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

Sathya Gopalakrishnan*
Dylan McNamara‡
Martin D. Smith§
A. Brad Murray†

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*Corresponding author; Assistant Professor, Department of Agricultural, Environmental and Development Economics, Ohio State University; 2120 Fyffe Road, Columbus, OH 43210; Email: gopalakrishnan.27@osu.edu; Phone: (614) 292-2853
‡Associate Professor, Department of Physics and Physical Oceanography and Center for Marine Science; UNC Wilmington / Center for Marine Science; Wilmington, NC 28403; Email: mcnamarad@uncw.edu
§Professor of Environmental Economics, Nicholas School of the Environment and Department of Economics, Duke University; Box 90328, Durham, NC 27708; Email: martin.smith@duke.edu
†Professor of Geomorphology and Coastal Processes, Division of Earth and Ocean Sciences, Nicholas School of the Environment and Center for Nonlinear and Complex Systems, Duke University; Box 90230, Durham, NC 27708; Email: abmurray@duke.edu

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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 strategic interaction between two neighboring towns, and explore welfare implications of spatial-dynamic feedbacks in the coastal zone. When communities are adjacent, the seaward community loses sand to the landward community through alongshore sediment transport. Strategic interactions create incentives for both communities 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.

Keywords: beach nourishment, sea level rise, spatial dynamic feedbacks, climate adaptation

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 (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 but are sensitive to changes in beach width (Landry, Keeler, and Kriesel 2003, Pompe and Rinehart 1995a, Gopalakrishnan et al. 2011). 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, U.S. expenditures on beach nourishment totaled $2.9 billion (U.S. EPA 2010), and as climate changes, demand for nourishment and other shoreline stabilization efforts likely will continue to grow. This growth raises questions about whether public funds are being spent most 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 (Pelnard-Considere 1956, Slott, Smith, and Murray

2008, Ells, Murray, and Slott 2011, Murray et al. 2013). When communities are adjacent, for example, a community that builds its beach seaward through nourishment loses sand to a neighboring landward community through the process of alongshore sediment transport (Slott, et al. 2008, Dean 2002). This process could induce strategic interactions and question the logic of the status quo decentralized approach. 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?

Our analysis, while specifically trying to inform coastal climate adaptation, is part of a growing literature on the spatial-dynamics of renewable resources (Brock and Xepapadeas 2010, Smith, Sanchirico, and Wilen 2009). The spatial interaction in our two coastal communities is similar to edge-effects in agricultural decision-making (Parker and Munroe 2007, Lewis, Barham, and Robinson 2011) as well as the control of a biological invasion that disperses over space creating incentives for property owners to coordinate management (Bhat and Huffaker 2007, Epanchin-Niell and Wilen 2012). Spatial-dynamic feedbacks also influence optimal patterns of harvesting renewable resources (Smith, Sanchirico, and Wilen 2009, Costello and Polasky 2008, Sanchirico and Wilen 2005). However, an important difference is that the ultimate source of value is the market for the extracted resource, which is beyond the spatial context of the resource, whereas the value of beach width is inherently tied to its location. In previous work, agent-based models of nourishment decisions with spatial interactions between coastal 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).

In this paper, we model the behavior of two adjacent communities adapting to shoreline change. Because nourishment provides benefits to the nourishing community itself and to neighboring communities, there are incentives for communities to free ride on their neighbor's nourishment efforts. The seaward community wants to decrease its cross-shore position relative to its neighbor to decrease loss of beach sand, while the landward community wants to maintain a difference in cross-shore positions to increase gains from sediment transport. Because both communities consequently nourish less, long-run beach width and therefore property values are lower in both communities under status quo decentralized management than they would be under spatially coordinated management, a result that parallels the classic prisoner's dilemma. Because of spatial-dynamic feedbacks in the coastal zone, decentralized management fails to achieve the coordinated social optimum. Intensifying erosion— consistent with accelerating sea level rise — exacerbates the problem and increases losses from failure to coordinate. Despite larger efficiency gains from coordination, higher erosion 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 what has been viewed traditionally as a local problem. We show how a policy that subsidizes local nourishment in a spatially targeted manner can achieve welfare-maximizing outcomes by removing incentives to free ride on neighboring communities. To our knowledge, this is the first attempt to incorporate strategic spatial interactions in a forward-looking model for managing the physical coastal environment.

In Section 2, we develop the two-community model by embedding a model of the coastal geomorphology in a differential game and parameterizing the model with a combination of prior studies and data on beach nourishment. Section 3 solves the model for both decentralized and optimal coordinated outcomes and explores the importance of economic heterogeneity (in property values) and increased climate forcing. Section 4 illustrates the optimal spatially targeted subsidy that mimics the coordinated outcome. The final section discusses implications for climate adaptation policy and directions for future research.

2. A two-community model of optimal nourishment with spatial-dynamic interactions

The unit of analysis is a coastal community making decisions about beach stabilization, where beach width is measured by the distance from the dune line or line of development to the cross-shore position of the coastline. We model shoreline stabilization as a two-player 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). Decentralized management is modeled as a non-cooperative game, in which the two communities choose nourishment rates $\left(u_i(t)\right)$ that maximize the discounted stream of net benefits from their own beach taking the actions of the neighboring community as given, and subject to a spatially explicit transition function for beach width $\left(x_i(t)\right)$ in each location.

$$\begin{aligned} &\underset{u_i(t)}{Max} \int_0^\infty e^{-\delta t}\left(B_i(x_i(t),t) - C_i(u_i(t))\right)dt \\ &s.t. \quad \dot{x}_i(t) = f\left(x_i(t),\, x_j(t), u_i(t)\right) \\ &\qquad i,j \in (1,2);\; i \neq j \end{aligned} \tag{1}$$

Spatial interaction is introduced through state equations representing the dynamics of the physical coastal system; at any given time beach width in Community 1 $(x_1(t))$ depends on the width in Community 2 $(x_2(t))$.

In general, shoreline 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).

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, Murray, and Arnoult 2001, Inman and Bagnold 1963). Beach nourishment alters both cross-shore and alongshore dynamics. A nourished section of the shoreline tends to erode faster in the cross-shore direction as the beach returns to its equilibrium profile. Nourishment at one location along the shoreline creates a bump and 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. 2006, Slott et al. 2008, Ashton and Murray 2006a,b). With two adjacent communities, nourishment at one location can cause the shoreline to accrete (or to erode more slowly) at the neighboring location. 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, Murray, and Ashton 2010, Slott, et al. 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 2006a,b).

Assuming that adjacent beaches face similar physical environments, if Beach 2 is wider than Beach 1 due to nourishment policy, then erosion in Beach 2 will correspond to sediment flux to Beach 1 at a rate proportional to the alongshore gradient in cross-shore position (difference in beach width between the two communities). 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 for Beach 1 drives changes to the cross-shore width of Beach 1 through time as:

(2) $$\frac{\Delta S}{\Delta t}=\left(\frac{\frac{\left(x_2(t)-x_1(t)\right)}{z}-0}{z}\right)=\left(\frac{\left(x_2(t)-x_1(t)\right)}{z^2}\right)\Rightarrow\frac{\Delta S}{\Delta t}\propto\left(x_2(t)-x_1(t)\right)$$

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, $\dot{x}(t)$, resulting from alongshore sediment transfer by $\dot{x}^S(t)=D(x_2(t)-x_1(t))$, 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 sand diffusing from the wider to narrower beach:

(3) $$x_i(t)=-\gamma_1-\gamma_2 x_i(t)+u_i(t)+D\left(x_j(t)-x_i(t)\right)$$

Change in beach width in town *i* depends on a linear erosion rate (γ_1) attributable to sea level rise and other factors that uniformly affect the domain, cross-shore exponential relaxation as the nourished beach returns to equilibrium (γ_2), the rate of nourishment $u_i(t)$, 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 γ_2 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 γ_2).

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, into a flow of amenities, the instantaneous benefits to each community can be written as an exponential function of beach width. However, as found in recreational demand studies (Parsons, Massey, and Tomasi 1999, Whitehead et al. 2008), benefits from a wider beach decline after reaching a critical maximum width.

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

$x_i(t)$ 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.

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

(5) $$C_i(t) = c\left(u_i(t)\right)^2$$

$u_i(t)$ is the rate at which beach width is added (m/yr) in town *i*. We assume quadratic costs because the volume of sand needed will increase non-linearly with the extent of beach build-out, as a greater depth needs to be filled with increases in the width added. The cost parameter *c* embeds both variable costs of nourishment sand and fixed costs, which are 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. 2009), and can be interpreted as averaging over discrete nourishment intervals. To determine the cost parameter c, we estimate the nourishment cost function using nourishment data from 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 is:

$$(6) \qquad C_{it} = L_i \phi u_{it}^2 \left(\sum_{t=1939}^{2006} \exp(\omega_t Y_t) \right) \varepsilon_{it}$$

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. Taking the natural log and rearranging yields:

$$(7) \qquad \ln(C_{it}) - \ln(L_i) - 2\ln(u_{it}) = \ln(\phi) + \sum_{t=1939}^{2006} \omega_t Y_t + \ln(\varepsilon_{it})$$

We then estimate the function:

$$(8) \qquad Z_{it} = \psi + \sum_{t=1939}^{2006} \omega_t Y_t + \eta_{it}$$

where $Z_{it} = \ln(C_{it}) - \ln(L_i) - 2\ln(u_{it})$ and $\psi = \ln(\phi)$.

Using ordinary least squares (OLS) regression, we recover the cost parameter,

$\hat{\psi} = \ln(\hat{\phi}) \Rightarrow \hat{\phi} = \exp(\hat{\psi})$.

We use the estimated nourishment cost function for a representative beach 10kms long, controlling for the time of nourishment using estimates $\hat{\omega}_t$ for the most recent year of nourishment in the data (2006). The estimated cost function can then be written as

$\hat{C}(t) = F\hat{\phi}\left(u(t)\right)^2$ where $F = L\exp(\hat{\omega}_t)$ is the fixed cost divided between N oceanfront properties. Assuming there are 50 oceanfront properties, the average nourishment cost per property is $\frac{\hat{C}(t)}{N} = \frac{F}{N}\hat{\phi}\left(u(t)\right)^2 = c\left(u(t)\right)^2$. Therefore the cost parameter in (5) is $c = \frac{F}{N}\hat{\phi}$. With $\exp(\hat{\omega}_{2006}) = \exp(4.589) = 98.396$, $\hat{\phi} = \exp(\hat{\psi}) = \exp(-2.481) = 0.0837$, $L_i = 10$ kms, and *N*=50, we get $c = \left(\frac{10}{50}\right)(98.4)(0.08) = 1.57$, which is the value of the cost parameter used in the numerical analysis. Estimation results are shown in the Appendix Table A1. We parameterize the benefits and cost function using empirical estimates for North Carolina but the model can easily be generalized to any sandy shoreline.

Shoreline evolution under decentralized management is characterized by solving the differential game in (1). We find the open loop solution with equilibrium strategies for both communities simultaneously choosing nourishment rates taking their neighbor's action as given. Optimal nourishment paths, chosen at the beginning of the planning horizon are only a function of time $\left(u_1(t), u_2(t)\right)$ and do not depend on the current state variables $\left(x_1(t), x_2(t)\right)$. We can write the current valued Hamiltonian for community *i* as:

$$
\begin{aligned}
&\tilde{H}_i(x_i, x_j, u_i, \lambda_i^{\,i}, \lambda_j^{\,i}) = \delta\alpha_i\left(x_i(t)\right)^\beta - \varphi\left(x_i(t)\right)^2 - c\left(u_i(t)\right)^2 \\
&+\lambda_i^{\,i}(t)\Big(-\gamma_1 - \gamma_2 x_i(t) + u_i(t) + D\big(x_j(t) - x_i(t)\big)\Big) \\
&+\lambda_j^{\,i}(t)\Big(-\gamma_1 - \gamma_2 x_j(t) + u_j(t) + D\big(x_i(t) - x_j(t)\big)\Big)
\end{aligned}
\tag{9}
$$

where $\lambda_i^i(t)$ and $\lambda_j^i(t)$ are the shadow values associated with a change in the beach width in community *i* and community *j*, respectively. Applying the Pontryagin's maximum principle, necessary conditions for optimal nourishment in community *i* (taking community *j's* actions as given) are:

(10) $$\frac{\partial \tilde{H}(\bullet)}{\partial u_i} = 0 \Rightarrow u_i^*(t) = \frac{\lambda_i^{i*}(t)}{2c}$$

(11) $$\dot{\lambda}_i^i(t) = \delta\lambda_i^i - \frac{\partial \tilde{H}(\bullet)}{\partial x_i}$$
$$\Rightarrow \dot{\lambda}_i^i(t) = \delta\lambda_i^i - \left(\delta\alpha_i\beta x_i^{\beta-1} - 2\varphi x_i - \gamma_2\lambda_i^i - D\left(\lambda_i^i - \lambda_j^i\right)\right)$$

(12) $$\dot{\lambda}_j^i(t) = \delta\lambda_j^i - \frac{\partial \tilde{H}(\bullet)}{\partial x_j}$$
$$\Rightarrow \dot{\lambda}_j^i(t) = \delta\lambda_j^i - \left(-\gamma_2\lambda_j^i - D\left(\lambda_j^i - \lambda_i^i\right)\right)$$

The state transition equations are:

(13) $$\dot{x}_i(t) = -\gamma_1 - \gamma_2 x_i(t) + u_i(t) + D\left(x_j(t) - x_i(t)\right);\ i,j = 1,2;\ i \neq j$$

and transversality conditions require:

(15) $$\lim_{t\to\infty} e^{-\delta t}\lambda_i^i(t)x_i(t) = 0$$

(16) $$\lim_{t\to\infty} e^{-\delta t}\lambda_j^i(t)x_j(t) = 0$$

We solve the boundary value problem characterized by equations (10)-(16) to determine the optimal nourishment paths for both towns.

In a coordinated management scenario, a coastal planner maximizes the joint present value net benefits to both communities and simultaneously chooses nourishment rates at each beach. The social planner's problem can be written as:

(17) $$\begin{aligned} &\underset{u_i(t),u_j(t)}{Max}\int_0^\infty e^{-\delta t}\left(\sum_{i=1}^{2}\left(B_i(x_i(t),t) - C_i(u_i(t))\right)\right)dt \\ &s.t.\quad \dot{x}_i(t) = f\left(x_i(t),\, x_j(t), u_i(t)\right) \\ &\qquad\ i,j \in (1,2);\ i \neq j \end{aligned}$$

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 with the collocation method (using a built-in routine BVP4C) in MATLAB to calculate the optimal nourishment path. Initial conditions for the beach width in each community ($x_1(0) = 20$ meters and $x_2(0) = 60$ meters) and terminal conditions (transversality conditions) for the co-state variables (λ_i, λ_j) are used to solve the system of ODEs in equations (10-16) 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 (17). For comparison, the baseline case for a single representative community without spatial interactions is shown in the Appendix (Figure A1, A2).

3. Decentralized versus Coordinated management

Two adjacent towns face similar physical and economic environments with differences only in initial beach widths. Base parameter values in the numerical analysis are α = 200, δ=0.06, $\gamma_1 = 1$, $\gamma_2 = 0.05$, c = 1.57, β=0.5, φ=0.001, and D =0.1. Both towns face a background erosion rate of 1m per year, exponential retreat of nourishment sand at 5% per year, and baseline property values $200,000. Community 1 has a narrower initial beach $(x_1^0 = 20m)$ and Community 2 has a wider initial beach $(x_2^0 = 60m)$. Alongshore variation in shoreline position determines the amount of sediment transfer. 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 24m 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 landward town initially gaining sand through alongshore sediment transport (Figure 1A, 1C). 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 35m in both communities (Figure 1B, 1D). 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 (Appendix Figure A1).

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, Pompe and Rinehart 1995b, Landry and Hindsley 2011), 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 values –calculated as the cumulative present value benefits $\left(\int_0^\infty e^{-\delta t}\left(\delta\alpha\left(x(t)\right)^\beta - \varphi\left(x(t)\right)^2\right)dt\right)$ using a baseline value $200,000, average beach width of 30m (based on data from North Carolina) and hedonic beach value coefficient of 0.5 – are higher under the coordinated policy. Although net benefits under coordination are lower in the early years, there are long-run benefits that more than offset these short-run costs. Coordination increases the value of an average coastal property by approximately 4%.

3.1. Economic Heterogeneity

Beach nourishment policies vary across space. Richer towns are more likely to nourish because benefits from nourishment are greater in towns with higher baseline property values, whereas costs are comparable. To explore the impact of economic heterogeneity, we vary the baseline property values across communities. 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 (Figures 2A, 2B).

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 (Figures 2C, 2D). There are net gains from coordination, but the richer town gains value and the poorer town loses value even when it is the landward 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 is the seaward community (Appendix Figure A3).

3.2. The Effect of Sea Level Rise

The impact of sea level rise is modeled by increasing the background erosion rate (higher γ_1). Optimal nourishment paths are calculated for background erosion scenarios ranging from 0.5 m/year to 6 m/year (Zhang, Douglas, and Leatherman 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. Both towns gain from coordination, but the landward community gains more due to alongshore sediment transfer (Figure 3A). 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 in 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 (Figure 3B). When background erosion is high (6m/yr), property values in the landward town are over 20% higher under a coordinated policy relative to decentralized management (Figure 3C). To determine the upper bound on erosion rate in which an optimal nourishment policy is preferred to no nourishment, we compare the cumulative present value net benefits for each town under the decentralized policy with the total value under a "do nothing" scenario of zero nourishment. Assuming that the value remains zero at any time after the beach is completely eroded ($x = 0$), we find that if the background erosion is 6 m/yr, it may be optimal to stop nourishment altogether (Appendix Figure A4).

When baseline property values vary across the two communities, the poorer town consistently loses value and the richer town gains under coordinated management (Figure 4A, 4B). Furthermore, relative gains and losses to each community increase with higher erosion rates (Figure 4C). When the poorer community is also the landward community, a high erosion rate (6m/yr) 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. Optimal spatial policy to solve the nourishment dilemma

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/yr) the net benefits from nourishment to community i at time t can be written as:

$$NB_i(t) = \delta\alpha_i\left(x_i(t)\right)^{\beta} - \varphi\left(x_i(t)\right)^2 - c\left(u_i(t)\right)^2 + s_i(t)u_i(t) \tag{18}$$

When the two neighboring towns make localized management decisions, the current valued Hamiltonian for community i with nourishment subsidy is:

$$\begin{aligned} \tilde{H}_i(x_i,x_j,u_i,s_i,\lambda_i^i,\lambda_j^i) &= \delta\alpha_i\left(x_i(t)\right)^{\beta} - \varphi\left(x_i(t)\right)^2 - c\left(u_i(t)\right)^2 + s_i(t)u_i(t) \\ &+\lambda_i^i(t)\Big(-\gamma_1 - \gamma_2 x_i(t) + u_i(t) + D\big(x_j(t) - x_i(t)\big)\Big) \\ &+\lambda_j^i\Big(-\gamma_1 - \gamma_2 x_j(t) + u_j(t) + D\big(x_i(t) - x_j(t)\big)\Big) \end{aligned} \tag{19}$$

Each town will then optimally choose its nourishment rate: $u_i^*(t) = \dfrac{\lambda_i^i(t) - s_i(t)}{2c}$.

The coastal planner determines optimal location-specific subsidy schemes for both communities to maximize joint benefits. The current valued Hamiltonian for the social planner's problem to determine optimal spatial subsidy scheme is:

$$\begin{aligned} \tilde{H}_i(x_i,x_j,s_i,s_j,\lambda_i,\lambda_j) &= \sum_{i=1}^{2}\delta\alpha_i\left(x_i(t)\right)^{\beta} - \varphi\left(x_i(t)\right)^2 - c\left(u_i(t)\right)^2 \\ &+\lambda_i(t)\Big(-\gamma_1 - \gamma_2 x_i(t) + u_i(t) + D\big(x_j(t) - x_i(t)\big)\Big) \\ &+\lambda_j\Big(-\gamma_1 - \gamma_2 x_j(t) + u_j(t) + D\big(x_i(t) - x_j(t)\big)\Big) \end{aligned} \tag{20}$$

We numerically solve for optimal location-specific subsidies $\left(s_i(t), s_j(t)\right)$ such that the solution to the decentralized management problem in (19) coincides with the social planner's solution in (20). 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 (Figure 5A). When baseline property values vary across towns $(\alpha_1 = 100; \alpha_2 = 250)$, 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 (Figure 5B). 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 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 (Figure 6A and 6B), but when baseline property values are different, uniform subsidy leads to over-nourishment in the town with high property value (Figure 6C and 6D), 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.

5. Discussion

As public expenditures on shoreline stabilization increase in response to sea level rise, changing storm patterns, and dense coastal development (NOAA 2006), concerns about the long-term sustainability of this resource-intensive policy are also growing. Although physical models clearly show that stabilization efforts in one location can influence erosion in other locations along the coast (Slott et al. 2008, Slott et al. 2010, Lazarus et al. 2011), the policy implications of these spatial interactions are not well understood. As coastal managers face the need to make long-term policy decisions under conditions of increasing sea level rise, a coordinated management policy can help coastal communities adapt better if richer communities with wider beaches can compensate communities with narrower beaches for the short term losses. When both communities face higher background erosion (e.g. from increased rates of sea level rise), coordination can increase long-term beach values by over 20% (Figure 3C).

Spatial interactions have been explored in renewable resource systems, highlighting the need for spatially explicit policy instruments to optimally manage the resource (Sanchrico and Wilen 2005; Brock and Xepapadaes 2009; Smith et al. 2009). In the first application of spatial-dynamic modeling of optimal shoreline management, we find that a uniform (aspatial) policy may closely mimic the optimal policy when towns have similar baseline values. However, the welfare loss and distributional inequality with a second-best policy that does not incorporate spatial interactions are significant when there is economic heterogeneity across coastal towns, leading to loss of value in the poor town and increased values in the rich town. A suboptimal policy that increases gains to high valued locations could perpetuate inequality in the distribution of value across space. Although 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, Dinar, and Williams 2006; Anthoff, Hepburn and Tol 2009), potentially creating a policy-induced housing bubble in the coastal real estate market.

We have made some 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 initial 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 a more realistic setting. A more significant assumption is modeling the differential game as an open-loop problem. Here too the benefit is tractability; no previous studies have solved closed-loop problems with two interacting state variables. However, the implication is that our solution is not Markov perfect. It is theoretically possible that a feature of the closed-loop problem 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.

Currently, nourishment projects in the US are primarily federally funded, but there is growing concern about the future availability of funds. 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. Although we do not observe cross-community subsidies, likely due to political barriers or failure to understand spatial linkages in the physical system, the need for coordination is beginning to influence planning decisions in some coastal communities in the US (Kemp 2010). Beyond the coordination benefits, perceptions of higher valued ‘natural’ (not nourished) beaches may also motivate communities with narrower beaches to subsidize nourishment in neighboring towns to increase indirect benefits. Can a market-based mechanism with sand permits or quotas, similar to other cap and trade systems for pollution permits (Montgomery 1972) or individually transferable quotas in fisheries (Christy 1973, Grafton 1996), mimic coordinated shoreline management? Our spatially targeted subsidy that mimics the coordinated social optimum is a Pigouvian subsidy, so in the absence of uncertainty, we would expect that a quantity instrument could achieve the same outcome. A challenging step in developing such an instrument would be to determine a cap on total nourishment.

Our modeling 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; 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, Sadoulet, and de Janvry 2001, Ostrom, Gardner, and Walker 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, Murray, and Smith 2011). These challenges further highlight the need to rethink coastal adaptation strategies and consider a coordinated approach to coastal management as climate changes.

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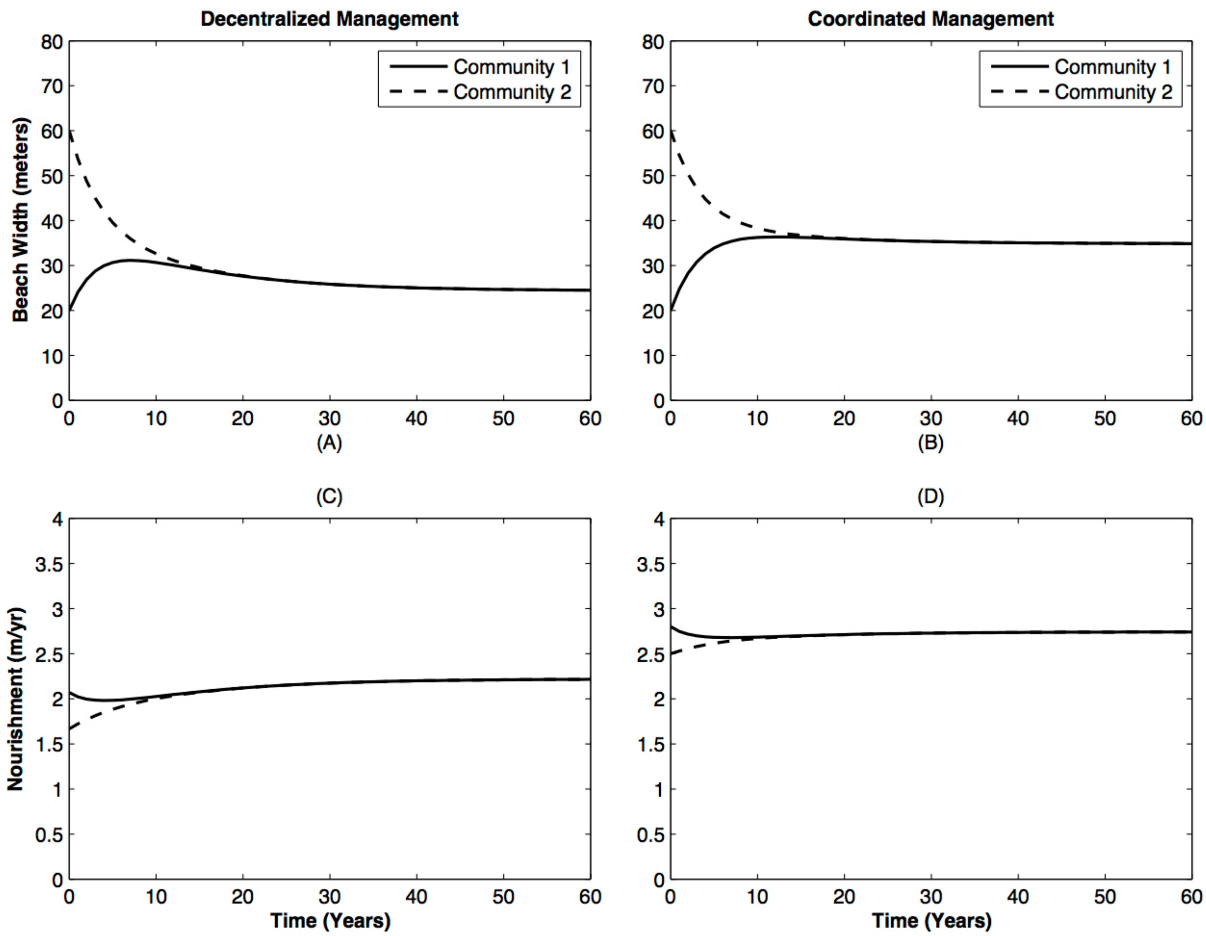

Figure 1: Optimal beach width under coordinated and decentralized management when both towns face similar physical and economic conditions. (1A, 1C) Decentralized management leads to a flat steady-state beach width of 24m. In the short term, the town with a narrower beach nourishes more but also benefits from its neighbor's nourishment effort via alongshore sediment transport. (1B, 1D) Coordinated management leads to a to a higher steady-state width of 35m. Both towns increase nourishment and receive higher long-term benefits.

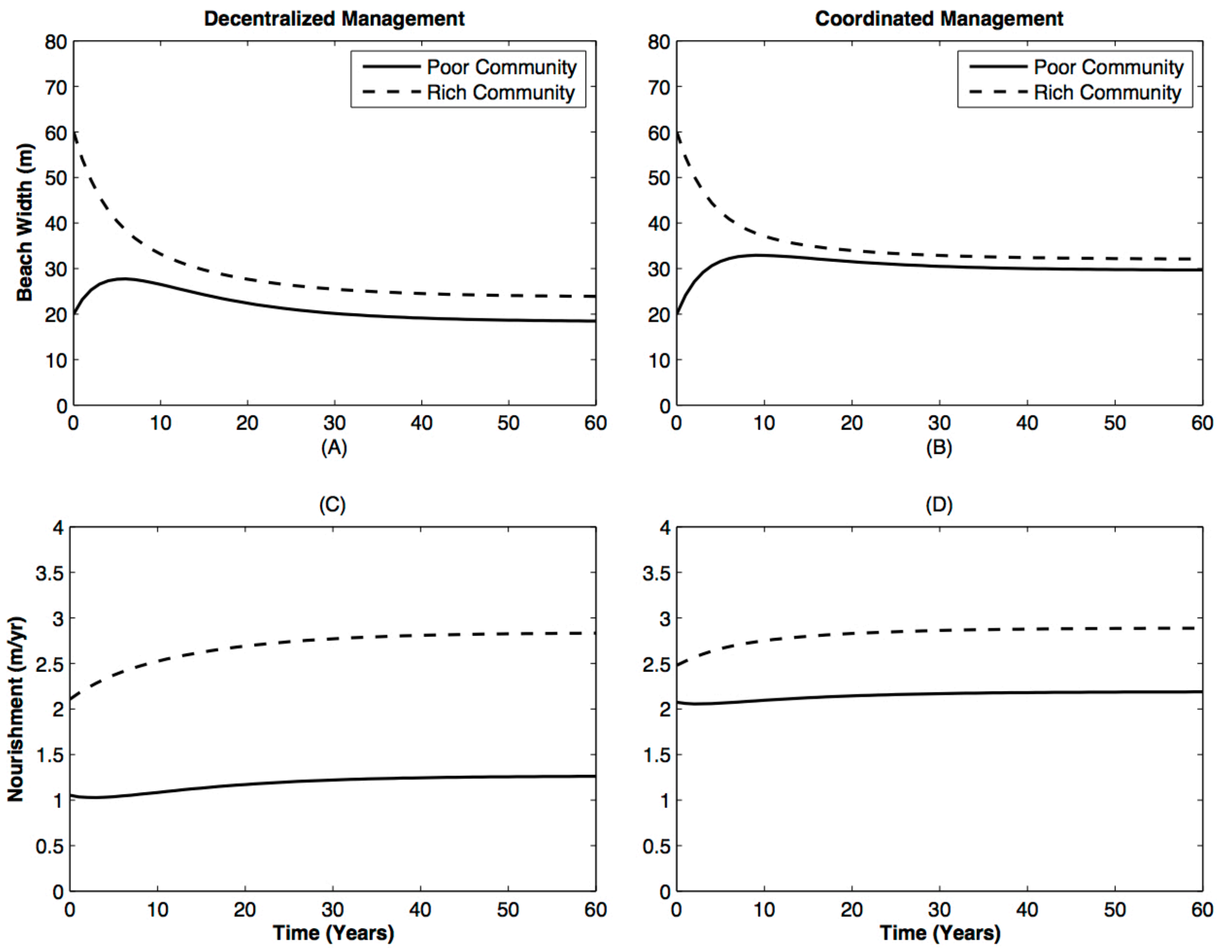

Figure 2: Optimal beach width under coordinated and decentralized management with economic heterogeneity. (2A, 2B) Steady-state beach widths are not equal with economic heterogeneity, but the difference is lower under coordinated management. Coordination leads to wider beaches in both towns. (2C, 2D) 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.

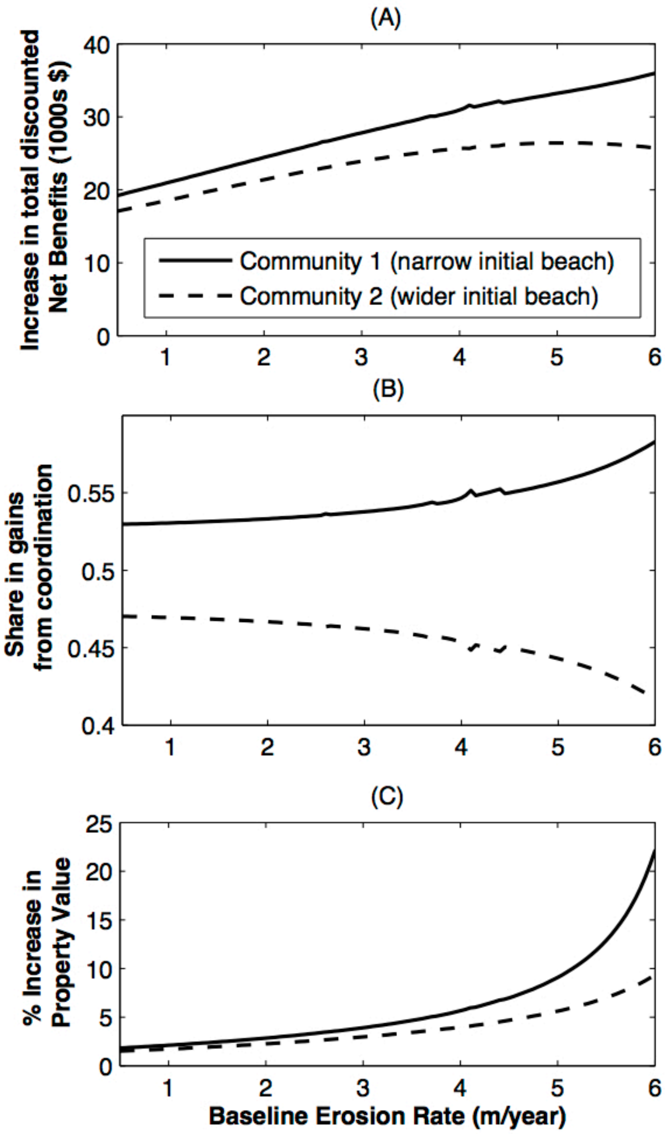

Figure 3: Gains from coordinated management with increasing background erosion when the two towns have similar baseline property values. (3A) Benefits from coordination increase for both towns as background erosion increases. (3B) The free rider town gets a greater share in the total benefits from coordination (through sediment transfer) and inequality in the distribution of benefits increases with higher erosion rates. (3C) 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.

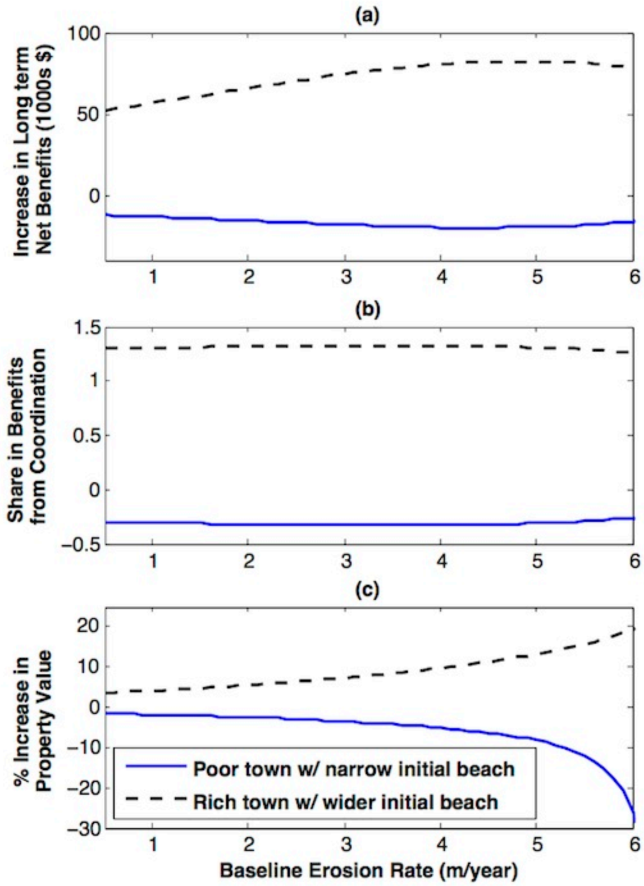

Figure 4: Gains from coordinated management with increasing background erosion when the two towns have different baseline property values. (4A) As background erosion increases, benefits from coordination increase for the richer town, but the poorer town loses value. (4B) The town with lower baseline 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). (4C) 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.

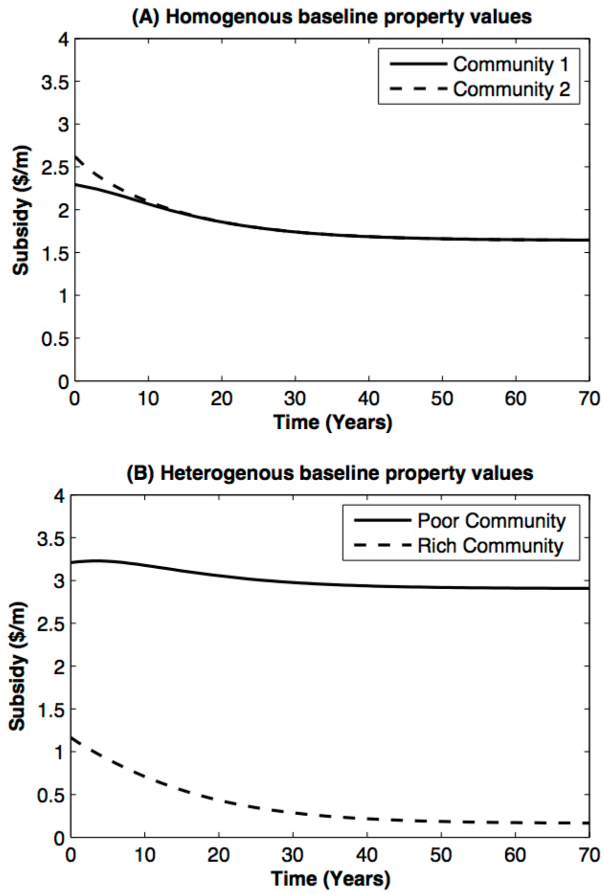

Figure 5: Optimal subsidy schemes (5A) Both towns have similar baseline property values and face identical physical environments. Town with wider initial beach receives higher subsidy in the short run until diffusion leads to a flat coastline. (5B) When there is economic heterogeneity, the town with lower baseline property values must receive a higher subsidy to enable optimal nourishment.

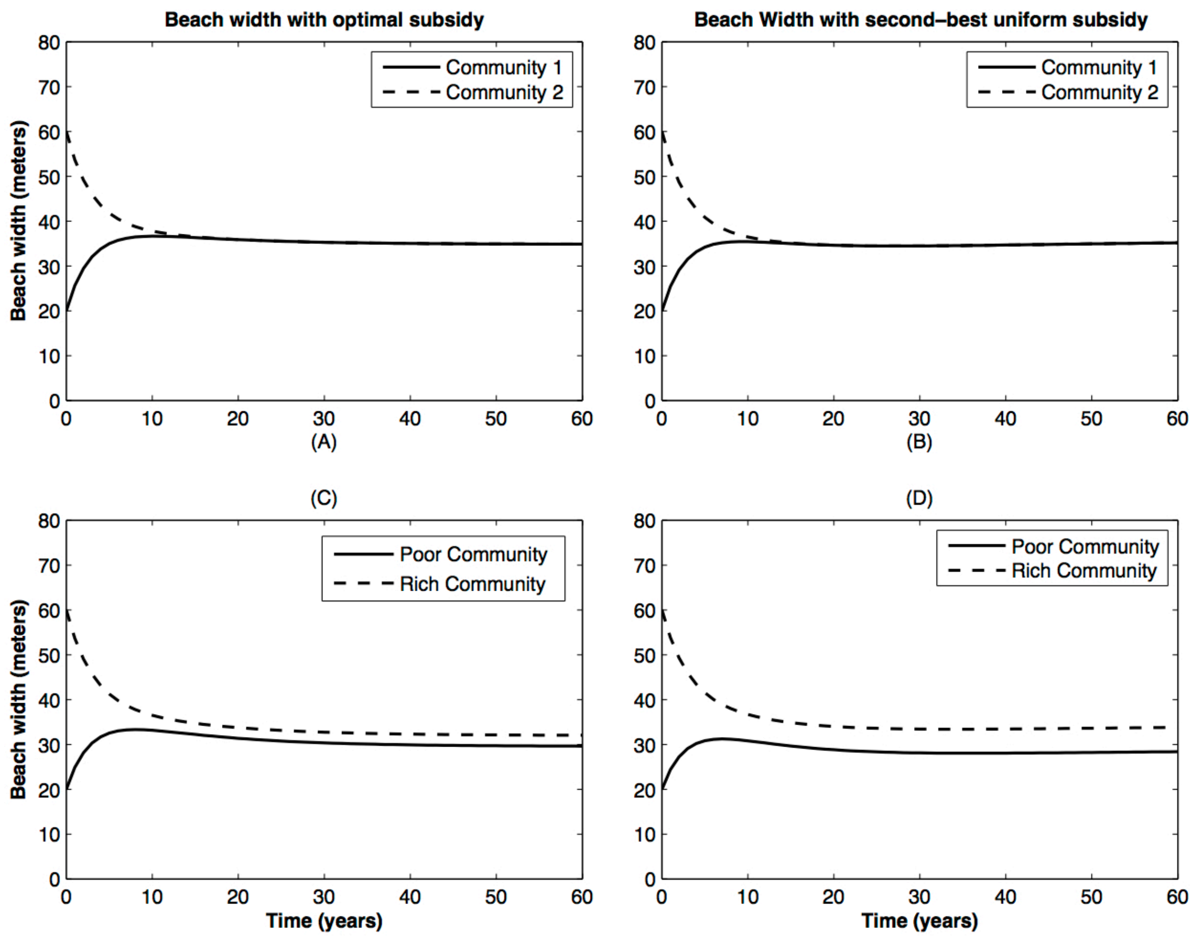

Figure 6: Shoreline evolution with optimal spatially targeted nourishment subsidy versus a uniform subsidy scheme (6A, 6B) When both towns have similar baseline property values, shoreline evolution under the second-best uniform subsidy scheme is similar to the outcome under optimal subsidy scheme. (6C, 6D) 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.

Figure Captions

Figure 1: **Optimal beach width under coordinated and decentralized management when both towns face similar physical and economic conditions**. (1A, 1C) Decentralized management leads to a flat steady-state beach width of 24m. 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. (1B, 1D) Coordinated management leads to a to a higher steady-state width of 35m. Both towns increase nourishment and receive higher long-term benefits.

Figure 2: **Optimal beach width under coordinated and decentralized management with economic heterogeneity**. (2A, 2B) 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. (2C, 2D) 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.

Figure 3: **Gains from coordinated management with increasing background erosion when the two towns have similar baseline property values.** (3A) Benefits from coordination increase for both towns as background erosion increases. (3B) 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. (3C) 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.

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Appendix

Beach Nourishment as an Optimal Control Problem in a Single Representative Community

The baseline case to compare outcomes of a two-community game is a dynamic model for optimal beach nourishment in a single representative community without spatial interactions. A beach manager chooses the rate of nourishment that maximizes an infinite stream of discounted net benefits from nourishment:

$$(18) \qquad \underset{u(t)}{Max} \int_0^\infty e^{-\delta t} \left(B(t) - C(t) \right) dt$$

$$(19) \qquad \underset{u(t)}{Max} \int_0^\infty e^{-\delta t} \left(\delta a \left(x(t) \right)^\beta - \varphi \left(x(t) \right)^2 - c \left(u(t) \right)^2 \right) dt$$

subject to the transition function for beach width:

$$(20) \qquad \dot{x}(t) = -\gamma_1 - \gamma_2 x(t) + u(t)$$

Change in the beach width at time *t* depends on the uniform erosion rate (attributable to sea level rise or gradients in alongshore transport) (γ_1) and the cross-shore exponential relaxation as the nourished beach returns to equilibrium (γ_2). $u(t)$ is the rate of nourishment (m/yr) and the initial width $x(0)$ is given.

The current valued Hamiltonian is:

$$(21) \qquad \tilde{H}(x,u,\lambda) = \delta\alpha \left(x(t) \right)^\beta - \varphi \left(x(t) \right)^2 - c \left(u(t) \right)^2 + \lambda(t) \left(-\gamma_1 - \gamma_2 x(t) + u(t) \right)$$

Applying the Pontryagin's maximum principle, necessary conditions for optimal nourishment are:

$$(22) \qquad \frac{\partial \tilde{H}}{\partial u} = 0 \Rightarrow u^*(t) = \frac{\lambda^*(t)}{2c}$$

(23) $\dot{\lambda}(t)-\delta\lambda(t)=-\frac{\partial\tilde{H}}{\partial x}\Rightarrow\dot{\lambda}(t)=\delta\lambda(t)-\left(\delta\alpha\left(x(t)\right)^{\beta-1}-2\varphi x(t)-\gamma_2\lambda(t)\right)$

(24) $\dot{x}(t)=-\gamma_1-\gamma_2 x(t)+u(t)$

(25) $\lim_{t\to\infty}e^{-\delta t}\lambda(t)x(t)=0$

Optimal nourishment is characterized by equations (22)-(25), which include state and co-state transitions as well as a transversality condition. Substituting Equation (22) in the state equation (24), and setting $\dot{x}=0$ and $\dot{\lambda}=0$, the equations for a fixed point are:

(26) $\lambda=2c(\gamma_1+\gamma_2 x)\Rightarrow u=\gamma_1+\gamma_2 x$

(27) $\lambda=\frac{(\delta\alpha\beta x^{\beta-1}-2\varphi x)}{\delta+\gamma_2}\Rightarrow u=\frac{(\delta\alpha\beta x^{\beta-1}-2\varphi x)}{2c(\delta+\gamma_2)}$

To determine the optimal nourishment path for a single representative town, we solve the boundary value problem characterized by the first-order conditions (22)-(25) using an initial beach width of 60 meters and a discount rate of 0.06. The parameter values used to solve the problem numerically are α = 200, δ=0.06, $\gamma_1=1$, $\gamma_2=0.05$, c = 1.57, β=0.5, φ=0.001, and D =0.1. For a single representative community, the system reaches an optimal steady-state width of 35 meters in our model within 75 years (Figure A1). Linear stability analysis and the phase diagram for the beach width and nourishment level show that the steady state equilibrium is an unstable saddle point (Figure A2)

Appendix Table 1A: 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

Appendix Figures:

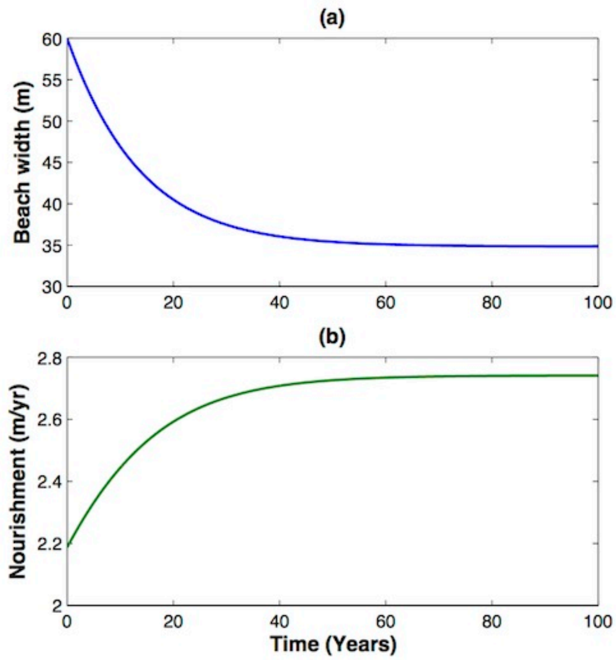

Figure A1: Optimal Nourishment in a single community with no spatial interaction over a 100-year horizon. (a) Optimal path for beach width reaching the steady state width of 35m in 75 years. (b) Optimal nourishment path.

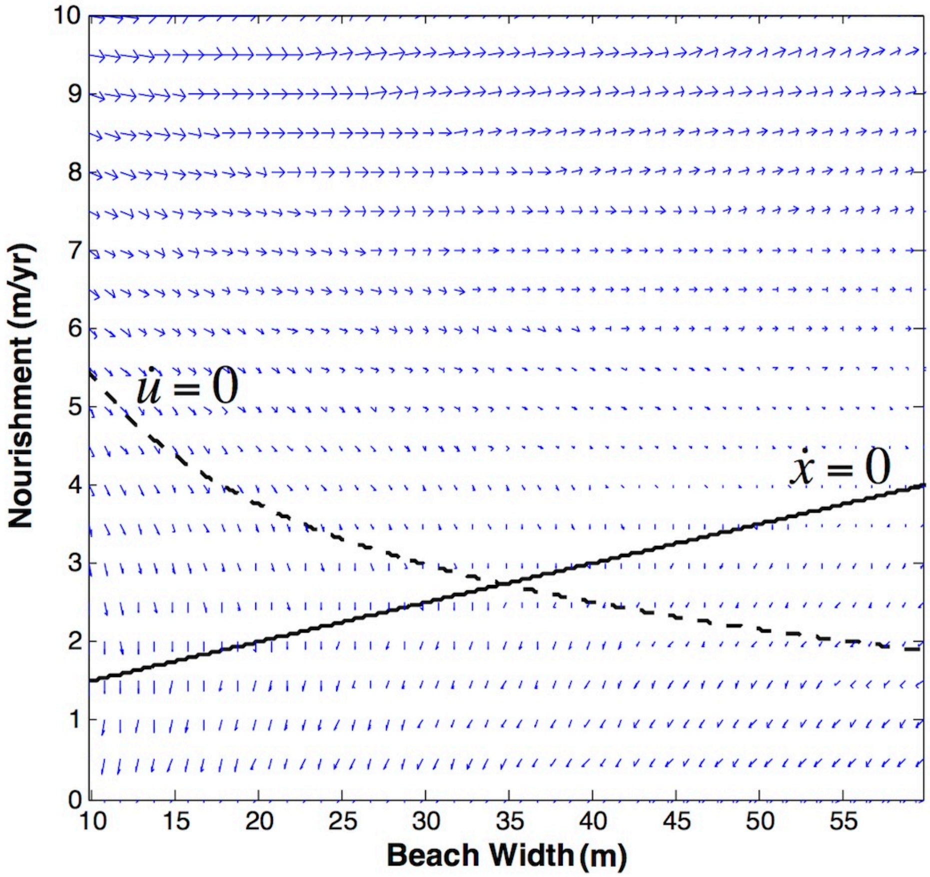

Figure A2: Phase plane for a single representative community shows that the steady state of the system is a saddle point.

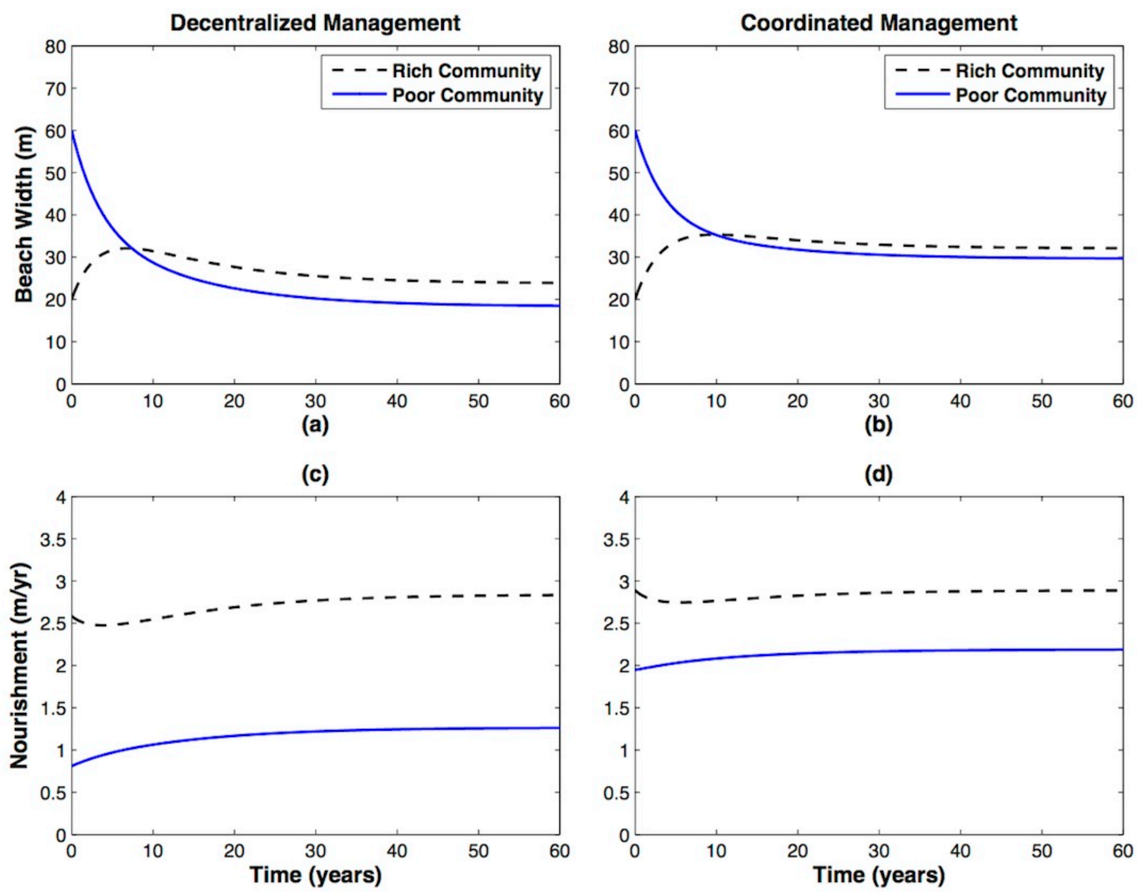

Figure A3: Comparison of optimal beach width under coordinated and decentralized management with economic heterogeneity**.** (1a, 1b) Steady-state beach widths are not equal with economic heterogeneity. The difference in optimal steady state widths is lower under coordinated management, and both towns have wider beaches. (1c, 1d) 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.

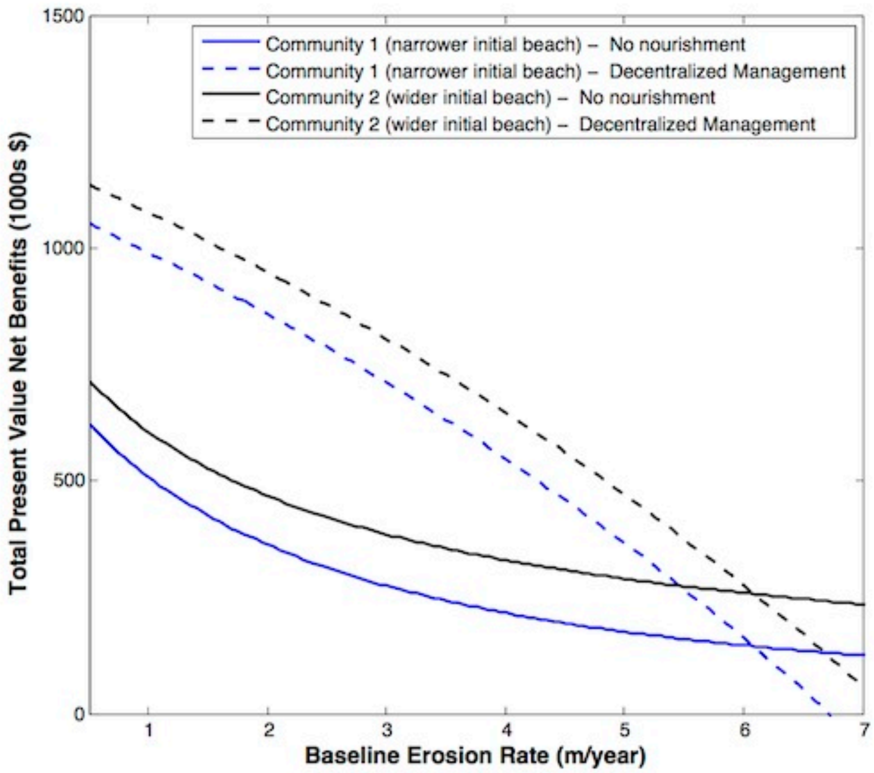

Figure A4: Comparison of total present value net benefits under "do nothing" scenario and decentralized management shows that the nourishment policy is not optimal when erosion rate is higher than 6 m/year.