

Threshold Management in A Coupled Economic-Ecological System *

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ABSTRACT Economic analysis of optimal ecosystem management in the presence of a threshold has typically ignored the potential for induced behavioral responses. This paper contributes to the literature on non-convex ecosystem management by considering the implications of a particular behavioral response in a regional economy - that of amenity-led growth - to changes in ecosystem services generated by a lake ecosystem subject to a eutrophication threshold. The essential policy challenge is to achieve optimal levels of lake nutrients and urbanization given that improvements to water quality will induce additional migration and urbanization in the region with attendant ecological impacts. We show that policies that ignore the recursive relationship between urbanization and water quality unintentionally exacerbate boom-bust cycles of regional growth and decline and risk pushing the system towards long-run economic decline. In contrast, the optimal policy accounts for the behavioral feedbacks to improved ecosystem services, and balances regional growth and ecological degradation.

KEYWORDS: ecosystem management, non-convex dynamics, dynamic optimization, safe minimum standard, resilience

1. Introduction

Ecological thresholds are critical points at which small changes in one or more system parameters or variables produce large responses in the ecosystem state or function [21]. Examples include sudden shifts in ecosystem states from clear to turbid water or from grassland to shrubland. Ecologists and economists have long hypothesized that these abrupt changes arise from systems characterized by multiple stable states [3, 22, 28] and conditions that, given a small change, push the system from the domain of one stable state into another. Such systems are viewed as having more or less resilience to external perturbations depending on their relative "distance" from a threshold or domain boundary. The ecological damages and potential irreversibility associated with breaching a threshold have led economists to consider optimal strategies for managing systems subject to threshold dynamics. However, until recently, the complexity of these ecological dynamics and the potential for policy to induce individual behavioral responses that generate feedbacks to the ecosystem have been ignored in the derivation of an optimal dynamic policy. In many cases human activities are a major determinant of ecological thresholds and thus policies that improve ecosystem services without addressing potential behavioral feedbacks are likely to be inefficient and may unintentionally degrade ecosystem services and reduce ecosystem resilience.

In this paper, we develop a simple model of a regional economy with a lake ecosystem and consider the role of a specific behavioral feedback: amenity-led growth that responds to changes in water quality. The lake ecosystem in this paper is subject to threshold dynamics in which nutrient loadings generated by human activities, including urbanization, can cause a shift from an oligotrophic to eutrophic lake state, which drastically reduces water quality [8]. The essential policy challenge is to achieve optimal levels of lake nutrients and urbanization given that improvements to water quality will induce additional migration and urbanization in the region with attendant ecological impacts. Because uncoordinated individual activities are simultaneously affecting and responding to ecological changes, the policy maker cannot fully control the polluting activities simply by controlling nutrient loadings. We show that policies that ignore this recursive relationship can result in pushing the lake ecosystem closer

to its threshold than is optimal. In contrast, the optimal policy, which accounts for both the impacts of urbanization and the migration response to changes in ecosystem services, permits ecological degradation, but avoids overdevelopment that pushes the system across the threshold by maintaining some level of resilience. These results echo the observations of Smith [29] in the context of managed fisheries: “what is biologically safe cannot meaningfully be determined without accounting for the behavioral responses”.

2. Literature Review

Economic studies of ecological threshold management have developed along two lines that are distinguished by how the ecological dynamics and economic-ecological interactions are modeled. One approach focuses on the appropriate economic decisions in the face of ecological thresholds, but greatly simplifies the ecological dynamics by assuming that ecological thresholds are exogenously determined discrete changes in the stock of natural resources. Ciracy-Wantrup [11] took this approach, for example, in proposing the need for safe minimum standards that ensure some amount of ecological preservation. The underlying assumption is that ecosystem functioning is dependent on maintaining ecological resources above a threshold level and that the net benefits of doing so outweigh the costs of breaching this threshold. Others have assumed the same type of exogenous threshold, but focused on the economic efficiency of dynamic policies that either do or don't permit the threshold to be breached. In the discussion of the optimal management of nonrenewable resources, Cropper [14] and Dasgupta and Heal [15] show that breaching the threshold, i.e., depleting the natural resource within a finite time, could be an optimal strategy either with or without substitutes for the ecological resource. Farzin [19] treats the ecological threshold as the critical stock of pollution at which the environmental damage jumps discretely from zero. He shows that when the threshold level is known with certainty, the optimal policy is to let the pollution stock gradually accumulate to the threshold level. When the location of threshold is a *priori* unknown, the optimal policy will create a continuum of equilibria so as to provide a buffer zone against breaching the threshold [31, 32]. Naevdal and Oppenheimer [26] extends the analysis to the case of multiple thresholds with unknown locations.

The other line of research on the optimal management of ecological thresholds, as pioneered by Carpenter, Brock and their coauthors [5, 8, 13, 16], explicitly considers the complex and nonlinear ecological dynamics that underlie ecological thresholds, which can give rise to various types of multiple equilibria [5]. Carpenter, Ludwig and Brock [8] model optimal lake management that is subject to nonlinear eutrophication. The social planner is assumed to have direct control over phosphorus loadings that lead to lake eutrophication. When the lake system allows open access by multiple polluters, Mäler [23] finds the similar over-exploitation result as in the tragedy of commons. Brock and Xepapadeas [6] consider the spatial spill-over effect driven by the diffusion process of phosphorus in the lake and show that under the optimal ecological management policy, a perturbation in phosphorus loadings can potentially flip the lake from oligotrophic state to eutrophic state and generate spatially heterogeneous steady state patterns. Dasgupta and Mäler [16] and Mitra and Roy [25] synthesize the literature by emphasizing the importance of threshold dynamics in economic analysis. The central contribution of these papers has been to provide policy analysis of a more complex ecological system that includes some interaction with the economy. However, they do not consider individual-level economic decisions and implicitly assume the policy maker has a full control over the economic activities that degrade the ecology. For example, the lake management models [5, 8, 16] assume that policy makers have direct control over phosphorus loadings whereas in reality, policy makers can only indirectly influence nonpoint source pollution of farmers, land developers and others whose individual actions generate these loadings. Such an approach overlooks the potential that individual behavioral responses to policy can influence the outcome of the policy.

A long tradition of analyzing thresholds exists in the fisheries literature beginning with Clark's critical depensation model in which production is assumed to be an S-shaped function. However, like [5, 8, 12], the social planner's optimal dynamic policy problem has not included consideration of policy-induced behavioral responses. Instead the focus has been largely on the implications of uncertainty regarding the location of the threshold. Alvarez [2], for example, investigates the optimal harvesting policy under stochastic fluctuations. He finds that the presence of critical depensation introduces a lower harvesting threshold

below which the population should be immediately depleted because the expected net population growth rate is non-positive. Woodward and Shaw [36] study the optimal water allocation when instream flows affect fish population. Employing robust control, they show that ambiguity averse strategy can be less cautious in terms of protecting the species.

Dynamic optimal policy analysis that incorporates individual responses is clearly difficult because of the endogenous feedbacks implied by these individual responses and the technical difficulty in accounting for these feedbacks in deriving the optimal policy solution. In setting the optimal dynamic policy, the policy maker must consider not only the ecological dynamics, but also anticipate the individual responses to the policy and the cumulative effects of these responses on ecological dynamics. A few articles incorporated individual responses. For instance, Chen, Irwin and Jayaprakash [9] explicitly model individual economic behavior and their two-way interactions with ecological threshold dynamics. Smith et al. [30] develops a dynamic fisheries model with recursive economic-ecological interactions and a critical depensation point. Eichner and Pethig and their coauthors [10, 18] propose a theoretical framework that incorporate individual decisions and ecological details. To the best of our knowledge, no one has addressed the question of optimal dynamic policy with both an ecological threshold and recursive economic-ecological interactions that arise from individual behavioral responses to policy-driven improvements in the ecosystem.

3. A Coupled Economic-Ecological System

We begin with a dynamic model that is a general abstraction of a coupled economic-ecological system and incorporate an ecological threshold triggered by uncoordinated individual economic activities. The interactions between the individual activities and the ecosystem are coupled in that individuals both affect and respond to ecological changes. When the stock of pollutants is low, the ecological system is able to absorb and biodegrade the pollutants. However, when the stock of pollutants becomes too high, an internal positive feedback mechanism is triggered that exceeds the absorption capacity of the system. The economic system affects and responds to ecological changes through optimal individual decisions regarding location and consumption. Individuals' location decisions are determined

in part by the quality of ecosystem amenities in a region, which are in turn affected by the number of people living in the region and their urban land consumption. Thus a well-functioning (malfunctioning) ecological system will accelerate (hinder) economic growth due to amenity-led growth. We use the lake ecosystem as our stylized ecological system because of the generality of the threshold specification [16].

3.1. Dynamics of Lake Water Quality and the Eutrophication Threshold

Following [8], our measure of lake water quality is reduced to a measure of total phosphorus concentration in the lake water under the assumption that phosphorus is the limiting factor in the lake eutrophication process. Phosphorus concentration increases with phosphorus loadings, decreases with outflow and sedimentation and is affected by phosphorus recycling. Because the phosphorus loadings are mainly determined by land uses around the lake, we assume that phosphorus loadings are proportional to the total area of urban land use in the region. The recycling term is assumed to be S-shaped, which is a mathematical simplification for the complicated bio-physical and ecological dynamics underlying the observed eutrophication threshold. When the phosphorus concentration level is low, this recycling term is insignificant. In this state of the lake, referred to as the oligotrophic state, the nutrient concentration level is relatively low in the water column, water is relatively clear and the ecosystem services are healthy. When phosphorus concentration goes beyond the eutrophication threshold, the over-enrichment of phosphorus will trigger a nonlinear response in the ecological dynamics that leads to a eutrophic state of the lake which typically associates with turbid water, high algae concentration and frequent fish kills. The over-enrichment in phosphorus due to excessive pollutant loadings triggers this so-called regime shift from the oligotrophic state to the eutrophic state. Once such a regime shift has occurred, reductions in loadings cannot guarantee an immediate reverse of the lake back into the oligotrophic state and thus the ecological dynamics exhibit hysteresis. When a recovery does occur, it may take a long time. For example, after the Cuyahoga River fire in 1969, substantial reductions in point sources around Lake Erie failed to bring about meaningful improvements in water quality until ten years after the controls had been implemented.

The dynamics of lake water quality is governed by an equation adapted from [8]:

$$\dot{P}(t) = l_0 + l_1 L(t) - sP(t) + r_1 \frac{P(t)^{r_2}}{P(t)^{r_2} + p_c^{r_2}}. \quad (1)$$

Here, $P(t)$ is the phosphorus concentration in the lake water at time t and \dot{P} is its change rate. The loadings consist of a constant l_0 and the total loadings from the residential land use $l_1 L(t)$. l_1 captures the average impact of land use on lake water quality. $L(t)$ gives the total developed land in the region. The phosphorus outflow is captured in $sP(t)$, where s denotes the proportional rate of P -loss from the system. It accounts for both sedimentation and outflow, which remove P from the water column. The last term represents phosphorus recycling. In shallow lakes, phosphorus at the bottom of the lake can be re-suspended back into lake water. In stratified lakes, recycling depends on oxygen depletion in the hypolimnion during the stratified season [8]. Recycling occurs only when the phosphorus concentration is sufficiently high. The maximum rate of recycling is r_1 and the steepness of the recycling curve is governed by r_2 . p_c is the P value at which recycling reaches half its maximum rate. The recycling term that gives rise to threshold responses is a general feature of many ecosystems [5]. Therefore, with appropriate modifications, the analysis presented in this paper is also applicable to more generic economic-ecological systems.

3.2. Migration and Regional Economy

The dynamics of the regional economy are driven by households' migration decisions is adapted from [9]. Households make decisions to migrate to the region by comparing the reservation utility u_0 that they receive from outside the region with the utility that they would receive from living in the region. Households that live in the region supply labor to produce the numeraire good X according to the production function: $X = E(N)F(N)$. N stands for regional population. $F(N)$ is a standard neoclassical production function. $E(N)$, according to Fujita and Thisse [20], captures agglomeration through scale effects that are external to individual firms. As we discuss below, this is a simplification that is nonetheless consistent with the empirical literature on this type of production externality. Assuming that regional output market is perfectly competitive, then the local wage rate is determined

by

$$W = E(N)F'(N). \quad (2)$$

Given the wage income, households maximize utility by consuming the composite good (X_i) and land (L_i), where the subscript i indicates individual consumption. The household optimization problem given the regional population (N) and ecological condition (P) is:

$$U(N, P, W, R) = \max_{X_i, L_i} \left\{ X_i^{c_x} L_i^{1-c_x} + U_c(N) + U_e(P) \right\} \quad (3)$$

subject to $X_i + R \cdot L_i = W$, where c_x is the consumption elasticity of the numeraire good with a normalized price of 1; R is the land rent; U_c is the disutility from congestion; U_e is the utility from enjoying the natural amenities; and P is the phosphorus concentration in the lake. The household's optimal consumption is given by $X_i = c_x W$ and $L_i = (1 - c_x)W/R$.

We assume that the supply of residential land is perfectly elastic given the abundance of homogeneous land in the region. In other words, residential land is supplied at constant price (r_0),¹ which is the sum of the opportunity cost of land, as measured by agricultural returns, and the construction cost of a housing unit. At the land market equilibrium, $R = r_0$.

Substituting the individual consumption of X_i and L_i along with the market clearing conditions into the individual utility function, we arrive at the the indirect utility of the household that lives in the region, which is conditional on N and P :

$$U^*(N(t), P(t)) = U(N(t), P(t), W = W(N(t)), R = r_0) \quad (4)$$

Assuming that the migration rate is proportional to the utility difference between migrating versus not migrating into the region, we can specify the dynamic equation that relates migration and regional economy as:

$$\dot{N} = U^*(N, P) - u_0, \quad (5)$$

¹This assumption ignores the possibility that construction costs may be endogenously determined in the region. Accounting for this endogeneity is quite involving. While we have not fully incorporated this endogeneity into our model, we explore the sensitivity of the model to this assumption in section 6 by investigating its potential impact on regional development and ecological conditions.

where \dot{N} stands for the migration rate. Other things equal, when the reservation utility u_0 is high, stronger agglomeration forces or preference for natural amenities are necessary to maintain the rigor of the regional economy. The argument t is suppressed from here on.

3.3. Dynamics of the Coupled Economic-Ecological System

The dynamics of this coupled economic-ecological system is governed by equations (1) and (5). The dynamic equation for the regional economy is hump shaped in the local population, which reflects a generic feature in regional development models. That is, at the initial stages of development, the in-migration rate increases with population as a consequence of agglomeration. However, as population increases, the congestion effect will eventually dominate and the migration rate will slow down. The inverse relationship between the migration rate and the ecological variable P reflects people's preference for high quality natural amenities. The changes in the ecological system are affected by human land use decisions and the nonlinear threshold dynamics captured in the recycling term that arise when phosphorus concentrations are sufficiently high. This recycling term generates the ecological threshold that is the essence of the policy challenge and at the same time makes the optimization problem analytically intractable. For this reason, we use numerical methods to solve the optimal policy. The model is parameterized using secondary data and estimates from the literature. Because of the potential sensitivity of our results to the specified parameter values, we conduct sensitivity analysis to evaluate the robustness of our results to a range of key parameter values. Here, we provide the rationale for the key specifications of the functional forms and parameter values, with a full list of parameters and their values in Table 1.

Lake dynamics: We model the dynamics of lake water quality on a quarterly base. Because the annual phosphorus loadings rate per acre is 0.13 in low-density residential areas [34] and the average lot size of new one-family house sold in 2000 is roughly 0.41 acre according to the U.S. Census, we set the quarterly loadings rate of residential land (l_1) to be $0.013 (\approx 0.13/4 * 0.41)$. The steepness of the recycling curve r_2 is assumed to be 8 which is close to 7.88 reported in [8, p.762] and the average rate of phosphorus outflow (s) is assumed to be 0.2 which is roughly a quarter of the mean annual rate of 0.817 in [8, p.762]. According

Table 1: Parameter specification.

Parameters	Description	Value
c_x	Consumption elasticity of the numeraire good	0.75
b_0	Constant term in production externality	1.0
b_1	Coefficient of production externality	0.043
c_c	Coefficient of disutility from congestion	0.003
c_e	Marginal disutility from ecological degradation	0.04
r_0	Agricultural land rent	0.065
u_0	Reservation utility	0.61
l_0	Agricultural phosphorus loadings to lake	0.2
l_1	Average phosphorus loadings from residential land use	0.013
s	Average rate of phosphorus outflow	0.2
r_1	Maximum rate of recycling	0.8
r_2	Steepness of the recycling curve	8
p_c	phosphorus level at half the maximum rate of recycling	5
ρ	Discount rate	0.01
α_1	Cost of economic intervention	100
α_2	Cost of ecological intervention	100

to [8, p.754], we set the spring P concentration at around 5% of the maximum concentration attained the preceding summer, the maximum rate of recycling per quarter (r_1) is around 0.8 in the baseline model. We set the half maximum rate of recycling (p_c) to be 5.²

Production: We assume that the neoclassical production function for X exhibits constant returns to scale: $F(N) = N$. The production externality term $E(N)$ is a linear approximation of the functional form suggested by empirical findings [17]³. In the baseline model, $a_0 \approx 0.09$ which corresponds to an approximately 6.5% increase in productivity when

²According to Nürnberg [27], the internal phosphorus loadings in the sampled stratified lakes range from 0 to 2100 $mg\ m^{-2}$. We take the midpoint of the interval to be the maximum rate of recycling.

³Empirical studies typically assume an exponential form for the production externality: $E(N) = N^{a_0}$, where a_0 controls the increase in productivity [17]. These studies estimate a_0 to vary in magnitude such

population doubles.⁴

Utility: The first term in the utility function specifies the relative consumption trade-off between land and numeraire consumption and is governed by the consumption elasticity c_x . Based on consumer expenditure reports on housing expenditures [7], we set c_x to be 0.75, reflecting the fact that households spend about one quarter of their quarterly income on housing and housing related services. We assume that the congestion effect is $U_c(N) = -c_c N^2$ and that the utility provided by the natural amenity service is of the form $U_e(P) = -c_e P$. The parameters c_c and c_e are the relative weighting coefficients that determine the respective contributions of congestions and ecological quality to utility. We specify these parameter values so that the “push” and “pull” migration effects that arise from population and natural amenities are in balance when the regional economy is in or near a steady state. We focus on population levels with an average steady state level of 75,000.⁵ Given a steady state of $N \approx 7.5$ (since N is expressed in units of 10,000), we specify c_c to be relatively small ($c_c = 0.003$), so that the incentive for out-migration due to congestion is dominated by the incentive for in-migration due to agglomeration. We specify a higher baseline value for the marginal disutility of ecological degradation ($c_e = 0.04$), so that the aggregate incentive for out-migration, due to either congestion or ecological degradation, balances the incentive for in-migration. To examine the sensitivity of the model to our specified baseline values, we conduct sensitivity analysis on the key parameters that govern the push and pull migration effects. The reservation utility u_0 is specified so that significant changes in regional population occur relatively slowly, i.e. on the order of decades.

Income normalization: Wages are a function of the total population living in the region as shown in Equation (2). Given the production function specified above, at an equilibrium

that a doubling of population generates a productivity increase that varies from about 3-10%. To simplify the model, we use a linear function $\hat{E}(N)$ to approximate $E(N) = N^{a_0}$ for $N \in [0, 8]$.

⁴In sensitivity analysis, we examine the impact of smaller production externality on our results.

⁵Based on descriptive analysis of US Census population data and county typology codes from the USDA Economic Research Service, recreation-based counties in the top quartile of population had a mean population of 71,567 in 2000 and an estimated population of 77,093 in 2007. Data <http://www.ers.usda.gov/Data/TypologyCodes/>

population level of $N = 7.5$, the relative household wage income is roughly $W = 1.3$. According to the 2000 US Census, the median household income for homeowners is roughly \$12,750(= \$51,000/4) per quarter, implying that expenditures on the numeraire good (which are normalized to one) equal to \$9,800(\approx \$12,750/1.3) in absolute terms. We use this to determine an appropriate relative value of the housing rent r_0 . The average value per acre cropland for U.S. in 2000 is \$1,460[33]. The construction cost is set to be \$96,200 calibrated using the average construction cost per unit single family house in nonmetropolitan areas in 2000.⁶ The total opportunity cost for the supply of residential land equals \$87,660 (= \$1,460 + \$96,200). We then convert this opportunity cost into quarterly rent by continuous compounding using the real thirty-year interest rate⁷. This results in a payment of \$635 which makes $r_0 \approx 0.065$ (\approx \$635/\$9,800).

With the assumed function forms of $F(N)$, $E(N)$, $U_c(N)$ and $U_e(P)$ mentioned above, the household optimal consumption functions X_i and L_i can be expressed as functions of N and P . Substituting the optimal X_i and L_i into equations (1) and (5) and rearranging the terms will give us the following dynamic equations. To simplify the presentation in the remainder of the paper, we relabel all the coefficients in the \dot{N} and \dot{P} equations as θ 's and δ 's, respectively:⁸

$$\dot{N} = \theta_1 + \theta_2 N + \theta_3 N^2 + \theta_4 P \quad (6a)$$

$$\dot{P} = \delta_1 + \delta_2 N + \delta_3 N^2 + \delta_4 P + \delta_5 \frac{P^8}{P^8 + p_c^8}. \quad (6b)$$

Figure 1 illustrates the dynamics of this coupled economic-ecological model for the baseline case. The N -nullcline is the set of points that eliminates the utility difference between the region and the rest of the world, that is $\{(N, P) | \dot{N} = 0\}$. This allows us to interpret

⁶The data is obtained from the U.S. Department of Housing and Urban Development. To control for the outliers, we exclude nonmetropolitan counties with per unit construction cost exceeding \$250,000. This excludes the top 1% of the observations.

⁷Calculated using the thirty-year nominal interest rate and the inflation rate in 2000 obtained from the Federal Reserve website.

⁸ $\theta_1 = c_x^{c_x} (1 - c_x)^{1 - c_x} b_0 - u_0$, $\theta_2 = c_x^{c_x} (1 - c_x)^{1 - c_x} b_1 r_0^{c_x - 1}$, $\theta_3 = -c_c$ and $\theta_4 = -c_e$. $\delta_1 = l_0$, $\delta_2 = l_1 (1 - c_x) b_0 / r_0$, $\delta_3 = l_1 (1 - c_x) b_1 / r_0$, $\delta_4 = -s$ and $\delta_5 = r_1$.

the N -nullcline as the household indifference curve. Its hump-shape reflects the trade-off between the household economic well-being and the desire for ecological services. When N is small, the agglomerative forces dominate the congestion effect and the expansion of the regional population increases the welfare of all the households in the region. This increase in household welfare needs to be offset by an increase in phosphorus loading in order to remain on the same indifference curve and thus, the slope of the N -nullcline is positive for smaller values of N . When N is so high that the congestion effect dominates, further expansion of the regional population becomes a “bad.” A decrease in phosphorus loading is necessary to make the household indifferent. This makes the slope of the N -nullcline slope negative for larger values of N . In states below (above) this N -nullcline, households will move into (out of) the region, because of better (worse) ecological services.

The P -nullcline is similarly defined. It is S-shaped because of the nonlinear dynamics captured in the recycling term. The lower (upper) branch of the P -nullcline corresponds to an oligotrophic (eutrophic) state of the lake. The curvature in the middle reflects the nonlinear dynamics of the threshold effect. In states to the right (left) of the P -nullcline, phosphorus concentration will increase (decrease) because of the higher (lower) P-loadings from economic activities in the region. The direction field is plotted in Figure 1. The length of the direction arrow is proportional to the velocity. In reality, an ecological regime shift from an oligotrophic to eutrophic lake can occur in a couple of years. In contrast, the regional migration is a much slower process which typically takes decades. Such a difference in the speed of change in P and N is manifested by the long and upward pointing arrows when N is large. Because households respond to severe ecological degradation changes through out-migration, lake eutrophication is slowly reversible in this model. In the baseline case, the recovery from eutrophication takes several decades.

The N - and P -nullclines intersect at the three fixed-points: A , B and C . Point (A) is a non-trivial stable fixed point associated with a moderate population size and an oligotrophic lake. Because population and ecology are “in balance” at this fixed point, we refer to it as the balanced economic-ecological equilibrium state. However, this point may be more or less resilient to unexpected increases in phosphorus concentrations. An ecological shock

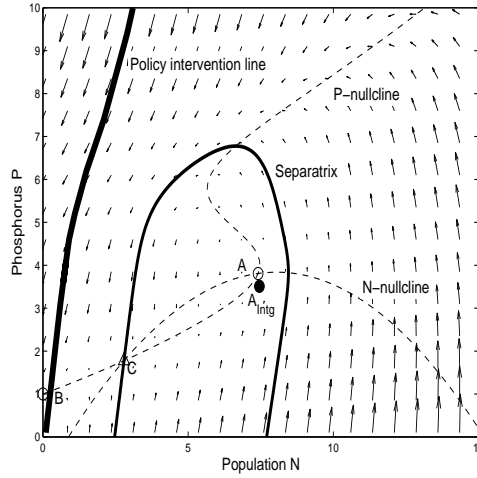


Figure 1: Dynamics of the coupled economic-ecological system for the baseline model.

that increases phosphorus concentration (such as a variation in rain fall) or an economic shock that increases land development (such as government policy that promotes economic development) could trigger the recycling process and shift the lake from the oligotrophic to eutrophic state. At fixed point B, with insufficient population to generate economic benefits, the pristine ecological services alone are unable to maintain local population. We refer to this steady state as the “ecology-dominated” equilibrium state.⁹ Point (C) is an unstable fixed point. The thin solid line that passes through this point, called the separatrix, is the stable manifold of the unstable fixed point (C). That is, if the system starts from a point on this line, it will eventually approach the unstable fixed point. The separatrix partitions the state space into two domains of attraction: that of the balanced equilibrium (A), which is the area bounded by the separatrix, and that of the ecology-dominated equilibrium (B), which is the remainder of the state space.

⁹In this model, we have not considered moving costs, irreversibility of development, household heterogeneity or other realistic factors that would introduce frictions in household relocation and prevent a region from emptying out. However, it is likely that the out-migration induced by ecological degradations may move the regional economy to a much lower level of steady state economic activities.

4. Optimal Policy Analysis

In this section, we discuss the technical challenges involved in the dynamic optimization of this integrated economic-ecological system with multiple equilibria and a non-convexity. Because of the existence of multiple equilibria, the policy maker must decide when to drive the system to one equilibrium versus the other. To consider the optimal policy problem, we assume that a social planner will choose the policy that maximizes the net social benefit, defined as the discounted utility of a representative household minus the per household cost of the policy.¹⁰ The social planner has two policy instruments: one acts as a migration incentive that affects the local economy, denoted as $v_1(t)$; the other acts on phosphorus loadings into the lake and affects lake water quality, denoted as $v_2(t)$. These policies are assumed to be continuous in their intensity and the cost of each is assumed to be increasing in intensity. The optimization problem is formulated as:

$$\max_{\{v_1(t), v_2(t)\}} \int_0^{\infty} e^{-\rho t} \left\{ U^*(N, P) - 0.5\alpha_1 v_1^2 - 0.5\alpha_2 v_2^2 \right\} dt \quad (7a)$$

subject to

$$\dot{N} = \theta_1 + \theta_2 N + \theta_3 N^2 + \theta_4 P + v_1, \quad (7b)$$

$$\dot{P} = \delta_1 + \delta_2 N + \delta_3 N^2 + \delta_4 P + \delta_5 \frac{P^8}{P^8 + p_c^8} - v_2, \quad (7c)$$

$$N(t) \geq 0, P(t) \geq 0, N(0) = N_0, P(0) = P_0. \quad (7d)$$

¹⁰Following the suggestion of one referee, we tried using the aggregate individual utility, i.e. $N(t)U(N, P, t)$ as the welfare measure. However, this specification increases nonlinearity in the Hamiltonian equations and prevents us from deriving a solution using the continuation method [1]. For this reason, we assume that social welfare is defined in terms of a representative agent's utility.

Using the current value Hamiltonian, the optimality conditions of interior solutions are:

$$v_1 = \lambda_1/\alpha_3, \quad v_2 = -\lambda_2/\alpha_3, \quad (8a)$$

$$\dot{N} = \theta_1 + \theta_2 N + \theta_3 N^2 + \theta_4 P + v_1, \quad (8b)$$

$$\dot{P} = \delta_1 + \delta_2 N + \delta_3 N^2 + \delta_4 P + \delta_5 \frac{P^8}{P^8 + p_c^8} - v_2, \quad (8c)$$

$$\dot{\lambda}_1 = \rho\lambda_1 - \lambda_1 \left[\theta_2 + 2\theta_3 N \right] - \lambda_2 \left[\delta_2 + 2\delta_3 N \right] - \theta_2 - 2\theta_3 N, \quad (8d)$$

$$\dot{\lambda}_2 = \rho\lambda_2 - \lambda_1 \theta_4 - \lambda_2 \left[\delta_4 + \delta_5 \frac{8P^7 p_c^8}{(P^8 + p_c^8)^2} \right] - \theta_4. \quad (8e)$$

Along with the initial conditions (7d) and the transversality conditions:

$$0 = \lim_{T \rightarrow +\infty} e^{-\rho T} \lambda_1(T) N(T), \quad \text{and} \quad 0 = \lim_{T \rightarrow +\infty} e^{-\rho T} \lambda_2(T) P(T). \quad (8f)$$

The policy-induced behavioral changes are embedded in this system of equations. A policy that improves the lake quality will attract in-migration as shown in the fourth term in Equation (8b). This increase in in-migration will then contribute more phosphorus loadings through increased land use as shown in the second and third terms in Equation (8c). The optimal policy considers this induced behavioral change as shown in the second term in Equation (8e). When the ecological intervention reduces the phosphorus, the marginal impact on the value function through this induced behavioral change equals the product of the ecological impact on population (θ_4) and the population shadow price (λ_1).

With the presence of multiple equilibria, the policy maker needs to decide when to intervene and drive the system to the balanced equilibrium (A_{Intg}) which lies off the original N - and P -nullclines, because v_1 and v_2 are non-zero at the steady state. Such a decision depends on the relative location of the system to the policy intervention line, denoted in Figure 1 as the bold solid line in the upper left corner. If the system starts from a point on this line, the optimal policy, as specified by Equations (8), that drives the system to A_{Intg} , generates the same social welfare as taking no action. To its right (left), the optimal policy leading to the balanced equilibrium generates higher (lower) social welfare than taking no

action. Because the transversality condition is automatically satisfied when $N(T)$, $P(T)$, $\lambda_1(T)$ and $\lambda_2(T)$ are finite as $T \rightarrow +\infty$, we use the population and phosphorus level at A_{Intg} as the boundary conditions for the differential equation system (8). For each initial condition (N_0, P_0) , we solve the corresponding boundary value problem and calculate the present value of the net social benefit, which is then compared with the social benefit with no intervention ($v_1(t) \equiv 0, v_2(t) \equiv 0$). If the two social benefits equal, the initial condition belongs to the policy intervention line.

The optimal policy effectively enlarges the attraction domain of the balanced equilibrium. As shown in Figure 1, many of the initial states that are outside the attraction domain of the balanced equilibrium (A) as delineated by the separatrix are nonetheless to the right of the policy intervention line. In the absence of any policy intervention, these initial states would result in a long-lasting decline of the region that eventually would converge to the ecology-dominating equilibrium. However, when considered from an optimal policy perspective, it becomes socially desirable to invest in policy interventions that offset this natural tendency and instead drive the system towards the balanced equilibrium at A_{Intg} .

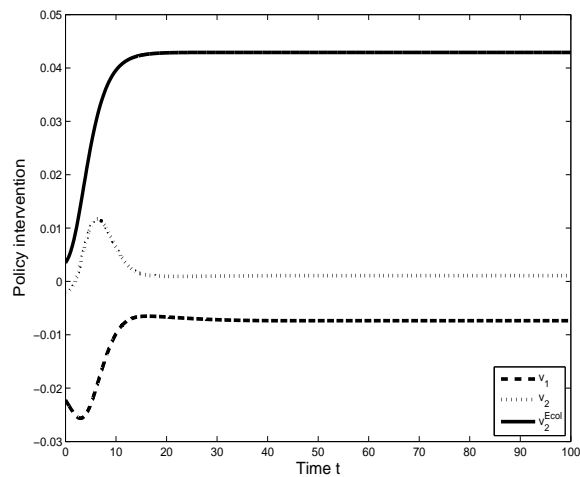


Figure 2: A comparison of the optimal policy in the integrated management model (v_1 and v_2) versus the ecological management model (v_2^{Ecol}) for an initial condition $(N_0, P_0) = (8, 1)$.

Figure 2 shows the optimal policy for specific initial condition $(N_0, P_0) = (8, 1)$, which corresponds to a case in which the coupled system is in danger of eutrophication due to

overdevelopment. This figure demonstrates that policy interventions in the transient period can be quite different from those at the steady state.

Our results also suggest that for threshold management, the ending phase of a policy in some cases can be crucially important for the final outcome of the policy. In our simulation, we find that in some cases, for example when the cost of policy intervention is low, the optimal policy can shift the balanced equilibrium across the separatrix into an otherwise unsustainable state. A sudden stop of policy intervention will result in long lasting economic decline because A_{Intg} lies in the attraction domain of the ecology-dominated equilibrium B . It is not uncommon that the financial resources supporting a policy may run out, like the budget cuts due to economically hard times. The results in this paper suggest that we should not simply stop the funding, but rather put aside some resources and implement policies that help to smooth the transition period when the policy fades out, either to mitigate the transient ecological degradation or to bring the system from the new equilibrium A_{Intg} back into the attraction domain of the balanced equilibrium A .

5. A Comparison of Alternative Policies

In this section, we discuss the policy implications when overdevelopment in the region may push the lake ecosystem across the ecological threshold. In particular, we first discuss the implications of the safe minimum standards (SMS) as proposed by Wantrup and Bishop [11, 4]. Then we discuss the implications of a naive ecological management policy (e.g. as in [5, 8]) in which the policy induced behavioral changes are not considered.

5.1. *The Safe Minimum Standard*

The SMS stipulates that as the ecosystem approaches an ecological threshold, concerns for economic efficiency should be set aside and policy intervention should be implemented to prevent the breach of the ecological threshold unless the cost of the policy becomes “intolerably too burdensome” [4]. In this section, we illustrate how the performance of this policy hinges upon the policy-induced behavioral changes and demonstrate how its implementation

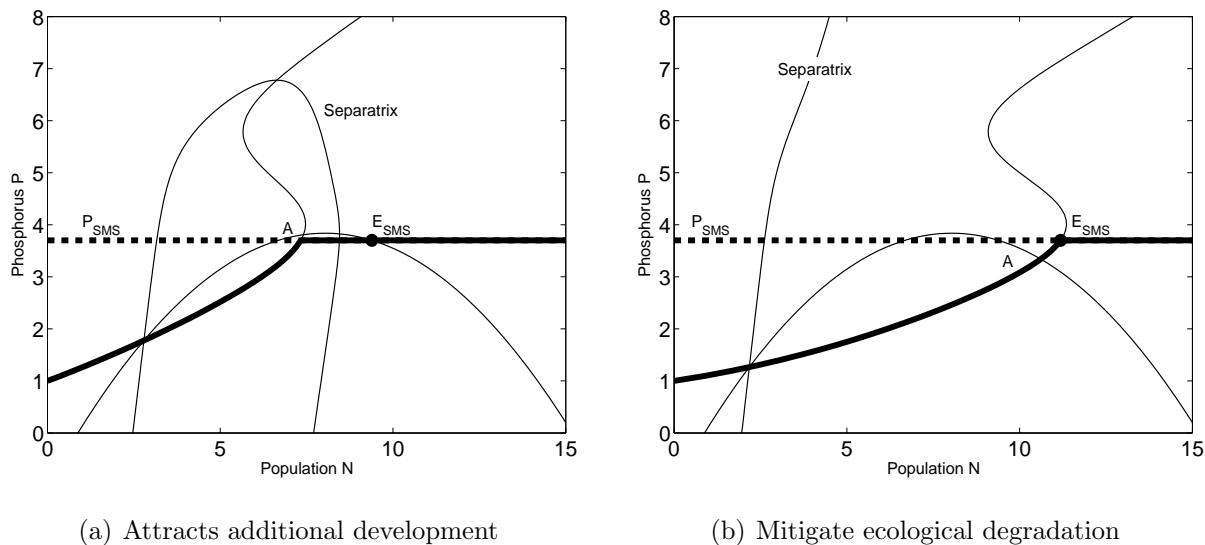


Figure 3: A SMS that limits P concentration in the lake and induces different behavioral responses.

can endogenously make the cost of the policy “too burdensome.” In particular, the SMS is not safe for local economies that are in an economic expansion phase.

Denote the SMS for phosphorus concentration as P_{SMS} . If chosen correctly by the policy maker, the value of P_{SMS} will not exceed the ecological threshold, which is the level of P at which the P -nullcline begins to bend back. Figures 3(a) and 3(b) illustrate this policy for two respective cases. The first case is when the agglomerative forces dominate congestion in the regional economy, which corresponds to the range of N values that the N -nullcline is increasing. We call this phase of development as the phase of economic expansion. The second case is when the congestion effects dominate, which corresponds to the range of N values that the N -nullcline is decreasing. We call it the phase of post-economic-expansion or simply the phase of post-expansion.

Because in reality the policy maker typically does not know the exact value of the threshold, he may set P_{SMS} more stringently below the true threshold level. This implies that the phosphorus dynamics follow the natural dynamics only if P level is less than P_{SMS} . When the natural evolution of the system tries to drive P levels above P_{SMS} , the SMS activates and keeps the phosphorus P at the constant level of P_{SMS} . Therefore, the actual P -nullcline

under the SMS is the thick solid line in Figures 3(a) and 3(b), which creates a new steady state E_{SMS} . To see this, let us assume the system resides at the balanced equilibrium (point A in Figure 3). The policy maker adopts the SMS which keeps P concentration at or below P_{SMS} . A small deviation, e.g., due to exogenous in-migration, will actually improve economic welfare and induce more in-migration because the full negative ecological impact is muted by the SMS. This in-migration will continue until the new steady state at E_{SMS} is reached. Thus, a SMS will lead to increased population and increased phosphorus loadings that increase the costs of maintaining a SMS. The more stringent the SMS, the larger the population at the steady state E_{SMS} and the more severe the consequences of overdevelopment if the SMS were removed.

Note that the implementation of the SMS results in a discrete change in the location of what was the balanced equilibrium fixed point: with a SMS in place, E_{SMS} is no longer in the attraction domain of the balanced equilibrium. Stated differently, the SMS fully erodes the resilience of the balanced state by pushing it outside the attraction domain of the balanced equilibrium and making it fully dependent on the successful enforcement of the policy. If the SMS were eliminated or not properly maintained, a worse outcome may result than had the SMS never been implemented. This is because, in the absence of a SMS, the full ecological impacts of overdevelopment would be felt. Without any further policy intervention, the system would be trapped in the ecology-dominated domain and the region would experience a prolonged period of out-migration.

The SMS may work when the regional economy is in the phase of post-expansion as shown in Figure 3(b). Assume the system is resting at the balanced equilibrium and is hit by a sudden influx of population that in the absence of any pollution control policy would drive P above the ecological threshold. The implementation of SMS can successfully prevent breaching the threshold. Meanwhile, because congestion is dominating, the influx of people will eventually leave the region and the system will recover to the balanced equilibrium. In the transient period, SMS successfully avoids breaching the ecological threshold.

In summary, the performance of the SMS hinges on the dynamic responses of households to the policy, which in turn depend on the relative balance between the agglomerative and

dispersive forces that influence migration. In the first example, the implementation of SMS allows households to exploit the untapped development potential which would otherwise be deterred because of ecological degradation. This eventually makes the SMS too costly. In the second example, SMS works effectively. In the transient period, the SMS successfully avoids the breach of ecological threshold. Meanwhile, because the congestion effect is dominating, households gradually leave the region until the balanced equilibrium is restored.

5.2. Naive Ecological Management

In this section, we consider the management policy as discussed in many resource and environmental analyses [5, 8]: policy makers respond to ecological degradation by reducing human impacts, but they do not consider the fact that the resulting improvements in ecosystem services can generate feedbacks that influence the behavior of autonomous economic agents. In other words, the problem is simplified to a one-way interaction in which the policy maker is able to control human impacts directly by controlling pollution and does not need to consider individual responses to the subsequent changes in ecosystem services. For situations in which behavioral feedbacks do not exist, this set-up of the problem is appropriate. However, when behavioral feedbacks exist, ignoring these effects may result in unintended consequences. In the context of our model, we consider this case by assuming that the policy maker seeks only to control phosphorus loadings and ignores the indirect effect of this policy on households' behavior to an improvement in ecosystem amenities. This leads to the following optimization problem:

$$\max_{\{v_2^{Ecol}(t)\}} \int_0^{\infty} e^{-\rho t} \left\{ \theta_1 + \theta_2 N + \theta_3 N^2 + \theta_4 P - 0.5\alpha_2 [v_2^{Ecol}(t)]^2 \right\} dt \quad (9a)$$

subject to

$$\dot{P} = \delta_1 + \delta_2 N + \delta_3 N^2 + \delta_4 P + \delta_5 \frac{P^8}{P^8 + p_c^8} - v_2^{Ecol}(t) \quad (9b)$$

where $v_2^{Ecol}(t)$ is the policy instrument with an increasing marginal cost. The current value Hamiltonian gives the following optimality condition:

$$\dot{P} = \delta_1 + \delta_2 N + \delta_3 N^2 + \delta_4 P + \delta_5 \frac{P^8}{P^8 + p_c^8} + \lambda_2^{Ecol} / \alpha_3 \quad (10a)$$

$$\dot{\lambda}_2^{Ecol} = \rho \lambda_2^{Ecol} - \lambda_2^{Ecol} \left[\delta_4 + \delta_5 \frac{8P^7 p_c^8}{(P^8 + p_c^8)^2} \right] + \alpha_2 \theta_4 \quad (10b)$$

The optimal intervention $v_2^{Ecol} = -\lambda_2^{Ecol} / \alpha_3$ is plotted as the solid line in Figure 2.

Policies that ignore the behavioral responses when in fact these responses to policy are present are clearly suboptimal. Comparing Equations (10) with Equations (8a), (8c) and (8e), they differ only by the term $(\lambda_1 \theta_4)$ in Equation (8e) which captures the indirect policy effect on household behavior. This difference is most significant if the marginal utility of ecosystem amenities (θ_4) is high and local economic development is a major concern, or in other words, the shadow price of development (λ_1) is high. Both conditions are satisfied by small communities experiencing amenity-led growth and rural communities attempting to restructure their traditional resource extractive industries into a more service-based economy. It is easy to prove that at the steady state, *Ceteris Paribus*, if $v_2^{Ecol} > 0$ as $t \rightarrow +\infty$ and if the shadow price for regional development is positive ($\lambda_1 > 0$), a failure to account for these behavioral responses will result in an underestimate of the shadow price for phosphorus (λ_2) at the steady state. Consequently, the ecological intervention will be insufficient and eutrophication is more likely to occur.

The potential failure of a naive ecological management approach when behavioral responses are present is illustrated in Figure 4. Let us consider the baseline case that overdevelopment puts the lake in the danger of eutrophication in the absence of any policy intervention. If the policy maker does not consider the behavioral responses to a pollution control policy, he will expect that population will be fixed at the current level N_0 and that the ecological system will evolve along the solid line passing through N_0 in Figure 4(a) and end up in the eutrophic state at an imaginary steady state A_{Imag} . Because the excessive phosphorus loadings are the key driver behind eutrophication, he will implement a policy to reduce phosphorus loadings, which will shift the P -nullcline to the right. Given the optimal

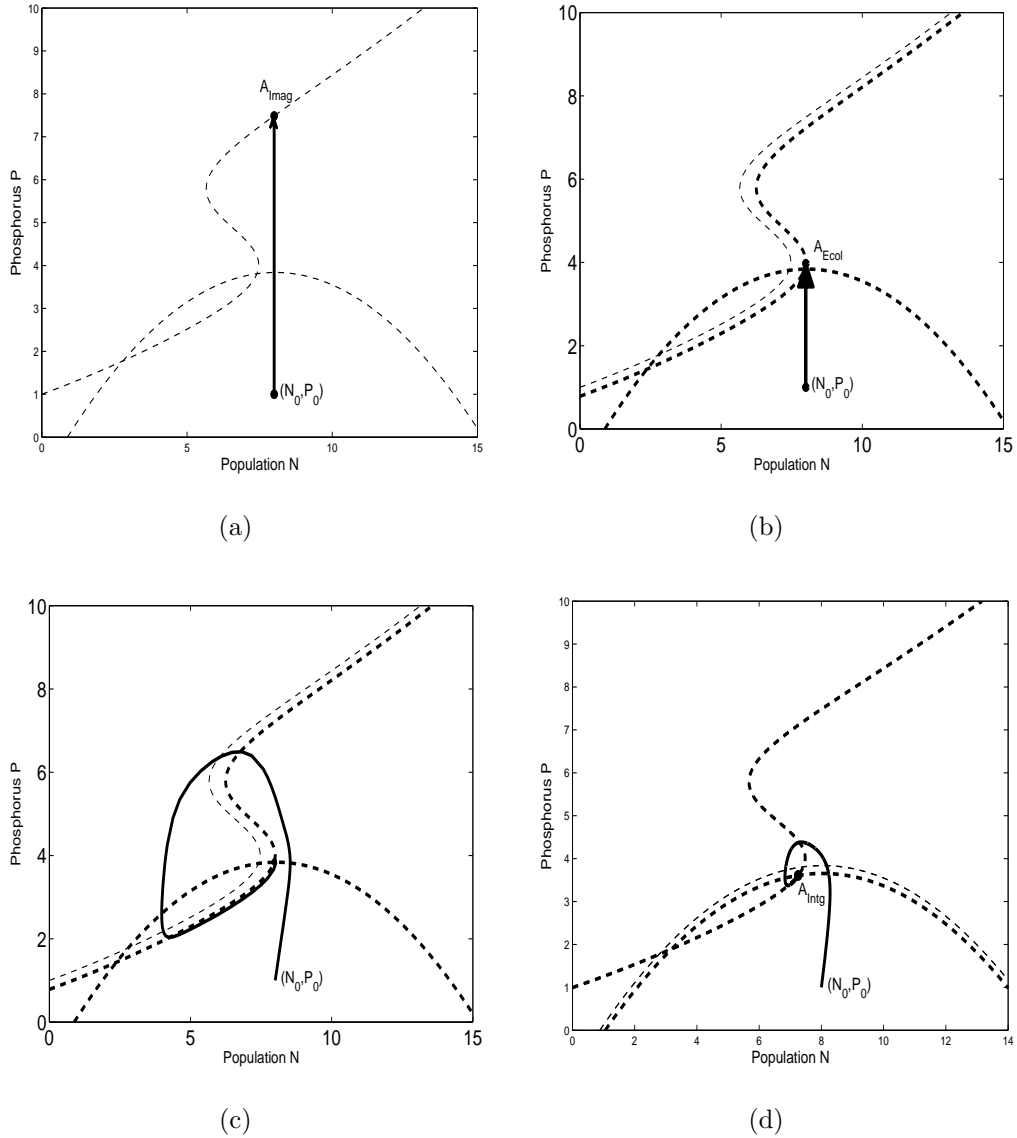


Figure 4: Comparison of a naive ecosystem management (Equation 10) versus integrated ecosystem approach (Equation 6). Figure(a) The policy maker's perceived ecological-economic dynamics before a policy intervention occurs: the policy maker with a naive view of the system believes that population is fixed at N_0 . Figure(b) The policy maker's perceived ecological-economic dynamics after a naive policy intervention occurs: the policy maker believes that he has optimally controlled the impact of P in the absence of any behavioral response. Figure(c) The actual ecological-economic dynamics after a naive policy intervention has occurred and a behavioral response is present: the policy maker fails to account for the behavioral response, which results in overdevelopment and ecological decline. Figure(d) The actual ecological-economic dynamics after the optimal policy intervention occurs in which the behavioral response is accounted for using the integrated model.

policy in the naive ecological management problem as specified in Equations (10), the policy maker believes that with this naive optimal policy in place, the system will evolve along the solid line in Figure4(b) and end up at equilibrium A_{Ecol} . While lake eutrophication is avoided, as A_{Ecol} locates on the lower branch of the P -nullcline, the phosphorus level at A_{Ecol} increases and is even closer to the eutrophication threshold as compared to the original balanced equilibrium at A . This is because policies that reduce the phosphorus loadings in effect enhance the carrying capacity of the lake so that it is able to accommodate more economic activities and higher phosphorus loadings.

When such a policy is implemented in the coupled economic-ecological system described in (6) in which behavioral feedbacks are present, the policy-induced behavioral changes can generate unintended consequences as shown in Figure4(c). Because the starting point (N_0, P_0) is below the N -nullcline, people will migrate into the region even without any policy intervention. An exclusive policy focusing on controlling pollution will improve the water quality and make the region more attractive. This will worsen the overdevelopment problem and result in increased ecological degradation, as illustrated by the initial increase in P in Figure4(c). In spite of the policy intervention, lake eutrophication occurs, the economy declines and it takes decades to recover to the original balanced equilibrium.

The necessity of the integrated approach is illustrated by the comparison between Figure4(c) and 4(d). Through the coordination of the ecological and economic policies, the policy from the integrated approach addresses the policy-induced behavioral changes, mitigates the ecological degradation and avoids the associated long-lasting economic decline.

6. Sensitivity Analysis

Given our focus on the two-way economic-ecological interactions between urban growth and water quality, our results are potentially most sensitive to the specification of these interaction terms, i.e., the individual disutility from ecological degradation (the P term in the \dot{N} equation) and the impact of the regional economy on the lake's ecology (the N terms in the \dot{P} equation). We explore the sensitivity of the optimal policy results to several key parameter values that govern the strength of these interaction terms.

First, we consider the baseline value of c_e , the coefficient that determine the households' relative disutility from ecological degradation, which is specified as 0.04. Sensitivity analysis shows that the optimal policies are robust for $c_e > 0.024$. We experiment by allowing c_e to range over the interval $[0.024, 0.08]$ ¹¹ and find similar results to the baseline case. Moreover, the topological structure of the system dynamics remains the same as the baseline. Specifically, both the balanced and ecology-dominating equilibria are stable, as they are in the baseline case. As c_e become larger, the disutility from ecological degradation becomes stronger and the economic benefits from agglomeration become insufficient to sustain the balanced equilibrium without a policy intervention. Technically, the N -nullcline falls below the P -nullcline and no longer intersects at the balanced equilibrium A as in Figure 1. In such a case, the optimal policy would create a balanced equilibrium (A_{Intg}) and sustain the system at this equilibrium state when the system lies to the right of the policy intervention line. On the other hand, as c_e becomes smaller, people will tolerate greater ecological degradation. Without any policy intervention, this can make the balanced equilibrium unstable. In this case, the optimal policy has an additional objective, which is to eliminate or mitigate the boom-and-bust cycles that otherwise would result when c_e is very low.

Second, we consider the sensitivity of the results to our specification of l_1 , the coefficient controlling the impact of urbanization on the lake ecology. We find analogous results. With a baseline value of $l_1 = 0.013$, we vary its value in the range of $[0.005, 0.024]$. We find that the basic topological structure, i.e., the bistability of both the balanced and ecology-dominated equilibria remains unchanged. As l_1 increases, the P -nullcline shifts upward because the ecological impact of urbanization at any population level increases. Because the ecological system becomes more sensitive to regional growth, the carrying capacity is reduced, as is the equilibrium population level associated with the balanced equilibrium. *Ceteris Paribus*, as l_1 increases further (≥ 0.025), the ecological degradation associated with the economic growth becomes so strong that the balanced equilibrium can no longer be sustained.

¹¹When $c_e = 0.08$, the out-migration incentive due to ecological degradation alone is strong enough to balance the in-migration incentive due to agglomeration given an equilibrium population of $N = 7.5$. When $c_e = 0.024$, the out-migration incentive is about half of the baseline case.

Thirdly, we explore the sensitivity of our results to the parameters that govern population dynamics. Recall that the quadratic form of population growth as a function of population level is specified to capture the agglomeration and congestion effects that are reported in the empirical literature on regional growth. Accordingly, we conduct a sensitivity analysis on the agglomeration coefficient b_1 . When $b_1 \in [0.015, 0.05]$, which roughly corresponds to the empirically estimated range of 3.1-10% increase in productivity when population doubles¹², the optimal policy is qualitatively similar to the baseline case.

As for the marginal cost of residential land provision (r_0), we change its value in the range of $[0.015, 0.15]$.¹³ A decrease in r_0 has both an income and substitution effect that increases the household's land consumption. Consequently, the N -nullcline is shifted upward since the income effect allows people to tolerate more pollution. The P -nullcline is shifted upward because the substitution effect pushes up the demand for land at any population level. The optimal solution is similar to the baseline with a shifted equilibrium state. So far, we have implicitly assumed that the construction of housing units is perfectly competitive. This implies that the unit construction cost is a constant. Alternatively, we may assume that the supply of housing units is not perfectly competitive and that local labor is used in housing construction. This will make the construction cost and r_0 endogenous to the regional development. It will also increase the demand for local labor. Intuitively, this increase in demand will increase household income in the region and enhance the incentive for in-migration. However, the increase in the labor demand will also push up the land rent r_0 and the cost of living, which will mitigate the incentive for in-migration. As for the demand for residential land, the income effect will increase the demand while the substitution effect will decrease it. To fully incorporate this endogeneity, the model has to be modified so that wage rate depends on the local demand of both the numeraire good and the housing production. In addition, local labor needs to be efficiently allocated between the production

¹²For the case of 3%, the agglomeration force is too weak to offset the ecological degradation and support the local economy.

¹³If we double (halve) either the construction cost or the interest rate used to calculate r_0 , the corresponding value of r_0 lies in this range.

of the numeraire good and housing construction. These changes are technically involving and distract the attention from our focus on threshold management. While we have not fully incorporate this endogeneity, the impact can be partially observed through the above sensitivity analysis. If endogenous construction cost enhances/mitigates the in-migration incentive, the effect on regional development can be learned by increases/decreases in the parameter (b_1), which controls the strength of agglomeration forces. After considering both the income and substitution effects, if endogenous construction cost increases/decreases the final demand for residential land, the ecological impact is similar to an increase/decrease in l_1 which controls the ecological impact of regional economic activities at the given population level.

Finally, we double the intervention cost for both policy instruments (α_1 and α_2) and change the relative weights between the economic and ecological interventions from 1 : 1 to 1 : 3 and 3 : 1. We only find quantitative changes in the optimal solutions, but no qualitative differences.

In short, the optimal policy results that we derive in the preceding section for this integrated economic-ecological system are robust to the specification of key parameter values, as is the basic bi-stable structure of the ecological-economic system. While the exact location of the optimal policy intervention line depends on the parameter specification, the existence of this line is robust to the range of parameter values explored above. This implies that for integrated economic-ecological systems such as this one, there exists a set of initial conditions that in the absence of policy would not evolve to a balanced equilibrium, but for which it is optimal to intervene with policies that guide the system to an equilibrium in which regional population and ecological degradation are in balance.

7. Conclusion

This study investigates threshold management in a dynamically interacting economic-ecological system in which the ecosystem responds to the cumulative impacts of individuals and individuals' respond to subsequent changes in the ecosystem due to amenity-led migration. While economic models of optimal ecosystem management have long accounted

for the direct effects of pollution policies on improvements to ecosystem services, relatively few have accounted for the indirect effects of these policies that arise if individuals respond to these ecological improvements. The optimal management of such a system rests on the consideration of both these direct and indirect effects. Here we consider the case in which policies improve the ecological condition of regions experiencing amenity-led migration, but in doing so also attract additional growth that exacerbates ecological degradation. We find a policy intervention line in this non-convex economic-ecological model which shows that the optimal policy effectively enlarges the attraction domain of the balanced equilibrium. For a range of initial conditions, it is optimal to intervene with policies that can push the system into the attraction domain of the balanced equilibrium in which balanced levels of regional population and ecosystem services are both sustained. We show that policies such as a safe minimum standard or a strict pollution control, which seek only to improve ecological conditions and ignore the indirect effects of these policies on regional migration responses, can exacerbate boom-bust cycles or drive the system to long-run ecological degradation and economic decline. We find that these outcomes depend critically on the state of the system when the policy is implemented. For example, when regional growth reaches the post-expansion stage in which congestion effects dominate agglomeration forces, a safe minimum standard policy can work as intended. However, when the regional economy is expanding and agglomeration forces dominate congestion effects, this policy can have the opposite effect by attracting more economic activities into the region and resulting in much greater ecological degradation. We find similar results for policies that seek to control pollution, but that fail to account for the indirect policy effects that arise from households' behavioral responses to the improvements in ecosystem amenities. When behavioral feedbacks are present, optimal ecosystem management relies on taking an integrated modeling approach that incorporates the dynamics of both the ecology and human behavior and the responses of each to the other.

Such an integrated modeling approach is technically challenging due to non-convexities that are characteristic of both regional economic growth and the dynamics of ecosystems subject to thresholds. Under these conditions, multiple equilibria are very likely, imply-

ing that the optimal policy cannot always be identified using analytical methods, as Brock and Starrett ([5]) and others [24, 35] have emphasized. Our results demonstrate that obtaining optimal policy prescriptions for non-convex systems is technically challenging and information-intensive, but possible. This approach also underscores the messiness of complex economic-ecological systems in which multiple equilibria are likely. Despite these challenges and the need for simulation methods to derive model results, we are able to obtain optimal policy results that are robust to a range of plausible parameter values.

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