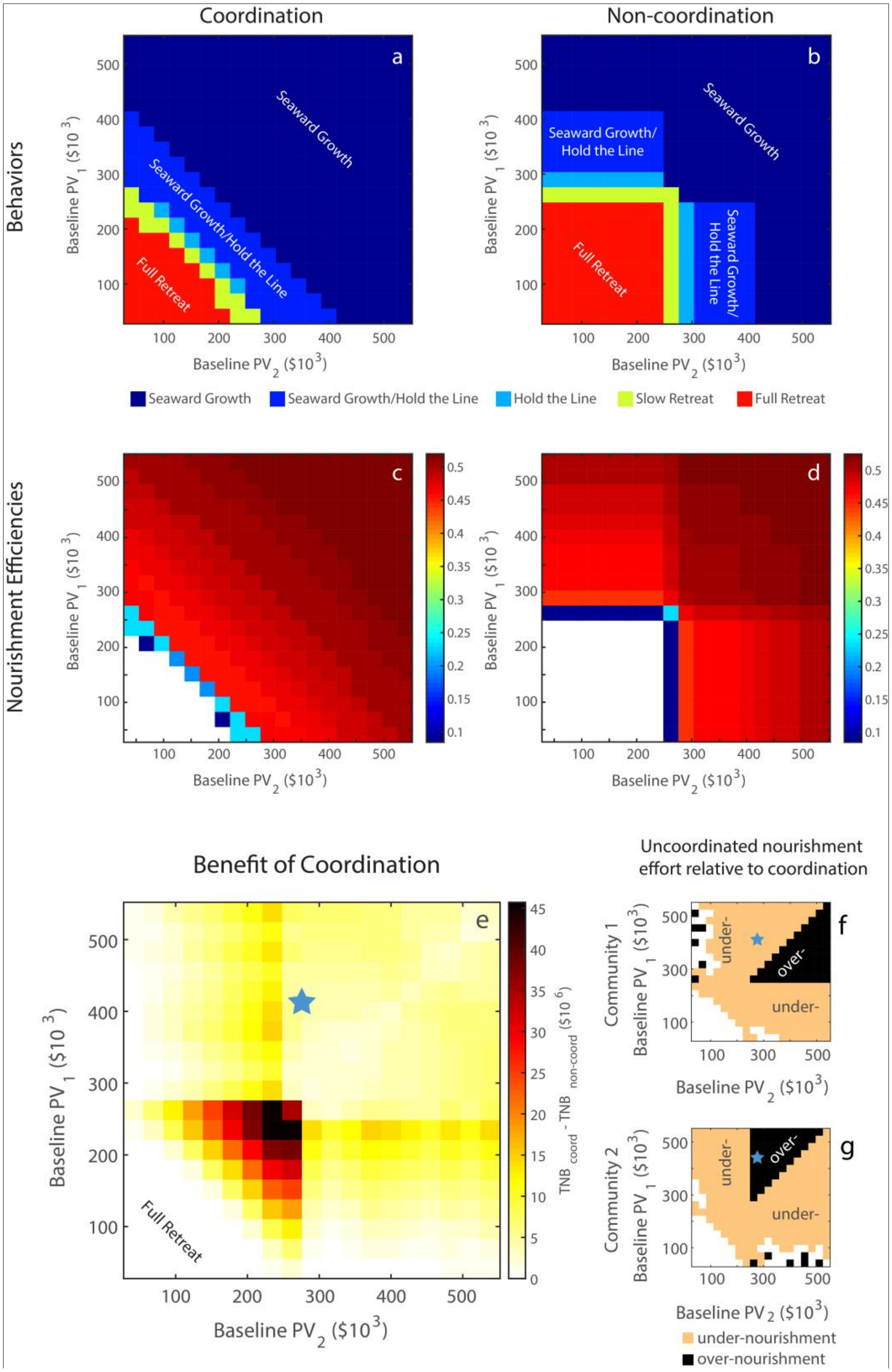

Figure 5. Emergent behaviors for coupled systems under (a) coordination and (b) non-coordination and (c-d) the nourishment efficiencies under the respective management schemes. Panel (e), the benefit of coordination relative to non-coordination indicates the economic

difference between management scenarios, and the community-specific regions of over- and under-nourishment for (f) community one and (g) community two reveals how uncoordinated strategies economically compare with their optimal strategies under coordination.

In general, nourishment efficiency increases as the wealth increases corresponding with decreasing rotation lengths (Figure 5c-d). While this increase in efficiency can be attributed in part to the larger volume of sand placed by frequent nourishment (Equation 9), triggering an increase in the volume of sand lost from the two communities (Equation 8), the fraction of volume lost relative to the nourishment volume decreases and the efficiency thus increases (Equation 10). These efficiencies differ between coordination schemes primarily in regions of wealth disparity, where coordination results in a higher physical efficiency than non-coordination (Figure 5c-d), corresponding with a higher economic efficiency (i.e. optimal solution) produced by coordination in this region as well.

The difference in behavioral outcomes depending on the coordination level highlights the baseline-property-value combinations for which coordination is most important. The benefit of coordination is the smallest (i.e., coordination is least important) for low wealth communities that cannot afford nourishment regardless of their coordination level (Figure 5e). It is also lowest for regions of high wealth disparity between neighbors because the marginal benefits provided by wide beaches in a wealthy community outweigh the marginal costs of frequent nourishment, and their less wealthy neighbor can neither afford nourishment on their own nor provide any appreciable benefit to the system if they work together.

The benefit of coordination is largest (i.e., coordination is most important) for lower-wealth communities that can afford beach nourishment by cooperating but not by acting alone. Coordination is also important for regions with moderate baseline-property-value asymmetry, identified by the blue star as an example (Figure 5e). This baseline-property-value combination corresponds with seaward growth behavior for both coordination levels (Figure 5a-b), but coordination is more beneficial to the two communities as a whole, assuming that a cost-sharing arrangement or transfer payment exists under coordination, because the less wealthy community over-nourishes and the wealthier community under-nourishes when acting alone (Figure 5f-g). This uncoordinated distribution of nourishment effort between the two communities results in a lower nourishment efficiency compared to coordination, meaning that the two communities lose more sand from their beaches relative to the amount they place if they neglect cooperation.

The optimal distribution of nourishment effort between communities for the blue star in figure (5e) under coordination, while representing the maximum total net benefit for the entire system, results in an asymmetric share in net benefits between communities (Figure 6). In fact, the less wealthy community that nourishes infrequently under coordination receives a larger share of the net benefits than the wealthier community that nourishes frequently (Figure 6a). This is due to the large asymmetry in nourishment effort, whereby the wealthier community bears the majority of the nourishment responsibility, and is a function of the level of interconnectivity between communities (i.e., that small alongshore length and the high diffusivity value). In regions where communities are more alongshore disconnected, the distributed nourishment effort and thus the corresponding community-specific breakdown in net benefits might be more comparable. A cost-sharing or transfer payment arrangement from the community nourishing less might be necessary here to ensure the wealthier community remains in a coordinated scheme.

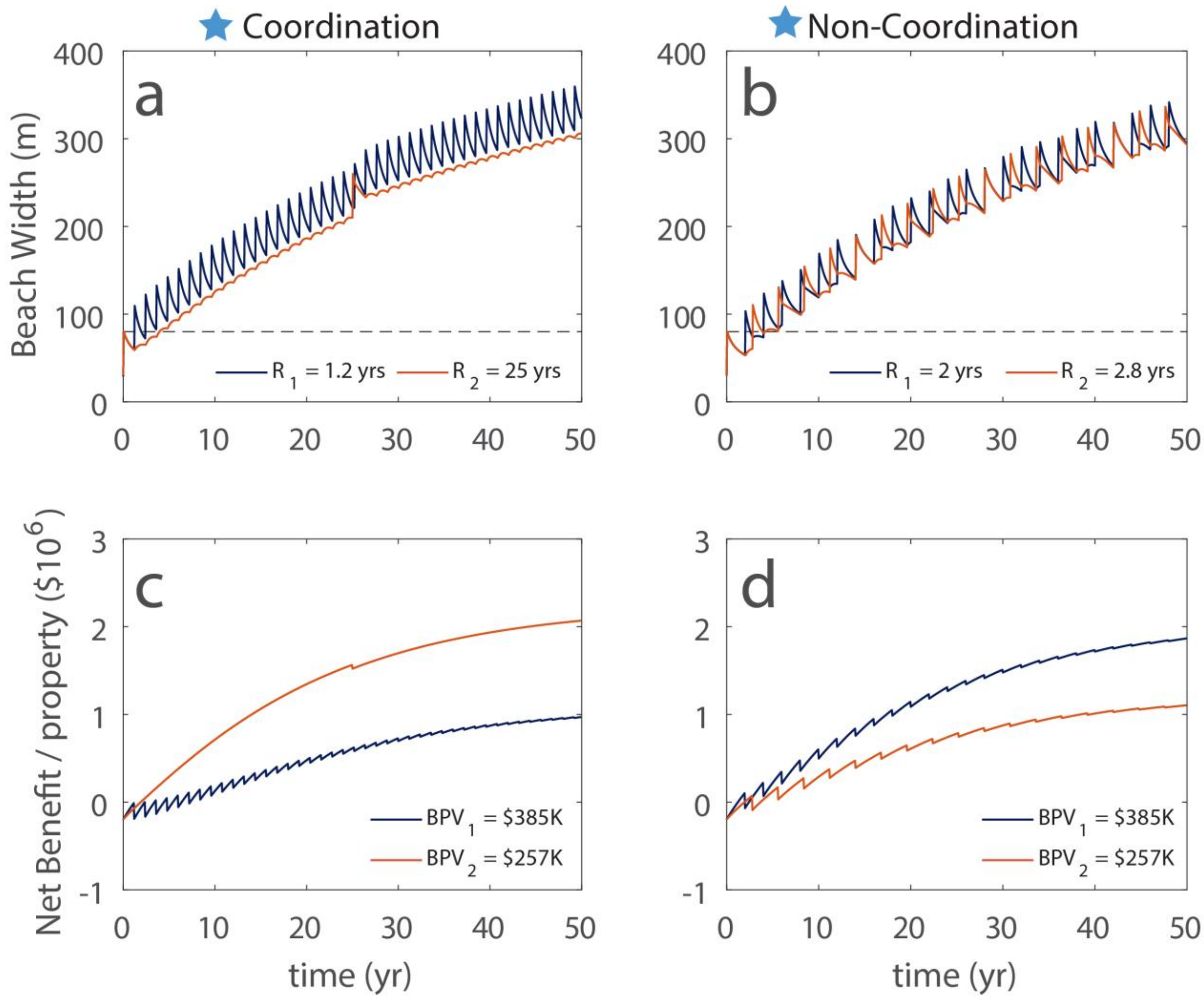

Figure 6. Beach widths for communities with baseline property values corresponding to the blue star in figure 5e under (a) coordination and (b) non-coordination, and (c-d) the resulting community-specific net benefits for coordination and non-coordination respectively.

If these two communities compare their own payoffs resulting from each coordination level rather than the total net benefit, however, there is an incentive for the less wealthy community to cooperate (i.e., to follow their coordinated nourishment choice) while there is an incentive for the wealthier community to defect (i.e., to follow their uncoordinated nourishment choice) (Figure 6c-d). The wealthier community realizes a higher net benefit from acting alone than coordinating because they not only nourish less and incur fewer costs, but their less wealthy neighbor nourishes more than they would have under the coordinated plan (Figure 6a-b). This combination of strategies, if followed, would result in reduced nourishment effort system-wide, which would lead to the suboptimal outcome of narrower beaches due to non-coordination as described by Gopalakrishnan et al. (2016). These individual incentives, in the absence of a cost sharing or transfer payment plan, might be a barrier to coordination, which could help explain why communities have historically operated in a decentralized manner.

4 Model Comparison with Field Decisions

While the historical level of coordination between real-world communities and their initial property values is unknown, we do see evidence of these two-community mode behaviors in the field. Specifically, we highlight two barrier island systems in southern New Jersey: Avalon/Stone Harbor and Strathmere/Sea Isle City. In both instances, the two communities experience seaward growth behavior due to their distributed nourishment effort. This evolution is evident both in historical aerial imagery (Figure 7a-d) and in the modeled shorelines (Figure 7e-f).

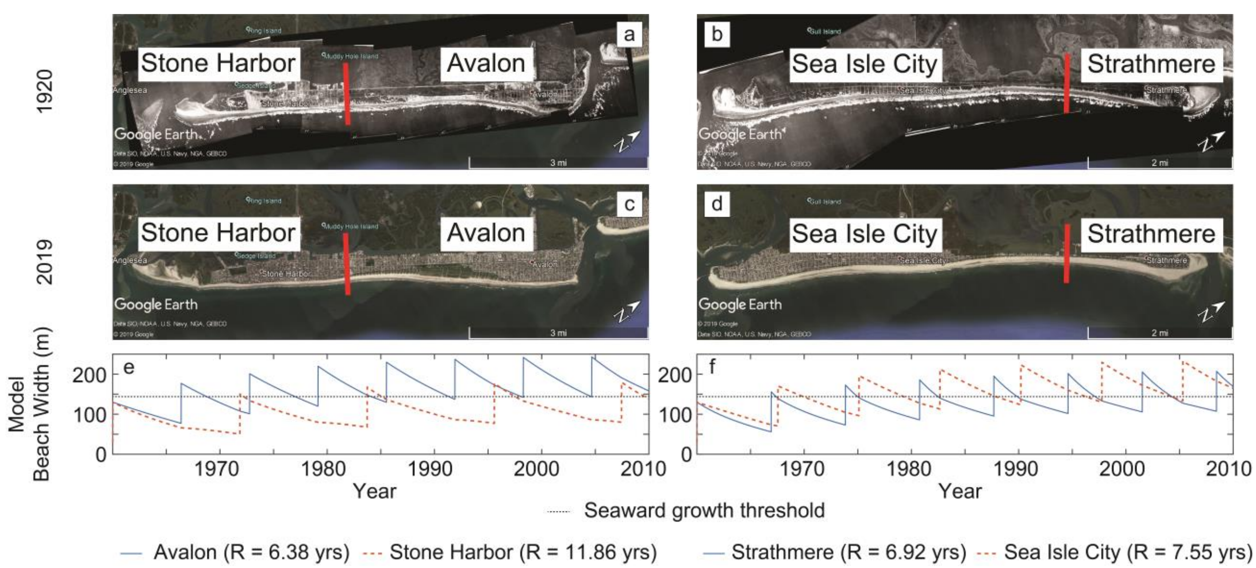

Figure 7. Example of dynamic interconnection between neighboring New Jersey communities: (a) Avalon and Stone Harbor and (b) Strathmere (Upper Township) and Sea Isle City. Historical aerial imagery from (a-b) 1920 and (c-d) 2019 illustrate their developmental and morphodynamic evolution. From the PSDS and ASBPA beach nourishment databases, we calculate each

community's rotation length, from which seaward growth behavior emerges for (e-f) both barrier island systems.

We group two-community neighbors for all New Jersey community pairs in our database and analyze their distributed nourishment choices (i.e., rotation length ratio) as a function of their distributed beachfront wealth (i.e., wealth ratio). Here, the beachfront wealth is defined as the sum of all beachfront property values in a community, which accounts for the community's alongshore length and number of properties adjacent to its beachfront. Some field community pairs result in a rotation ratio that is larger than one, meaning the less wealthy community nourishes more than the wealthier community nourishes. We find that the commercial real estate influences associated with high tourism areas such as Seaside Heights and Atlantic City could bias these examples. Similarly, the natural dynamics of shorelines adjacent to fully hardened (i.e. two jetties) tidal inlets and the resultant sediment deficits downdrift of these inlet jetties, for which our model does not account, could be affecting nourishment decisions in communities such as Avon-by-the-Sea and Barnegat Light. For these reasons, we remove the field pairs composed of these communities.

We plot the rotation-length ratios as a function of wealth ratios (relative to the lower-wealth community for each two-community pair) for coordinated and uncoordinated model scenarios and shade each region surrounding the corresponding observations, terming these regions the coordinated and uncoordinated model envelopes. These field-model comparisons include both small communities (Figure 8a) and large communities (Figure 8b) to cover most New Jersey community sizes. In general, increasing the wealth ratio results in a decreasing rotation-length ratio because when neighboring communities have more wealth disparities (i.e., large wealth ratios) their rotation lengths are more dissimilar (i.e., small rotation-length ratio). If neighboring communities have high wealth disparities but similar rotation lengths, this may indicate that they are misallocating their distributed nourishment effort compared to their economically optimal levels.

The slope of this decreasing rotation ratio for small wealth ratios is steeper under coordination than non-coordination for smaller communities, and the rotation ratios are small for large wealth ratios under coordination (Figure 8a), meaning that nourishment decisions are more different between the two communities when they coordinate and more similar between the two communities when they act independently. We then overlay field data from neighboring New Jersey communities to see how two-community pair decisions might compare with the model's output. Given that many field communities have alongshore lengths (median length = 2.68 km) similar to the case presented in Figure 8a, the regions enveloping field pairs in this subplot might serve as an indicator of their underlying decision-making scheme, i.e., whether or not they coordinated their nourishment plans. An example of non-coordination could include Sea Isle City/Avalon, NJ, which is plausible given they are on different barrier islands and separated by a partially hardened (i.e., one jetty) tidal inlet. Whereas, Loveladies/Harvey Cedars could be an example of coordination given they are tightly coupled alongshore and subject to the same USACE regional beach nourishment plan (1999).

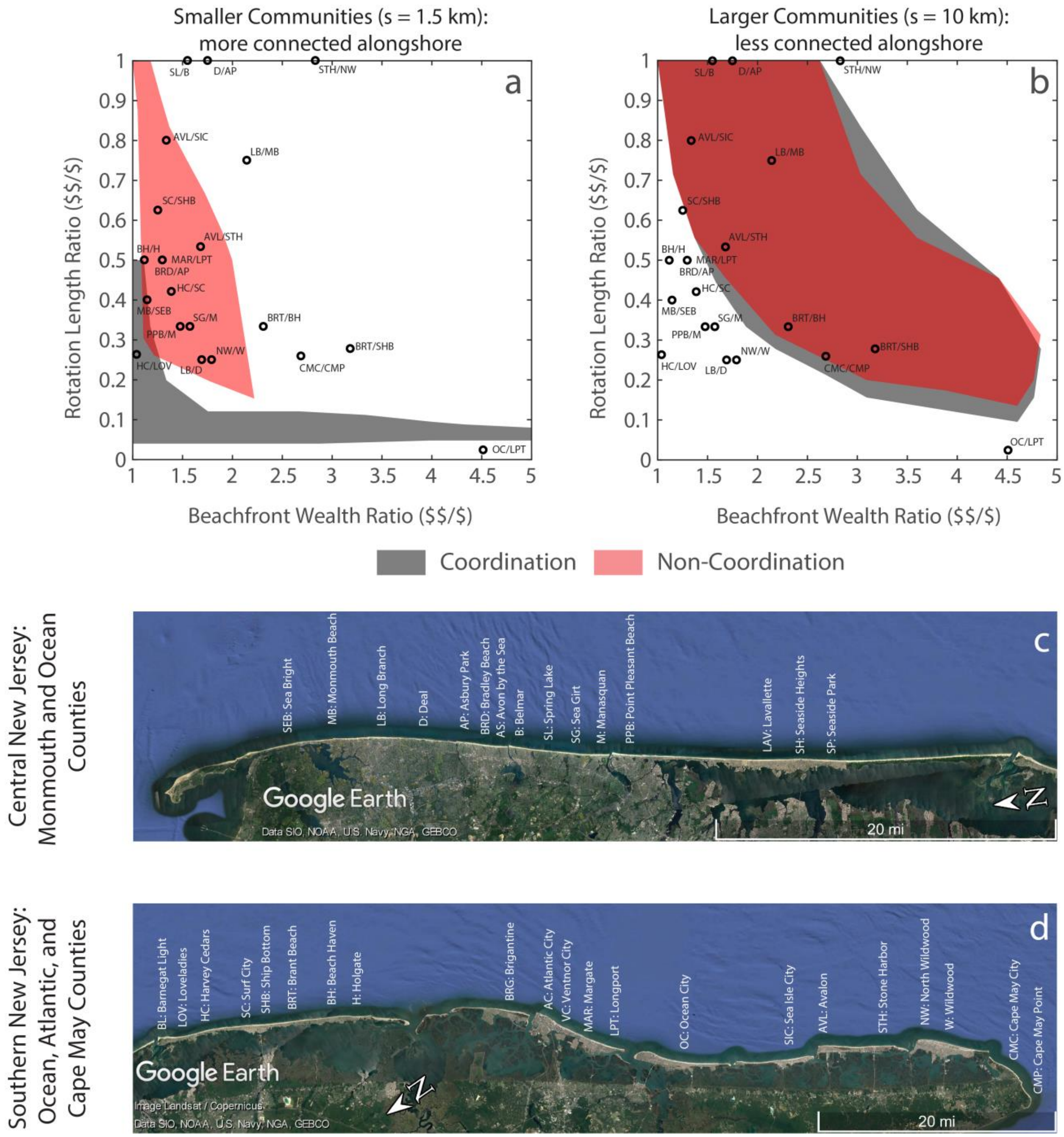

Figure 8. Comparison of rotation-length ratio vs. wealth ratio between model (coordination/non-coordination) and field observations for (a) small communities and (b) large communities. Field pair locations identified by the abbreviations used in subplots a-b are shown for the (c) central and (d) southern New Jersey coast regions.

Field examples that do not fall in either model envelope in figure (8a) could be influenced by other underlying factors. One such factor could be the shoreline orientation effects whereby one community protrudes farther seaward than its landward neighbor thus necessitating more frequent nourishment than expected due to its reduced nourishment efficiency (e.g. Stone Harbor/North Wildwood). Another factor could be an asymmetry in how the neighboring communities value their beach for recreational purposes where wealthier communities value these amenities less than poorer communities do (e.g. Deal/Asbury Park and Monmouth Beach/Long Branch). This relates to the beach amenity value β in equation (11). Such factors are not considered here, although future work will be necessary to explore these dynamics further.

A simple test within the model's framework, however, is increasing the alongshore community length (Figure 8b). This serves to reduce the connectivity between communities and results in nourishment decisions that are less dependent on the dynamics of neighboring communities. The coordinated scheme for large communities, especially, yields rotation lengths that are more similar (i.e., rotation ratio that is closer to one) than the same scheme for smaller communities. The model envelopes for large communities (Figure 8b) cover nearly all remaining data points not covered by the model envelopes for small communities (Figure 8a), including larger field communities such as Long Branch (length = 6.95 km). One data point that remains uncovered by the large community envelopes, Ocean City/Longport, could be a result of the disparity in community lengths (Ocean City = 11.47 km; Longport = 2.27 km) or their separation by a large tidal inlet (Great Egg Harbor Inlet) that is partially hardened, which could be disrupting alongshore flow between communities.

Furthermore, when we include community-average nourishment volumes as well as frequencies in our analysis, presented below as nourishment flux, we find that community pairs might be allocating their nourishment effort in an economically inefficient manner. For instance, in figure 9a, poorer communities in a moderate wealth-disparate pair tend to nourish with larger fluxes than wealthier neighbors do, on average, indicating that these poorer communities are likely over-nourishing or that their wealthier neighbors are under-nourishing compared to their economically optimal levels in the context of a two-community framework. In addition, these emergent flux differences result in quantitative differences in beach width, such that poorer communities often realize wider beaches than their wealthier neighbors (Figure 9b).

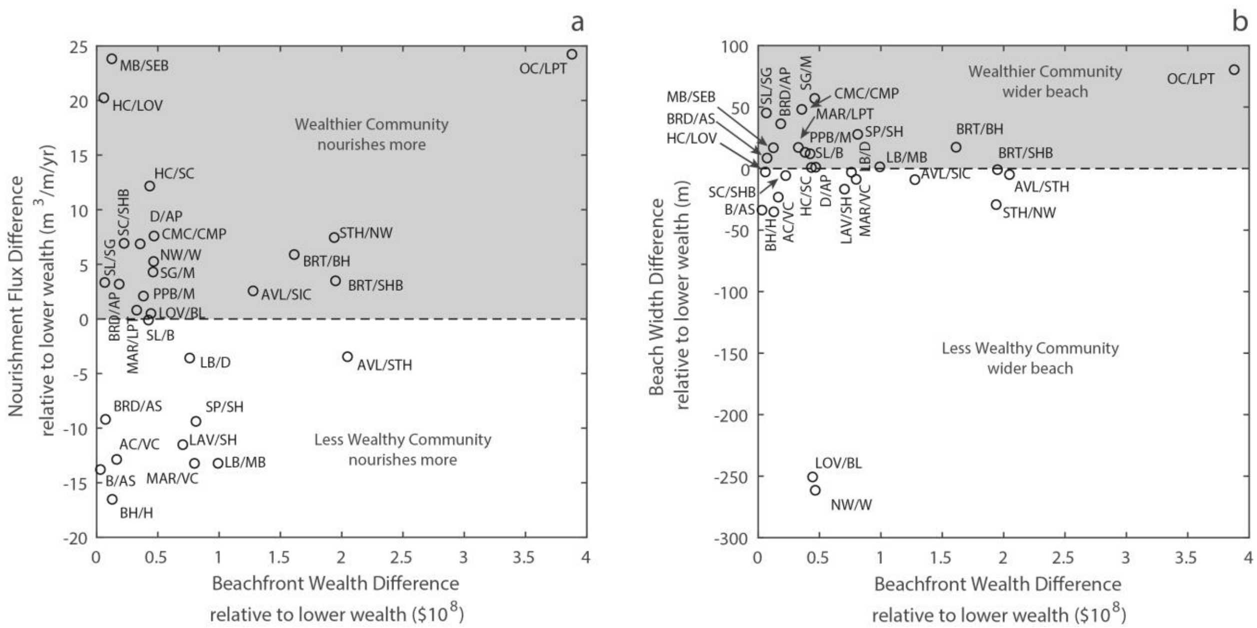

Figure 9. (a) Nourishment flux differences and (b) beach width differences for each two-community pair as a function of their beachfront wealth differences revealing that poorer communities often nourish more than wealthier communities do and supporting the model's result that poorer communities might be over-nourishing compared to their economically optimal level of effort under coordination. This over-nourishment, in many cases, yields wider beaches for poorer communities compared to their wealthier counterparts.

While it is unclear whether each two-community pair actually coordinated their nourishment plans or chose their strategies alone in the past, these field observations compared with our model's results do suggest that neighboring communities with large wealth disparities may have foregone benefits by failing to coordinate regional nourishment strategies. In the face of climate change impacts on coastal New Jersey communities and worldwide, it will be important to understand how these neighboring community interactions might change in the future and the potential paths of coupled coastal behavior based on the different coordination schemes they might undertake.

5 Future Conditions: Effect of a Higher Sand Cost and Background Erosion Rate

Subsequent nourishment decisions might rely on a different suite of underlying physical and economic conditions. A likely future scenario involves higher background erosion associated with sea-level rise and increases in the cost of sand. The prevalence of beach nourishment on regional scales increases the demand for sand (Brauchle, 2013). Additionally, reductions in near-shore-sediment supply shift dredge operations further offshore, implying that sand is a non-renewable resource (McNamara et al., 2011). Both expanding demand and diminishing supply drive up the price of sand for beach nourishment.

Under the asymmetric wealth scenario represented by the blue star in Figures (5-6), behavioral sensitivities to increasing background erosion rate and increasing sand cost for both coordination levels are depicted in Figure (10).

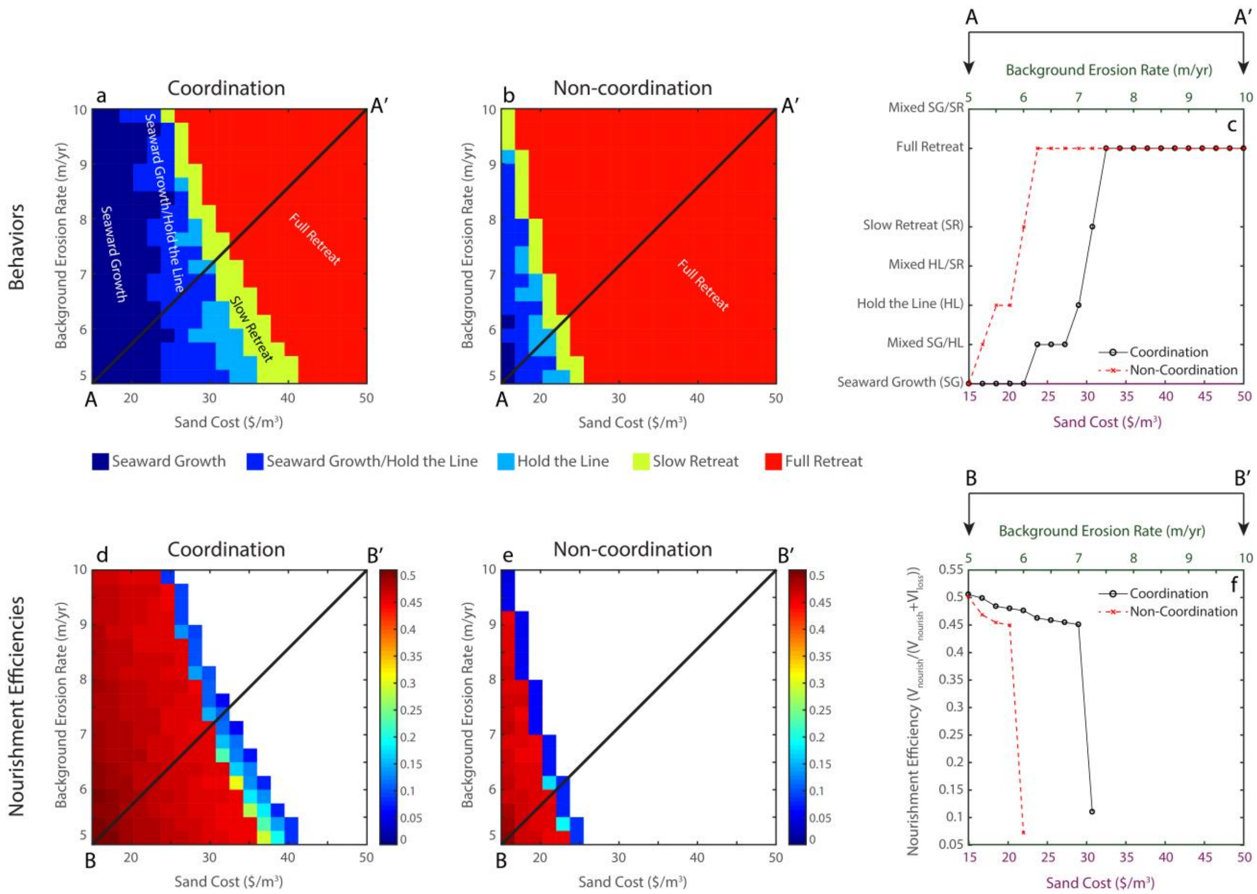

Figure 10. Emergent behaviors under (a) coordination and (b) non-coordination based on the background erosion rate and the sand resource cost, a diagonal transect (A-A') through the regime space showing (c) the behavioral transgression from seaward growth to full retreat, the corresponding nourishment efficiencies for (d) coordinated and (e) uncoordinated regime spaces, and (f) the decreasing nourishment efficiency along the diagonal transect (B-B').

Communities that coordinate will experience a progression from seaward growth to seaward growth/hold the line to slow retreat to full retreat, highlighting their added difficulty in maintaining beaches when faced with more extreme geo-economic forcings (Figure 10a). In contrast, uncoordinated communities will experience this shift from seaward growth to full retreat much sooner, i.e., for lower sand costs and lower erosion rates (Figure 10b-c). This drives a threshold switch for uncoordinated systems from over-nourishment in the less wealthy community to under-nourishment system-wide, as evidenced by the loss of property sooner than had the communities coordinated. The switch from over-nourishment to under-nourishment occurs because, when choosing a nourishment strategy alone, the less wealthy community can no longer justify over-nourishing, or in other words, the cost of nourishment inefficiency (Figure 10e) outweighs the benefit of protecting beachfront properties. Ultimately, the less wealthy community acting alone will be unable to nourish at all and will abandon properties sooner than if it had cooperated with its wealthier neighbor (Figure 10a-c). Together, the uncoordinated communities will reduce their nourishment efforts due to the increased marginal cost of nourishment inefficiency compared to the benefit provided by frequent nourishment. These decisions correspond with lower nourishment efficiencies and a more rapid decline in efficiency than coordinated communities might experience (Figure 10d-f).

The vulnerability to property loss for uncoordinated systems in the future mirrors what is already happening in many communities across the United States, both wealthy and not, who are struggling to protect their beachfront properties in the face of eroding beaches and rising seas. Wealthy homeowners in Nantucket, Massachusetts are self-funding their protection efforts (Keneally & Simon, 2020). Likewise, upscale neighborhoods in Nags Head, North Carolina, and Malibu, California who both lose approximately 5-6 feet of beach width per year plan to spend $48 million and $55-60 million respectively to restore their beaches and keep their homes from falling into the sea (McMullen, 2018). Especially at risk, however, are property owners with fewer means such as those in Manistee, Michigan whose homes have begun tumbling into Lake Michigan due to coastal bluff erosion following record-high lake levels in recent years (Reynolds, 2020). These homeowners often either abandon their properties after their property values depreciate or sell to developers, which results in bigger homes and thus more wealth in the most vulnerable locations (Capuzzo, 2017; Lazarus et al., 2018).

These instances and many more around the world will undoubtedly become commonplace under more extreme conditions in the future. Property-value disparities might amplify these risks, triggering a sharp transition from seaward growth to property abandonment for communities that neglect to coordinate their management plans with their neighbors.

5 Discussion and Future Work

A geomorphic-economic model to understand the key drivers influencing a dynamically coupled-coastal system with two communities was developed. The model predicted a broad array of emergent-behavioral pathways based on nourishment rotation length as the control variable.

For instance, communities might choose to nourish their beaches so frequently that their shorelines grow seaward. Conversely, communities might choose to nourish their beaches infrequently or not at all, such that they lose nearshore properties as a result.

Whether this dynamical system can produce the observed coastal anthropic signatures typically ascribed to uncoordinated management was examined. The model predicted that communities might accidentally nourish more frequently than is optimal under a coordinated management program, although this is not a blanket result. Instead, this behavior persists mainly when neighboring communities have different property values, and in particular, less wealthy communities in such situations tend to over-nourish.

Irrespective of the coordination scheme, neighboring communities with high baseline property values are predisposed to nourishing frequently, leading ultimately to seaward growth. These outcomes shed light on how coastal communities might have behaved in the past; specifically, they might have misallocated nourishment efforts when the underlying socioeconomic conditions such as alongshore wealth asymmetry between coastal neighbors was large.

Preliminary evidence of these model trends appears in New Jersey beach communities. Other local factors that distinguish these systems could affect a comparison, however. First, groin fields are widespread along the New Jersey coast, thereby limiting the interconnection between neighboring communities. Second, barrier islands, comprising most of the southern New Jersey coast, experience washover (i.e., the transport of sediment from the shoreface to the top or back of the barrier), a process for which the model does not account at present. Future work should explore how groin fields and barrier processes interact with the coupled model by extending it to include hard structures (Janoff et al., 2019; Kraus & Batten, 2006) and overwash dynamics (Lorenzo-Trueba & Ashton, 2014).

Third, high recreational values associated with beaches in tourism-centric zones, where commercial beachfront real estate likely controls nourishment decisions more than residential properties do, could add complexity to this inter-community relationship. In particular, potential asymmetries in these beach amenities between neighboring communities could play a role in determining how they plan their beach nourishments and whether or not they coordinate such plans. New Jersey is a perfect example of variability in beach recreational values as evidenced by the wide distribution of beach badge (use fee) revenues by community, especially from one community to the next (Hoover, 2017). We plan to explore how these community-scale economic differences dictate how communities interact with each other when forming their management plans.

Finally, the efficiency of these nourishment projects could differ by community, namely for those in regions with cross-shore or alongshore sediment deficits. Sand supply limitations could be due to local effects such as inlets or inlet jetties, which trap sand updrift, or underlying geologic characteristics on a regional scale. Similarly, communities that protrude seaward might experience limited alongshore supply. All of these conditions might decrease the efficiency of nourishment projects for certain communities, which would force more frequent nourishment than the model predicts. Building off the efficiency approximation (Equation 10) presented in this paper, future work will explore how the amount of sand lost from nourishment projects to nearby sediment sinks over time, and community perceptions about the sustainability of such projects, could affect community nourishment decisions.

These analyses would help clarify some of the behavioral variability observed in New Jersey (Figure 8). Nonetheless, the comparison between field data and model results presented in this paper suggests that many neighboring communities in New Jersey may have adopted an uncoordinated approach, which is also consistent with anecdotal evidence (Gopalakrishnan et al., 2016; Lazarus et al., 2011; Pilkey & Clayton, 1989).

If these communities have benefited economically from their past nourishment decisions, however, and the consequence of their beachfront property vulnerability (i.e., property damage) is largely subsidized by external sources (i.e., federal disaster relief, federally-/state-funded beach maintenance, flood insurance policy discounts, etc.), perhaps there is little incentive to overcome potential barriers to coordination and change behavior in the future. If this is indeed the case, the model suggests that decentralized communities might experience a rapid switch from over-nourishment to under-nourishment in the face of rising sea levels and increasing sand resource costs, and less wealthy communities are at particularly high risk of losing coastal properties. This underscores that communities that choose not to coordinate might realize disparities in the distribution of wealth along the coast, leading eventually to the persistence only of wealthier communities there.

As sand resources dwindle and sea levels rise, costs will continue to increase, beaches will erode more rapidly, and fewer communities will be able to afford beach nourishment. Using a coordinated scheme, communities could dampen their vulnerability, but they cannot prevent the eventual loss of properties. Managed retreat is a topic of growing interest for the scientific community (Rott, 2019), and it has already become a reality for some homeowners from the heavily developed shores of New York City (Binder et al., 2015) to the remote coasts of Alaska (Agyeman et al., 2009; Mach et al., 2019).

While managed retreat approaches focus largely on buyouts as a mechanism for property removal, the model explored here revealed a different but possibly complementary strategy of slowing the rate of retreat via infrequent beach nourishment to incorporate near-term benefits of property preservation in conjunction with relocation. Interestingly, the model suggests that this behavior of slow retreat is a viable strategy even without including the incentives comprising buyout programs. If such incentives are included in our modeling framework, slow retreat could be an even more attractive solution looking to the future.

It will be difficult to balance the private benefits provided for beachfront properties, resulting in tax revenues for small coastal municipalities, and the broader public benefits of beach access for all (Fallon et al., 2017). A framework that accounts for all stakeholder components is most likely to succeed, perhaps requiring a mix of incentives for property owners (buyouts), subsidies for coastal community welfare (beach nourishment), and reducing coastal development in the most vulnerable areas.

Ultimately, efforts to coordinate climate change adaptation plans such as beach nourishment might prove to be inadequate against the risks associated with coastal life on centennial scales. Subsidizing a neighboring community's beach maintenance might not avoid the vulnerabilities associated with coastal life, amplified by rapid sea-level rise rates in the future. Instead, top-down master plans, including planned region-scale migration from the coast, may be inescapable.

Conflicts of Interest

The authors report no real or perceived financial conflicts of interest. The authors do not have any other affiliations that may be perceived as having a conflict of interest with respect to the results of this paper.

Data Availability Statement

All field observations, model codes, data produced by model experiments, and scripts used to generate manuscript figures are available at our Github repository page https://github.com/aryejanoff/Nourishment-Coordination.

Author Contributions

AJ conceptualized the overarching research themes, constructed the numerical modeling framework, and performed all model experiments with guidance from JLT. AJ compiled all field data for comparison with model results and took the lead in manuscript writing, with JLT, PH, DJ, and AA all providing critical feedback and revisions.

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Appendix

We present the alternative end-member assumption that uncoordinated communities make about their neighbor when choosing strategies independently, as discussed in section (2.3). In contrast with the representative non-coordination assumption presented previously, communities assume their neighbor nourishes with high frequency here, which we consider a risky assumption. Given this expectation, communities nourish less than they would have under coordination, resulting in full retreat for most baseline-property-value-combinations and slow retreat when one or both communities are wealthy (Figure A1b). This extreme behavioral difference results in a maximum benefit of coordination that is an order of magnitude larger than our representative non-coordination (Figures A1c, 7a) and corresponds with under-nourishment in both communities for most of the regime space (Figure A1d-e).

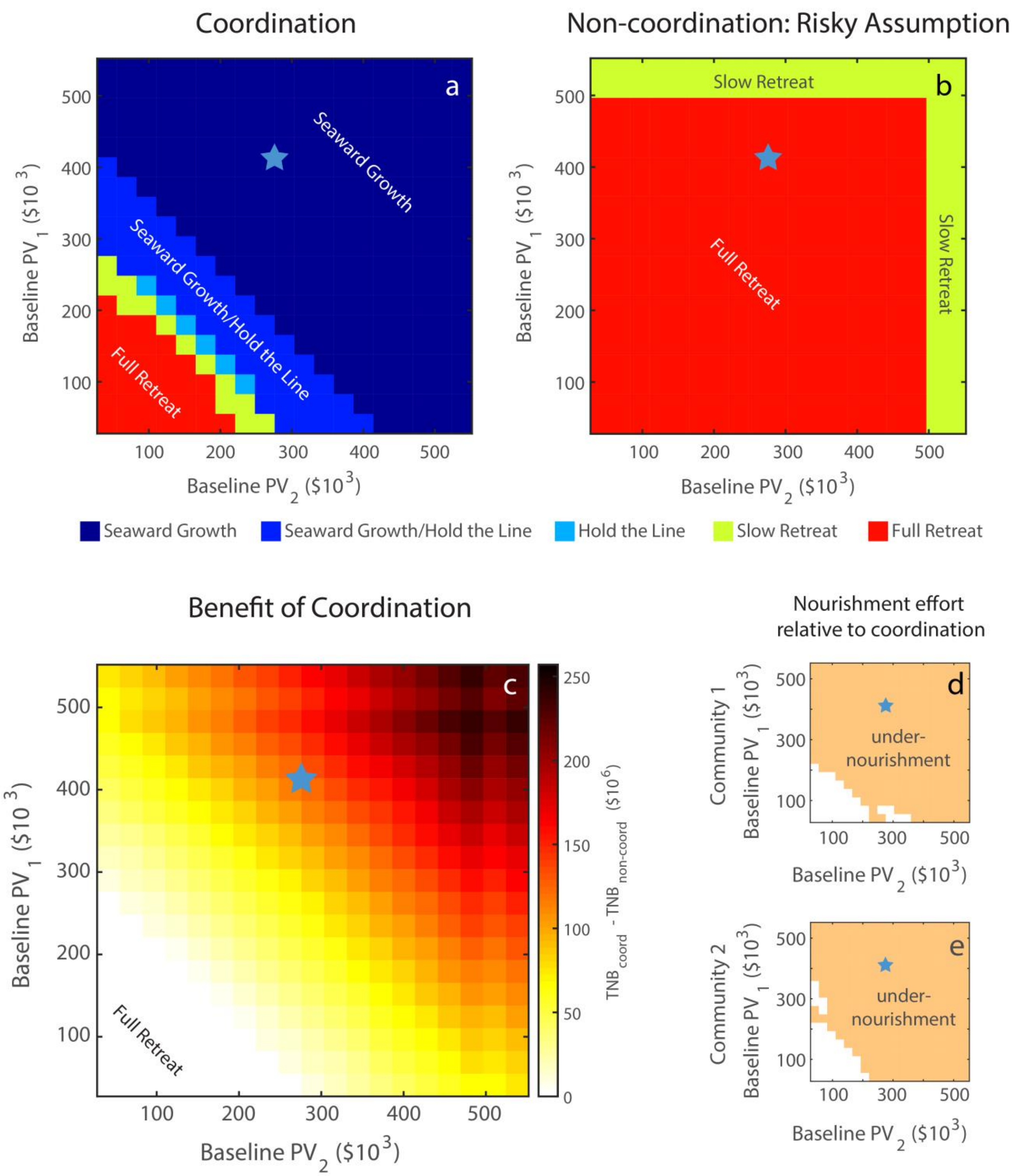

Figure A1. Emergent behaviors from (a) coordinated and (b) uncoordinated management schemes, (c) the benefit of coordination between the two, and regions of over-/under-nourishment in (d) community one and (e) community two. We highlight the same baseline-property-value combination as Figure 7 (blue star) for sensitivity analyses to future conditions.

We test how these coordination regimes using the same baseline-property-value distribution presented in figure (7) and represented by the blue star in figure (A1) will differ under increases in background erosion rate and sand resource cost. Unsurprisingly, uncoordinated communities operating under a risky assumption will never choose to nourish, thereby experiencing full retreat behavior under all future conditions (Figure A2b). This results in a large benefit of coordination in the near future and no benefit in the distant future when both coordination schemes result in full retreat (Figure A2c).

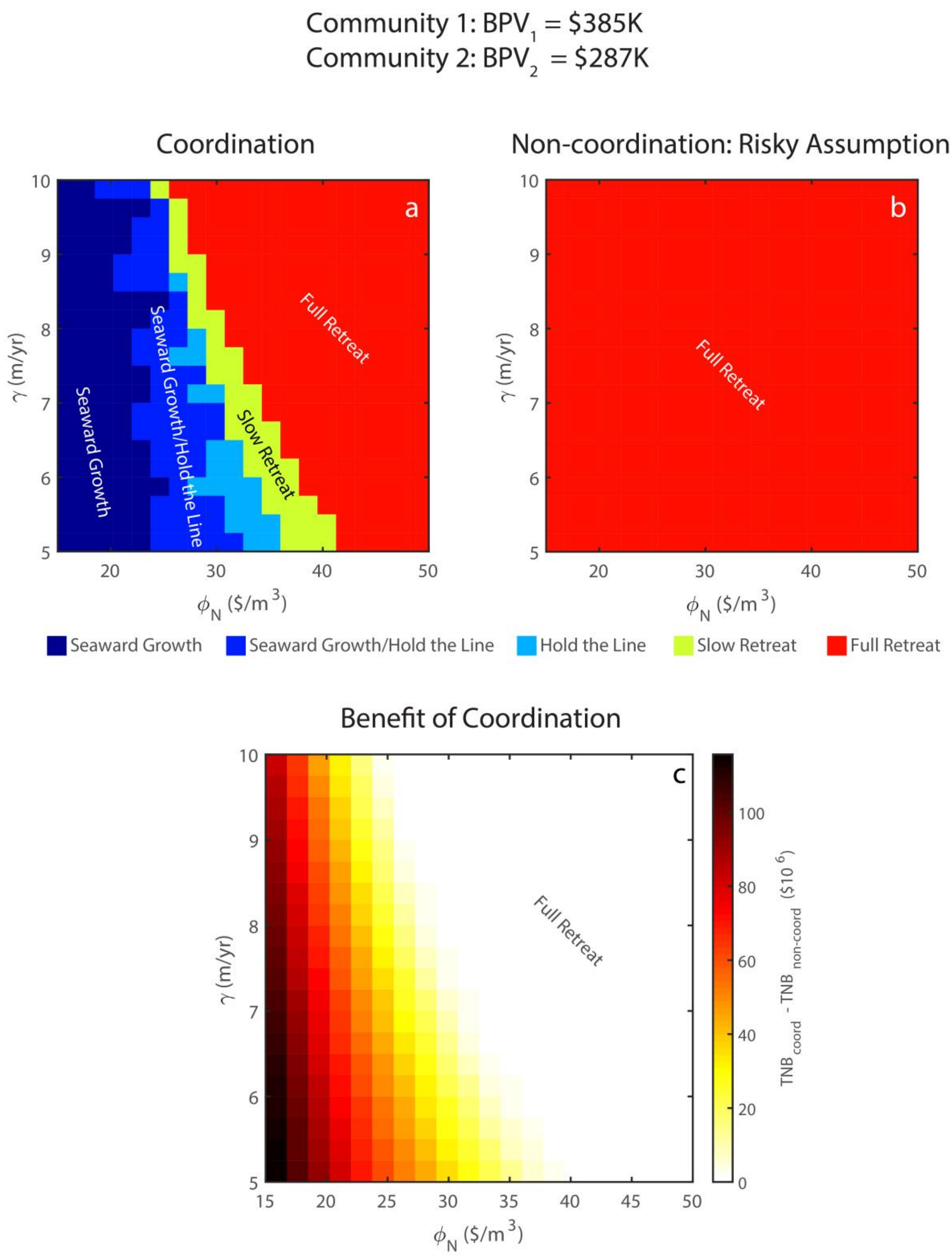

Figure A2. Emergent behaviors under future increases in background erosion rate and sand resource cost for (a) coordinated and (b) uncoordinated communities, and (c) the benefit of coordination between these two schemes.

Overall, risky non-coordination results in systematic under-nourishment and thus property abandonment under both current and future conditions. Given that many communities along U.S. coastlines and worldwide have not behaved in this way, this uncoordinated scheme (i.e., the risky assumption) is less common than our representative uncoordinated scheme (i.e., the cautionary assumption). Nevertheless, we present this end-member case to show the two boundaries between which communities might operate when choosing beach maintenance independently, highlighting the variation of response based on the assumptions communities make about their neighbors' behaviors.