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Decentralized Management Hinders Coastal Climate Adaptation: The Spatial-dynamics of Beach Nourishment

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Abstract Climate change threatens to alter coastline erosion patterns in space and time and coastal communities adapt to these threats with decentralized shoreline stabilization measures. We model interactions between two neighboring towns, and explore welfare implications of spatial-dynamic feedbacks in the coastal zone. When communities are adjacent, the community with a wider beach loses sand to the community with a narrower beach through alongshore sediment transport. Spatial-dynamic feedbacks create incentives for both communities to nourish less, resulting in lower long-run beach width and lower property values in both communities, a result that parallels the classic prisoner's dilemma. Intensifying erosion—consistent with accelerating sea level rise—increases the losses from failure to coordinate. Higher erosion also increases inequality in the distribution of benefits across communities under spatially coordinated management. This disincentive to coordinate suggests the need for higher-level government intervention to address a traditionally local problem. We show that a spatially targeted subsidy can achieve the first best outcome, and explore conditions under which a second-best uniform subsidy leads to small or large losses.

1 Introduction

Climate change threatens to alter coastline erosion patterns in space and time by contributing to sea level rise (IPCC 2014) and increasing the frequency and intensity of large storms

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(Bender et al. 2010; Slott et al. 2006). Coastal communities adapt to these threats with shoreline stabilization measures such as beach nourishment, the process of periodically rebuilding an eroding section of the beach with sand dredged from other locations. Benefits from beach nourishment—lower storm damage and higher recreational benefits from wider beaches—are capitalized into coastal property values and coastal real estate markets are sensitive to changes in beach width (Gopalakrishnan et al. 2011; Landry et al. 2003; Pompe and Rinehart 1995a, b). The costs—planning, construction, and periodic maintenance—are primarily paid by the federal government in the United States through the Army Corps of Engineers (ACE). As of 2009, federal expenditures on beach nourishment in the United States totaled $2.9 billion (Coburn 2009), and as climate changes, demand for nourishment and other shoreline stabilization efforts will continue to grow. This growth raises questions about whether public funds are being spent effectively and whether our current approach to shoreline stabilization is a viable long-term coastal climate adaptation strategy.

Although shoreline stabilization projects that receive federal funding are subjected to a benefit-cost analysis by ACE, projects are neither spatially coordinated nor prioritized on the basis of spatial-dynamic shoreline changes; in essence, individual communities make local decisions about beach nourishment without regard for the impacts on other communities. Because shoreline stabilization alters future coastline change, actions of an individual community potentially create spatial externalities (positive or negative) through spatial-dynamic feedbacks in the physical coastal system (Murray et al. 2013; Ells and Murray 2012; Slott et al. 2008; Pelnard-Considere 1956). Spatial-dynamic models are distinct from spatial models with dynamics; when a system exhibits spatial-dynamics, the current state variable in one location influences the state variable in another location in future periods (Smith et al. 2009a). When communities are adjacent, for example, a community that widens its beach through nourishment loses sand to a neighboring community with a narrow beach through the process of alongshore sediment transport (Dean 2002). The state of one beach directly affects the state of the other beach in the future, and the strength of this influence depends on the spatial gradient in coastline position. In previous work, numerical models of coastline evolution with spatial interactions between alongshore towns have found the emergence of an alternating pattern of towns that nourish less frequently due to spillover benefits from a neighboring town ("free riders") and towns that nourish more frequently because of sediment loss to neighboring town ("suckers") (Williams et al. 2013). Whereas spatial feedbacks in the physical shoreline dynamics have been studied (Williams et al. 2013; Slott et al. 2008), the policy implications of these spatial-dynamic interactions remain largely unexplored. The physical dynamics of shoreline change induce spatial interactions that ultimately question the logic of the status quo decentralized approach. What are the distributional consequences of such spatial-dynamic interdependence? Can coastal communities better adapt to climate change and rising sea levels if they coordinate nourishment decisions? If so, how might the ACE facilitate this coordination by altering its current approach to subsiding nourishment? We explore these questions using a dynamic model of beach nourishment decisions in two adjacent communities with spatial spillovers in the evolution of beach width.

In this paper, we model the behavior of two adjacent communities that adapt to shoreline change through beach nourishment policy, and the spatially linked evolution of beach width in response to nourishment and physical processes (Fig. 1). Spatial externalities are due to the alongshore spread of beach sand from a wide beach to a neighboring narrow beach. The spread of sand creates incentives for the community with a wider beach to minimize loss of beach sand by decreasing its cross-shore position relative to its neighbor. Similarly, the community with a narrow beach has an incentive to maintain a difference in cross-shore positions to increase gains from sediment transport. Therefore both communities nourish suboptimally.

(A) Stylized Coastal Dynamics

(B) Alongshore Diffusion of Beach Nourishment

(C) Cross-shore Diffusion of Beach Nourishment
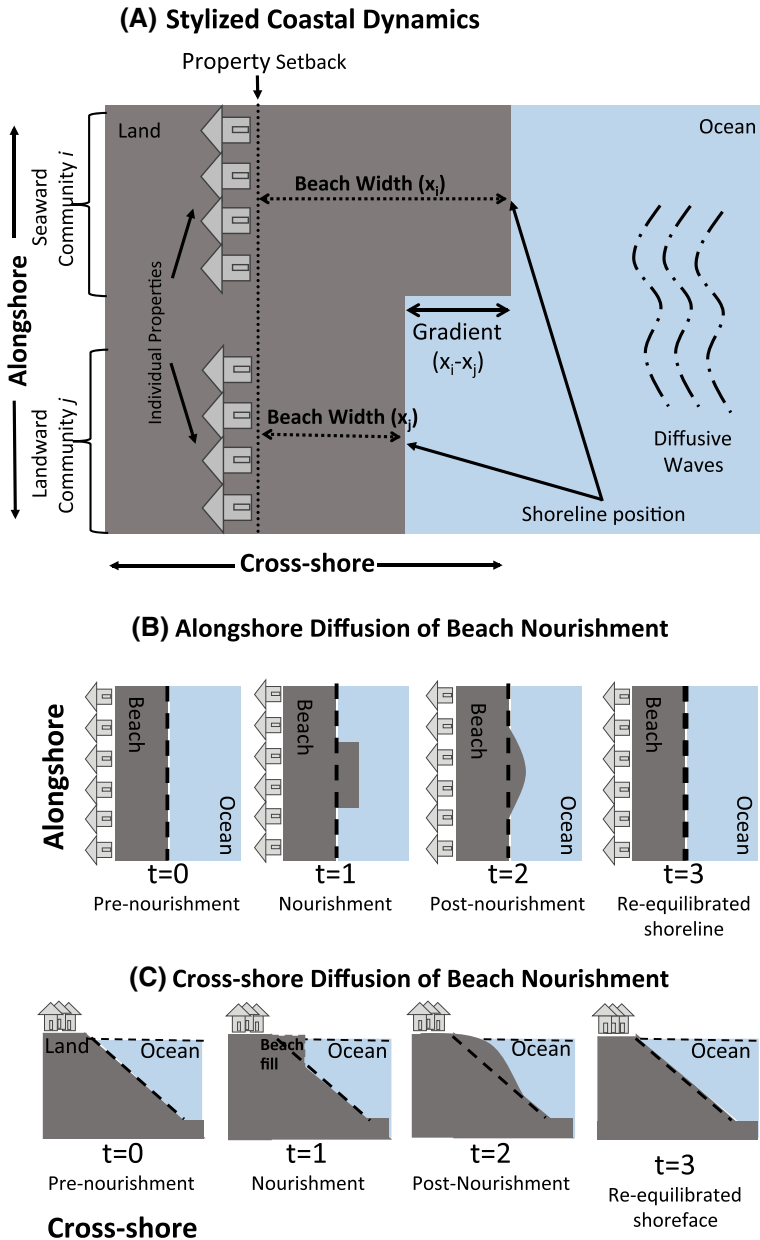
Fig. 1 Simplified coastal dynamics with nourishment. **A** Diffusion of nourishment sand from the wide beach to narrow beach depends on the gradient in shoreline position. **B** Alongshore diffusion of nourishment sand. **C** Cross-shore relaxation of nourishment as shoreface returns to equilibrium profile

Consequently long-run beach width and property values are lower in both communities under the status quo decentralized management than they would be under spatially coordinated management, a result that parallels the classic prisoner's dilemma. Intensifying erosion—consistent with accelerating sea level rise—exacerbates the problem and increases losses from failure to coordinate. Decentralized management fails to achieve the social optimum

and the disincentive to coordinate suggests the need for higher-level government intervention to address what has been viewed traditionally as a local problem.

Our analysis, while specifically applied to coastal climate adaptation, is part of a growing literature on the spatial-dynamics of renewable resources (Brock and Xepapadeas 2010; Smith et al. 2009a). Spatial interaction between two coastal communities is similar to edge effects in agricultural decision-making (Lewis et al. 2011; Parker and Munroe 2007) as well as the control of a biological invasion that disperses over space creating incentives for property owners to coordinate management (Fenichel et al. 2014; Epanchin-Niell and Wilen 2012; Bhat and Huffaker 2007). Spatial-dynamic feedbacks also influence optimal patterns of harvesting renewable resources (Costello and Polasky 2008; Sanchirico and Wilen 2005). However, an important difference in our application is that the value of shoreline stabilization (beach width) is inherently tied to its location, unlike other resources where the ultimate source of value is the market for the extracted resource, which is beyond the spatial context of the resource.

Our work adds to the existing literature in three ways. To our knowledge, this is the first attempt to incorporate spatial-dynamic interactions in an empirically grounded forward-looking model for managing the physical coastal environment. Second, we show that the distributional consequences of decentralized management can be significant in the presence of spatial externalities. Despite large efficiency gains from coordination, both sea level rise and economic heterogeneity increase inequality in the distribution of benefits across communities and hinder coordination. Finally, we show that a spatially targeted policy that differentially subsidizes local nourishment can achieve welfare-maximizing outcomes.

2 Beach Nourishment with Spatial–Dynamic Interactions

We model beach stabilization as a differential game, where the payoff-relevant state for each player is a set of first order differential equations and the payoff functions are integrals of the instantaneous benefits over time (Fudenberg and Tirole 1991). The unit of analysis is a coastal town making decisions about beach stabilization. Beach width is measured by the distance from the line of development to the cross-shore position of the coastline. Instantaneous benefits from beach amenities are an increasing concave function of width $x(t)$; $B(x(t)) \geq 0$, $\frac{\partial B}{\partial x} \geq 0$, $\frac{\partial^2 B}{\partial x^2} \leq 0$. Nourishment costs are convex and increasing in the level of nourishment (width added $u(t)$); $C(u(t)) \geq 0$, $\frac{\partial C}{\partial u} \geq 0$, $\frac{\partial^2 C}{\partial u^2} \geq 0$. The beach manager in each town chooses continuous nourishment levels to maximize the discounted sum of net benefits.

$$\max_{u_i} \int_0^\infty e^{-\delta t} \left[B_i(x_i(t)) - C_i(u_i(t)) \right] dt$$
$$s.t. \quad \dot{x}_i, \dot{x}_j; \quad i, j \in [1, 2], \; i \neq j \tag{1}$$

2.1 Spatial–Dynamic Interdependence

In general, beach erosion responds to cross-shore sediment transport caused by changes in sea level (Bruun 1962) and to gradients in the alongshore transport of sediment (Wolinsky and Murray 2009). Figure 1 provides a stylized introduction to coastal management terminology, how state variables are defined, and forces that influence the state equations. Alongshore sediment transport is caused by surf zone currents driven by local wave action, and the magnitude of sediment transport depends on the relative angle that approaching waves make with the shoreline (Ashton et al. 2001; Inman and Bagnold 1963). Beach nourishment alters both alongshore and cross-shore dynamics (Fig. 1B, C). Nourishment at one location along the

shoreline creates a bump that perturbs alongshore sediment transport by changing the relative angle between approaching waves and the shoreline. On most shorelines, wave action tends to smooth the resulting plan view bump (Slott et al. 2008; Ashton and Murray 2006a). With two adjacent communities, nourishment at one location can cause the shoreline to accrete (or to erode more slowly) at the neighboring location (Fig. 1B). The relative gain of beach sand occurs equally strongly in both the 'downdrift' direction (the direction of net sediment transport) and the 'updrift' direction (Slott et al. 2010, 2008). Alongshore spatial impacts of nourishment can be modeled as diffusion of the plan-view shoreline shape (e.g. Dean 2002; Ashton and Murray 2006a). The relative wave angle determines instantaneous diffusivity, and the wave climate, which is the distribution of wave influences from different approach angles, determines the long-term effective diffusivity of the coastline shape (Ashton and Murray 2006b). A nourished section of the shoreline also tends to erode faster in the cross-shore direction and spread sand in the alongshore direction as the beach returns to its equilibrium profile (Fig. 1C).

In this model, spatial-dynamic interaction is introduced through state equations. At any given time beach width in Community i $(x_i(t))$ depends on the width in Community j $(x_j(t))$. Because beach amenity benefits that accrue to each community are tied to width at that location, and the sand transfer from (or to) the neighboring community, each town's optimal nourishment decision depends on the two state variables $(x_i(t), x_j(t))$. The beach manager's problem is distinct from other models characterized by spatial differential games (e.g. List and Mason 1999) because of the nature of spatial-dynamic interactions in which the gradient between the two states determines flows across space. Transition dynamics of beach width in a location therefore depend on the level of nourishment, current width, and the difference in beach width (gradient) between the two communities.

$$\dot{x}_i = f(x_i, u_i) + D(x_j - x_i) \tag{2}$$

Beach width increases with the level of nourishment, $\frac{\partial f(x_i, u_i)}{\partial u_i} > 0$. A wider beach due to nourishment policy erodes faster as the shoreline tends to return to its equilibrium profile, $\frac{\partial f(x_i, u_i)}{\partial x_i} < 0$. Sediment transfer from (or to) a neighboring beach depends on the relative width in the neighboring beach, $\frac{\partial \dot{x}_i}{\partial x_j} = D \geq 0$. Shoreline dynamics and active management via nourishment, make beaches in neighboring towns strategic complements (Bowles 2009). The diffusion constant, D, determines the rate of sediment transfer. In the context of beach management, $D \in [0, 1]$ can be interpreted as the distance between two adjacent beaches; lower values of D imply that the two beaches are farther away and actions in one location have a lesser impact on the width in the other location.

2.2 Decentralized Management

Decentralized management is modeled as a non-cooperative open loop game, in which the two communities choose nourishment rates $(u_i(t))$ that maximize the discounted stream of net benefits from their own beach taking the actions of the neighboring community as given, and subject to two state equations $(\dot{x}_i, \dot{x}_j)$ representing the shoreline dynamics in each location. The Current Value Hamiltonian (CVH) for community i is given by:

$$\tilde{H}_i\left(x_i, x_j, u_i, \lambda_i^i, \lambda_j^i\right) = B_i(x_i) - C_i(u_i) + \lambda_i^i\left(f_i(x_i, u_i) + D(x_j - x_i)\right)$$
$$+ \lambda_j^i\left(f_j(x_j, u_j) + D(x_i - x_j)\right) \tag{3}$$

where λ_i^i and λ_j^i are the shadow values associated with a change in the beach width in town i and town j, respectively. Applying the Pontryagin's maximum principle, necessary conditions for optimal nourishment in town i (taking town $j's$ actions as given) imply:

$$\frac{\partial \widetilde{H}_1}{\partial u_i} = 0 \Rightarrow \lambda_i^i \left(\frac{\partial f_i(\cdot)}{\partial u_i}\right) = \left(\frac{\partial C}{\partial u_i}\right). \tag{4}$$

The marginal value of adding a unit of beach width in each community is equal to the marginal cost of nourishment.

$$\dot{\lambda}_i^i = \delta \lambda_i^i - \left(\frac{\partial B_i}{\partial x_i} + \lambda_i^i \left(\frac{\partial f_i(\cdot)}{\partial x_i}\right) - D \left(\lambda_i^i - \lambda_j^i\right)\right) \tag{5}$$

$$\dot{\lambda}_j^i = \delta \lambda_j^i - \left(\lambda_j^i \left(\frac{\partial f_j(\cdot)}{\partial x_j}\right) + D \left(\lambda_i^i - \lambda_j^i\right)\right) \tag{6}$$

Under steady state conditions $\dot{\lambda}_i^i = \dot{\lambda}_j^i = 0$, Eq. (5) implies that

$$\lambda_i^i = \frac{\left(\frac{\partial B_i}{\partial x_i}\right) - D \left(\lambda_i^i - \lambda_j^i\right)}{\left(\delta - \left(\frac{\partial f_i(\cdot)}{\partial x_i}\right)\right)} \tag{7}$$

The shadow value of a wider beach in town i represented in Eq. (7) reflects a discount-adjusted perpetuity value of amenity flow from the width added net the loss from sediment transfer to the neighboring beach. Equation (7) includes three components (i) the perpetuity value of direct amenity flow benefits from the additional width, (ii) loss in the indirect benefits of sediment flow from neighboring beach (if $x_i < x_j$) resulting from a lower gradient (or cost of additional sediment transfer to the neighboring beach if $x_i > x_j$), and (iii) adjusted discount due to increased erosion rate. Because $\frac{\partial f(x_i,u_i)}{\partial x_i} < 0$, increase in erosion as the nourished beach returns to equilibrium profile increases the discount rate of perpetuity benefits. Accelerated erosion of a nourished beach can be interpreted as a depreciation rate of investment in natural capital, which reduces the shadow value of beach width. In the absence of spatial interaction $D = 0$ and the shadow value is the depreciation-adjusted perpetuity value of benefit from capital investment in additional beach width. Equation (7) shows that spatial-dynamic interactions reduce the shadow value of beach width by subtracting value of sediment transfer from the marginal benefit of beach width.

Strategic interaction in management decisions between the two towns arises because of potential gains from sediment transfer. Under steady state conditions, Eq. (6) implies

$$\lambda_j^i = \frac{D \left(\lambda_i^i - \lambda_j^i\right)}{\left(\delta - \left(\frac{\partial f_j(\cdot)}{\partial x_j}\right)\right)} \tag{8}$$

The shadow value of a wider neighboring beach is the erosion adjusted perpetuity value of benefits from sediment flow (if $x_i < x_j$) resulting from a higher gradient in width (or savings in sediment transfer, if $x_i > x_j$, to neighboring beach due to decrease in gradient). The value of indirect benefits through the diffusion of nourishment sand depends on the diffusion constant (D) and the difference in marginal value of increased beach width in the two locations $\left(\lambda_i^i - \lambda_j^i\right)$. In the absence of any spatial interaction, the community derives no indirect benefits from sediment transfer. To determine optimal nourishment paths, the system of Eqs. (4)–(6) can be solved with state transition equations $\dot{x}_i, \dot{x}_j$ given by (2) and transversality conditions that require $\lim_{t \to \infty} e^{-\delta t} \lambda_i^i x_i = 0$.

2.3 Social Planner's Problem

In the coordinated management scenario, a social planner simultaneously chooses nourishment levels in both towns to maximize the joint net benefits.

$$\max_{u_1, u_2} \int_0^\infty e^{-\delta t} \sum_{i=1}^2 \left(B_i \left(x_i \left(t \right) \right) - C_i \left(u_i \left(t \right) \right) \right) dt, \; s.t. \dot{x}_1, \dot{x}_2, \text{ with CVH given by:}$$
(9)

$$\tilde{H} = \sum_{i=1}^2 \left[B_i \left(x_i \left(t \right) \right) - C_i \left(u_i \left(t \right) \right) \right]$$
$$+ \sum_{i=1}^2 \left[v_i \left(f \left(x_i, u_i \right) + D \left(x_i - x_j \right) \right) \right], \; j \in [1, 2], \; i \neq j$$
(10)

Optimality conditions, similar to the case of decentralized management, imply that marginal benefits from nourishment equal the marginal costs at each beach.

$$\frac{\partial \tilde{H}}{\partial u_i} = 0 \Rightarrow v_i \left(\frac{\partial f_i \left(\cdot \right)}{\partial u_i} \right) = \frac{\partial C_i}{\partial u_i}$$
(11)

$$\dot{v}_i = \delta v_i - \left(\frac{\partial B_i}{\partial x_i} + v_i \left(\frac{\partial f_i \left(\cdot \right)}{\partial x_i} \right) - D \left(v_i - v_j \right) \right)$$
(12)

Under steady state conditions, $\dot{v}_i = 0$ and $v_i = \frac{\frac{\partial B_i}{\partial x_i} - D(v_i - v_j)}{\left(\delta - \frac{\partial f_i (\cdot)}{\partial x_i} \right)}$, similar to Eq. (7). The shadow value of a wider beach reflects the erosion adjusted perpetuity value of increased amenity flow net of loss due to sediment transfer to neighboring beach (or reduced sediment flow from neighbor). By internalizing the benefits from sediment transfer, the social planner eliminates the incentive to free ride; the shadow value of indirect benefits from sediment transfer from a wider beach in the neighboring town $\left(\lambda_j^i \right)$ is eliminated. The system of Eqs. (11), (12) can be solved with state transition equations $\dot{x}_i, \dot{x}_j$ given by (2) and transversality conditions to determine socially optimal nourishment paths. Key analytical results are summarized in Table 2.

3 Empirical Calibration and Numerical Methods

3.1 Benefits Function

Benefits from nourishment are based on empirical estimates of beach value for the coast of North Carolina (Gopalakrishnan et al. 2011). Converting beach value, capitalized in coastal property values in a hedonic price function, into a flow of amenities, the instantaneous benefits to each community can be written as an exponential function of beach width. Benefits from a wider beach decline after reaching a critical maximum width as shown by previous recreational demand studies (Whitehead et al. 2008; Parsons et al. 1999).

$$B_i \left(t \right) = \delta \alpha_i \left(x_i \left(t \right) \right)^\beta - \varphi \left(x_i \left(t \right) \right)^2$$
(13)

$x_i \left(t \right)$ is the beach width in town i at time t, α_i is the baseline value (attributable to all structural, neighborhood and environmental characteristics except beach width) of an average property in community i, β is the marginal value of beach width (price elasticity of width) estimated in a hedonic price function, δ is the discount rate (also assumed to be the capitalization rate) and φ is a parameter that causes beach values to decline beyond a threshold width.

We parameterize the capitalized benefits from nourishment to reflect coastal property values in North Carolina. Assuming an average width of 30 m, baseline property value of \$200,000 ($\alpha_i = 200$), price elasticity of width $\beta = 0.5$, and $\varphi = 0.001$, the value of a oceanfront property in the base case is approximately \$1,000,000, which is representative of housing prices in North Carolina based on previous studies (Gopalakrishnan et al. 2011). We examine the effect of economic heterogeneity by allowing baseline property values (α_i) to vary across towns. Future values are discounted (δ) at 6%.

3.2 Cost Function

The costs of nourishment in community i are an increasing function of rate of nourishment:

$$C_i(t) = c(u_i(t))^2 \tag{14}$$

$u_i(t)$ is the rate at which beach width is added (m/year) in town i. We assume quadratic costs because the volume of sand needed will increase in a non-linear manner with the extent of beach build out. A greater depth needs to be filled with increases in the width added or rate of nourishment. The cost parameter c embeds both variable costs of nourishment sand and the fixed cost, which is divided among the total number of oceanfront properties in the community. By folding both into one parameter, our model predicts continuous rather than periodic nourishment (Smith et al. 2009b), and can be interpreted as averaging nourishment over discrete intervals. To determine the cost parameter c we estimate the cost function using data on nourishment projects in North Carolina between 1939–2006 (PSDS 2006).

The cost of a single nourishment project at time t in a coastal town i with N oceanfront properties can be written as $C_{it} = L_i \phi u_{it}^2 \left(\sum_{t=1939}^{2006} e^{\omega_t Y_t} \right) \varepsilon_{it}$, where L_i is the alongshore length of the nourished beach, Y_t is an indicator variable that takes the value 1 in the year of nourishment, u_{it} is the nourishment rate and ε_{it} is an idiosyncratic error term. After taking logs and rearranging terms we estimate the function $Z_{it} = \psi + \sum_{t=1939}^{2006} \omega_t Y_t + \eta_{it}$, where $Z_{it} = \ln(C_{it}) - \ln(L_i) - 2\ln(u_{it})$ and $\psi = \ln(\phi)$ We use the estimated nourishment cost function for a representative beach 10 km long, controlling for the time of nourishment using estimates $\hat{\omega}_t$ for the most recent year of nourishment in the data (2006). See Appendix Table 3 for estimation results. The estimated cost function can then be written as $\hat{C}(t) = F\hat{\phi}(u(t))^2$ where $F = L\exp(\hat{\omega}_t)$ is the fixed cost divided between N oceanfront properties. Assuming there are 50 oceanfront properties and $L_i = 10$kms, the average nourishment cost per property is $\frac{\hat{C}(t)}{N} = \frac{F}{N}\hat{\phi}(u(t))^2$ We get $c = \frac{F}{N}\hat{\phi} = 1.57$, which is the parameter used in the numerical analysis.

We parameterize the benefits and cost function using empirical estimates for North Carolina, however, the model can easily be generalized to any sandy shoreline.

3.3 Sand Diffusion Dynamics

The state equations representing transition dynamics for beach width are based on geomorphological models of coastal evolution (Ashton and Murray 2006a, b). We assume that adjacent beaches face similar physical environments and erosion rates. Suppose the alongshore length of each community is z kms and there is no sediment flow at the boundary (zero-flux boundary condition), the community-scale discretized alongshore gradient in sediment flux (ΔS) drives changes in the cross-shore width of beach i through time as:

$$\frac{\Delta S}{\Delta t} = \left(\frac{\frac{(x_j(t) - x_i(t))}{z} - 0}{z} \right) = \left(\frac{(x_j(t) - x_i(t))}{z^2} \right) \Rightarrow \frac{\Delta S}{\Delta t} \propto (x_j(t) - x_i(t))$$

Table 1 Parameters used in numerical simulation

Parameter	Description	Value
α	Baseline property value (1000s $)	200
β	Price elasticity of beach width	0.50
c	Nourishment cost	1.57
Υ	Linear erosion rate due to SLR (m/year)	1.00
μ	Exponential retreat of nourished beach	0.05
D	Sand diffusion rate	0.10
δ	Discount rate	0.06

The sediment transfer function above indicates that, in continuous space, alongshore sediment transfer becomes a diffusion function $\left(\frac{\Delta S}{\Delta t} = K \frac{\partial^2 x}{\partial z^2} \right)$. Here, we represent the component of shoreline-change resulting from alongshore sediment transfer by $D\left(x_2\left(t\right) - x_1\left(t\right)\right)$, where the constant D absorbs the diffusion coefficient (K), the alongshore length (z), and the depth to which erosion is distributed across the seafloor (the effective 'shoreface' depth). State transition equations for beach width in each town reflect diffusion of sand from the wider to narrower beach:

$$\dot{x}_i = -\gamma - \mu x_i\left(t\right) + u_i\left(t\right) + D\left(x_j\left(t\right) - x_i\left(t\right)\right); \quad i, j \in [1, 2], \ i \neq j \quad (15)$$

Change in beach width in town i depends on a linear erosion rate (γ) attributable to sea level rise and other factors that uniformly affect the domain, cross-shore exponential relaxation as the nourished beach returns to equilibrium (μ), the rate of nourishment ($u_i\left(t\right)$), and the diffusion constant D. Although we treat beach nourishment as a continuous addition of width, rather than explicitly treating beach-width variations within discrete nourishment intervals, varying the value of μ represents variation in the initial cross-shore geometry of a nourishment project. Additional beach width can be associated with varying amounts of subaqueous sand addition, spread over varying depths. Holding the extent of beach build-out constant, adding more subaqueous sand spread to a greater depth reduces the rate at which nourishment sand is lost to cross-shore redistribution (corresponding to a smaller value of μ). Nourishment in town i increases its own beach width $\left(\frac{\partial \dot{x}_i}{\partial u_i} \geq 0 \right)$ and causes accretion (or less erosion) in location j $\left(\frac{\partial \dot{x}_j}{\partial x_i} \geq 0 \right)$.

We parameterize the model using average erosion rates for North Carolina. We assume that both towns face a background erosion rate (γ) of 1 m per year, exponential retreat of nourishment sand (μ) at 5% per year, and a diffusion constant D = 0.1. All parameters used in the numerical analysis are presented in Table 1.

3.4 Numerical Methods

We model the behavior of adjacent towns as an open loop problem because beach managers are not presumed to behave strategically in response to contemporaneous actions in the neighboring beach. Rather, incentives are transmitted through the spatial-dynamic interactions of the state variables. Moreover, the funding approach for beach nourishment requires communities to commit to long-term nourishment strategies. Strategically adapting in a closed loop fashion to one's neighboring community may not be a realistic behavior in the context of our policy problem.

Shoreline evolution under decentralized management is characterized by solving the differential game in (1) to determine equilibrium strategies for both communities simultaneously choosing nourishment rates taking their neighbor's action as given. Steady state width in each location is a saddle point determined by the setting transition functions $\dot{x}_i$, $\dot{x}_j$, $\dot{\lambda}_i^i$ and $\dot{\lambda}_j^i$ equal to zero. We solve the boundary value problem characterized by Eqs. (4–6) and state transition functions in Eq. (15) to determine the unique saddle path for optimal nourishment in each town given initial width x_1^0 and x_2^0. Optimal nourishment paths represent an open loop Nash equilibrium (OLNE) that are only a function of time $(u_1(t), u_2(t))$ and do not depend on the current state variables $(x_1(t), x_2(t))$. We similarly solve the coordinated management problem as a boundary value problem to recover optimal paths of beach width and nourishment decisions for both communities. The boundary value problem is solved numerically (using a built-in routine BVP4C in MATLAB) to calculate the optimal nourishment path. Initial conditions for the beach width in each community, $x_1^0 = 20$ m and $x_2^0 = 60$ m, and terminal conditions for the co-state variables $\left(\lambda_i^i, \lambda_j^i\right)$ are used to solve the system of ODEs represented by the first order conditions for each community with the action rule for the other community implicit in the transition equation. In the case of coordinated management, we solve the boundary value problem simultaneously choosing optimal nourishment paths for both communities with the first order conditions for maximization problem represented in (9).

4 Results

4.1 Decentralized Versus Coordinated Management

Two adjacent towns face similar physical and economic environments with differences only in initial beach widths. Using parameters described in Table 1, we solve the optimal control problems given by Eqs. (1) and (9). The decentralized management outcome, determined in a non-cooperative game when each community chooses nourishment taking its neighbors actions as given, leads to the same steady-state width of 24 m in both communities. Because the two towns are identical except for initial beach width (due to nourishment policy), the system converges to a flat shoreline with the town 1 (lower initial width) initially gaining sand through alongshore sediment transport (Fig. 2A, C). Under coordinated management, where a coastal planner simultaneously chooses nourishment in both towns to maximize the joint net benefits, the system converges to a flat shoreline with a higher steady-state beach width of 35 m in both communities (Fig. 2B, D).[1]

Beach nourishment with spatial interaction between two communities is not a zero-sum game in which one participant's gain or loss is exactly balanced by the losses or gains of the other participant. A concave benefits function, which the empirical literature supports (Gopalakrishnan et al. 2011; Landry and Hindsley 2011; Pompe and Rinehart 1995a), implies that the benefits from sediment transfer to the town with a narrower beach (Community 1) are greater than the losses to the town with a wider beach (Community 2). The community with a wider beach will nourish its beach as long as the marginal benefits are greater than the sum of nourishment costs and value of width lost due to sediment transfer. Long-term value of beach stabilization is higher under the coordinated policy. Although net benefits under coordination are lower in the early years, there are long-run benefits that more than

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[1] The long-run equilibrium under coordination is equal to the optimal steady-state width in the baseline case of a single representative community without spatial interaction.
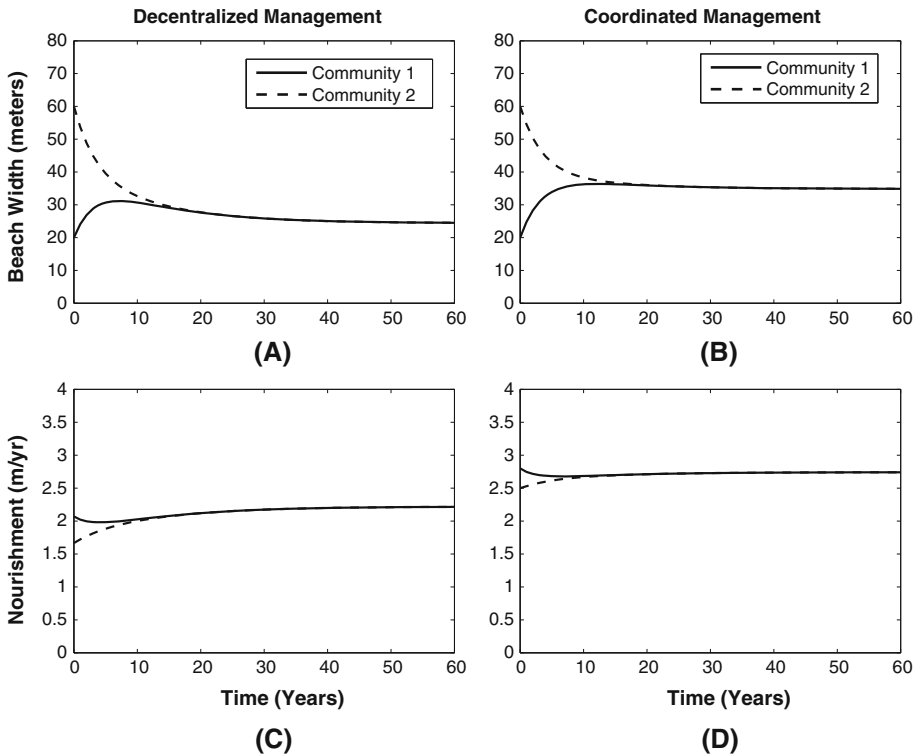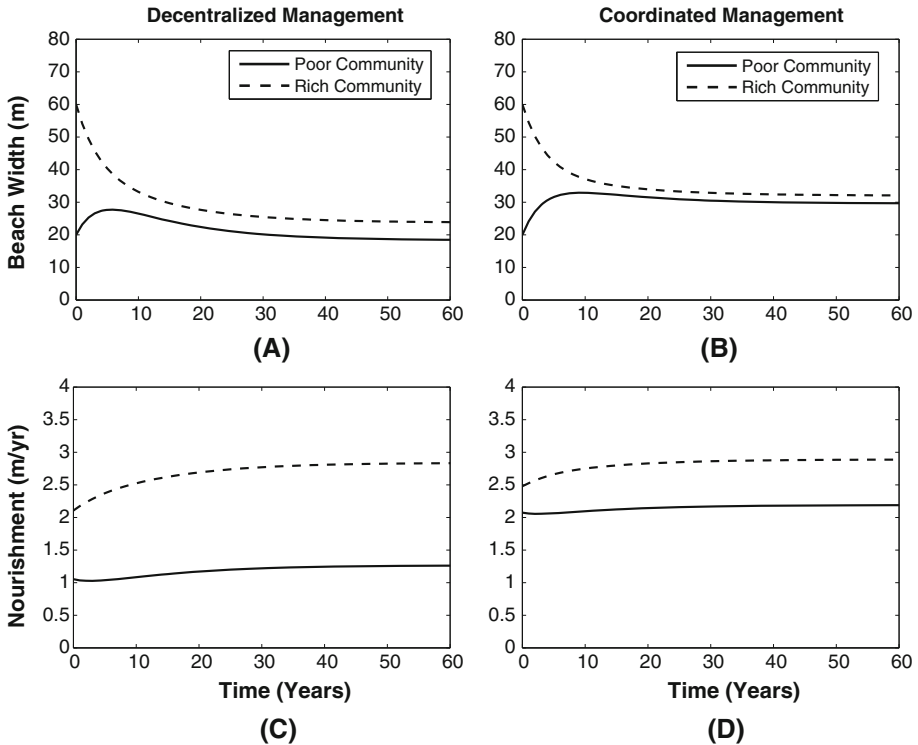
Fig. 2 Optimal beach width under coordinated and decentralized management when both towns face similar physical and economic conditions. **A**, **C** Decentralized management leads to a flat steady-state beach width of 24 m. In the short term, the town with a narrower beach nourishes more but also benefits from its neighbor's nourishment effort via alongshore sediment transport. **B**, **D** Coordinated management leads to a to a higher steady-state width of 35 m. Both towns increase nourishment and receive higher long-term benefits

offset these short-run costs. Coordination increases the value of an average coastal property by approximately 4 %.

4.2 Gains from Coordination in the Presence of Economic Heterogeneity

Beach nourishment policies vary across space. Empirical work has shown that richer towns are more likely to nourish because benefits from nourishment are greater in towns with higher baseline property values, whereas costs are comparable (Gopalakrishnan et al. 2011). To explore the impact of economic heterogeneity, we vary the baseline property values across communities and allow the rich community to begin with the wider beach. We assume parameter values that reflect beachfront properties in Wrightsville Beach (rich town with baseline property values of \$250,000; $\alpha_2 = 250$) and Carolina Beach (poorer town with baseline property values of \$100,000; $\alpha_1 = 100$) in North Carolina (Gopalakrishnan et al. 2011). Comparing optimal trajectories we find that the rich community always maintains a higher steady-state width. However, relative to the decentralized outcome, coordination leads to wider beaches in both communities, and decreases the difference in the beach width across communities (Fig. 3A,B).

Fig. 3 Optimal beach width under coordinated and decentralized management with economic heterogeneity. **A**, **B** Steady-state beach widths are not equal with economic heterogeneity, but the difference is lower under coordinated management. Coordination leads to wider beaches in both towns. **C**, **D** Coordination leads to more nourishment in both towns but the poorer community (with narrower initial beach in this case) significantly increases nourishment (relative to decentralized management) and subsidizes the richer town (with wider initial beach) by reducing diffusive losses

Economic heterogeneity has significant distributional consequences by placing a greater cost on the poorer community. It is optimal for the poorer town to increase nourishment effort even when its costs outweigh its private benefits (Fig. 3C, D). There are net gains from coordination, but the richer town gains value and the poorer town loses value even when it is the town that benefits through sediment transfer. Relative to the decentralized outcome, coordination results in 6% reduction in average property values in the poorer town and 5% increase in the richer town. Results are qualitatively similar when the poorer community starts with the wider beach (Appendix Fig. 8).

4.3 Gains from Coordination in Adapting to Sea Level Rise

The impact of sea level rise is modeled by increasing the background erosion rate (higher γ). Optimal nourishment paths are calculated for background erosion scenarios ranging from 0.5 to 6 m/year (Zhang et al. 2004). When the two towns are economically similar, increasing background erosion decreases the optimal long-run width and long-term net benefits. However, the loss in total benefits is lower with coordinated management.
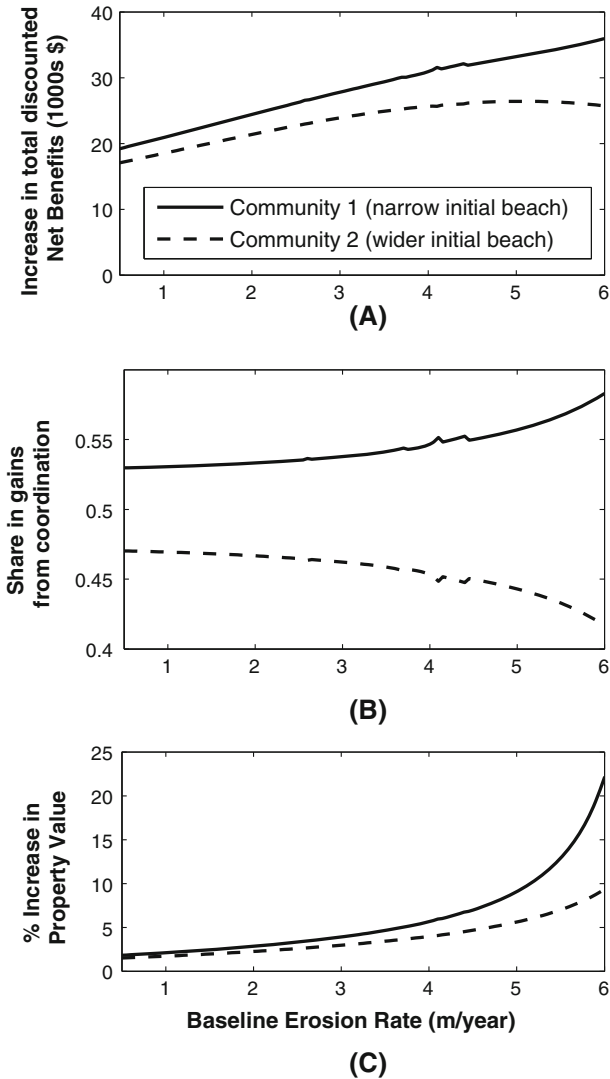
Fig. 4 Gains from coordinated management with increasing background erosion when the two towns have similar baseline property values. **A** Benefits from coordination increase for both towns as background erosion increases. **B** The free rider town gets a greater share in the total benefits from coordination (through sediment transfer) and inequality in the distribution of benefits increases with higher erosion rates. **C** Loss of property values with increased background erosion is lower relative to decentralized management. Relative increase in average property values (loss avoided) from coordination also increases with higher erosion rates

Both towns gain from coordination, but the community with narrow initial beach gains more due to alongshore sediment transfer (Fig. 4A). If coastal planners incorporate an expected increase in sea level rise into the decision process, communities can better adapt to climate change by adopting a coordinated shoreline management strategy. Inequality the distribution of benefits also increases with higher erosion rates, and the *"free rider"* community gets a larger share of the total benefits from coordination (Fig. 4B).
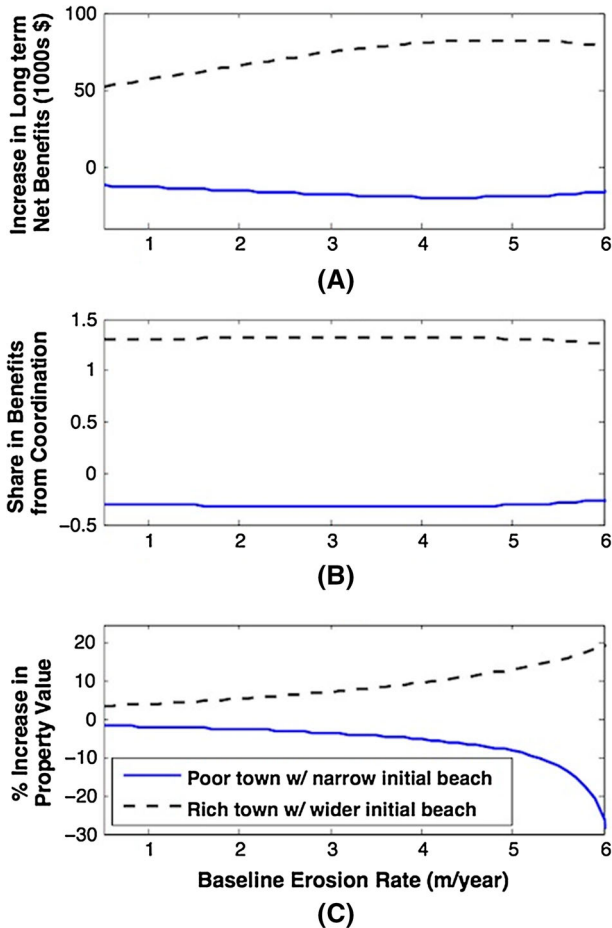
Fig. 5 Gains from coordinated management with increasing background erosion when the two towns have different baseline property values. **A** As background erosion increases, benefits from coordination increase for the richer town, but the poorer town loses value. **B** The town with lower baseline property values consistently subsidizes the richer town by increasing nourishment even when the costs outweigh private benefits (negative share in the total benefits from coordination). **C** Coordination enables the rich town to avoid loss of property values, but the value of an average property in the poor town could decrease by up to 30 % relative to decentralized management

When background erosion is high (6 m/year), property values in the landward town are over 20% higher under a coordinated policy relative to decentralized management (Fig. 4C).

When baseline property values vary across the two communities, the poorer town consistently loses value and the richer town gains under coordinated management (Fig. 5A, B). Furthermore, relative gains and losses to each community increase with higher erosion rates (Fig. 5C). When the poorer community is also the landward community, a high erosion rate (6 m/year) can lead to nearly 30% lower property values under a coordinated policy relative to decentralized management. Net gains from coordination remain positive, as the gains to the rich town outweigh losses to the poorer town.

4.4 Sensitivity Analysis

We examine sensitivity of results to parameter values for the price elasticity of beach width ($\beta \in [0.05, 0.75]$) and nourishment costs ($c \in [0.05, 5]$). Results are qualitatively similar and welfare gains from coordination persist. However, increasing beach values tend to increase the gains from coordination and higher nourishment costs tend to decrease the difference between decentralized and coordinated management. These sensitivity results are intuitive because a higher value of the state variable exacerbates the externality from coordination failure, whereas higher costs lead to lower optimal beach widths and thus dampen the externality. Figures 9 and 10 in the appendix show optimal steady state width and nourishment rates as a function of benefit and cost parameters.

We also test the sensitivity of results to alternative specifications of benefits and cost functions. To preserve concavity of benefits and convex costs, we assume $B_i(t) = \alpha_i \beta' \ln(x_i(t))$ and $C_i(t) = c'(x(t))^3$. With parameter values $\beta' = 0.1$, $c' = 1$, we resolve for optimal nourishment paths and compare decentralized management outcomes with coordinated management. Results, shown in the Appendix Fig. 11, are qualitatively similar to what we find in Sect. 4.1 with empirically grounded functional forms and parameters. Decentralized management leads to a flat steady-state beach width of 34 m. Coordinated management leads to a to a higher steady-state width of 41 m and both towns receive higher long-term benefits.

5 Optimal Spatial–Dynamic Policy

Coordinated management may allow beach nourishment to remain a climate adaptation strategy for a longer period and higher beach values in both towns along the coast. However, tradeoffs between higher total benefits and distributional equity create disincentives for communities to self-organize, requiring regulation to overcome barriers to coordination. We calculate an optimal spatially explicit nourishment subsidy policy to achieve the coordinated management outcome. With a subsidy $s_i(t)$ per unit of beach build-out (width added m/year) the net benefits from nourishment to community i at any given time can be written as:

$$NB_i(t) = \delta \alpha_i x_i(t)^\beta - \varphi x_i(t)^2 - cu_i(t)^2 + s_i(t) u_i(t) \qquad (16)$$

We numerically solve for optimal location-specific subsidies $(s_i(t), s_j(t))$ such that the solution to the decentralized management problem in (1) coincides with the social planner's solution in (9). Treated as transfer payments, subsidies do not enter the social planner's objective function, but they affect local nourishment decisions and can have distributional consequences through the impact on property values. To achieve the outcome of coordinated management the optimal subsidy must be equal to the external benefits from the diffusion of nourishment sand reflected in the shadow value of beach width. When the two towns have similar baseline property values ($\alpha_1 = \alpha_2 = 200$) and face similar physical environments, we find that the town with a wider initial beach receives a larger subsidy in the short run, but once optimal sediment transfer equalizes width in both towns they transition to a uniform subsidy policy (Fig. 6A). When baseline property values vary across towns ($\alpha_1 = 100$; $\alpha_2 = 200$), the welfare-maximizing outcome requires a larger subsidy for the poorer town. The richer town receives a lower subsidy and the subsidy decreases over time (Fig. 6B). Economic heterogeneity across coastal towns requires spatially targeted policies to achieve the first-best outcome. To further highlight the role of spatial heterogeneity, we compare the optimal location-specific policy with a second-best uniform subsidy policy, in which the total subsidy
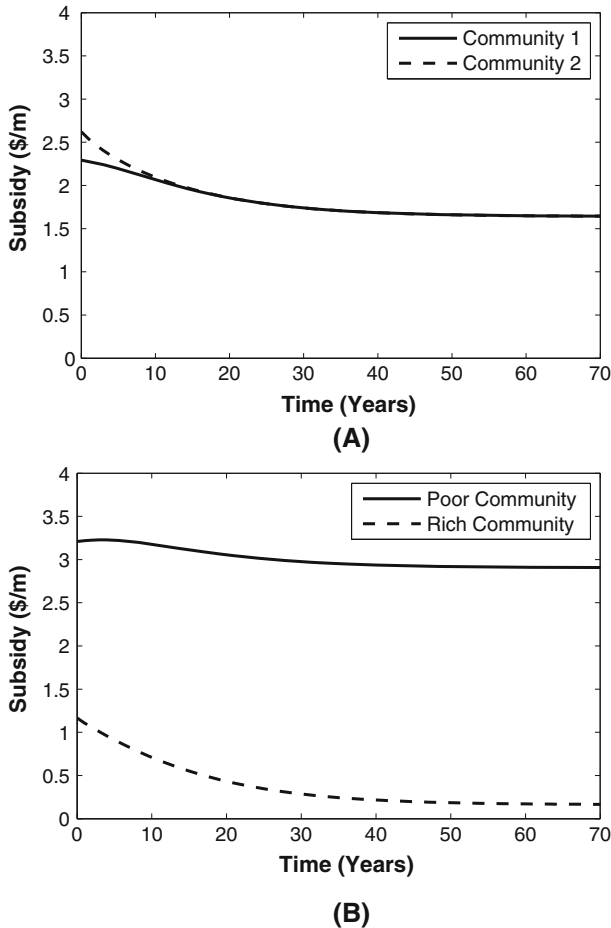
Fig. 6 Optimal subsidy schemes. **A** Both towns have similar baseline property values and face identical physical environments. Town with wider initial beach receives higher subsidy in the short run until diffusion leads to a flat coastline. **B** When there is economic heterogeneity, the town with lower baseline property values must receive a higher subsidy to enable optimal nourishment

calculated under the optimal policy is distributed uniformly to both communities. We find that the second-best policy leads to nourishment outcomes that are close to the optimal solution when the two towns have similar baseline property values (Figs. 7A, B), but when baseline property values are different, uniform subsidy leads to over-nourishment in the town with high property value (Fig. 7C, D), which gains value whereas the town with lower property values loses value, regardless of which town has a wider initial beach. A policy of uniform nourishment subsidy to heterogeneous towns exacerbates distributional inequality. A uniform subsidy policy results in 1.6% lower values in both towns relative to optimal spatially targeted subsidies when the two towns have similar baseline values. However, when there is economic heterogeneity, a uniform subsidy results in 8% lower value of an average coastal property in the town with lower baseline values and 1% increase in the value of an average property in the town with higher baseline values. Key numerical results and policy implications are summarized in Table 2.
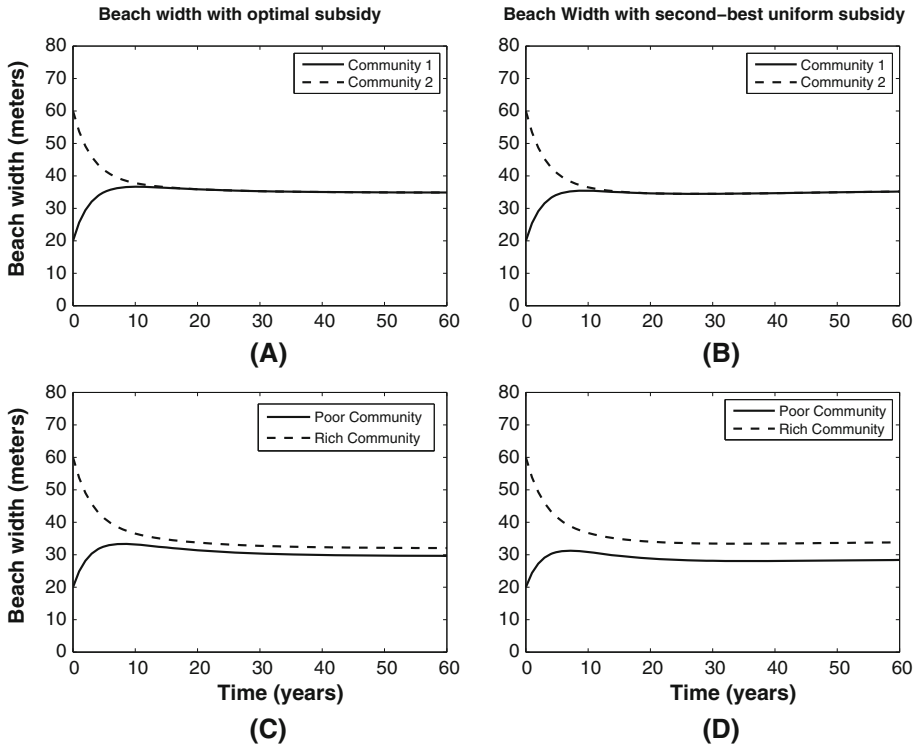
Fig. 7 Shoreline evolution with optimal spatially targeted nourishment subsidy versus a uniform subsidy scheme **A**, **B** When both towns have similar baseline property values, shoreline evolution under the second-best uniform subsidy scheme is similar to the outcome under optimal subsidy scheme. **C**, **D** With economic heterogeneity, a uniform subsidy scheme results in over nourishment in the rich town. Poorer town loses value and the rich town gains value

6 Discussion

We made simplifying assumptions in our analysis that suggest areas for future research. For example, our model takes a community as the unit of analysis, and we do not model alongshore sediment transport within a community. This assumption affords us tractability in the control theory but limits our ability to interpret the quantitative results. Also, the magnitudes of effects, both physical and economic, are likely to change if we increase the geographic scale beyond two communities. However, we do not expect the qualitative results to change, and our exploration of the feedbacks between human actions and coastal dynamics offers insights for both scientific and policy domains. Generalizing the model to include multiple communities along a spatially extended coastline provides an avenue to introduce more realism and explore the robustness of our results in more complex settings. A more significant assumption is modeling the differential game as an open loop problem. Here too a benefit is tractability; there are no previous studies that have solved closed loop problems with nonlinear payoff functions and two interacting state variables. However, the implication is that our solution is not Markov perfect. From a policy perspective, an open loop solution conditional on initial states is appropriate when beach managers have to commit to a management strategy at the beginning of the planning horizon. It is theoretically possible that a closed loop feedback

Table 2 Key results and implications

	Implications
Analytical results	
1. Spatial-dynamic interactions reduce the shadow value of beach width by subtracting from the marginal benefit of beach width (Eq. 7)	Communities cannot capture the full value of their coastal management interventions; the benefits are shared by neighbors
2. Beach nourishment reduces the shadow value of beach width by adding capital depreciation to the discount rate (Eq. 7)	The adjustment to the discount rate in the beach problem is analogous to the adjustment of the discount rate by marginal net growth of a fish stock in optimal management of a renewable resource (Clark 2005)
3. Combining 1 and 2, in the absence of spatial-dynamics and beach nourishment, the shadow value of the beach is the perpetuity marginal benefit of beach width	Coastal management must account for both the spatial-dynamic features of the underlying geomorphology and the way in which nourished beaches behave differently from natural beaches
4. Decentralized beach management incentivizes free riding in proportion to: a) the diffusion coefficient, which controls spatial-dynamics in the physical system, and b) the economic gradient, which is the difference in values for marginal beach width. Free riding vanishes under centralized management. (Eq. 7 and 8)	The status quo, decentralized approach to coastal management in the U.S. underprovides coastal protection
Numerical results	
1. Coordinated management leads to wider beaches in both towns regardless of whether there is economic heterogeneity (Figs. 2, 3)	Underprovision of coastal protection specifically takes the form of narrower beaches that are more vulnerable to storms. This underprovision could increase the need for disaster relief
2. Coordinated management reduces the gradient between rich and poor towns but can force the poorer town to subsidize the richer town (Fig. 3)	There are strong economic incentives that prevent communities from coordinating on their own. Side payments from wealthier communities to poorer communities to nourish beaches could increase overall welfare
3. Increased erosion from sea-level rise increases the potential total gains from coordination across communities (Figs. 4, 5)	Coordinated coastal management will become increasingly important as climate changes
4. Increased erosion from sea-level rise increases inequality across communities (Figs. 4, 5)	The barriers to coordination increase as climate changes. Coordination is most difficult to achieve in a decentralized manner difficult when it is needed the most
5. Inequality is greater when economic gradients (rich versus poor town) align with physical gradients (wide versus narrow beach) (Fig. 5)	Properties of the physical system can exacerbate or mediate challenges stemming from economic heterogeneity
6. A second-best uniform subsidy leads to similar beach widths as a spatially delineated subsidy when communities have similar baseline property values despite an initial physical gradient (Fig. 7)	The status quo in the U.S. to subsidize beach nourishment is a reasonable approximation to the optimum in a hypothetical world with no variation in property values
7. Beach widths diverge under the uniform second-best subsidy and the spatially delineated subsidy when there is economic heterogeneity (Fig. 7)	In reality, because property values are heterogeneous across communities, a spatially delineated subsidy would be a superior policy instrument compared to the status quo

solution would address some (or all) of the spatial-dynamic externality that our spatially targeted subsidy seeks to address. But it is also possible that the externality is more severe than we have characterized it because communities in our model are making non-credible commitments (and potentially would nourish even less if following closed loop strategies). We leave these issues for future research.

Our model does not address the non-market environmental impacts of nourishment. Dredging nourishment sand can affect the benthos and even threaten endangered megafauna such as sea turtles. As such, there may be benefits in pursuing a quantity-based instrument for nourishment because a cap on total nourishment would provide a means to address cumulative environmental impacts. As nourishment activity increases in response to climate change, cumulative impacts will increase and marginal damages may also increase. Currently, environmental damages of dredging are not counted in the benefit-cost analyses done by the ACE; in the U.S. environmental impact studies are required under the National Environmental Policy Act, but impacts are not translated into non-market damages. Future research could explore tradeoffs across benefits (market and non-market) and costs (engineering costs and non-market damages) from nourishment and other shoreline stabilization efforts. Benefit-cost analyses along these lines will inform the role engineering solutions should play in coastal climate adaptation and to what extent retreat from rising seas is warranted.

The "nourishment dilemma," which stems from spatial-dynamic interactions in the coupled system, is different from the extensively studied problem of non-cooperation in managing a common pool resource (McCarthy et al. 2001; Ostrom et al. 1994). Coordination failures in our model emerge without constraints on the availability of nourishment sand. Nevertheless, sand and funding for nourishment projects are both scarce resources in reality, and as these dwindle, scarcity might reinforce coordination failures and trigger a race to dredge (McNamara et al. 2011). These challenges further highlight the need to rethink coastal adaptation strategies and consider a coordinated approach to coastal management as climate changes.

7 Policy Implications and Conclusion

Our analysis unequivocally shows that decentralized coastal management fails to address spatial-dynamic externalities that result from the physical system. Physical models show that stabilization efforts in one location can influence erosion in other locations along the coast for a wide range of coastline types (Lazarus et al. 2011; Slott et al. 2008, 2010). Our modeling casts these features in an optimal control framework and highlights circumstances in which spatial-dynamic externalities are more or less pronounced. Despite its long history in U.S. public policy, treating beach width as a non-spatial public good needs to be replaced by a higher level of coordination that recognizes the effects local shoreline interventions on neighboring and even distant beaches. In that sense, our problem echoes models of other renewable resource systems that highlight the need for spatially explicit policy instruments (Sanchirico and Wilen 2005; Brock and Xepapadeas 2010; Smith et al. 2009a).

Our analysis also clearly shows that climate change intensifies the need for coordinated coastal management. Sea-level rise and climate-induced changes in alongshore sediment transport accelerate coastline changes. This acceleration increases the benefits from coordination. These effects mean that communities feel the effects of each others' coastal interventions on shorter time scales. Failure to coordinate is a more immediate concern than in the past. Because spatial-dynamic interactions are transmitted through alongshore diffusion, this acceleration also implies that climate change effectively brings coastal neighbors closer to each other in space.

Unfortunately, coordination is unlikely to happen without top-down intervention. As the benefits of coordination grow, the inequality in outcomes also grows. While rich and poor coastal towns along sandy coastlines in the U.S. is largely a relative distinction, this phenomenon echoes broader themes in the climate literature that focus on disproportional impacts of climate change on the less fortunate (Mendelsohn et al. 2006). Along sandy coastlines, the effects of climate change may disproportionately fall on the less fortunate communities. We find that for some coastline configurations, optimal management would require a poor town subsidizing a rich town. We do not observe such cross-community subsidies empirically, either due to political barriers or due to failure to understand spatial linkages in the physical system. Nevertheless, the need for coordination is beginning to influence planning decisions in some coastal communities in the US (Kemp 2010).

Despite coordination challenges, there are elements of the current approach to coastal management that will facilitate effective coastal climate adaptation. Currently, nourishment projects in the US are primarily federally funded; roughly two thirds of nourishment costs are paid by the federal government. Requests from funding come from local communities as if projects provide local public goods and without any recognition of spatial interactions among communities. The conduit of federal funding for local projects is a precursor to a more spatially tailored approach with three possibilities. First, it may be possible for ACE to approve projects in a manner that approximates the coordinated management solution. Second, ACE may be able to adjust the federal subsidy rate to implement the spatial-dynamic Pigovian subsidy that we derive. Some communities would receive more than the two-thirds subsidy, while others would receive less. The difficulty, as in any Pigovian scheme, would be to determine the community-specific rates to achieve the desired outcome in the physical system. Third, because our results suggest the potential for a market in which a community with a narrow beach will be willing to pay a neighboring community to undertake nourishment, ACE may be able to facilitate a nourishment cap and trade system with sand permits or quotas, similar to other cap and trade systems for pollution permits (Montgomery 1972) or individually transferable quotas in fisheries (Grafton 1996; Christy 1973). Because our spatially targeted subsidy that mimics the coordinated social optimum is a Pigouvian subsidy, in the absence of uncertainty we would expect that a quantity instrument could achieve the same outcome. The challenge, however, would be developing the transfer coefficients that govern trading; sand in one location is not equivalent to sand in another location, and the shadow value of that sand changes over time. In other words, transfer coefficients would need to reflect spatial-dynamic factors (and not just spatial features as in the pollution hotspots literature).

Finally, beach nourishment has a role in climate adaptation but is not a panacea. We focus on nourishment because it is important for sandy coastlines and illustrates the broader spatial-dynamic challenges. However, the analytical model shows that beach nourishment ultimately depreciates and dampens the value of adding beach (compared to a natural beach). The more communities nourish beaches, the greater the cost and the higher the average erosion rates will be. With enough pressure from climate change, at some point beach nourishment may no longer be a viable option for coastal adaptation, and some communities will need to retreat from the encroaching shoreline. Although we do not model this long-term possibility, by guiding the use of scarce resources in the short run our results can help to smooth the transition to such a future.

Appendix

See Appendix Tables 3 and Figs. 8, 9, 10 and 11.

Table 3 Nourishment cost function estimation

Variables	OLS	Robust SE
Dependent variable $= Z_n = \ln(Cost_n) - \ln(L_n) - 2\ln(u_n)$		
Constant	−2.481***	(0.000)
Year = 1965	−0.574*	(0.300)
Year = 1966	2.144***	(0.000)
Year = 1967	0.634***	(0.000)
Year = 1970	0.559	(0.782)
Year = 1971	1.128***	(0.280)
Year = 1973	1.509***	(0.423)
Year = 1974	1.490***	(0.000)
Year = 1977	2.233***	(0.000)
Year = 1978	1.575***	(0.000)
Year = 1980	2.329***	(0.000)
Year = 1981	2.112***	(0.000)
Year = 1982	1.177***	(0.000)
Year = 1984	2.941***	(0.000)
Year = 1985	1.822***	(0.000)
Year = 1986	1.930***	(0.356)
Year = 1988	2.387***	(0.545)
Year = 1989	2.887***	(0.000)
Year = 1990	4.076***	(0.000)
Year = 1991	2.095***	(0.231)
Year = 1992	2.693***	(0.526)
Year = 1993	2.980***	(0.487)
Year = 1994	1.469	(1.044)
Year = 1995	2.836***	(0.326)
Year = 1997	2.170***	(0.000)
Year = 1998	0.000	(0.000)
Year = 2001	3.429***	(0.355)
Year = 2002	0.000	(0.000)
Year = 2003	3.709***	(0.000)
Year = 2004	4.870***	(0.431)
Year = 2005	4.081***	(1.257)
Year = 2006	4.589***	(0.454)
Observations	57	
R-squared	0.849	

Robust standard errors in parentheses, *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$
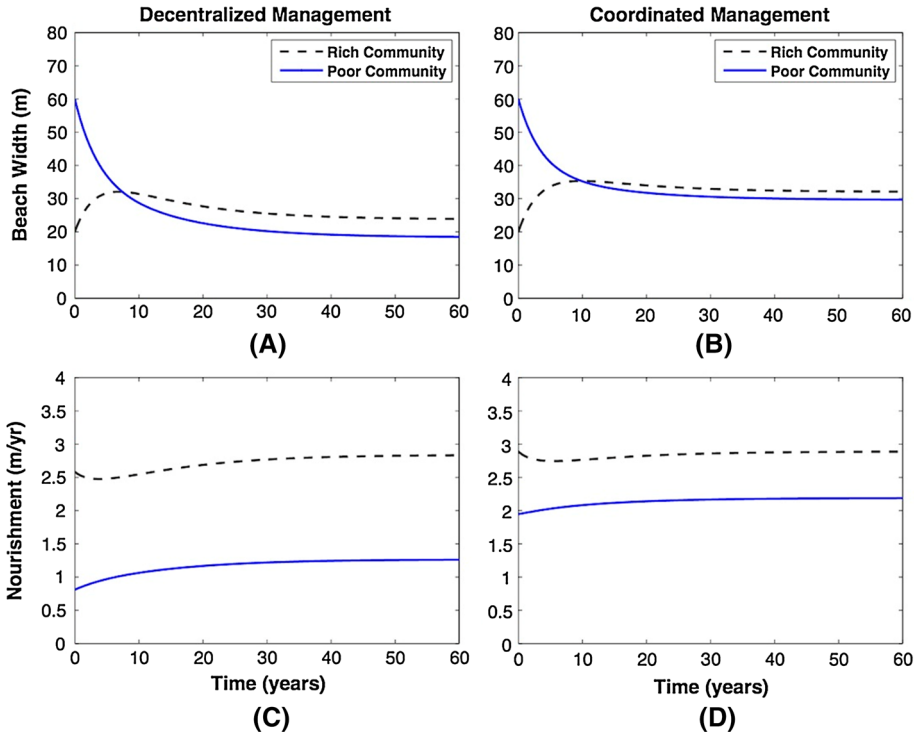
Fig. 8 Comparison of optimal beach width under coordinated and decentralized management with economic heterogeneity. **A**, **B** Steady-state beach widths are not equal with economic heterogeneity. The difference in optimal steady state widths is lower under coordinated management, and both towns have wider beaches. **C**, **D** Coordination leads to more nourishment in both towns, but the poorer community (with wider initial beach in this case) significantly increases nourishment (relative to decentralized management) and subsidizes the richer town (with wider initial beach) by reducing diffusive losses
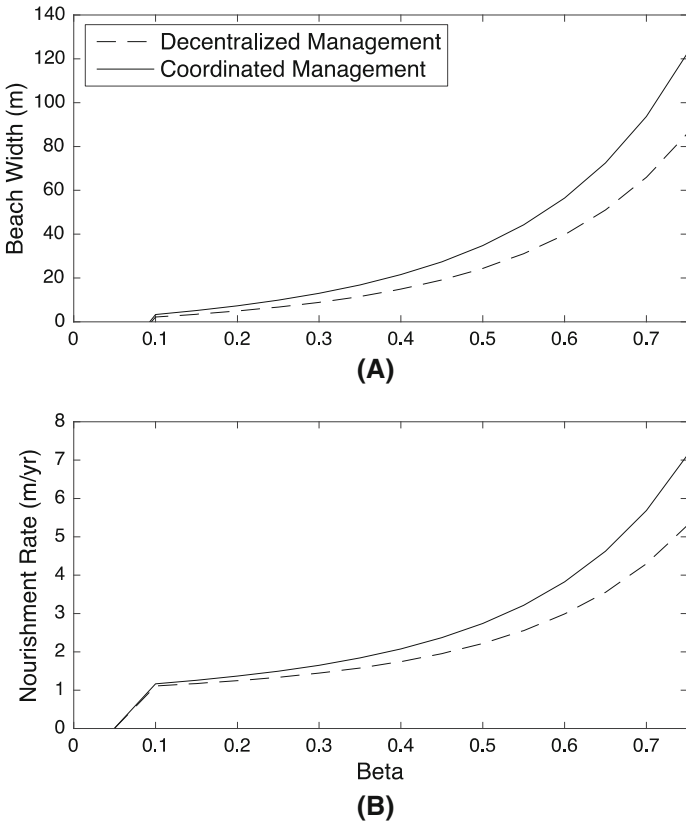
Fig. 9 Sensitivity to price elasticity of beach width. Optimal beach width and nourishment rates increase as the value of beach width increases. Gains from coordination also increase as when property markets are more sensitive to changes in beach width
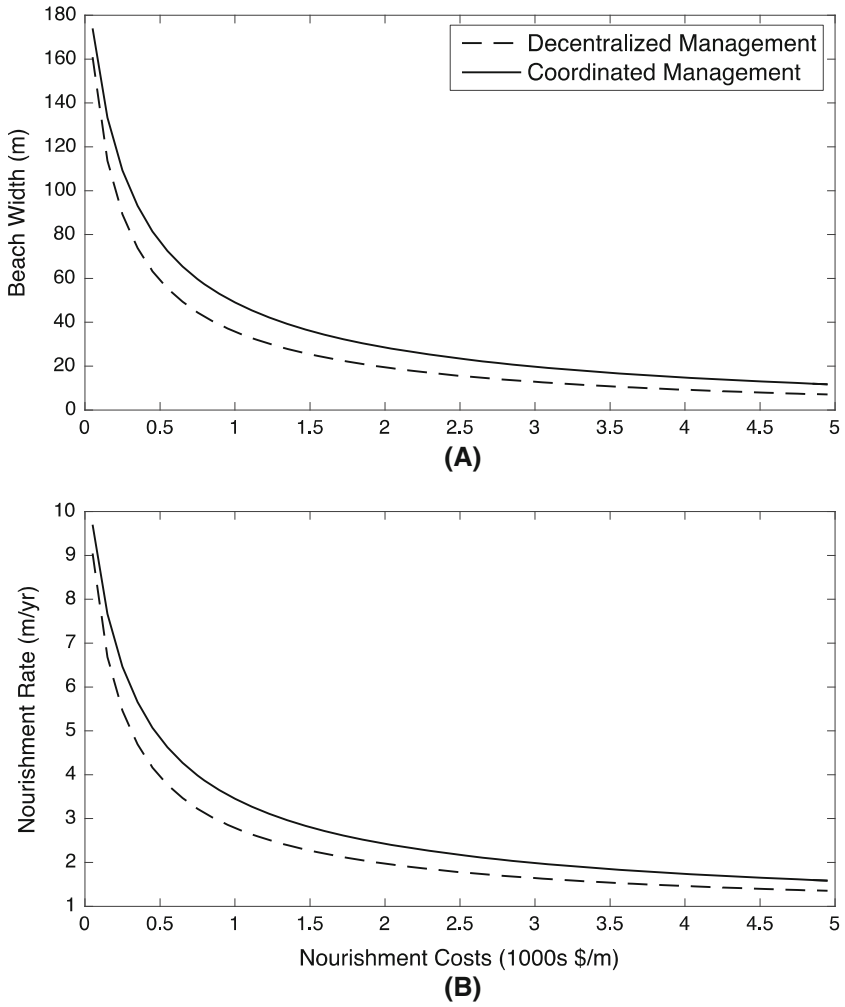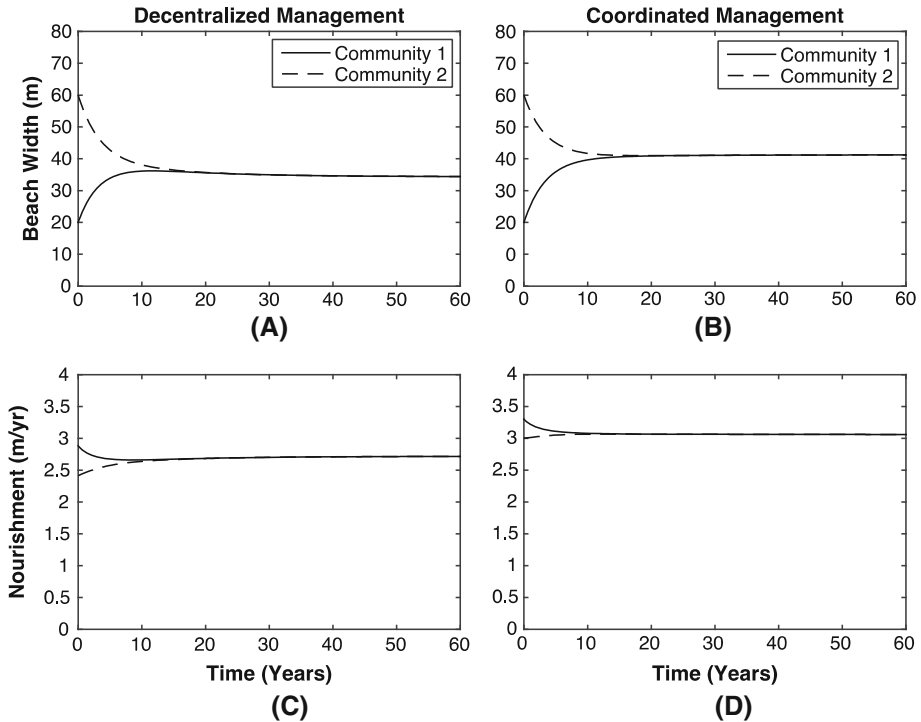
Fig. 10 Sensitivity to nourishment costs

Fig. 11 Comparison of optimal beach width under coordinated and decentralized management with alternative functional specifications. **A**, **C** Decentralized management leads to a flat steady-state beach width of 34 m. In the short term, the town with a narrower beach nourishes more but also benefits from its neighbor's nourishment effort via alongshore sediment transport. **B**, **D** Coordinated management leads to a to a higher steady-state width of 41 m. Both towns increase nourishment and receive higher long-term benefits

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