A Dynamic Model of Household Location, Regional Growth and Endogenous Natural Amenities with Cross-Scale Interactions

Elena G. Irwin*, Ciriyam Jayaprakash§ and Yong Chen† **

February 12, 2007

Selected Paper prepared for presentation at the American Agricultural Economics Association Annual Meeting, Portland, OR, July 29 – August 1, 2007

* Associate Professor, Department of Agricultural, Environmental and Development Economics, Ohio State University, 2120 Fyffe Rd., Columbus, OH 43210. Please send all correspondence to: irwin.78@osu.edu; 614-292-6449 (ph); 614-292-2701 (fax).

§ Professor, Department of Physics, Ohio State University, 1040 Physics Research Building 191 West Woodruff Ave, Columbus, Ohio 43210.

† PhD student, Department of Agricultural, Environmental and Development Economics, Ohio State University, 2120 Fyffe Rd., Columbus, OH 43210.

** Authorship is equally shared among all three coauthors

We are grateful for the generous input and feedback from David Culver, Jay Martin, Eric Roy, Alan Randall, Keith Warren and others associated with the Ohio State University Biocomplexity Project. This research is supported by the National Science Foundation Biocomplexity Program and NOAA/Ohio Sea Grant Program. An earlier version of this paper was presented at the Frontiers of Environmental Economics Conference in Feb 2007.

A Dynamic Model of Household Location, Regional Growth and Endogenous Natural Amenities with Cross-Scale Interactions

Abstract

We develop a coupled model of regional migration and lake ecology to study the influence of ecological-economic interactions and relative time scales on transient and asymptotic dynamics. Cross-scale interactions fundamentally change system dynamics by eliminating steady states that are present in the decoupled economic model and introduce important time dependence. We find that the relative time scales of interacting variables are a key determinant in system dynamics and resilience and that the system's asymptotic behavior cannot be determined without considering the full dynamics of the system. Other time-dependent effects are found to matter, e.g., when households base their perceptions of environmental amenities on past observation, a path dependence is introduced that can lead to oscillations or decline in transient population. Finally, interactions are found to multiply the costs and benefits of policy by inducing a positive feedback between the ecological and economic components that can reinforce or offset the direct effect of the policy. Such effects imply that the economic and ecological costs of getting the policy wrong can be large. Our findings underscore the critical importance of accounting for multiple time scales and time dependence and suggest that models that ignore such complications can be quite misleading. At best, such models will fail to capture the full dynamics of the system and at worst, could provide a misleading characterization of the basic dynamical structure of these systems.

Introduction

In post-industrial countries such as the U.S., the attractiveness of regions as places to live and work is increasingly determined by their quality of life. Rising incomes, retiring baby boomers and the ease of electronic communication have contributed to an increasingly footloose population that is less constrained by employment location and more concerned with place-specific amenities. Primary among these are natural or environmental features. Cities located in sunnier regions and along coasts, mountainous rural regions of the "New West" and exurban counties with abundant open space amenities have witnessed the fastest population growth rates of the U.S. in recent decades (Glaeser, Kolko and Saiz, 2001; McGranahan, et al; Hansen et al., 2002; Rappaport and Sachs, 2003; Sutton and Day 2004). Such trends reflect a fundamental transformation in the economic value of local natural resources: rather than production based on resource extraction, regional migration and growth is increasingly associated with high quality *in situ* environmental amenities.

Environmental amenities depend on ecological functioning and thus are dynamic and evolve over time. While some ecological processes, such as climate, operate at global scales and evolve over long time scales, many others operate at spatial and temporal scales that are responsive to regional development. For example, increased impervious surfaces due to land development greatly increase the sediment loadings to streams and lakes and limit the filtration of rainwater into the soil. These impacts build up in urbanizing areas over relatively short time scales (Booth and Jackson 1997). In an area that is undergoing rapid urbanization, these effects can have immediate effects on water turbidity due to construction activities and impacts on the water quality of streams and lakes within just several years. Other effects of population growth and land development that occur on relatively fast time scales include the loss of habitat patches and connectivity due in particular to low density, fragmented development and the negative impacts on species survival and reproduction due to loss of natural lands and increased human presence in natural areas (e.g., Gude, et al. 2006).

Amenity-driven growth presents a double-edged sword to policy makers concerned with both economic growth and ecological sustainability. Clearly the protection of environmental amenities is important, but what is the right balance between ecosystem protection and regional growth processes that simultaneously respond to and degrade ecological resources? The dynamic nature of both processes and the coupled, two-way interactions that link them make it exceedingly difficult to understand the full range of possible economic and ecological outcomes. Both systems may be subject to nonlinearities due to so-called fast-slow dynamics, i.e., slow-moving feedbacks that accumulate over time and generate threshold responses in faster-moving processes. Such effects are well known in ecological systems (Levin 1999), but can also emerge in human systems. Positive production externalities or negative congestion effects that depend on the total population of a region, for example, can cause the rate of migration to respond nonlinearly as population increases (Krugman, 1991). When coupled together, the joint dynamics of these already complex systems depends critically on the nature of the cross-system linkages and the relative time scales over which fast and slow variables evolve.

Environmental economists have a long tradition of modeling this two-way interaction between natural resources and human production and consumption activities (e.g., Clark 1990, Gordon 1954, Smith 1968). This work has produced many key insights into the economics and management of dynamic natural resource systems (e.g., see Brown 2000 for a partial review). Traditional models necessarily simplified the ecosystem dynamics as to make analysis of optimal policies tractable. More recently economists and ecologists alike have argued for the need to better integrate economics and ecology (e.g., Arrow et al. 2000; Holling 2001; Levin et al. 1998). Despite many structural similarities in the systems each study (Levin 2006), such interdisciplinary efforts are not without their challenges. Economists tend to prefer smooth relationships between economic and ecological variables to facilitate analytical solutions whereas ecologists often focus on strong nonlinearities, multiple stable states and the potential for discontinuous change in ecological dynamics. Such complexities almost always require numerical simulation, an approach that economists have been slow to embrace (Judd 1997). Developing more highly integrated models would appear to require relaxing the assumptions necessary for full analytical solutions so that ecological complexities can be considered. It is an open question, then, as to how consideration of these additional complications matters and whether the effort necessary to develop and analyze more complicated simulation-based models is worthwhile.

Among the existing literature, models of optimal resource depletion and harvesting have investigated dynamic resource stocks that simultaneously constrain and respond to economic activity. However, these models (Perrings and Walker 1995, 2004; and Jeanssen et al. 2004) most often contain a single economic scale, e.g., the actions of a single manager or producer, who seeks an optimal management strategy that maximizes the discounted sum of expected profits. In such cases complex dynamics arise due solely to nonlinearities in the resource regeneration.

The literature on human-environment interactions that has most seriously considered two-way, cross-scale interactions among ecological-economic systems is, not surprisingly, concerned with resource-dependent communities (Brander and Taylor 1998, Krutilla and Reuveny 2006; Anderies 2003, 2004) in which resources are used as an input into production or consumption and whose depletion or degradation has direct impacts on human activity, e.g., by constraining production, consumption or population change.

Because we focus on the two-way interactions between population and the ecosystem, our model is most closely related to the literature on resource-dependent societies and endogenous demographic change. However, the nature of the linkage and the relevant time scale in these models is quite different: population growth is driven by fertility, which is a function of per capita resource consumption. The time scale over which population growth changes as a function of per capita resource consumption is quite long, e.g., Anderies' (2003) model evolves over several centuries. In contrast, we develop a model that posits a strong interdependence between population migration and ecological change, both of which evolve over much shorter time scales, e.g., on scales that range from a year to several decades.

There is another closely related literature that considers the human-ecological interactions but in a slightly different way, which we regard as one-way interaction models. This includes many environmental economics models and many of the ecological models that incorporate policy considerations. In these articles (Scheffer et al. 1993; Perrings and Walker, 1997; Carpenter et al., 1999; Scheffer et al. 2000), human activity generates a pollution externality that degrades the ecosystem and generates a cost to social welfare. Many of these models also consider optimal policy responses to the ecological change. They typically let a manager or social planner to identify a policy that considers such cost and induces individuals to choose the optimal level of abatement. The feedback from the ecosystem on individuals is channeled solely through policy. Because, there is not a direct feedback from the ecological change to the agents who cause this change and thus we consider these to be one-way interaction models between humans and the ecosystem.

Some researchers have considered the role of cross-scale interactions in these one-way interaction models. Results show that slow-moving ecological variables can push the coupled system towards the boundary of a stability domain and thus reduce the resilience of the system. Ludwig et al. (2003) take up this case for shallow lakes subject to anthropomorphic loadings. By including a slow-moving variable (the stock of sedimented phosphorus), it demonstrates that policies that neglects the slow-moving mud variable will be suboptimal unless the discount rate is very high or conversely the mud dynamics are very slow. However, they have not demonstrated how this variable alters the steady state dynamics of the system nor have they explored the time-dependent features of the cross-scale interaction. Thus it is not clear how the slow-moving variable affects the asymptotic behavior, the time scale on which the system approaches a steady state or how it influences other aspects of the transient dynamics

We attempt to shed light on this question by developing a coupled ecological-economic model that focuses on one aspect of complex ecological dynamics: interactions among variables operating at multiple time scales, sometimes referred to as cross-scale interactions (Holling 2001; Levin 1999). This is believed by ecologists as one major characteristic of most ecological systems. We develop a simple dynamic model of an amenity-dependent regional economy with migration and ecosystem change to study the role of interactions in a coupled ecological-economic system. The interactions can be described as both cross-system and cross-scale in the sense that they link economic and ecological processes that evolve at different time scales. Population is attracted to the region by environmental amenities and increasing population generates urban amenities that spur further growth. This process is constrained by relatively slow-moving migration dynamics. Land development and population growth generate impacts that degrade the ecosystem and that can lead to "sudden" regime shifts from a good to bad ecological state. Such events diminish the environmental amenities and thus impact regional migration and economic activities which, in turn, affect the process of ecological recovery. We assume that the ecosystem is a lake and specify the human-ecological interaction as sediment loadings generated by urbanization that influence lake dynamics and the quality of ecosystem services associated with the lake. The integrated framework is sufficiently general that it can be adapted, with appropriate modification of the ecological components, to model the interactions of amenity-driven growth and other ecosystems, including coastlines and terrestrial systems.

The analysis generates a number of findings that are relevant to the modeling of coupled ecological-economic systems. First, the results demonstrate the importance of accounting for interactions in coupled systems, particularly when these interactions occur between fast and "not too slow" variables. In such cases, when processes are jointly but not simultaneously determined, a small change in relative time scales can cause the fast and slow processes to become synchronized, which can destabilize the system (Pikovsky et al. 2001). For example, we find that a change in the rate of migration, such that it becomes synchronized with either the fast or slow moving ecological variable, causes population to transition from a long run steady state to continual oscillations over time. We also find that the resilience of the system to external shocks, as determined by the domain of attraction associated with a desirable state, depends critically on relative time scales. As the time scale over which the slow variable evolves becomes shorter, the domain of attraction associated with the desirable state shrinks, making the system more susceptible to bad surprises.

In addition to altering system dynamics and resilience, we find that interactions cause important differences in the robustness of different policies due to a positive feedback between the economic and ecological components. A reinforcing dynamic between substitution effects and ecological change arises in the coupled system that reinforces either the intended or unintended effect of a tax on the system's resilience and steady state population level. Thus the costs and benefits of policy are "multiplied up" due to interactions. The penalty associated with getting the policy wrong can be high: in addition to reducing the steady state population level and causing the regional economy to shrink, the system's resilience is reduced and the likelihood of irreversible decline increases.

These results underscore the importance of accounting for out-of-equilibrium or transient effects in systems characterized by cross-scale interactions and other time dependencies. They also demonstrate the fundamental dependence of these dynamics on relative time scales. Our findings suggest that models that ignore time-dependence can be quite misleading. At best, such models will fail to capture the full dynamics of the system and at worst, could provide a misleading characterization of the basic dynamical structure of these systems.

Regional Migration Model

Despite the increasing importance of environmental amenities in regional growth processes and the clear potential for ecological degradation, the joint dynamics of amenity-driven migration and ecosystem change have not been formally modeled.[1] We

[1] Roback (1982) develops a static general equilibrium framework with mobile labor for considering the capitalization of exogenous quality of life attributes into equilibrium wages and land rents. The new economic geography literature (Krugman, 1991; Fujita, Krugman and Venebles, 1999; Fujita and Thisses, 2002) considers the role of production externalities and agglomeration economies in regional economic growth. The environment is considered to be fixed and matters only to the extent that heterogeneity can generate initial locational advantages.

begin with a simple general equilibrium model of a regional economy in which households consume land and a regionally produced composite good. Households supply labor, which is combined with land to produce the regional good. The regional good is produced with land and household supplied labor using Cobb-Douglas technology: $x_p = n_p^{\beta_1} l_p^{\beta_2}$, where x_p is the output produced by the firm, n_p and l_p are the amounts of labor and land respectively used in production and β_1 and β_2 are production parameters. Cost minimizing firms will choose inputs such that the value of the marginal products of land and labor are equated to the respective input prices:

$$\begin{aligned} pf_{n_p} &= w \\ pf_{l_p} &= r \end{aligned} \tag{1}$$

In addition to consumption of the regional good and land for residential use, households derive utility from two regional public goods: urban and environmental amenities. Urban amenities are posited to be a nonlinear function of population, *N*, to reflect both agglomeration and congestion effects.[2] Environmental amenities depend on ecosystem functioning and services and thus represent a key interaction between the economic and ecological systems. We postpone a discussion of how environmental amenities are "produced" in the model so that we can first present the economic model. For the initial decoupled economic model we treat environmental amenities as a function of an exogenous and fixed level of ecosystem services, *e*. Households maximize utility by choosing the optimal amounts of the market goods subject to a budget constraint. For simplicity we assume that utility is additively separable in the market and nonmarket components:

$$\max_{x_c, l_c} U\left(x_c, l_c; N, e\right) = x_c^{\alpha_x} l_c^{\alpha_l} + U_u(N) + U_e(e) \tag{2a}$$

$$\text{subject to } w + I = ps_c + rl_c \tag{2b}$$

where x_c and l_c are the quantities of the composite good and land respectively that are consumed by households, *p* and *r* are the respective prices, U_u and U_e are the utility from urban amenities and environmental amenities respectively, *w* is wage and *I* is

[2] For simplicity, urban amenities are assumed to enter the consumption side only—i.e., production externalities are not considered in this model.

exogenously determined income with which the household is endowed. The resulting optimal demands for x_c and l_c are:[3]

$$x_c^* = \frac{\alpha_x(w+I)}{p} \text{ and } l_c^* = \frac{\alpha_l(w+I)}{r}. \quad (3)$$

Substituting (3) into the utility form specified in (2a) yields the indirect utility function.

Utility is increasing in both the urban and environmental amenities. For simplicity, we assume $U_e > 0$ and $U_{ee} = 0$. To capture both agglomeration effects as well as congestion in the urban amenities function, we assume that urban amenities are very small for low *N*, increase rapidly over a midrange of *N* and decline for large values of *N*. These assumptions are captured by the following functional forms for the environmental and urban amenities respectively:

$$U_e(e) = \alpha_e e \qquad \text{and} \quad (4a)$$

$$U_u(N) = \frac{\alpha_u^0 + \alpha_u^1 N}{1 + \left(\frac{N}{N_u}\right)^\rho}, \quad (4b)$$

where α_u^0 is the initial level of urban amenities, α_u^1 reflects positive urban benefits that increase with population, N_u is the level of population at which congestion sets in and ρ determines the relative influence of congestion on overall amenities.

Migration behavior is governed by the maximum utility attainable from this region relative to other regions. Rather than modeling other regions explicitly, we treat them as exogenous and thus migration is driven by $\Delta U = U\left(p, w, r; N, \theta, t\right) - \bar{U}$, where $\bar{U}$ is the exogenously defined indirect utility that is attainable from the rest of the world and $\theta = \left(I, e, \alpha, \beta\right)$ is a vector of parameters that includes exogenous income, environmental amenities and other parameters of the utility and production functions. A long run steady state is reached when there is no longer an incentive for households to

[3] Because of the additively separable specification, the two public goods, urban and environmental amenities, do not affect the optimal demands of the market goods directly. We alter this assumption in a subsequent section to allow e to enter as a household produced environmental amenities. The qualitative aspects of the model are unchanged by this modification.

migrate and thus the condition for $\dot{N} = 0$ is $\Delta U = 0$. However, because we are interested in the relative time scales of fast vs. slow variables and the evolution of the coupled ecological-economic system over time, we do not impose this long run condition. Instead, we allow migration to occur slowly in response to regional differences in utility and assume that markets adjust in each time period *t* to a temporary equilibrium that is conditional on population in period *t*. The migration rate is assumed to be proportional to the utility difference so that:

$$\dot{N} = \frac{\Delta U}{\tau_N} \tag{5}$$

where τ_N determines the time scale over which population adjusts to regional differences in utility.

To close the regional economic model and solve for a reduced form expression for *U(t)*, we assume that labor is fully employed in the production of the regional good and that the output market for this good clears:

$$n_p = N \tag{6a}$$

$$x_p = Nx_c \tag{6b}$$

A final condition with respect to land is needed to close the model. Rather than constraining the total amount of land in the region, we assume that the urban area will expand with increasing population into the surrounding rural area in which land is used solely for agriculture. Land for developed uses (in this case, residential or commercial) will be bid away from agricultural uses so long as the rent associated with developed land is greater than the agricultural land rent, $r > r_a$, and the total amount of developed land will be determined by the equalization of rents across developed and agricultural uses. We assume that agriculture is produced and sold on a global market, so that output price is exogenously determined, and that the agricultural product is produced with constant returns to scale. Given these two assumptions, r_a is exogenously determined and constant across l_a. This condition determines our final closing condition:

$$r = \overline{r}_a \quad . \tag{6c}$$

Equations (1), (3) and (6) ensure that the regional good and land markets clear and that a temporary equilibrium is reached in each time period for a given population level. These conditions generate an equilibrium price ratio, p^*/w^*, that depends on *N(t)* and the parameters of the utility and production functions, $\theta = (I, e, \alpha, \beta)$. Using explicit expressions for w^* and p^* and the utility function specified in (2) and (4), an expression for the maximized utility as a function of the slow-moving population variable can be obtained, $U^*(N,t;\theta)$ (see Appendix A for details). This yields a reduced form expression for the migration rate given in (5) that is an explicit function of *N(t)*:

$$\dot{N}(t) = \frac{U^*(N,t;\theta) - \bar{U}^*}{\tau_N}. \qquad (7)$$

The explicit form for this expression is given in Appendix A.

Decoupled Model Results

We use the expression for $\dot{N}(t)$ in (7) to analyze the behavior of the decoupled regional migration model in which environmental amenities are exogenous and fixed. To do this, we use a combination of computer-assisted bifurcation analysis and simulation analysis. Using this approach in tandem allows us to both examine the steady state behavior as a function of key parameters and explore the system's transient dynamics. Specification of the model parameters are necessary to do this. Appendix B contains the full list of parameters and their values; here we provide the rationale for key parameter specifications. We assume that the Cobb-Douglas utility and production parameters are such that $\alpha_x + \alpha_l \leq 1$ and $\beta_n + \beta_l \leq 1$ respectively. The weights assigned to the urban and environmental amenities, α_e, α_u^0 and α_u^1, are varied relative to α_x and α_l to explore their effect on population dynamics. We arbitrarily assign a constant value to $\bar{U}^*$ and then determine a baseline set of values by tuning the parameters such that the model predicts a target steady state population when $\Delta U^* = 0$ that plausibly would be reached given a small base of initial population. We consider it unlikely that, even with substantial growth, amenity-driven growth will transform small rural regions into large metropolitan areas with large cities. Moderately sized metropolitan areas in the U.S. are in the range of 50-100,000 people and thus we scale our parameters such that the steady state population under conditions of amenity-driven growth corresponds to about 75,000 people. This assumption yields the baseline values for the parameters of U^* that correspond to our baseline case of amenity-driven growth for both the decoupled and coupled models (Appendix B). Finally, the parameter governing the time scale of migration, τ_N, is a key parameter in the coupled model because population is a slower moving variable that generates cross-scale effects. However, its impact in the decoupled model is simply to govern the time scale over which the system evolves to a steady state. The appropriate value should thus produce an average annual growth rate that corresponds with annual growth rates typical of rural or moderately-sized high-amenity environmental regions. Annual migration rates for the period 1990-2000 for selected non-urban dominated states characterized by higher environmental amenities range from 2.5 percent for states like Vermont, Utah and Montana to 3.1 for Wyoming (U.S. Census Bureau, 2003). Given this, we choose τ_N such that the average annual growth rate for $\dot{N}$ that is generated by the baseline parameter values is about 2.8 percent. Figure 1 illustrates the trajectories of population and the maximized utility $U^*(N)$. For these baseline conditions, population increases smoothly from a small initial population to a steady state population of just over 70,000 over the course of about 40 years.

Using our set of baseline parameters, we first plot $U^*(N)$ and $\bar{U}^*$ vs. N to examine the values of N for which a steady state, as defined by $\dot{N} = \Delta U^* = 0$, emerges. The dashed line in Figure 2 illustrates this case. We find that under conditions of amenity-driven growth, the system is characterized by three equilibria or fixed points, two of which are stable (N_1^* and N_3^*) and one of which is unstable (N_2^*). Intuitively, the intermediate value of N_2^* is unstable since $\Delta U^* > 0$ for $N = N_2^* + \Delta N$ (or conversely, $\Delta U^* < 0$ for $N = N_2^* - \Delta N$), indicating that a small increase (decrease) in N will cause population to increase (decrease) and diverge from N_2^*. In contrast, the opposite holds for small perturbations around N_1^* and N_3^*. Thus $N = N_2^*$ represents a threshold for urban growth such that, for a given set of parameter values, $N(t) > N_2^*$ will lead to urban agglomeration. This condition is met if the initial population of the region is sufficiently large or if processes exogenous to the model (e.g., urban decentralization, economic restructuring) cause sufficient increases in the population over time.

Figures 2(a) and (b) demonstrate the respective roles of urban and environmental amenities in generating this bi-stability. Weak urban amenities, as represented by a lower value of α_u^1, cause the strong nonlinearity in $U^*(N)$ to disappear and the system is characterized by a global long-run equilibrium at the low *N* fixed point, N_1^* (Figure 2a). Conversely, weak preferences for the environmental amenity shift $U^*(N)$ downward (Figure 2b), which also causes the bi-stability to disappear and again the system is characterized by the low *N* long-run equilibrium at N_1^*. Together, this illustrates the importance of both urban and environmental amenities in generating the conditions in which amenity-driven growth, as represented by N_3^*, can emerge: (1) a self-reinforcing urban dynamic must be present to generate agglomeration, which is possible only once the population reaches a critical threshold ($N = N_2^*$) and (2) the pull of environmental amenities must be strong relative to amenities available in the rest of the world.

To fully illustrate the steady state dynamics as a function of the urban and environmental amenities, we plot the corresponding bifurcation plots of *N* as a function of environmental amenities (Figure 3a) and the urban amenities parameter (Figure 3b). In both cases, the system undergoes a transition from a globally stable to bi-stable regime in which the upper and lower branches of *N* are stable and the middle branch connecting the two is unstable. For example, Figure 3a demonstrates that a single, globally stable equilibrium exists only for very low values of the environmental amenities ($e < 2$) and that for values greater than this, the system is bi-stable ($e > e^*$). This implies that a transition from a higher to lower population base will not occur gradually and that once such a transition has occurred, the process is irreversible. Suppose, for example, that exogenous changes pushed the system along a steady state path from the point (*N(0)*, *e(0)*) in the plot so that reductions in *e* cause *N* to decline gradually. When *e* reaches the critical threshold e^*, the dynamics are irreversible: the system falls to the stable lower branch of *N* and any increases in *e* at this point is moot: the system is trapped in the low *N* equilibrium irrespective of the level of environmental amenities. These results mimic the standard result of the new economic geography models, in which the benefits of urban agglomeration are captured through a positive production externality (e.g., Fujita and Thisse 2002). A sufficiently strong production externality offsets diminishing returns to labor and generates increasing returns to scale in labor at the industry level, which leads to urban concentration. Thus the relative strength of the production externality parameter plays an analogous role to the urban and environmental amenity parameters in our model.

The importance of the bistability in determining the steady state dynamics of the system is illustrated in Figure 4, which compares $U^*(N)$ with bi-stable dynamics vs. nonlinear dynamics without bi-stability. The nonlinear model is characterized by a single global equilibrium and like Figure 2(a), corresponds to a case in which the urban amenity benefits are moderate, but not sufficiently strong to induce a bi-stability. When the relative utility from the rest of the world is high, this single equilibrium corresponds to the low-*N* equilibrium for the bi-stable regime, $N_2^{NL} = N_0^{BIS}$. However, another stable fixed point is possible at a high value of $N = N_2^{BIS}$ and thus the bi-stability presents an opportunity for regional growth that is not possible in its absence.

Ecological Dynamics and Ecological-Economic Interactions

Our main interest is in modeling the two-way interactions between a regional economy and ecosystem and exploring the implications of this coupling for the joint evolution of the system. We seek a simple representation of these interactions, which requires that the ecological dynamics can be represented with one or at the most two dynamical variables. In addition, we are most interested in ecological dynamics that are tightly coupled with human activities and that evolve on a relatively fast time scale, so that changes in the ecosystem are perceptible by individuals and induce changes in behavior. With these considerations in mind, we take our regional ecosystem to be a lake surrounded by the developing region. Impacts from land development and urbanization on sediment loading can aggregate up quickly over time to generate substantial impacts on water quality (Booth and Jackson 1997), which in turn can greatly influence lake-based amenities. Rapidly urbanizing areas in the Lake Erie basin, for example, have contributed to increased non-point source loadings of nutrients into the lake, which has steadily increased since the mid-1990s (Conroy et al. 2005). These changes significantly degrade water clarity and can combine with other biophysical conditions to generate "surprise events," such as anoxic "dead zones," fish kills and harmful algal blooms. Such events greatly diminish the quality of amenities associated with the lake, including recreation activities such as swimming, boating and fishing, and aesthetic benefits. Taken together, the ecological-economic interactions as represented by loadings and changes in lake amenities are a tightly coupled, two-way linkage between the economic and ecological systems.

Well-established models of nutrient dynamics demonstrate that nonlinear recycling processes can cause external loadings to induce a regime shift from an oligotrophic (good) to eutrophic (bad) state of the lake (Scheffer, 1998; Carpenter, Ludwig and Brock, 1999). An oligotrophic lake is characterized by low-nutrient inputs, relatively clear water and healthy ecosystem services that generate environmental amenities; on the other hand, the eutrophic state is characterized by high-nutrient inputs, high concentrations of algae, toxicity, turbidity and is much more prone to anoxic conditions and undesired events such as fish kills and noxious algal blooms. Nutrient dynamics can exhibit hysteresis (Scheffer 1998), implying that reduced loadings may not bring the lake back to an oligotrophic state once a regime shift has occurred or that the recovery time could be substantial. In the case of Lake Erie, for example, substantial reductions in point sources in the 1970s did not result in meaningful improvements in water quality until ten years after the controls had been implemented.

We follow a simple model developed by Carpenter, Ludwig and Brock (1999) to capture the basic dynamics of nutrient loading and lake eutrophication:

$$\dot{P} = L_0 + L_1 N l_c - sP + \sigma_1 \frac{P^{\sigma_2}}{P_c^{\sigma_2} + P^{\sigma_2}}, \tag{8}$$

where P is the mass (or concentration) of phosphorus and $\dot{P}$ fully captures the ecological dynamics. The rate of nutrient input per unit time is the loading: to make the interaction with different human activities explicit, we separately define L_0 to be the loadings from agriculture and $L_1 N l_c$ to be the total loadings from the developed region, where L_1 is the urban loadings coefficient and Nl_c is the total amount of land in a residential use.[4] The two final terms that govern the dynamics of P are the rate of P loss from the system, sP, and P recycling. The loss rate s accounts for processes such as sedimentation and outflow that remove P from the water column. However, P can be recycled after it sediments to the lake bottom. The recycling process is nonlinear, as represented by the sigmoid function. The maximum rate of recycling is σ_1, The steepness of the recycling curve is governed by σ_2 and P_c is the value of P at which recycling reaches half its maximum rate. In specifying the parameters of this model, we note that the scale for defining the concentration can be factored out and we assume that P is measured in terms of a basic unit. The loss rate was chosen to be between 0.4 and 0.8 per year while the recycling coefficient σ_1 was varied between 0.5 and 1.0. The crossover value of P_c was picked to be 2.4 or 1.0. The external loading was fixed to be 0.10 per year and L_1 was varied to obtain various behaviors.

Phosphorus dynamics evolve on the time scale of about one year. Loadings from land use in the lake's watershed are transported to the lake by its tributaries, a process that occurs on the time scale of months. Nutrients that are bound to sediments become suspended in the water column and contribute to the eutrophication of the lake over the late spring and summer seasons. Sedimentation of suspended matter occurs on the time scale of months. Phosphorus build-up occurs throughout the year and can become

---

[4] Loadings are simplified in two ways. First, because we do not constrain the total amount of land, we implicitly assume that the supply of agricultural land is limitless and therefore it is reasonable to treat the loadings as constant. Of course in a more detailed model of loadings we would want to keep track of agricultural-urban land conversion in a much more careful way. We leave this for the development of a fully spatially articulated model in which total loadings will depend critically on the type and location of land conversions. Second, we assume that land used in production, l_p, does not generate loadings and that all nutrient run-off is generated by residential land conversion and use. This omission simplifies the problem and, because the scale of N is much greater than that of l_p, it does not qualitatively change the results.

sufficiently high by late summer to spur nonlinear recycling. In comparison to population migration, phosphorus is a fast moving variable.

Accounting for the evolution of P in the regional economic model introduces another dynamical variable into the analysis, making the coupled ecological-economic a joint, two-variable dynamical system. We have specified one of the linkages that couples these two dynamical variables together: the loading term $L_1 N l_c$ specifies how $\dot{P}$ depends on N. To complete the coupled model and make the interaction two-way, the dependence of $\dot{N}$ on P, which arises through endogenous environmental amenities, must also be specified. We posit that P is a key determinant of ecosystem services, $q(P)$, that generate amenities, $e(q)$, which enter the household's utility. For example, water clarity is an important ecosystem service that is determined largely by P and that directly impacts the attractiveness of environmental amenities associated with the lake. We assume small changes in P do not influence q and that P has to build up in the lake before q is detrimentally affected; q is sensitive to P over a mid-range, reflecting the fact that when P is sufficiently high, small changes can induce qualitative shifts in the lake (from oligotrophic to eutrophic), which has more substantial effects on ecosystem services. The following sigmoid function captures this relationship:

$$q(P) = \frac{q_0}{1 + q_1 P^{\eta_q}} \quad \text{and} \tag{9a}$$

$$e(q) = \eta_e q \,, \tag{9b}$$

where q_0 is the pristine level of ecosystem services, q_1 is a slope coefficient, η_q determines the level of P at which q starts to degrade and η_e is the parameter that transforms ecosystem services into amenities.[5] Substituting (9) into (7), which is the expression for $\dot{N}$ from the economic model, yields an expression of $\dot{N}$ as a function of P, which along with (8) provides a complete description of the dynamics of the coupled system:

---

[5] Here the distinction between q and e is unnecessary. In a subsequent section of the paper, we consider a slightly different specification in which e is a household produced good and q affects the quality of e that is consumed by the household.

$$\dot{N}(t) = \frac{U^*\left(N, P, t; \theta\right) - \bar{U}^*}{\tau_N}. \tag{10}$$

Figure 5 presents a schematic diagram of the full coupled ecological-economic system with a rough indication of time scales.

Coupled Model: Basic Results

Because our system is now a two-variable dynamical system, bifurcation plots are much harder to draw as they require at least three dimensions (the two dynamical variables and one or more parameters that determine how the system dynamics are changing). To avoid this complication, we use phase plane diagrams (or what mathematicians refer to as phase plots) to plot the nullclines for the two dynamical variables in the two variable space for a given set of parameter values. This approach allows for a full description of the system dynamics for any initial conditions and a given set of parameters.

Figure 6 presents a phase plot of *P* vs. *N* for the baseline set of parameter values used in the coupled model (Appendix B). The intersections of the *P* and *N* nullclines yield three fixed points, two of which are stable (indicated by circles) and the other of which is unstable (indicated by a triangle). The system dynamics are illustrated by the two dynamical lines that are plotted. The separatrix is the stable manifold of the unstable fixed point. It separates the *N*-*P* space into two domains of attraction that correspond to the two stable attractors. In this case, any point to the right of the separatrix flows to the large *N* stable fixed point and any point to the left flows to the low *N* stable fixed point. Points near the separatrix correspond to points with low resilience (as defined by Holling) since an external perturbation in the system can cause them to pass over this unstable manifold into another domain of attraction. The other dynamical path illustrated is the heteroclinic orbit, which is the unstable manifold of the saddle node. It illustrates the dynamics of the system away from a fixed point; here it illustrates the path away from the saddle point that connects with the high *N* stable fixed point. The path approaches the high *N* fixed point and converges to the fixed point, indicating that it is a steady state.

The coupling of the economic and ecological system fundamentally alters the system dynamics. To see this, focus on the N nullcline and assume for the moment that P is an external parameter of the system. With the exception of a lower branch of $\dot{N} = 0$ that occurs extremely close to $N=0$ and which is not visible in this figure,[6] the phase plot illustrates the bifurcation dynamics of the would-be one-variable dynamical system. As the decoupled results showed (Figure 3a), there is a bifurcation in the population dynamics as a function of the fixed ecological variable: for low values of P (low values of e in the decoupled model), there are three branches, two of which are stable—the lower branch at $N = 0$ (not visible here) and the higher branch that corresponds to approximately $N \geq 60{,}000$. In the absence of interactions between the systems, a much larger equilibrium population is a feasible steady state of the system, provided P is sufficiently low (e.g., a population of 150,000 is a feasible steady state when $P \cong 1$). In the coupled system, however, this is no longer the case. A population larger than about 100,000 is not sustainable given the interaction between N and P and their joint dynamics. If a large external shock were to push the coupled system to such a large population, N would fall over time due to the repelling effect of degraded environmental amenities. Similarly, if we ignore migration dynamics and treat N as a parameter, we would falsely conclude that a high-P eutrophic state (corresponding to the upper stable branch of the P nullcline for approximately $P > 2.5$) is stable. In the absence of the human behavioral response to highly degraded amenities, this would be true. Once we consider the joint N and P dynamics, it is clear that the system will not stay at this point since substantial out-migration would cause P to eventually adjust downward over time. Thus we find that the joint dynamics can offset the irreversibility that arises in a one-variable dynamical system from hysteresis. When interactions between the economic and ecological systems are considered, the system is much less likely to get trapped in an undesirable state (e.g., high P), but conversely it is also much less likely to be sustained in a desirable state (e.g., high N).

[6] We were unable to plot this lower branch because it lies so close to $N = 0$. It extends from the visible intersection of the N nullcline with $N = 0$ along this axis for all values of P plotted in Figure 6. See Figure 3(a) for an illustration of this lower branch in the decoupled model.

Because the domain of attraction associated with the high-N state is relatively large in the phase plot illustrated in Figure 6, external forces that may cause an overshoot in N or P will not result in a full decline or "crash" of the economic system to the low-N fixed point. We find that this is no longer the case when we consider changes in key interaction parameters of the system: L_1, the loadings coefficient associated with urban development (Figure 7). Increases in L_1 change both the stability of the fixed points and topology of the system. An increase from $L_1 = 0.08$ to 0.1 alters the stability of the large-N stable fixed point (Figure 7a) such that a stable limit cycle emerges around the fixed point (Figure 7b) via a Hopf bifurcation. Further increases in L_1 increase the amplitude of the cycles (Figure 7c). The $N > 0$ stable fixed point reappears for larger values of L_1 (Figure 7d), but the steady state value of N is much lower and the associated domain of attraction is much smaller. This change in the system's topology results in a lower level of resilience for the high-N fixed point and thus the economy is much more susceptible to external forces. In comparing the domains of attraction for the desirable high-N state for this and the baseline cases (as illustrated in Figure 6), we now see that an overshoot in either P or N due to external forces is much more risky when the impact from loadings is high as a slow and irreversible decline in N is much more likely.

To consider the time evolution of the system, we plot the evolution of N and P for the same parameter values as used in Figures 6 and 7 for several different initial conditions. Figures 8(a) and (b) illustrate the importance of initial conditions and how small changes in the initial level of P determine whether the system evolves to the large-N steady state (Figure 8(a)) or empties out (Figure 8(b)). The time scale on which these changes occur may be quite different. For example, Figures 8(a)-(b) show that for an initial population of 20,000, the system evolves over 50 years to a stable state population of about 100,000, but takes less than 5 to year to empty out in the absence of sufficiently strong amenities. Figure 8(c) illustrates the case in which an increase in loadings can induce boom-bust cycles in N and P. Population cycles evolve over a relatively long period of time (about 60 years) in response to the cyclical behavior of the ecosystem. Because there is a phase difference between the N and P oscillations, the maxima do not coincide. The peaks and troughs (maxima and minima) of N are separated by about 30 years and the maxima occur roughly in the middle of the increasing portion of the *P* curve. This offset induces the observed oscillations.

Of course, in reality migration is a much stickier process than our highly stylized model and there are many factors that would be expected to mitigate this cyclical behavior. Migration costs, social and professional networks, differences in the perception vs. reality of ecosystem changes are just a few of the factors that we reasonably would expect to offset the tight ecological-economic coupling of that we assume in the model. Figure 8(d) illustrates the offsetting influence of urban amenities, which postpones population decline. Figures 8(e)-(f) make a related point about the importance of urban amenities in the model. If the region's evolution starts with a critical mass of population, then the agglomeration benefits that accrue are enough to offset a low initial level of environmental amenities (i.e., high $P(0)$) and the system flows to the large-*N* fixed point (Figure 8(f)). In contrast, a slightly smaller initial population may not provide a sufficient base from which to build up urban amenities and thus, even if the initial level of *P* is lower, the region will decline to the low-*N* fixed point.

Time-Dependent Effects

The relative time scales over which *N* and *P* evolve can have important implications for the system dynamics and thus we turn to investigating the role of time-dependent effects in our model. We begin with an investigation of the time scale over which slow-moving variable *N* evolves relative to fast moving variable *P*. Figure 9 presents phase plots for different values of the parameter that governs the time scale of population migration, τ_N,. Figure 9(a) considers a slower time scale, twenty years, in comparison to the baseline case of ten years and Figures 9(b) through 9(d) illustrate the results for faster time scales. While slowing down the rate of migration does not qualitatively alter the system dynamics (as compared to the base case in Figure 7(b)), speeding it up so that it is closer to the time scale of the fast moving variable does have substantial effects. For example, doubling the rate of migration intensifies the cycles associated with the large-N fixed point, as shown in figure 7(b), and substantially alters the domains of attraction associated with the two stable attractors.

Next we introduce an ecological variable that is slow moving and consider how the time scale of migration relative to this slow moving ecological variable influences the system dynamics. We follow Ludwig, Carpenter and Brock (2003), who expand the P-model developed by Carpenter, Ludwig and Brock (1999) to account for slow-moving sedimented phosphorus. As discussed earlier, this slow-moving variable accumulates in the sediments at the bottom of the lake and then is released when a critical level of phosphorus is reached. This contributes to the nonlinear recycling process that is included in the P-only model (Equation 8). We adapt the discrete model used by Ludwig et al. (2003) to model the dynamics of this slow moving variable and its modification of the fast moving P dynamics as follows:

$$\dot{M} = bM + sP - \sigma_1 M \frac{P^{\sigma_2}}{P_c^{\sigma_2} + P^{\sigma_2}} \tag{11}$$

$$\dot{P} = L_0 + L_1 N - (s+h)P + \sigma_1 M \frac{P^{\sigma_2}}{P_c^{\sigma_2} + P^{\sigma_2}}, \tag{12}$$

where *b* is the outflow rate of M. We follow the parameterization of the model by Ludwig et al. (2003) as well, which are reported in Appendix B. With these parameter values M evolves extremely slowly over time, e.g., it may take a century for M to reach a steady state equilibrium.

Given this specification, we simulate the evolution of N, P and M over time for the baseline value of the migration rate, τ_N = 10 years, and a doubling of this rate, τ_N = 20 years. In the absence of another slow moving variable, we did not find that increasing the time scale over which migration occurs mattered (Figure 9(a)). This is no longer the case, however, in the presence of another slow moving variable. As Figure 10 illustrates, a reduction in the migration rate allows the system to gradual adjust to its long run steady state and M to build up slowly (Figure 10(b)). In contrast, a faster migration rate pushes M to build up more rapidly and results in a sudden spike in phosphorus when the slow accumulation of M reaches a critical threshold and is released into the lake (Figure 10(a)). This causes a sudden flip in the system to the eutrophic state, which is followed by an emptying out of the region.

Finally, we consider the role of time-dependence in households' expectations formation over environmental amenities. So far we have assumed that households observe the amenity with certainty. Now we assume that the contribution to the utility from environmental amenities at time t depends on a uniform average of *e* over the preceding time interval τ. By a simple trick this integro-differential equation can be converted into a delay-differential equation and solved using MatLab. We consider the base case when the decision based on the instantaneous value leads to cyclic behavior as shown in Figure 11(a). We note that *N* and *P* show oscillations with almost the same period once the transients have decayed but, similar to the cycles that we observed in the base model (Figure 7(c)), there is a phase difference between them: the maxima do not coincide. The peaks and troughs (maxima and minima) of *N* are separated by about 18-20 years and the maxima occur roughly in the middle of the increasing portion of the *P* curve. An instantaneous evaluation uses the value of *P* at that point. Averaging over the previous 5 years yields a phosphorus value that is lower and this allows *N* to build up more due to the increased utility. Thus the amplitude of the oscillations will increase. As the amplitude increases the time at which it occurs is delayed and this naturally leads to a slight increase in the period. This effect is clearly visible when $\tau = 5$ years as displayed in Figure 11(b). Note also that the phase lag between the oscillations in *N* and *P* has also decreased. The build-up of *N*, due to the averaging becomes unstable once the maximum increases beyond a critical value, leading to a rapid increase in *P*, causing a rapid decline in *N.* An overshoot occurs and once *N* falls below a minimum value the system is trapped in the domain of attraction of the low *N* fixed point and collapse ensues.

Policy Model and Results

To consider the effect of a policy that seeks to reduce the negative impact of loadings, we modify the model slightly so that *e* is a scalar that represents the number of lake recreational visits per year—e.g., fishing, boating or beach trips—and ecosystem services, *q(P)*, contribute to the utility that the household derives from a trip. We do this in the simplest way possible by assuming that *e* and *q* are perfectly substitutable: $e(q,P) = eq(P)$, where *q(P)* is given in Equation (9). We abstract from the purchase of market goods (e.g., fishing rods, boats) that the household potentially uses to produce *e*. Households must pay a per visit user fee, *f*, which is assessed by the government. These modifications imply that the household now chooses *e*, in addition to the market goods x_c and l_c, to maximize utility and that an addition term, *fe*, enters the household's budget constraint. Using this model, we compare the effects of the user fee, *f*, with a tax is assessed on the consumption of land. The latter policy raises land rents so that in equilibrium, $r^* = r_a + r_g$, where r_g is the tax assessed by government.

Our purpose in considering these policies is not to identify an optimal policy that maximizes net discounted social welfare.[7] Instead we focus on the possible effects of policy on the transient and asymptotic behavior of the system and use a simpler rule to evaluate policy that accounts for economic and ecological concerns in a straightforward way. In a world of complex dynamics that present the possibility of "bad" surprises, one goal of the manager should be to identify robust policies that strengthen the resilience of the desirable state (Anderies et al. 2004; Levin et al., 1998). However, the manager cannot do this in the absence of economic considerations and thus a second goal is to maintain or increase the size of the region. A welfare-improving policy, then, is one that maintains or increases the steady state population that is attainable while also ensuring that the resilience associated with this state is nondecreasing. As previously discussed, resilience is increasing in the size of the domain of attraction associated with the desirable state and decreasing in the presence of transient or stable oscillations that can temporarily force the system closer to an unstable manifold.

[7] To consider the optimal policy requires maximization of total discounted net benefits from the consumption of *e* over time, subject to the highly nonlinear evolution of the two state variables, *N* and *P* in a system that has multiple stable states. While the optimal policy is certainly an interesting benchmark to calculate for the purposes of model analysis, it is unreasonable to expect that a policymaker will know with any certainty the evolution of *N* or *P* or the form of households' utility. Thus to model the policymaker's behavior also requires accounting for his or her substantial uncertainty over the basic components of the policy model. With such considerations the policymaker's problem becomes a stochastic optimization problem subject to the evolution of two nonlinear state variables in a system with multiple state states. This is a complex optimization problem that is far from "well behaved" and it's unclear that traditional optimal control or dynamic programming methods would be successful. Alternative optimization methods designed to deal with complex optimization problems are possible, e.g., genetic algorithms or simulated annealing (e.g., see Janssen et al. (2004) for an example). We forgo such considerations for now and focus instead on a simpler and arguably more realistic policy goal that incorporates both economic and ecological considerations.

Figure 13 illustrates the phase plots corresponding to these two policies and Figure 14 provides the time evolution of *N* and *P* for each scenario. To accentuate the policy effects, we choose a relatively high value for the loadings parameter so that the ecological degradation from human impacts is substantial. Figure 13(a) illustrates a base case in which the two policies are relatively balanced. The system exhibits multiple stable states and oscillatory transient dynamics. The domain of attraction associated with the desirable high-*N* state is relatively small and the corresponding steady state population is about 75,000. A circle indicates the initial conditions used in the corresponding time plot shown in Figure 14(a). Starting from an initial population of 40,000, the population of the region initially overshoots and then is adjusted downward over the first 40 years, after which the system settles down into the steady state population. Figure 13(b) illustrates the effect of a tax on residential land that increases equilibrium land rents by about 18%. The policy is clearly welfare improving: the tax eliminates the transient oscillation, reduces the steady state level of phosphorus and results in a much higher steady state population of about 90,000 that is reached in a much shorter period of time—about 20 years, as shown in Figure 14(b). The domain of attraction associated with the desirable high-*N* state has been expanded relative to the baseline case, largely due to the increased resilience of the ecosystem to human (as evidenced by the *P* nullcline shifting right). In addition, the *N* nullcline remains stable, suggesting that the maximum attainable utility remains essential constant under this tax. Next we compare the effect of a 10% increase in the visitation fee associated with lake recreational trips. Figure 13(c) illustrates the phase plot, which demonstrates a marked increase in the transient cycles before eventually settling down to a reduced steady state population of about 60,000. We also note the smaller size of the corresponding domain of attraction, caused by both a shifting leftward of the *P* nullcline and a downward shift in the *N* nullcline. These shifts suggest that the tax actually worsens the human impacts on the ecosystem and reduces the maximum attainable utility in the region. The time plot shown in Figure 14(c) exhibits an increase in transient oscillatory behavior: the cycles are amplified in the near-term and extend much further into the future. Finally, Figure 13(d) illustrates a larger increase in the visitation fee of about 25% relative to the baseline case, in which case the system fails to converge to a steady state.

The behavior of the system under the two different policy scenarios can be explained as the result of a substitution effect that operates through the ecological system to either offset or reinforce the out-migration that is spurred by the tax. In both cases, the tax reduces real income and, all else equal, reduces the maximum utility associated with the region, which reduces the steady state population. A substitution effect that feeds back into utility via the interactions between the economic and ecological components either offsets or reinforces this effect on population migration, which explains the divergence between the two policies. A land tax causes a significant amount of substitution away from land consumption towards consumption of the regional market good by households and towards labor in the production of the regional good by firms. Both effects bid up the demand for labor and increase the absolute wage rate. Depending on the change in the relative output price, which also increases due to increased household demand, the relative wage may rise. In addition, a reduction in the amount of developed land reduces loadings and leads to substantial improvement in environmental amenities. This effect is reinforcing in the sense that improvements in environmental amenities further reinforce substitution away from land. The result is to increase the maximum utility that is possible in the region, which more than offsets the negative impact of the income effect on utility and thus new in-migrants are attracted to the region. The opposite occurs when recreational trips are taxed: a substitution effect induces increased consumption of land, which degrades environmental amenities. This effect is reinforcing, as before, but in the opposite direction: degradation of environmental amenities reinforces substitution towards land. The demand for the regional market good also increases, but in this case firms substitute away from labor toward land because labor is fixed whereas land is not. This reduces the relative wage. The reduction in environmental amenities and relative wage act to reduce the maximum utility that is feasible in the region. These effects act in concert with the negative income effect from the tax and destabilize the desirable high-N state, leading to an increase in transient oscillations and a reduction in the steady state population that can be sustained.

These results suggest an interesting dynamic that can arise when interactions are present and can lead to self-reinforcing tendencies that can destabilize the system. Here we find that the positive feedback mechanism between substitution effects and ecological change magnifies the effect of the policy. When the manager gets it right, a marked improvement in the system's resilience and long-run population the region results; conversely, when the manager gets it wrong, the unintended consequence of the policy is magnified and results in a precipitous decline in resilience and steady state population. Thus the costs and benefits of policy are "multiplied up" due to interactions and the penalty of getting it wrong can be quite large as the likelihood of an irreversible decline increases. These results support a cautious approach, such as a precautionary approach as advocated by others concerned with the potential for nonlinear and irreversible changes (e.g., Arrow et al. 2000).

Conclusions

We develop a coupled model of regional migration and lake ecosystem dynamics to study the role of ecological-economic interactions and relative time scales on the transient and asymptotic behavior of the system. We find that interactions fundamentally change system dynamics by eliminating steady states that are present in the decoupled model and that the relative time scales of interacting variables determine much of the system's dynamics and resilience. Other time-dependent effects are found to matter: in particular we find that when households base their perceptions of environmental amenities on past observation, a path dependence is introduced that can alter the asymptotic dynamics. Finally, interactions are found to multiply the costs and benefits of policies by inducing a positive feedback between the ecological and economic components. Such effects imply that both the economic and ecological costs of getting the policy wrong can be large and thus support a precautionary approach. These findings suggest that models that ignore time-dependent effects may be quite misleading. At best, such models will fail to capture the full dynamics of the system and at worst, could provide a misleading characterization of the basic dynamical structure of these systems.

Our results are subject to several limitations of the model in its current version. First, we do not attempt to model forward-looking behavior of agents and instead assume that households are myopic. This greatly simplifies the analysis, but at the cost of not accounting for expectations that will most likely change households' migration and consumption decisions in non-marginal ways. Expectations are sure to matter, particularly if households interact in ways that influence each others' expectations. As the analysis of memory in determining households' perception of amenities demonstrates, these effects introduce a path dependence that can fundamentally alter the system's behavior. Second, we ignore many of the economic or behavioral realities that make regional migration a much stickier, if not irreversible, process. In reality there are many factors that would be expected to mitigate the cyclical behavior that emerges in our model under various conditions. Migration costs, social and professional networks, differences in the perception vs. reality of ecosystem changes are just a few of the factors that we reasonably would expect to offset the tight ecological-economic coupling of that we assume in the model. A related limitation is that we do not deal with the flow vs. stock of land development. In reality the stock of development is irreversible over short and intermediate time scales. We ignore this irreversibility here, but it could be an important consideration since it prevents the region from adjusting quickly to changes that cause population decline and thus makes it harder to recover from such events. Finally, we have not attempted to analyze the full dynamics of the system for all possible (or reasonable) combinations of parameter values, which is a much more exhaustive process. Instead we have sought to choose a reasonable set of baseline parameters and then looked for interesting behaviors of the system subject to plausible ranges of the parameter values. This approach is somewhat opportunistic, but allows us to focus on possible and likely outcomes rather than an exhaustive investigation of all outcomes.

Despite these limitations, the model sheds new light on the importance of cross-system and cross-scale interactions in the modeling and management of ecological-economic systems and suggests the following specific implications. First, the results underscore the critical importance of identifying and accounting for the relevant time scales of analysis. A single scale may be sufficient in the simplest cases, e.g., for modeling processes in the very short run, isolated processes or processes that operate at such divergent time scales that one can be treated as exogenous and the other as conditional. Neither of the first two cases is appropriate for describing ecological-economic systems that by definition interact and in whose evolution over time we are expressly interested. The last case may be appropriate when the fast time scale is the scale of interest and the slow variable is sufficiently slow that only the one-way interaction of the slow variable's effect on the fast dynamics need be considered. However, most ecological-economic systems exhibit multiple scales and multiple interactions, making such a simplification less plausible. Given these considerations, we believe that two-way, cross-scale interactions are the rule rather than the exception in these coupled systems. As we demonstrate, such interactions fundamentally change the system dynamics.

Second, our results demonstrate the necessity of explicitly accounting for time dependence when the interactions occur across multiple time scales. Because interactions fundamentally change both the transient and asymptotic properties of a system and because the nature of interaction effects depends on the relative time scales over which the variables co-evolve, it is impossible to characterize the system without explicit consideration of this time dependence. A critical implication is that the system's asymptotic behavior cannot be determined without considering the full dynamics of the system. An analysis that characterizes only the time independent states (i.e., steady states or steady growth paths) of a system rather than their time-dependent evolution, as is standard in many economic analyses, is not only insufficient, but would misrepresent even the asymptotic dynamics.

The findings underscore the importance of tracing the full dynamics of a system when the time scale on which a steady state is not immediately reached. In our case, the steady state population and ecological state is not reached for several decades; in some cases it may take much longer. Economists are typically loathe to make predictions beyond five to ten years because they understand the likelihood that external shocks or structural change will cause the system to deviate from their predicted results. For the same reasons, economists should be equally circumspect of relying solely on steady state descriptions when analyzing dynamical systems that may be far from equilibrium and may never reach the eventual steady state. This is particularly true in the presence of interactions, which can introduce oscillations and other transient behavior that is not exhibited in the eventual steady state.

Third, our analysis demonstrates the importance of accounting for slow variables, interaction effects and the resulting nonlinear bi-stabilities that may be present in economic systems. To-date most if not all of the literature on ecological-economic modeling has focused on complex dynamics in the coupled system arising from nonlinearities in the ecological system. As we show, it is equally important to account for such processes when they arise in economic systems.

References

Anderies, J. M. 2003. Economic development, demographics, and renewable resources: a dynamical systems approach. *Environment and Development Economics* 8:219-246.

Booth, D.B. and C.R. Jackson 1997. Urbanization of aquatic systems: Degradation thresholds, stormwater detection and the limits of mitigation. *Journal of the American Water Resources Association* 33(5): 1077-90.

Brock, W. A., and S. N. Durlauf. 2001. Discrete choice with social interactions. *Review of Economic Studies* 68 (2):235-260.

Carpenter, S. R., and W. A. Brock. 2004. Spatial complexity, resilience, and policy diversity: Fishing on lake-rich landscapes. *Ecology and Society* 9 (1).

Carpenter, S. R., D. Ludwig, and W. A. Brock. 1999. Management of eutrophication for lakes subject to potentially irreversible change. *Ecological Applications* 9 (3):751-771.

Clark, C.W. 1990. Mathematical bioeconomics: The optimal management of renewable resources. 2nd ed. NY: John Wiley and Sons.

Conroy, J.D., D.D. Krane, D.M. Dolan, W.J. Edwards, M.N. Charlton and D.A. Culver. Temporal trends in Lake Erie plankton biomass: Roles of external phosphorus loading and dreissenid mussels" *Journal of Great Lakes Research* 31(Suppl 2): 89-110.

Fujita, P. Krugman and A.J. Venables. 1999. The spatial economy: Cities, regions and international trade," MIT Press, Cambridge, MA.

Fujita and J.F. Thisse. 2002. Economics of agglomeration: Cities, industrial location and regional growth. Cambridge University Press, Cambridge, UK.

Glaeser, E., J. Kolko, A. Saiz. 2001. Consumer city. *Journal of Economic Geography* (1): 27-50.

Gordon, H.S. 1954. The economic theory of a common property resource: The fishery. *Journal of Political Economy* 62: 124-42.

Gude, P.H., A. Hansen, R. Rasker, B. Maxwell. 2006. Rates and drivers of rural residential development in the Greater Yellowstone. *Landscape and Urban Planning* 77: 131–151.

Gunderson, L., and C.S. Holling, Eds., 2002. Panarchy: understanding transformations in human and natural systems. Island Press, Washington, D.C.

Hansen, A.J., R. Rasker, B. Maxwell and P.H. Gude, Ecological causes and consequences of demographic change in the new west, *Bioscience* 52 (2), 151-162 (2002).

Hastings, A. 2004. Transients: the key to long-term ecological understanding? *Trends in*

Ecology and Evolution, 19, 39-45.

Holling, C.S. 1973. *Annual Review of Ecology and Systematics*, 4: 1-23.

Janssen, M. A., J. M. Anderies, and B. H. Walker. 2004. Robust strategies for managing rangelands with multiple stable attractors. *Journal of Environmental Economics and Management* 47 (1):140-162.

Judd, K.L. 1997. Computational economics and economic theory: substitutes or complements. *Journal of Economic Dynamics and Control*, 21(6): 907-42.

Levin, S.A. 2006. Learning to live in a global commons: socioeconomic challenges for a sustainable environment. *Ecological Research* 21:328-33.

Levin, S.A. 1999. *Fragile Dominion*. Reading (MA): Perseus Books.

Levin, S.A. and many others 1998. Resilience in natural and socioeconomic systems. *Environment and Development Economics* 3(2): 222-35.

Ludwig, D., S. Carpenter, and W. Brock. 2003. Optimal phosphorus loading for a potentially eutrophic lake. *Ecological Applications* 13 (4):1135-1152.

Maler, K. G. 2000. Development, ecological resources and their management: A study of complex dynamic systems. *European Economic Review* 44 (4-6):645-665.

McGranahan, D. 1999. Natural amenities drive rural population change. Agricultural Economic Report No. 781. US Department of Agriculture. Washington D.C.

Perrings, C., and B. Walker. 1997. Biodiversity, resilience and the control of ecological-economic systems: The case of fire-driven rangelands. *Ecological Economics* 22 (1):73-83.

———. 2004. Conservation in the optimal use of rangelands. *Ecological Economics* 49 (2):119-128.

Pikovsky, A., M. Rosenblum and J. Kurths. 2001. *Synchronization: A universal concept in nonlinear sciences*. Cambridge: Cambridge University Press.

Rappaport, J. and J.D. Sachs. 2003. The United States as a coastal nation. *Journal of Economic Growth*, 8: 5-46.

Roback, J. 1982. Wages, rents, and the quality of life. *Journal of Political Economy* 90 (6):1257-1278.

Romer, P. M. 1986. Increasing returns and long-run growth. *Journal of Political Economy* 94 (5):1002-1037.

Scheffer, M., W. Brock, and F. Westley. 2000. Socioeconomic mechanisms preventing optimum use of ecosystem services: An interdisciplinary theoretical analysis. *Ecosystems*

3 (5):451-471.

Scheffer M. 1998. *Ecology of shallow lakes*. London: Chapman and Hall

Scheffer M, Hosper SH, Meijer ML, Moss B. 1993. Alternative equilibria in shallow lakes. *Trends in Ecology and Evolution* 8:275–279

Schelling, T.C. 1971. Dynamic models of segregation. *Journal of Mathematical Sociology* 1:143-86.

Smith, V.L. 1968. Economics of production from natural resources. *American Economic Review* 56: 409-31.

Sutton, P. D., and F. A. Day. 2004. Types of rapidly growing counties of the US, 1970-1990. *Social Science Journal* 41 (2):251-265.

U.S. Census Bureau. 2003. Domestic migration across regions, divisions, and states: 1995 to 2000. Accessed online: http://www.census.gov/prod/2003pubs/censr-7.pdf.

van Ness, E.H. and M. Scheffer. 2007. Slow recovery from perturbations as an indicator of a nearby catastrophic shift. Forthcoming in *American Naturalist*.

Wainger, L. A., and E. W. Price. 2004. Evaluating quality of life, economic vulnerabilities, and drivers of ecosystem change. *Environmental Monitoring and Assessment* 94 (1-3):69-84.

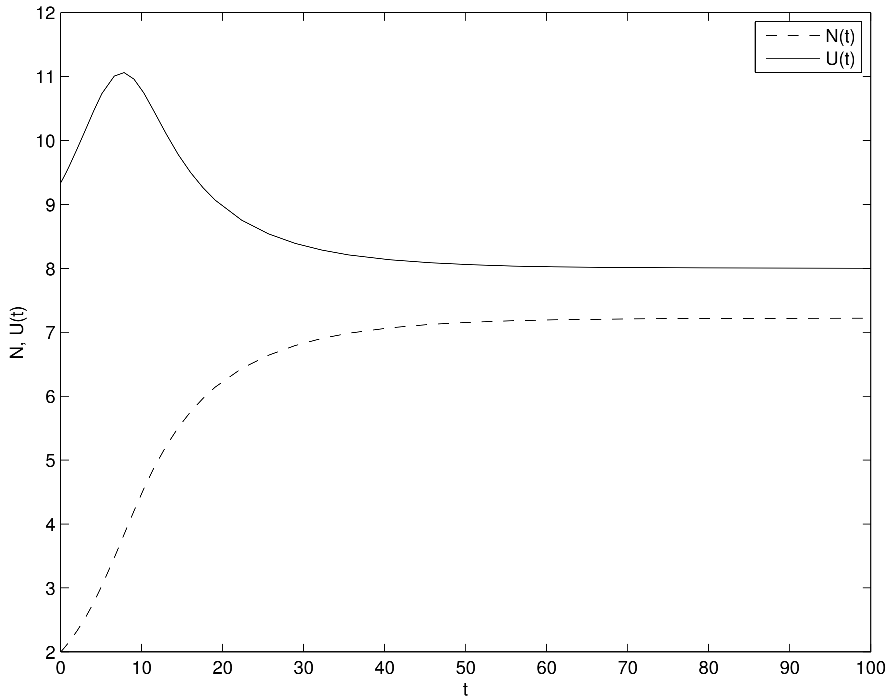

Figure 1: Evolution of population, *N,* and maximized utility, U^{*}, for the decoupled economic model; N is in units of 10,000. All parameters set at their baseline values for the decoupled model, as reported in Appendix B.

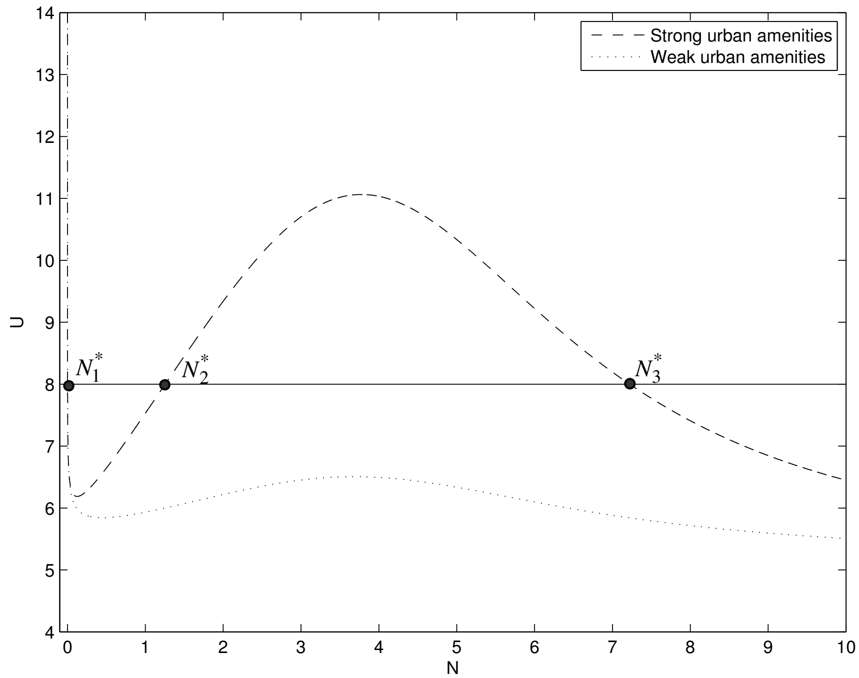

Figure 2a: Maximized utility as a function of population (N) and steady state dynamics for the case of weak ($\alpha_u^1 = 0.2$) and strong ($\alpha_u^1 = 1.0$) urban amenities for the decoupled model.

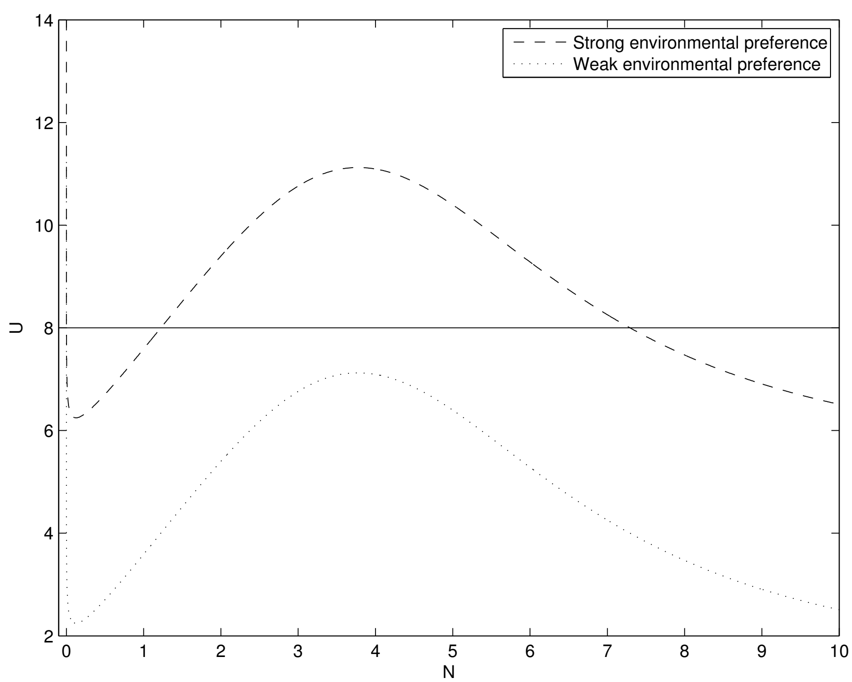

Figure 2b: Maximized utility as a function of population (N) and steady state dynamics for the case of weak ($\alpha_e = 1$) and strong ($\alpha_e = 5$) environmental amenities preferences for the decoupled model.

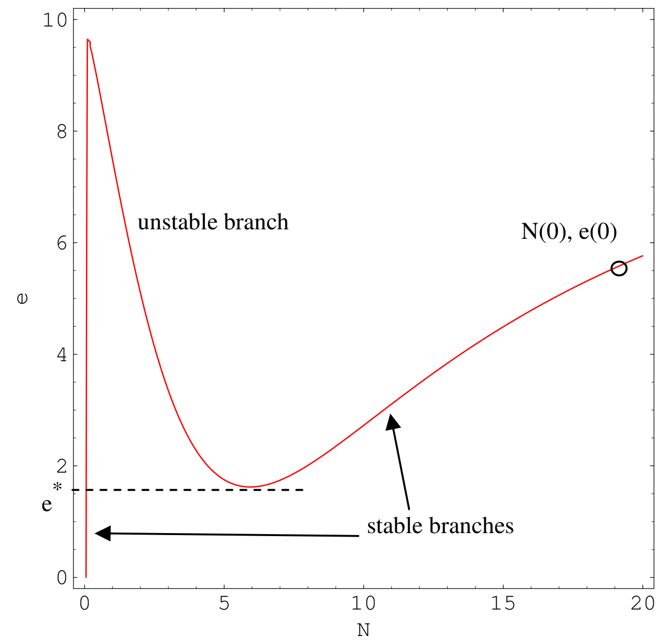

Figure 3a: Bifurcation plot of population (*N*) as a function of exogenous environmental amenities for the decoupled model.

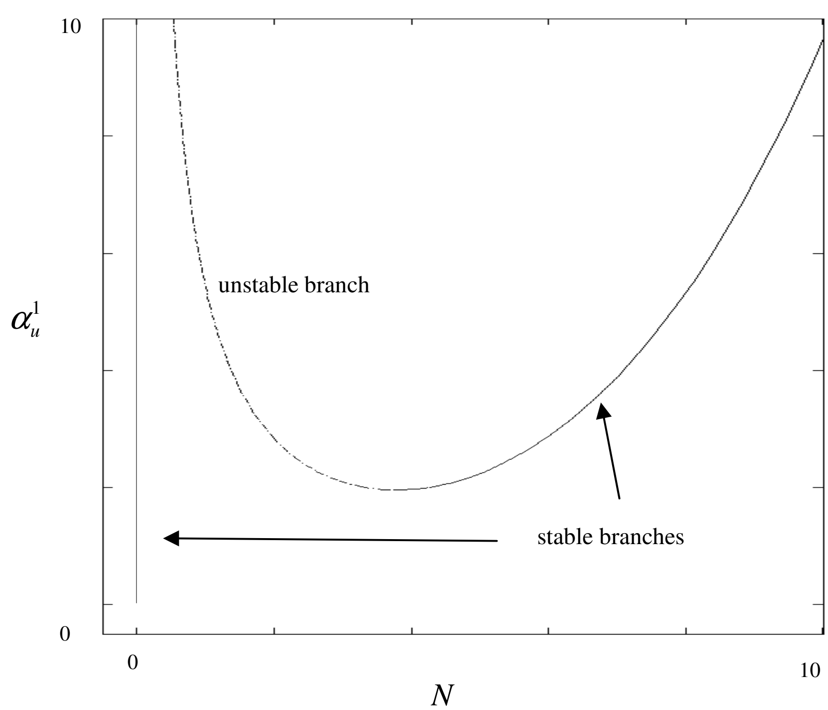

Figure 3b: Bifurcation plot of population (*N*) as a function of the urban amenities parameter α_u^1 for the decoupled model.

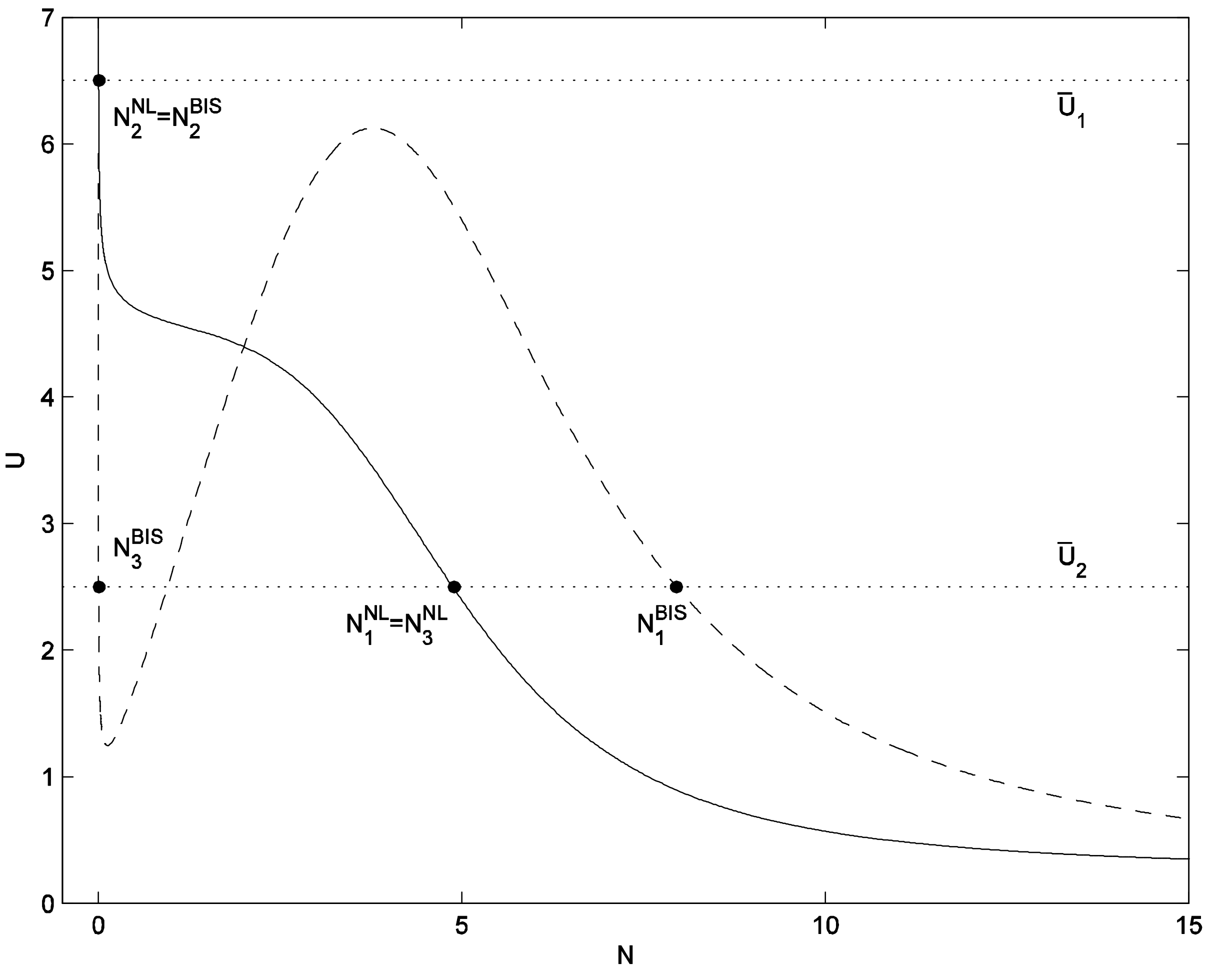

Figure 4: *U*(N)* given non-linear specifications with and without bi-stable economic dynamics: dotted line indicates bi-stable dynamics; solid line indicates nonlinear dynamics without bistability. The bi-stability arises due to urban agglomeration benefits. In the absence of agglomeration benefits, the utility is monotonically declining in *N*.

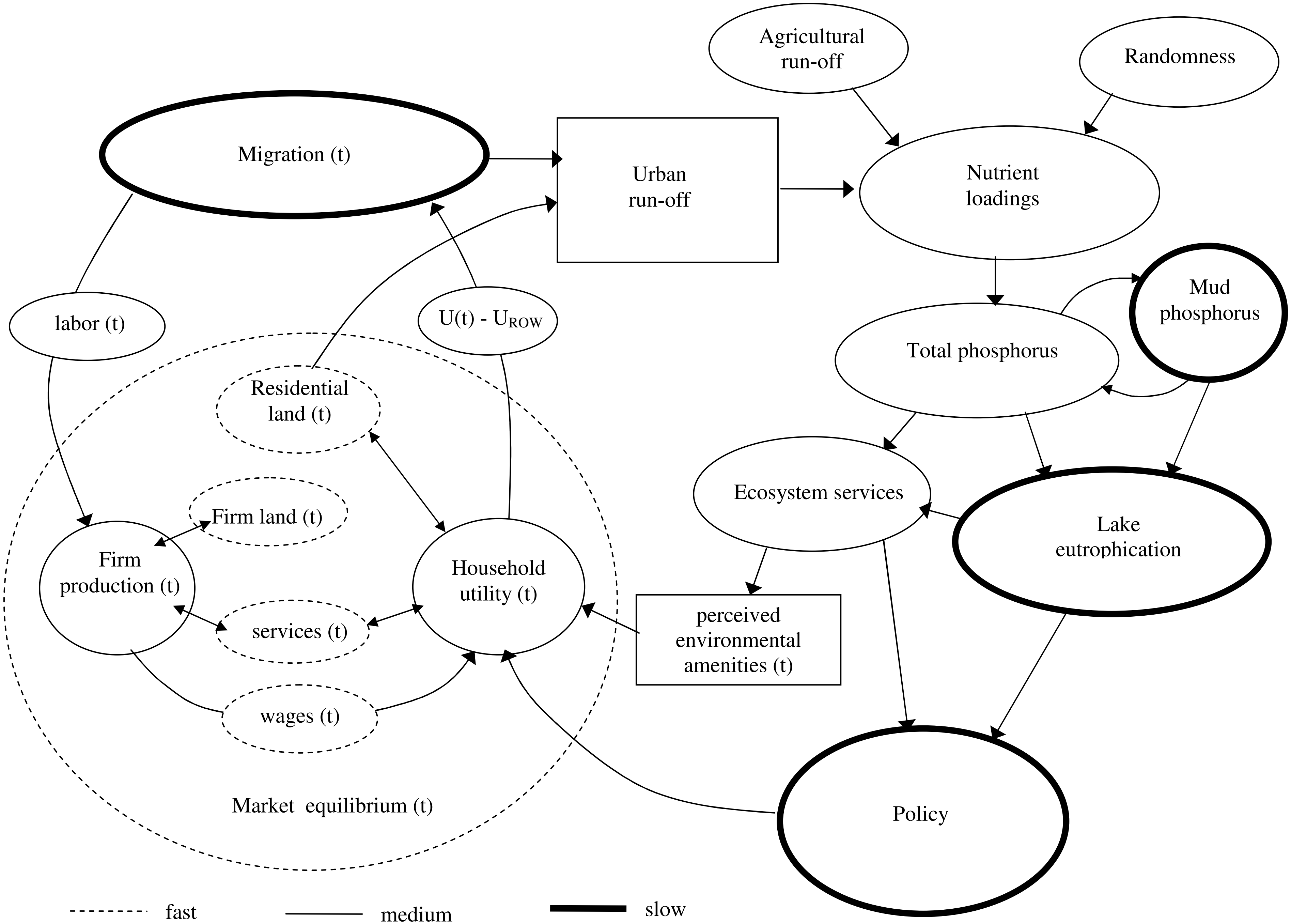

Figure 5: Conceptual Model of Regional Economy with Endogenous Environmental Amenities

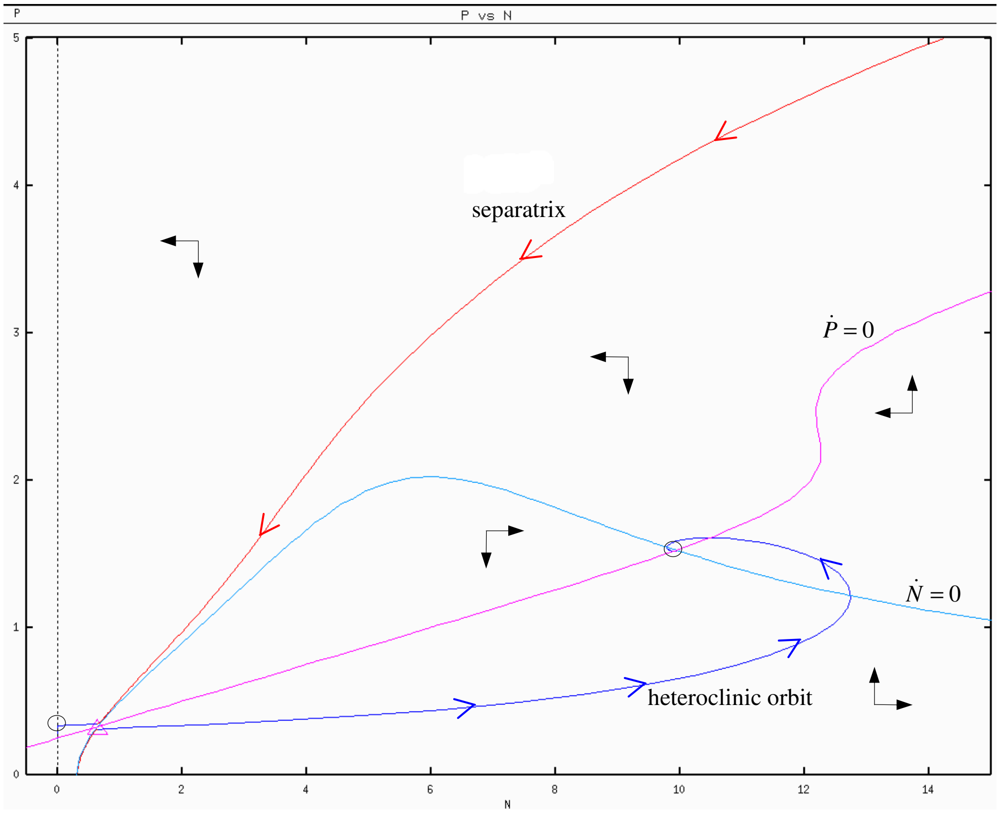

Figure 6: Phase plot of phosphorus, P, on vertical axis vs. population, N, on horizontal axis illustrating bi-stability with coupled model. The system exhibits two stable fixed points, one at N = 0 and the other at N > 0, both indicated with a circle. The triangle indicates an unstable fixed point and arrows indicate dynamical paths of the separatrix and heteroclinic orbit. All parameters are set at their baseline values for the coupled model, as reported in Appendix B.

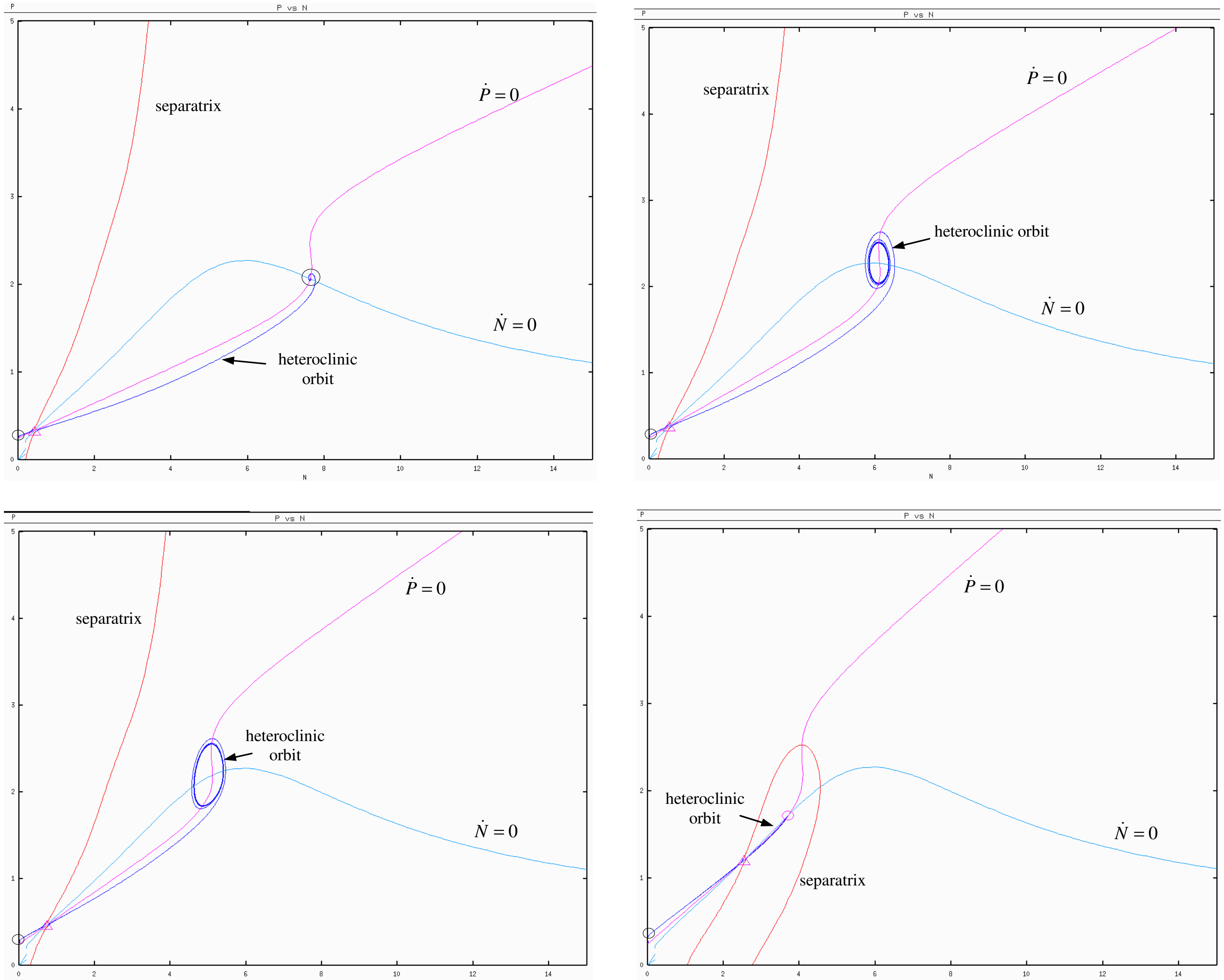

Figure 7: Phase plots of phosphorus, P, on vertical axis vs. population, N, on horizontal axis for coupled system given increasing values of the loadings coefficient L_l: (a) L_l=0.08 (top left), (b) L_1=0.1 (top right), (c) L_l=0.12 (bottom left), (d) L_l = 0.15 (bottom right). In all cases, a stable fixed point exists at N = 0, as indicated by the circle. In cases (a) and (d) a second stable fixed point exists for N > 0 and P > 0, also indicated with a circle. In cases (b) and (c) the stable fixed point disappears and instead a stable limit cycle emerges. Note for case (d) the system only converges to the stable fixed point for a small range of parameters (those located within the separatrix). The triangle indicates an unstable fixed point.

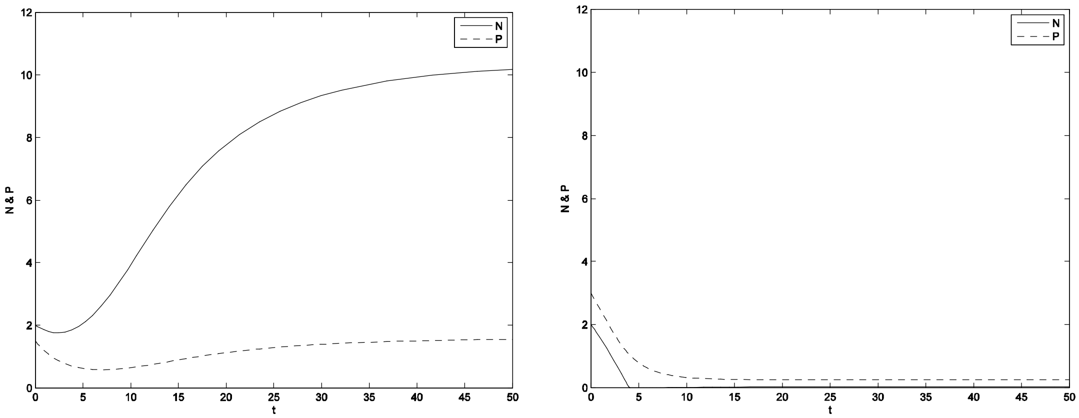

Figure 8(a) and (b): Illustration of bi-stability and initial condition dependence. Time evolution of phosphorus, P, and population, N, for different initial values of P(0): (a) P(0)= 1.5 (left) and (b) P(0) = 3 (right). (L_1 = 0.05).

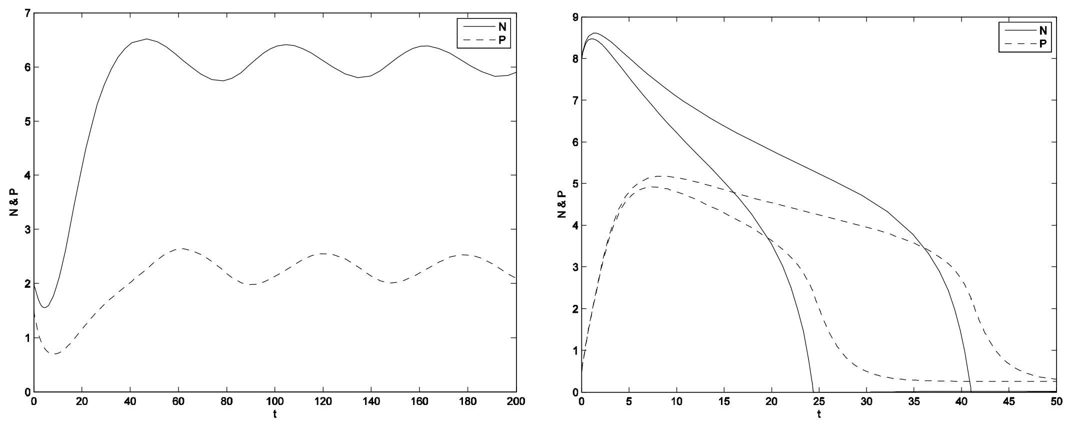

Figure 8(c) (left): The system evolves to a stable limit cycle given same conditions in (a) except L_1 = 0.1.
Figure 8(d) (right): Strong urban amenities offset the decline to N = 0: an increase in urban amenities parameter from 3.0 to 3.2 results in a shifting out of N(t) and P(t) and delays the eventual crash by about 15 years (L_1=0.2)

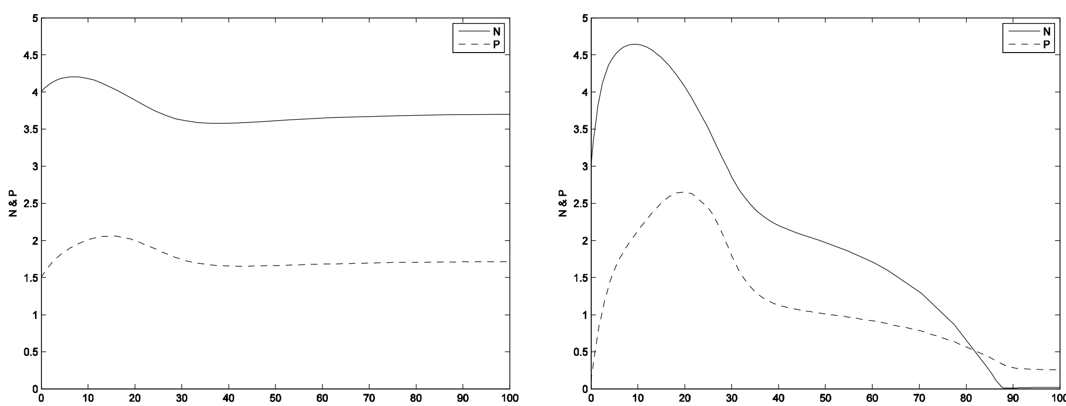

Figure 8(e) and (f) illustrate the offsetting effect of strong urban amenities on the asymptotic behavior of the system.
Figure 8(e) with initial condition N(0)=4, P(0)=1.5. Figure 8(f) with N(0)=3, P(0)=0.1. L_1=0.15 for both cases.

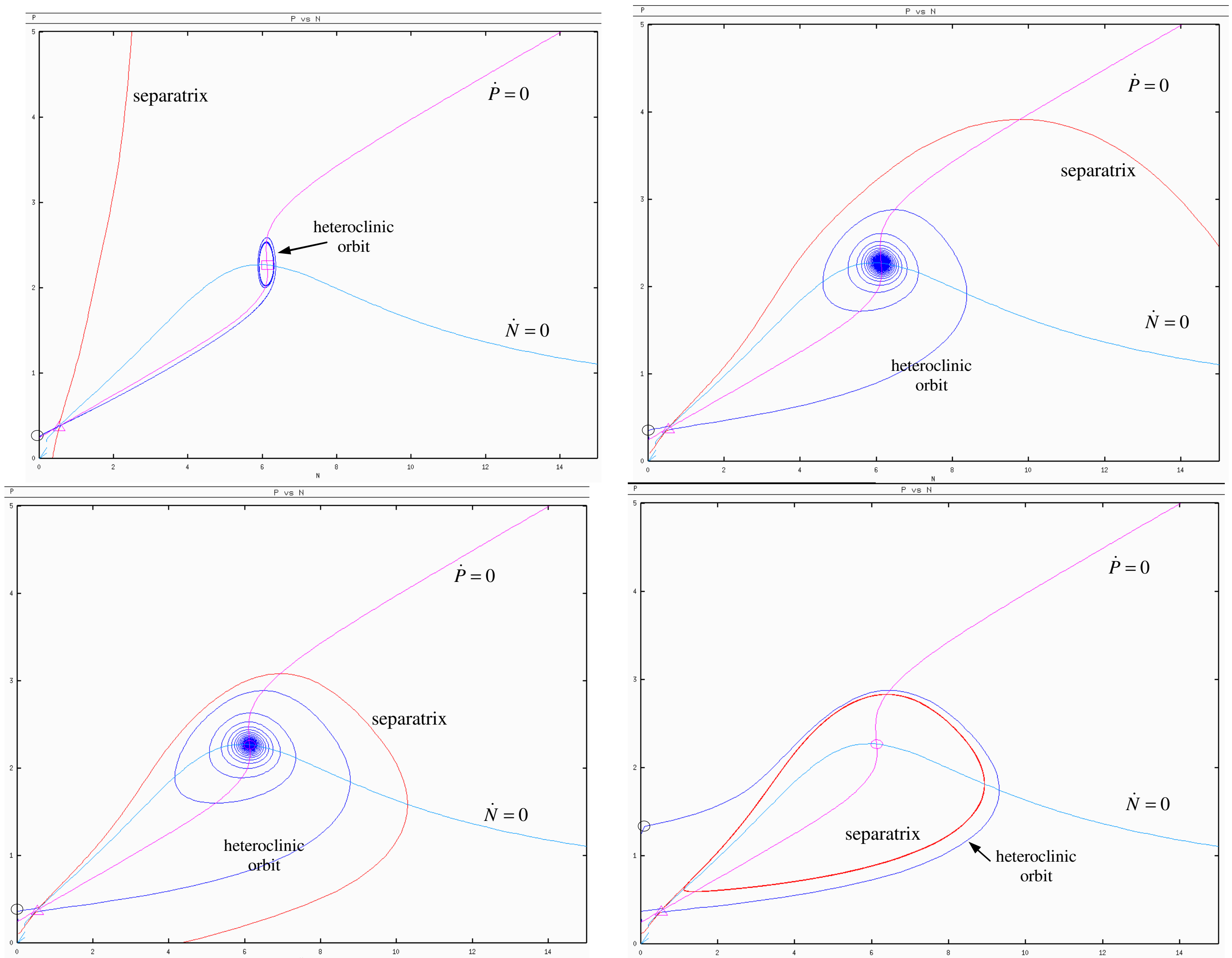

Figure 9: Phase plots of phosphorus, P, on vertical axis vs. population, N, on horizontal axis with $L_1 = 0.1$ and different time scales for $\dot{N}$ relative to $\dot{P}$. All other parameters held constant. Time scales for migration are: (a) 20 years (top left), (b) 5 years (top right), (c) 1.6 years (bottom left), and (d) 1 year (bottom right). For comparison, see Figure 7(b), which illustrates the phase plot for $L_1 = 0.1$ for the base time scale of 10 years.

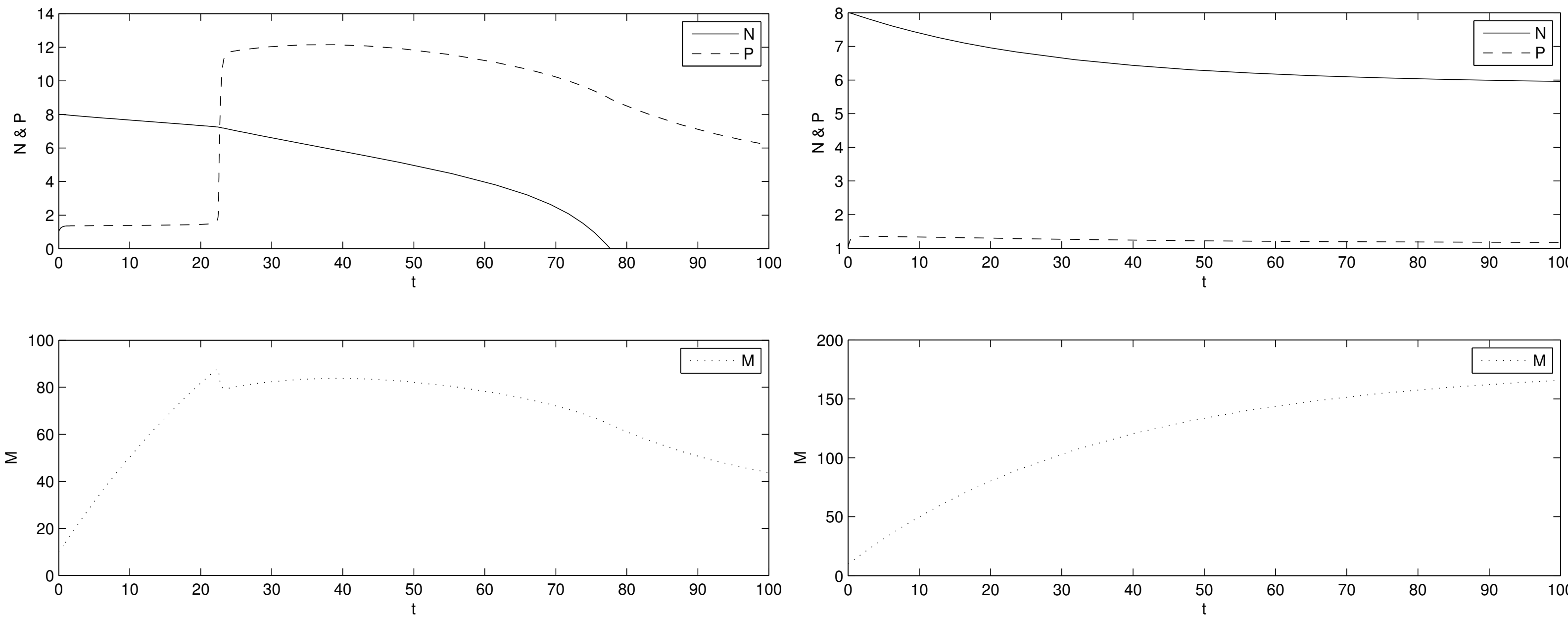

Figure 10: Changing relative time scale of τN vs τM for the coupled model with slow-moving sedimented Phosphorus, M:
(a) migration time scale is 10 years (left); (b) migration time scale is 20 years (right). All other parameters are held constant at the values reported in Appexdix B for the couple model with M dynamics.

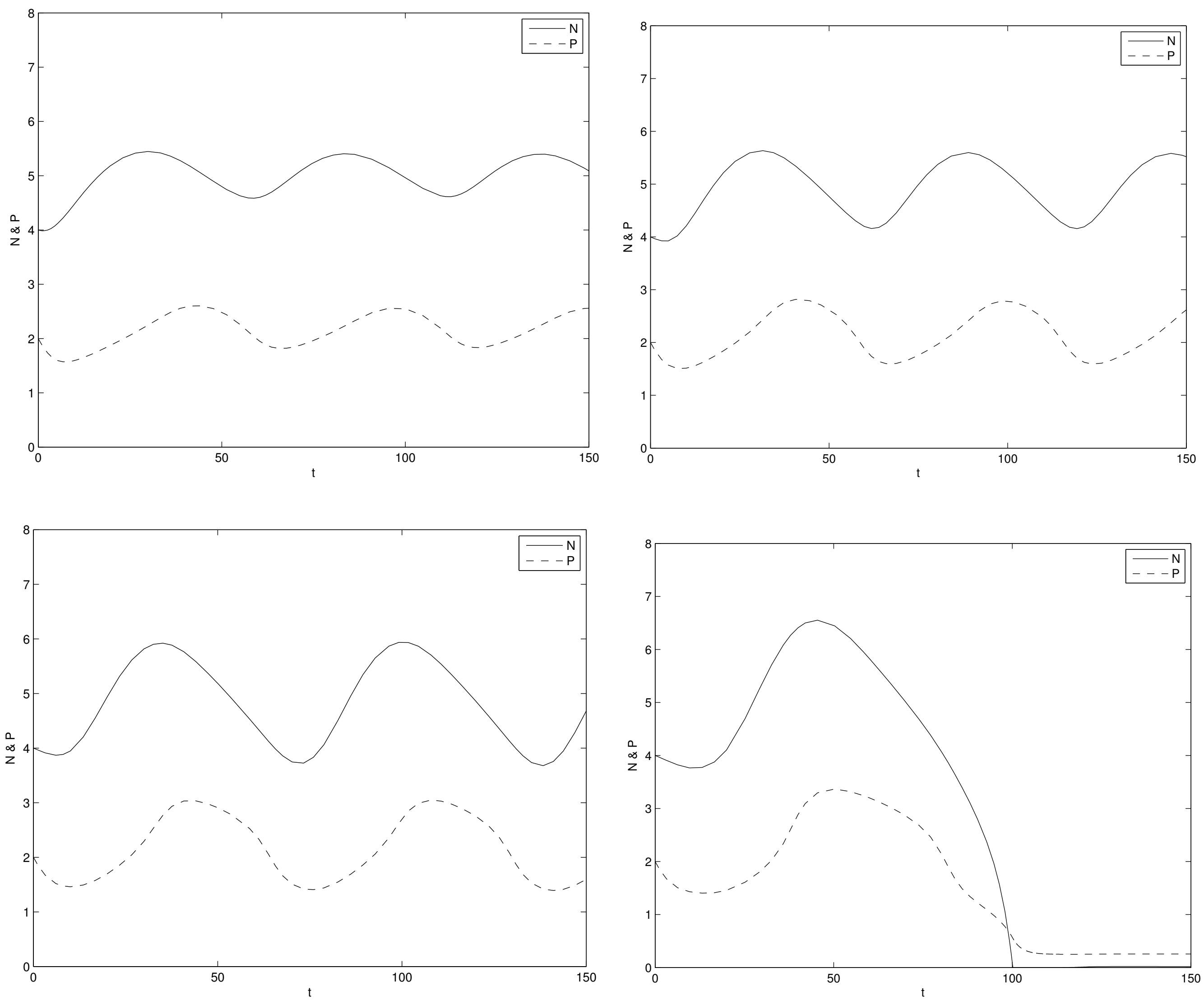

Figure 11: The effect of memory in the formation of household expectations over environmental amenities. Household form expected e(t) by taking a simple average over past values of observed e(t-1), …, e(t-k) where k is the memory length. The plots correspond to the following values of k: (a) no time lag (instantaneous updating of e_c) (top left), (b) 5 years (top right), (c) 10 years (bottom left) and (d) 20 years (bottom right). L1=0.12

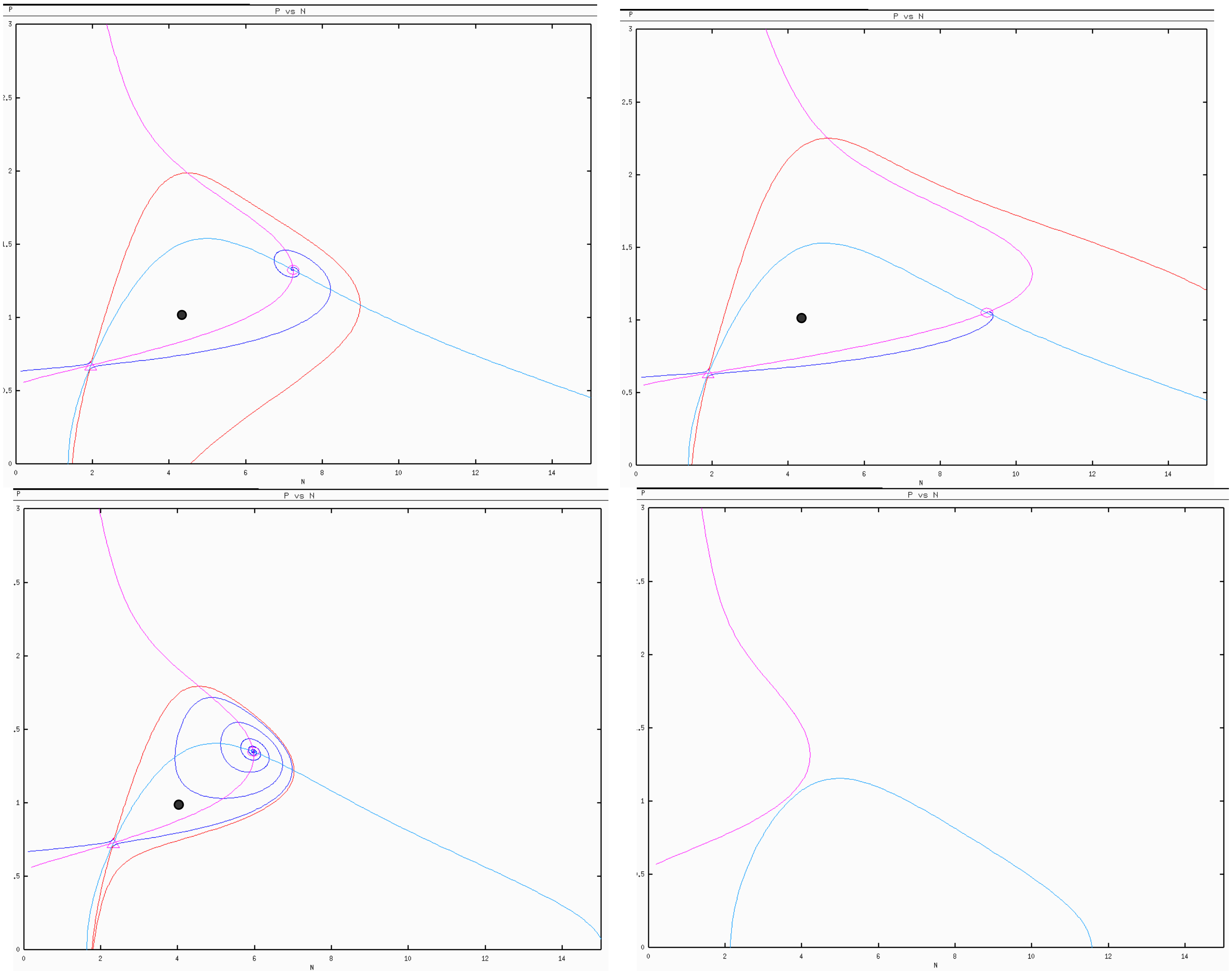

Figure 13: Phase plots for policy case with household produced e(q) for the following cases: (a) no tax; r = 0.125, f = 1.0 (top left); (b) tax on residential land; r = 0.15, f = 1.0 (top right); (c) tax on environmental amenity; r = 0.125; f = 1.1(bottom left); (d) somewhat higher tax on environmental amenity; r = 0.125, f = 1.3. All other parameters are held constant at the values listed in Appendix B for the household good policy model. The small circle indicates the initial conditions for the plots in Figures 14(a)-(c).

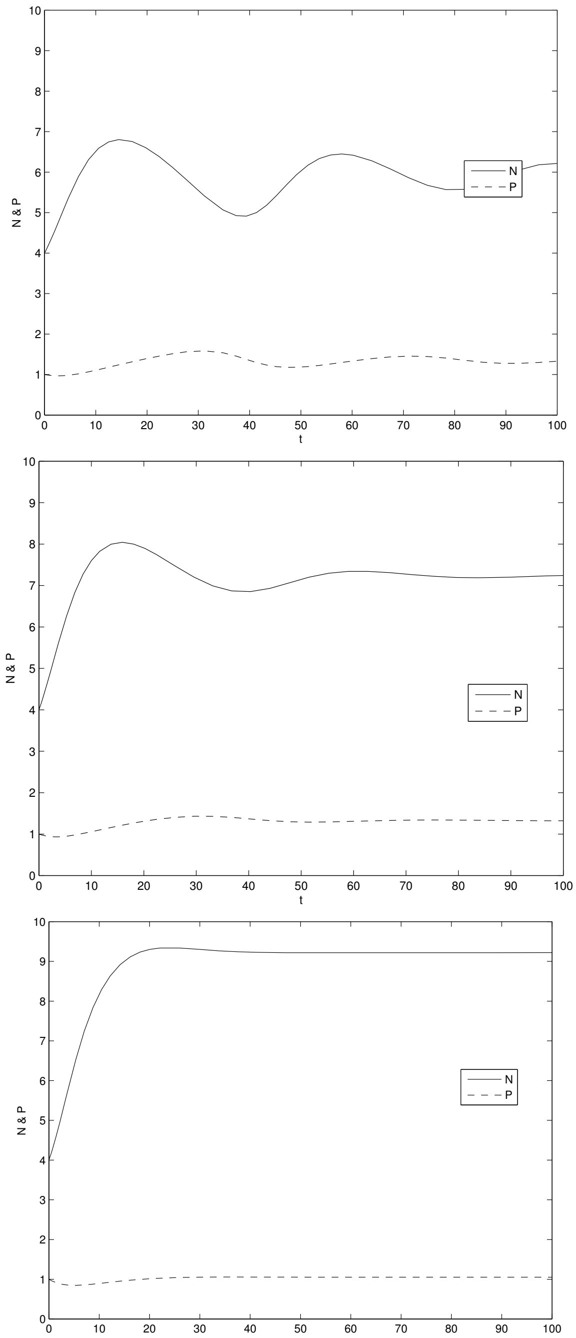

Figure 14: Time evolution of P and N for policy case with (a) no tax, (b) tax on household produced good e(q) and (c) tax on residential land l_c. Initial conditions: N(0) = 4, P(0) = 1. Parameter values correspond to the phase plots in figure 13(a)-(c) respectively.