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

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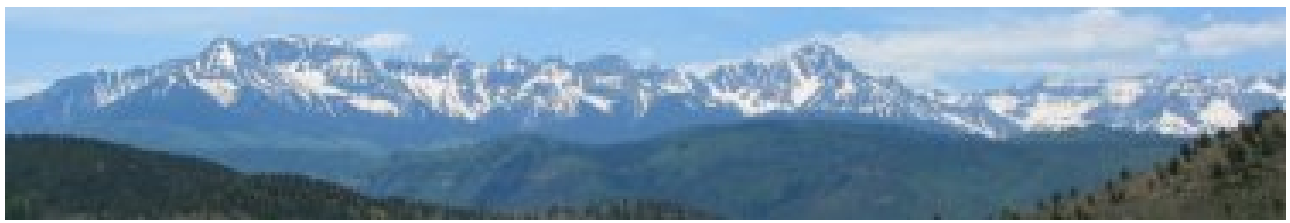
What are amenities?

- Amenities can broadly be defined as qualities of a region that make it an attractive place to live and work. Common characteristics:
  - Location-specific and spatially immobile
  - Public good attributes
  - Responsive (i.e., endogenous) to human activities and actions
  - Different types: urban, natural, social, cultural



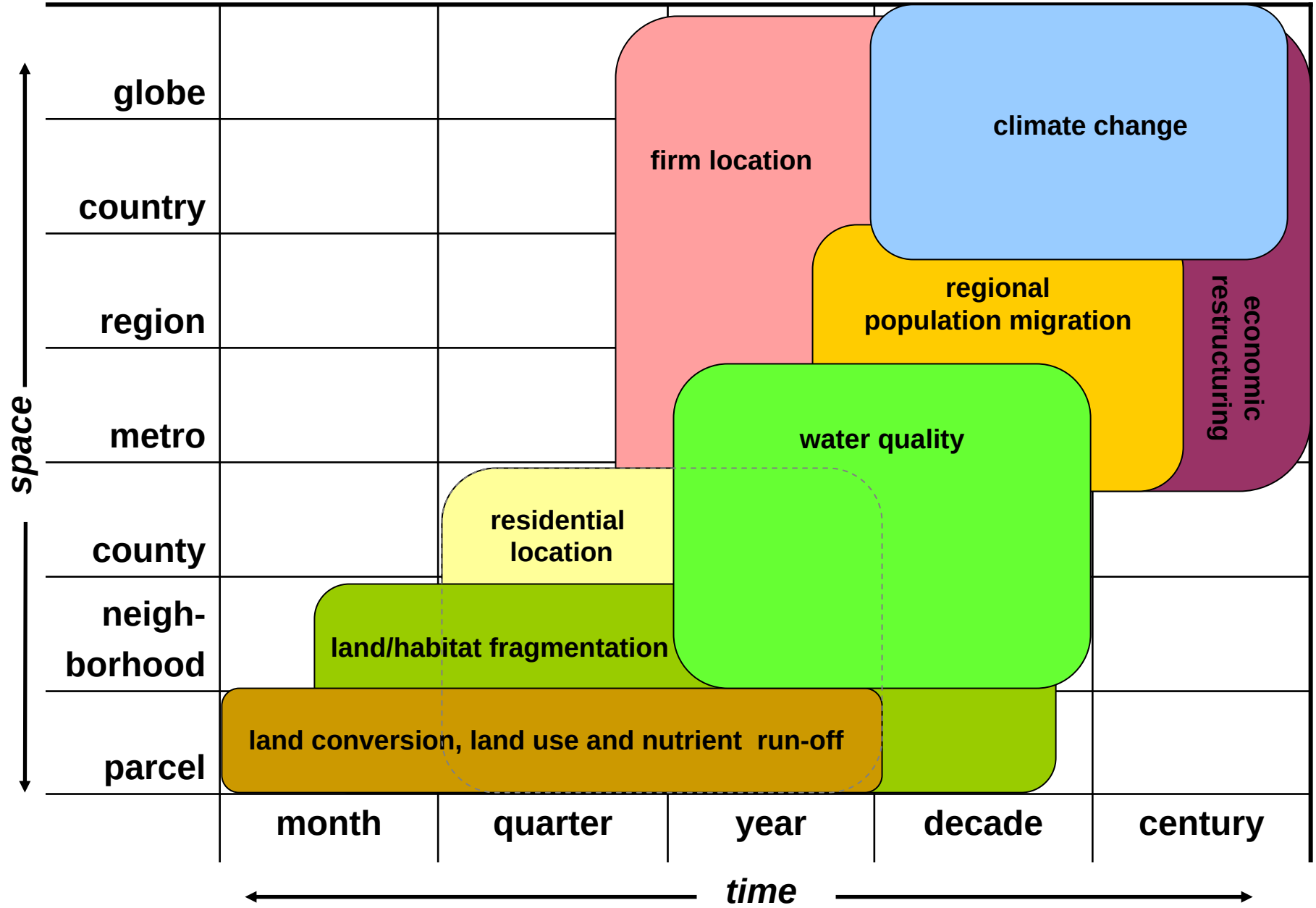
Natural amenities, migration and economic growth

- The Mountain West was the fastest growing region in the U.S. in the 1990's with a population growth rate of 25% (Hansen et al., 2002)
- Northwest residents survey: almost as many people "moved to the region because I wanted to live here and then looked for a job" as did moved for a job opportunity (Dearien, et al. 2005)
- Areas with a concentration of winter recreational amenities, resorts, national parks and other land amenities experienced higher population and employment growth between 1985-95 (Deller et al., 2001)
- Rappaport and Sachs (2003): productivity advantages had greater influence on coastal population growth than quality of life effects for period 1920-1960, but quality of life substantially increase after 1960

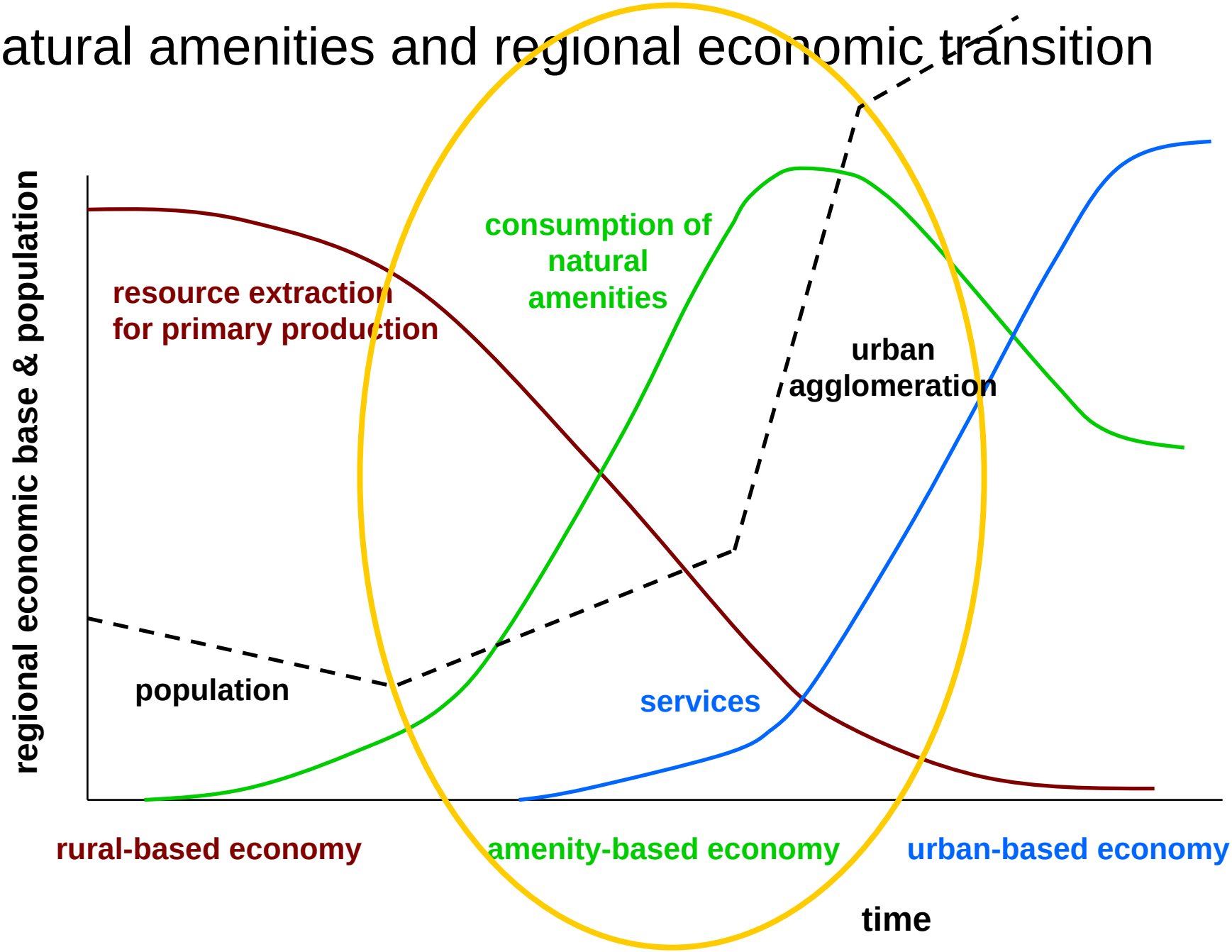
Why natural amenity-driven growth?

- Economic restructuring
  - New economy is service-based; information and creation of knowledge are drivers of growth; firms follow households; amenities attract people and firms
  - Decline in manufacturing and primary production industries; regeneration of natural environment
- Increasing household wealth
- Declining transportation and communications costs
  - Information and communications technologies allow information to be generated and transmitted cheaply and nearly instantaneously around the world.

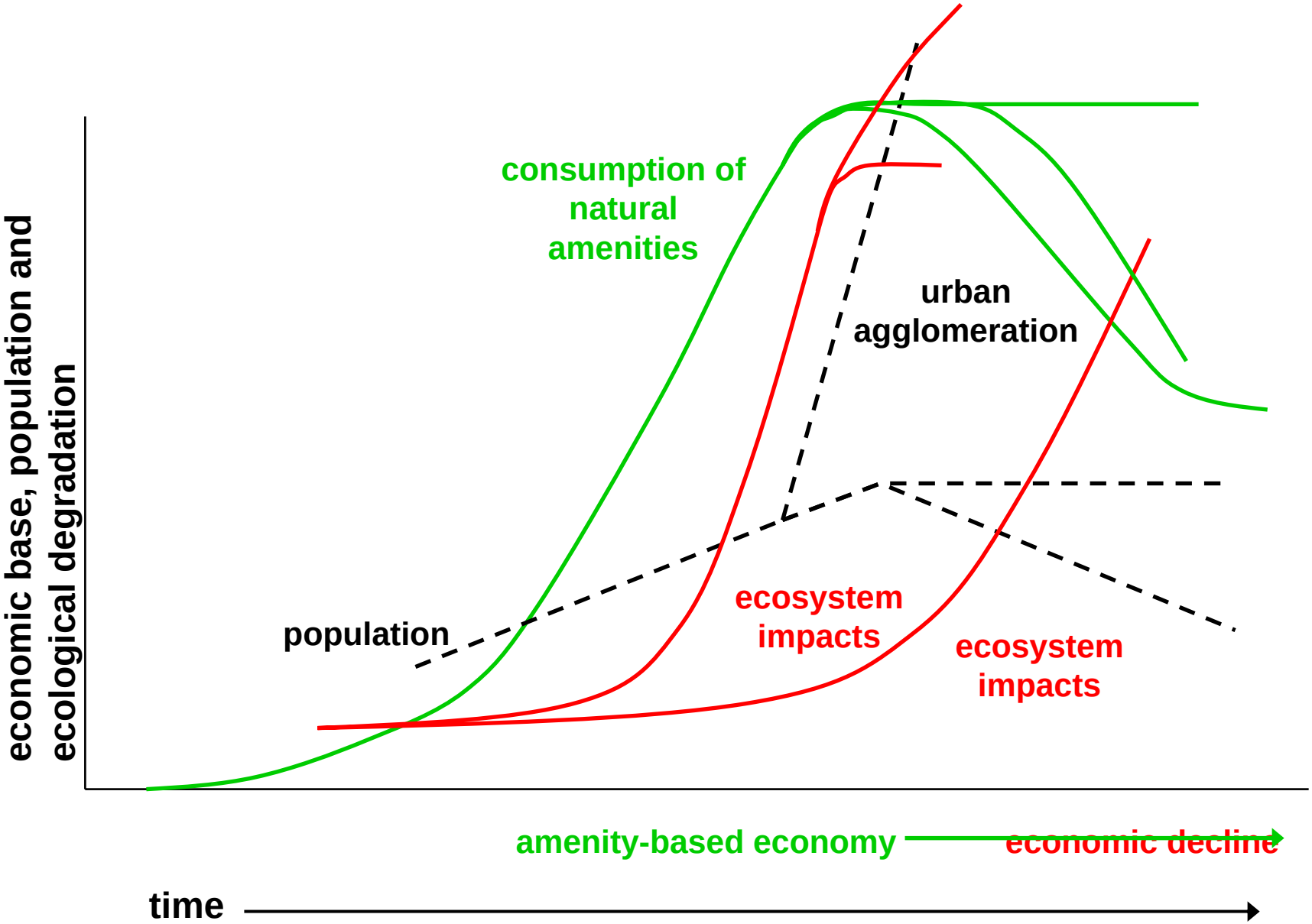
Scale-dependent interactions between regional growth and ecological change



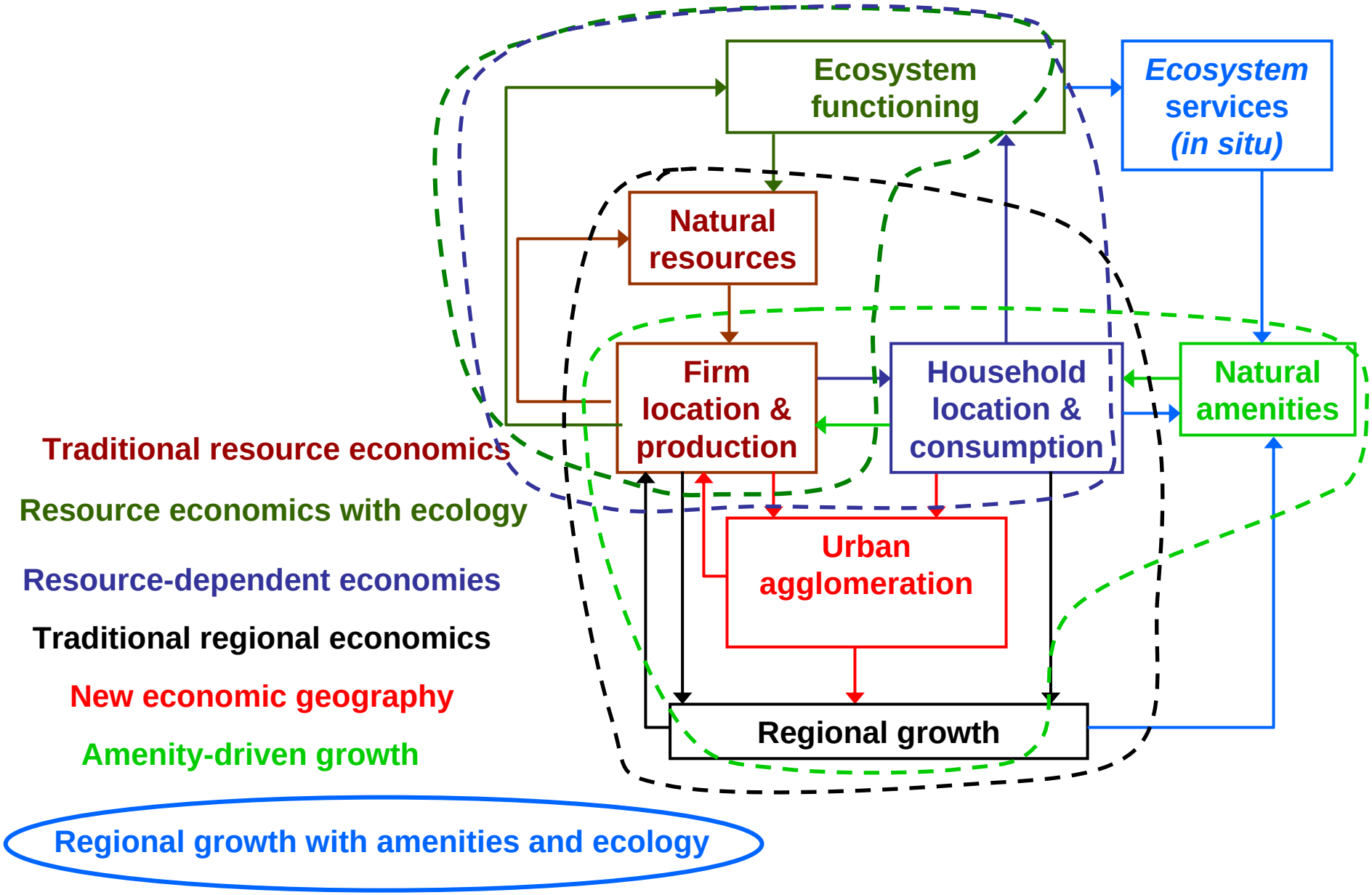
Natural amenities and regional economic transition



Natural amenity-driven growth and ecological change



Models of resource and regional economics



This paper: ecological-economic model of amenity-driven migration and ecosystem change

Our primary focus is on how:

- **two-way interactions** between population migration and ecological change
- **relative times scales** of population migration, urban agglomeration and ecological change

influence the dynamics of the regional ecological-economic system.

→ Time dependence, multiple time scales and cross-scale interactions are key features of our model

We also consider the role of:

- **heterogeneity** in preferences and income
- **memory** in influencing households' perception of ecological quality

Consideration of ecological-economic interactions in economic models

- One-way interaction (human activities degrade ecosystem) is the most common formulation
- Resource economics has a long history of considering two-way interactions, most often at a single economic scale of analysis (e.g., individual firm or manager)
- Models of resource dependence at community level (e.g., Brander and Taylor's Easter Island model) have considered two-way interactions in a general equilibrium framework

Consideration of cross-scale interactions in economics

- Interactions across multiple **organizational scales** are a fundamental feature of economic models
  - General equilibrium models: individual and aggregate scales
  - Social interactions models: individual and group scales
- Economic models have started to account for interactions across multiple **spatial scales**, e.g.,
  - Patch-level heterogeneity → aggregate fish stocks
  - Parcel-level land use heterogeneity → sprawl

Consideration of cross-scale interactions in economics

- Economic models have not focused as much on interactions across multiple **time scales** – why?
  - General equilibrium approach: allows for explicit consideration of how individual actions and market outcomes are related, but treats outcomes as time independent
  - Interactions across multiple time scales implies that time dependence and out-of-equilibrium dynamics must also be considered
    - Creates challenges for aggregating up from individual to market level outcomes
    - Consideration of out-of-equilibrium dynamics almost always requires non-analytical methods
  - Modeling ecological-economic interactions necessitates explicit consideration of time dependence and cross-scale interactions

Consideration of agent heterogeneity in economics

- Traditional economic models assume a ‘representative agent’
- Importance of heterogeneity has been clearly demonstrated by household sorting models.
  - Despite this, the role of heterogeneity in economic models remains understudied
- Consideration of agent heterogeneity is a critical step towards fuller spatial model in which agents are also distinguished in space

Our research findings and contribution

- Account for divergent time scales in both economic and ecological systems and model intermediate and slow moving processes as time dependent
  - This allows us to consider how processes evolving over different time scales interact and give rise to thresholds and other nonlinear effects
  - We find that short term vs. long term dynamics can be quite different
- Account for two-way interactions across ecological and economic systems and across different time scales (cross-system, cross-scale interactions)
  - We find that relative time scales are key determinants of system dynamics and the resilience of the “good” state
  - We find that interactions lead to a positive feedback that can magnify the cost and benefits of a policy

Our research findings and contribution

- Explore the role of agent heterogeneity: when does it matter in determining system dynamics and regional outcomes?
  - We find that sufficient heterogeneity induces sorting, but doesn't always affect dynamics; qualitatively changes dynamics near a threshold
- Explore the role of memory: how does memory over past ecological quality influence system dynamics
  - We find that memory can destabilize system dynamics by magnifying oscillations of population and inducing population overshoots

Research findings

- Two-way interactions fundamentally change the short-term and long-term dynamics of the coupled vs. decoupled systems
- Interactions cause a multiplier effect associated with costs and benefits of policy
- Relative time scales of interacting variables are a critical determinant of the “good” state and the resilience of the system in this state
- Memory and expectations over ecological quality can work in opposite ways: memory can magnify population and ecological oscillations whereas rational expectations dampen these oscillations
- Agent heterogeneity doesn’t always matter, but it matters critically when system is near a threshold
- Short vs. long-term dynamics can be substantially different

Contribution

This paper provides preliminary results regarding several issues that have been understudied by environmental economists:

- Threshold effects and regime shifts that are time dependent
- Multiple time scales and cross-scale interactions
- Implications of memory vs. rational expectations for system dynamics
- Agent heterogeneity and sorting

Comprehensive models that address temporal and spatial dependencies and interactions across multiple scales are necessary for policy analysis

Consideration of agent heterogeneity is a critical step towards fuller spatial model in which agents are also distinguished in space

Regional economic model with endogenous amenities

- Households maximize utility by purchasing the composite good (x_c) and land (l_c) subject to a budget constraint with endogenous wage:

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

$$\text{subject to } \; w + I = px_c + rl_c$$

  - Urban amenities: nonlinear function of population, N, that reflects agglomeration benefits as well as congestion
  - Natural amenities: $U_e = \alpha_e e$ where *e* = natural amenities
  - Endogenous natural amenities: *e* declines nonlinearly with *P*

$$e(P) = \frac{q_0}{1 + q_1 P^{\eta_q}}$$ where *P* = ecological “bad”

Population dynamics

- Market equilibrium: instantaneous adjustment conditional on population

- Population: slow adjustment to maximized utility difference in region vs. rest-of-world

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

where τ_N determines the population migration time scale

Baseline case: significant changes in population occur over 10 year time scale

Ecological dynamics

- A simple model of a lake ecosystem that captures the basic dynamics of nutrient loading and lake eutrophication (adapted from Carpenter, Ludwig and Brock, 1999):

$$\dot{P} = \underbrace{L_0 + L_1 N l_c}_{\text{run-off from ag and urban land uses}} - \underbrace{sP}_{\text{sedimentation and outflow}} + \underbrace{\sigma_1 \frac{P^{\sigma_2}}{P_c^{\sigma_2} + P^{\sigma_2}}}_{\text{nutrient recycling}}$$

where P = phosphorus

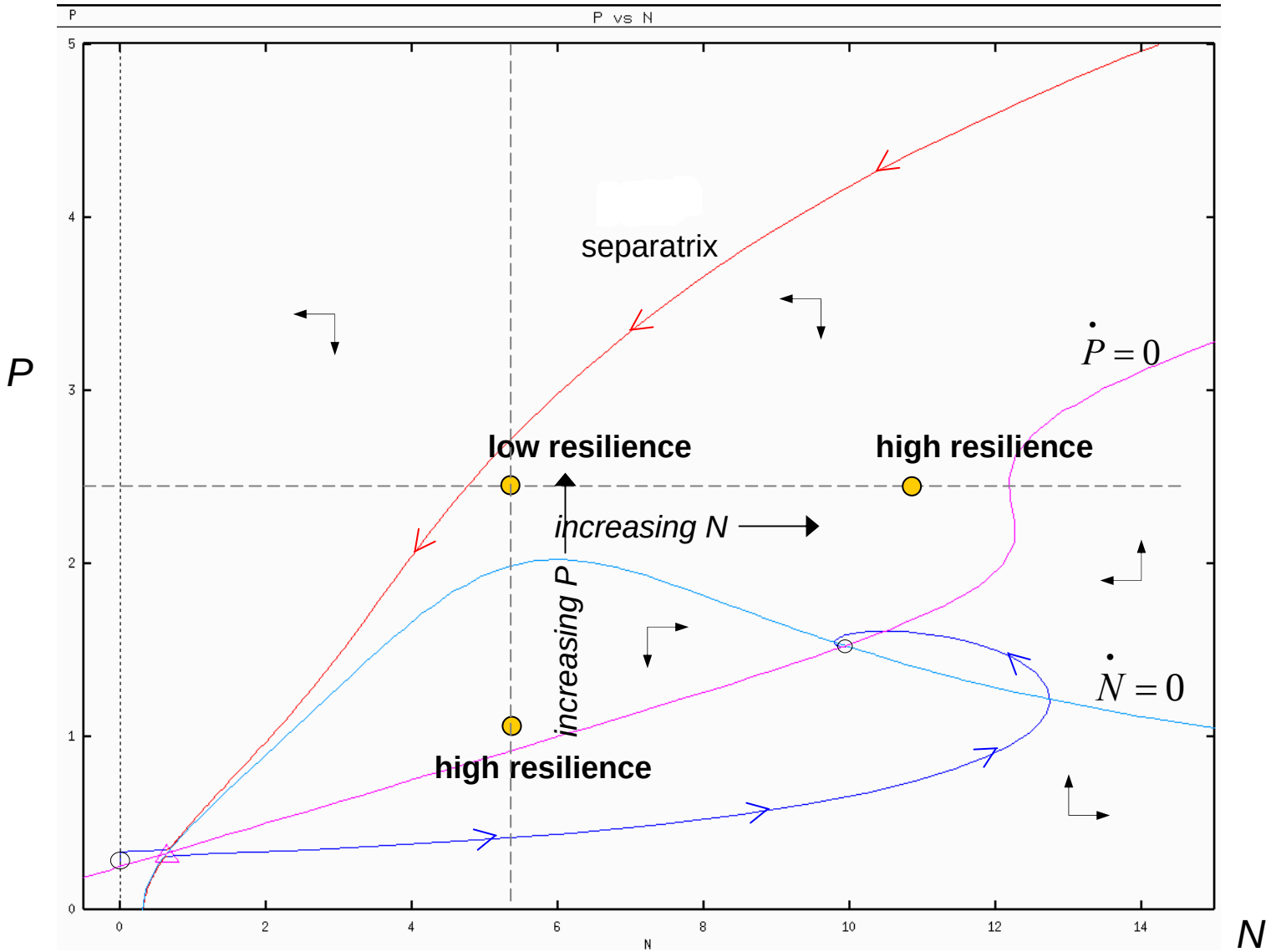
Time scale: P dynamics evolve over 1-2 years

Two dynamical variable model with cross-scale interactions

- Phosphorus dynamics (fast): $\dot{P} = \dot{P}(P, N; \theta_P)$
- Population dynamics (slow): $\dot{N} = \dot{N}(P, N; \theta_N)$

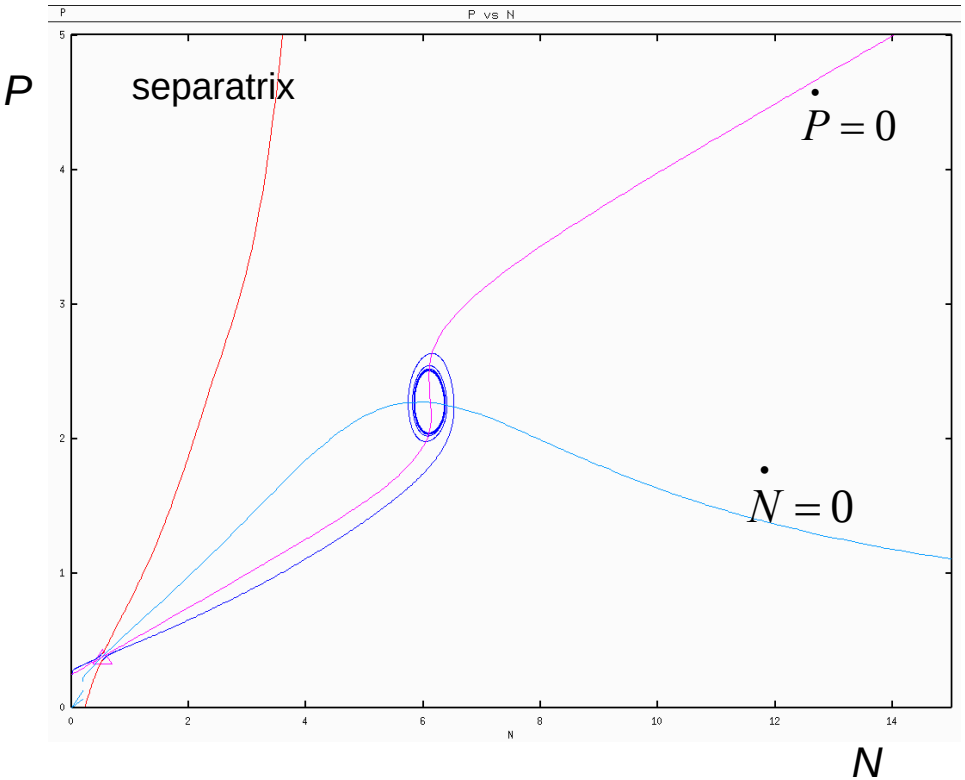
- Multiple time scales necessitate numerical-based approach vs. relying on analytical local stability analysis of fixed points
- We use phase plots and plots over time to investigate *N* and *P* dynamics for given parameters
- Software: Mathmatica, Matlab, XPP

Joint population and phosphorus dynamics

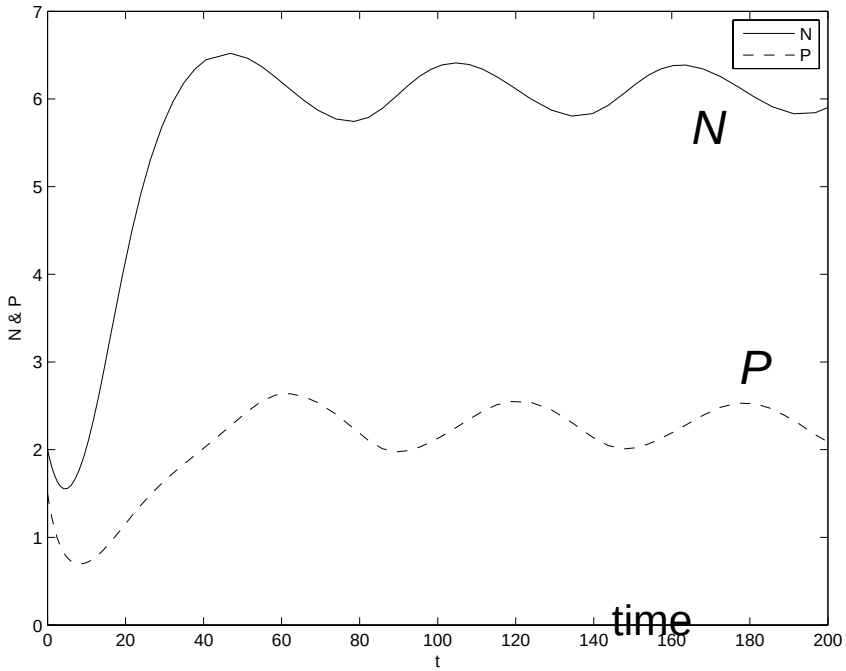


Key parameter: loadings coefficient

An increase in the loadings coefficient destabilizes the large-N fixed point and causes a stable limit cycle to emerge

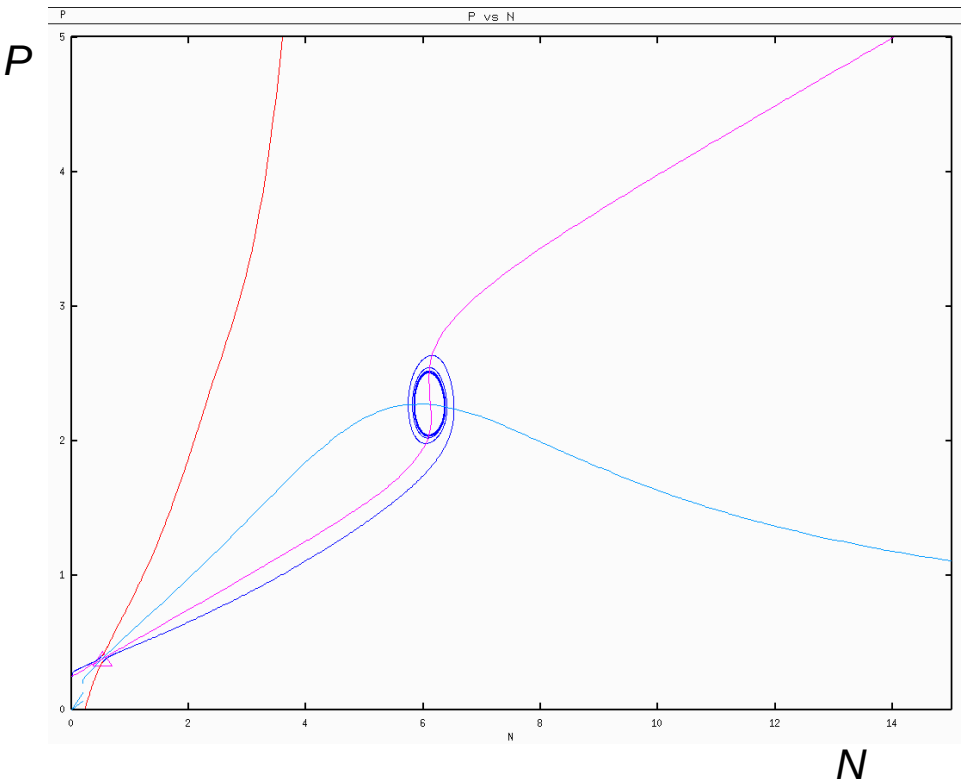


Phase plot with increase in L_1

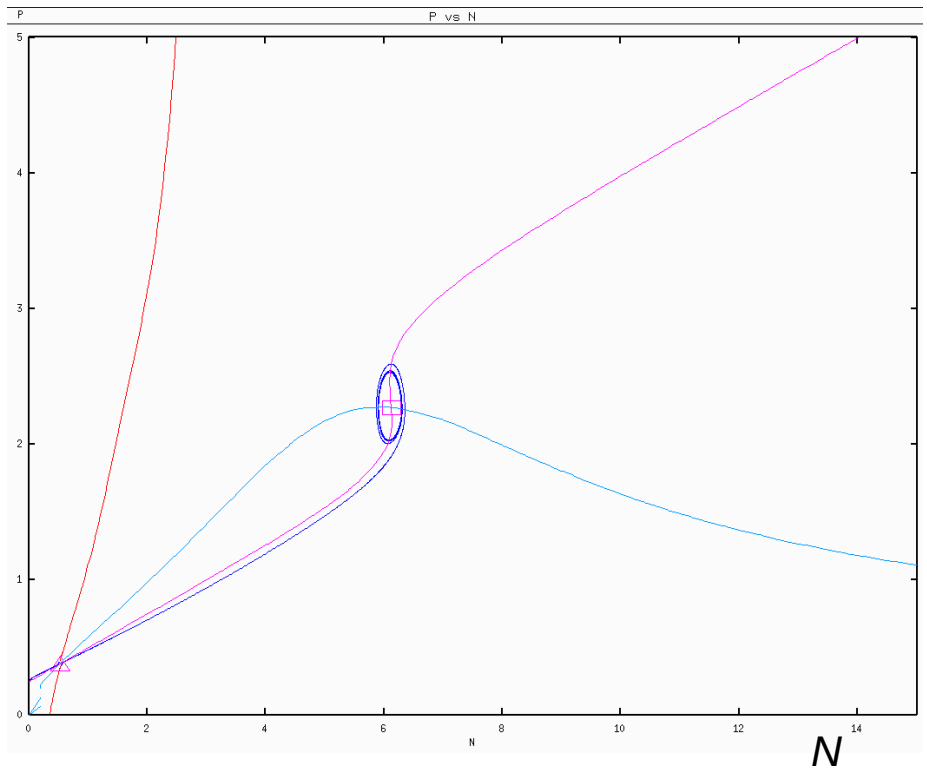


Time plot of N and P

Relative time scales of fast and slow processes: making slow variable slower

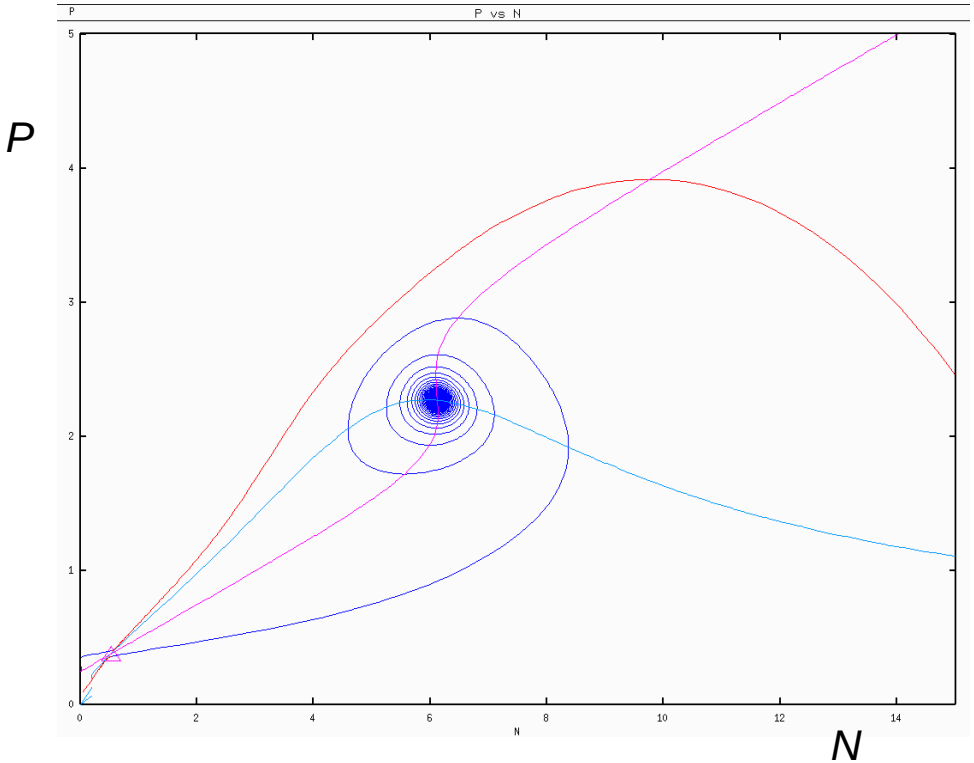


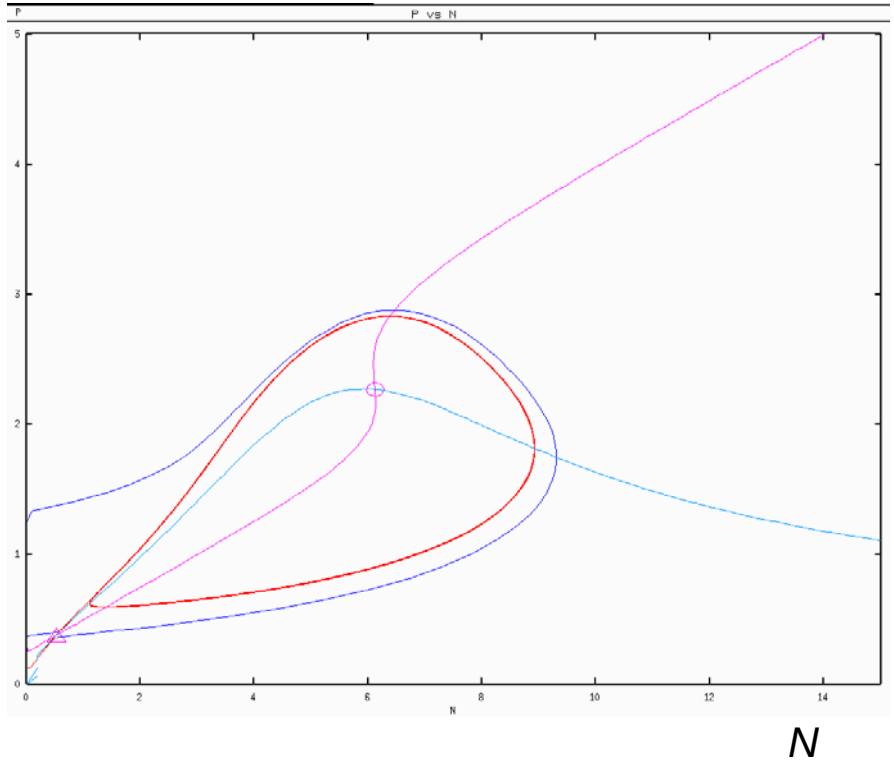
Baseline case: migration time scale = 10 years and L_1 is sufficiently strong to cause stable limit cycle; high resilience associated with this stable attractor



Migration time scale is <u>increased</u> to 20 years; oscillations are somewhat dampened; resilience remains unchanged

Relative time scales of fast and slow processes: making slow variable faster

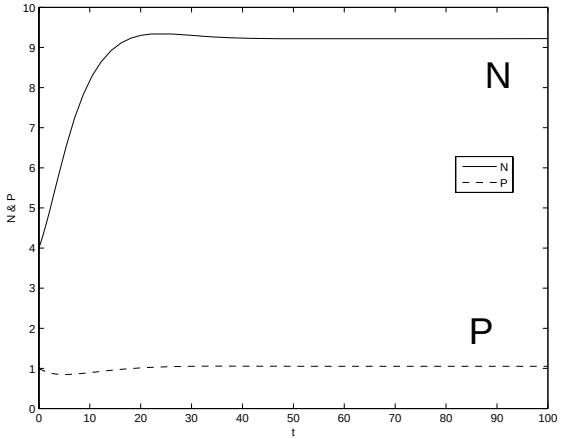




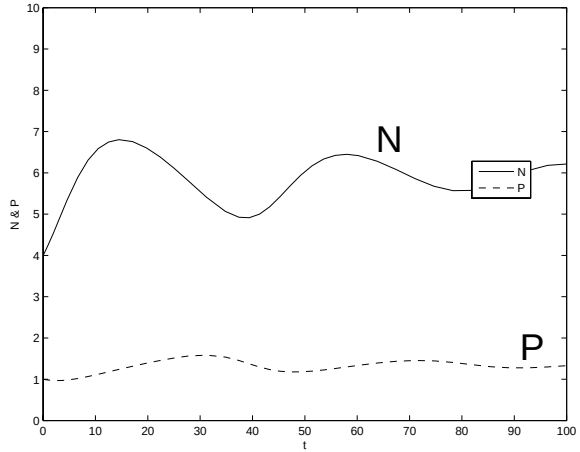
Migration time scale is <u>decreased</u> to 5 years; oscillations increase substantially; resilience declines

Migration time scale is <u>decreased</u> further to 1 year (approximately the same time scale as P dynamics); stable fixed point emerges, resilience is substantially reduced

The influence of a tax on dynamics and resilience



time



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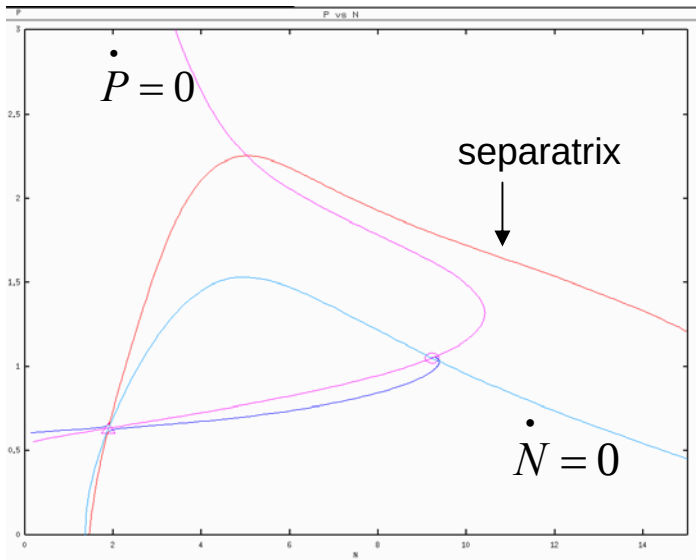
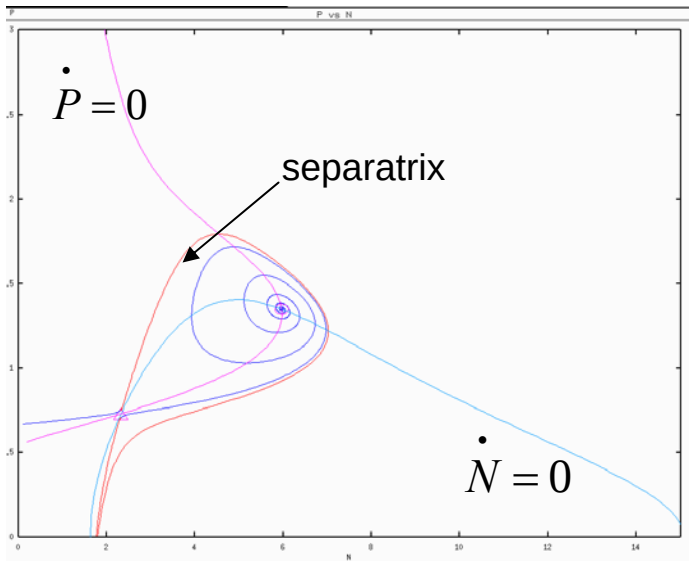
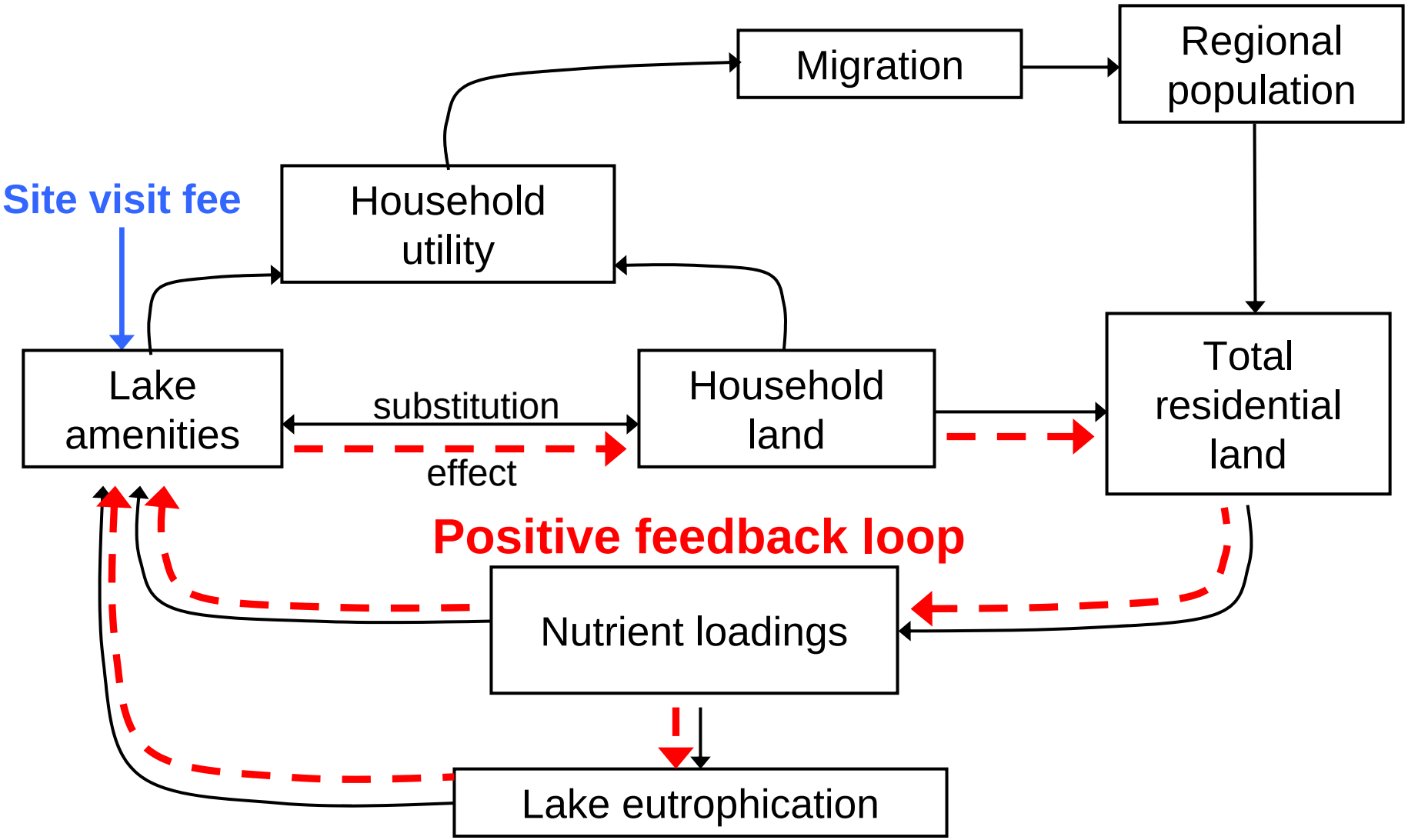




<u>Tax on land consumption</u>: eliminates oscillations, increases asymptotic N, and increases resilience of good state

<u>Tax on lake visits</u>: increases oscillations, reduces asymptotic N and reduces resilience associated with good state

Substitution effect and interactions create a policy "multiplier" effect

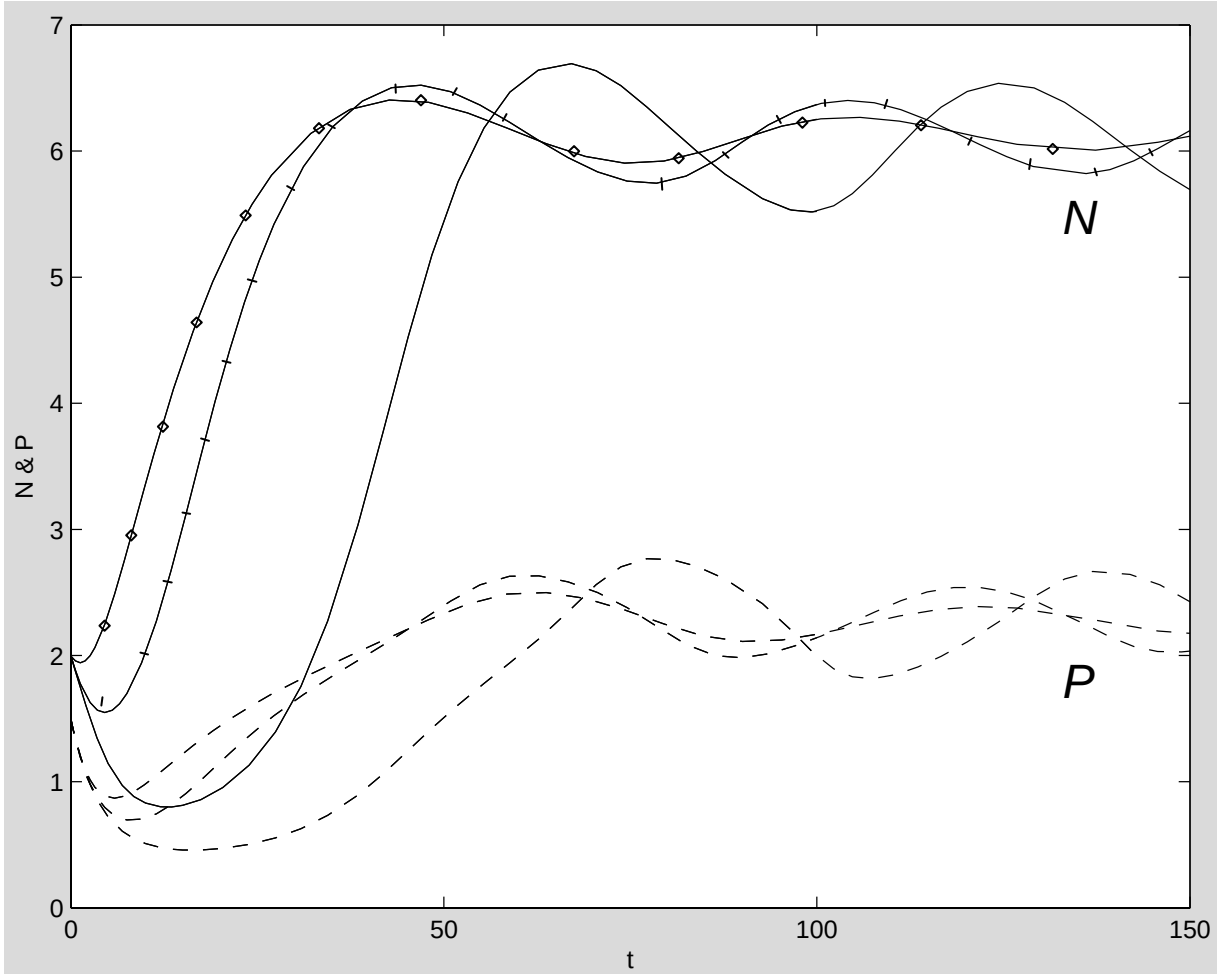


Memory vs. rational expectations

Perfect information about current P

Current P based on memory

Rational expectations over future P

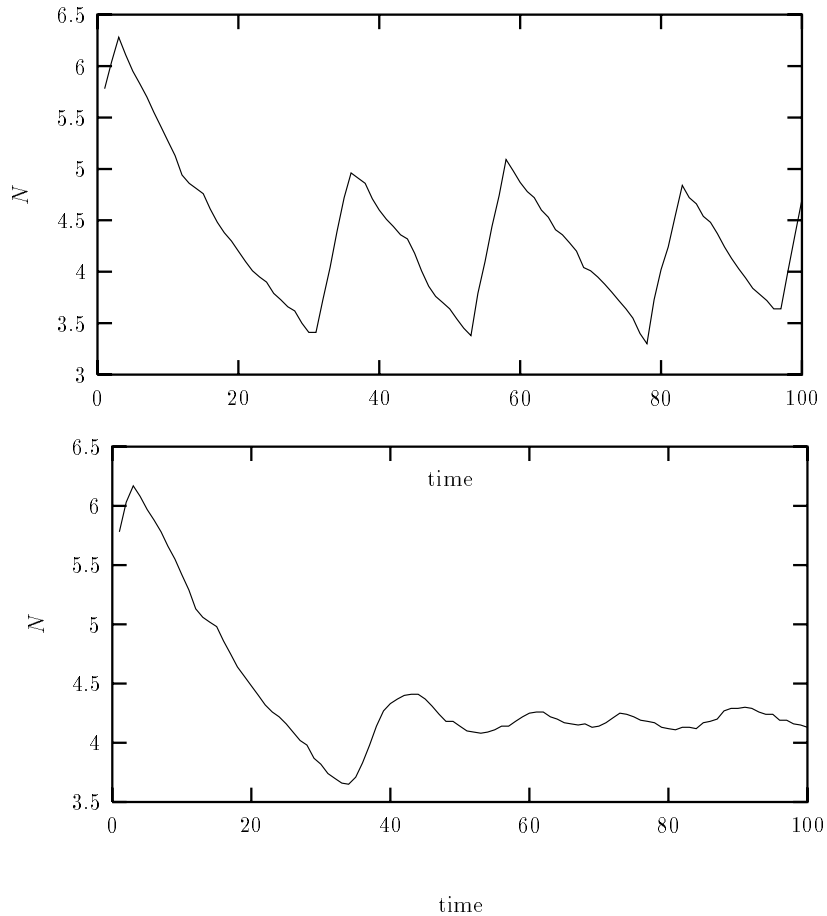


time

Accounting for agent heterogeneity

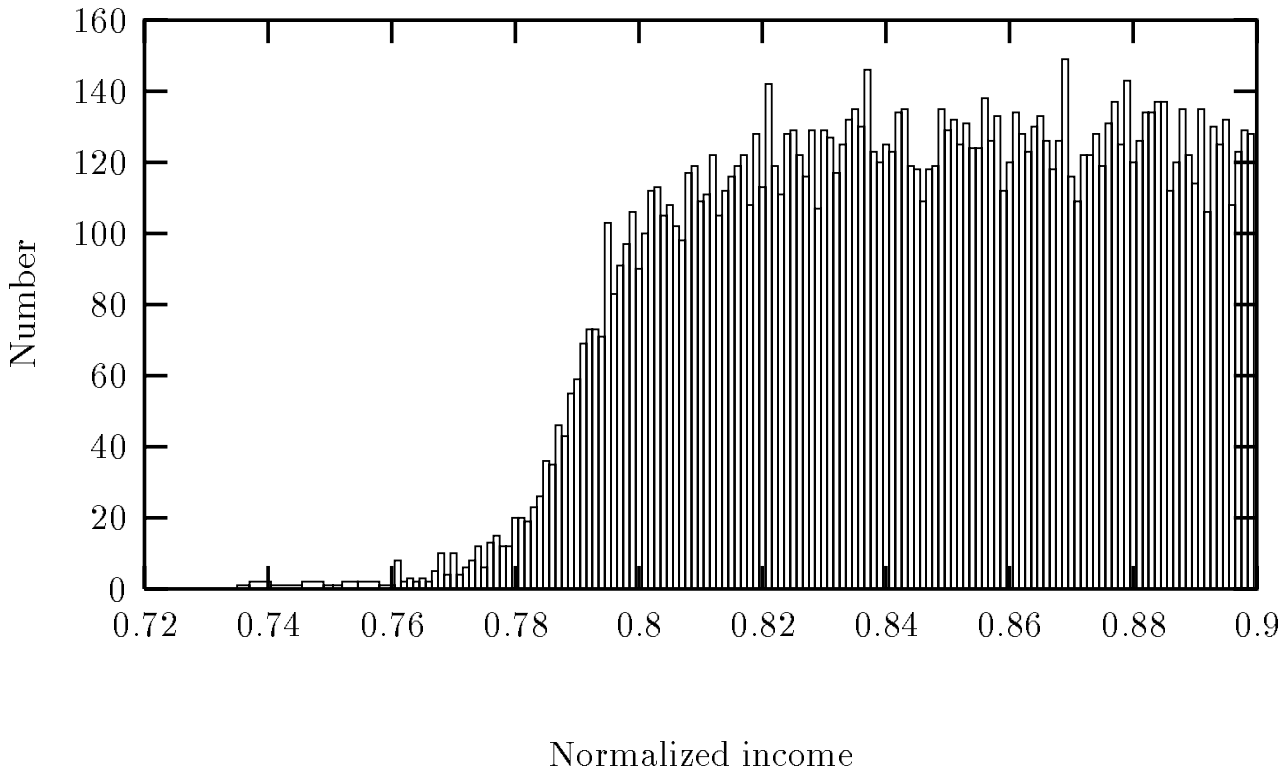
- Consider heterogeneous income or heterogeneous preferences over the relative trade-off between urban and natural amenities
- Simulate heterogeneous agent model by (1) deriving discrete time expression for population migration and (2) recalculating market-clearing conditions under assumptions of heterogeneity.
- Updating scheme: in each time period a fraction of agents are randomly selecting to move in or out of region.
- P dynamics are assumed to be the same
- Results:
  - Sufficient heterogeneity induces sorting
  - Agent heterogeneity doesn’t always matter; it matters most when system is near a threshold.
  - When system is near a threshold, heterogeneity can induce or avoid regime shift

Influence of agent heterogeneity



Preference heterogeneity offsets cyclical migration dynamics: homogeneous agents (top), 5% variation in preferences over urban amenities (bottom)

Influence of agent heterogeneity



Distribution of income in asymptotic state: only households in top 40% of income range stay; in homogeneous case, population goes to zero

Conclusion: Two-way ecological-economic interactions

- Results of decoupled economic and ecological models vs. coupled model are qualitatively very different → Interactions fundamentally change the short and long-term dynamics and system resilience

Conclusion: Cross-scale ecological-economic interactions

- Relative time scales of interacting variables are a critical determinant of system dynamics and resilience
- When is a single scale analysis appropriate?
  - when slow variable is sufficiently slow that it can be treated as a constant
  - results from the paper show that even a very slowly moving ecological variable qualitatively alters dynamics and resilience

Conclusion: Policy and ecological-economic interactions

- Interactions magnify the costs of getting the policy wrong
  - this argues for policies based on a precautionary principle
- Resilience is an important policy consideration
  - separatrix determines the resilience of the “good” state → necessitates analysis of full dynamics and not just fixed points

Conclusions: Agent heterogeneity

- When system is near a threshold, representative agent model is insufficient to predict the system dynamics
- Prevalence of threshold effects and regime shifts in many ecosystems suggests that agent heterogeneity is an important consideration in ecological-economic models

Conclusions: Memory and expectations

- Rational expectations dampen oscillations and offset population overshoots, but assumption of rational expectations is extreme given uncertainty of ecological change
- Simple averaging over the past can magnify oscillations and make population overshoots more likely
- Suggests that expectations based on memory can destabilize system

So What?

Models will never replicate reality or predict the future with any certainty

However, models can

- Clarify when and under what conditions particular features of the system are important
- Provide useful quantitative analysis of complex dynamics, e.g., by sorting out the effects of offsetting effects on system dynamics
- Identify a range of possible future outcomes
- Illustrate policy scenarios

For these reasons, models that identify critical features and how they influence system dynamics are useful for policy

- More work is needed to identify these critical features, possible dynamics and to illustrate policy scenarios

Future directions: policy and modeling

- Policy effects and implications
  - More thorough investigation of interactions and policy multiplier effect
  - Formal model of regional economic transition
  - Consideration of a broader set of policies, including regional development policies, lake protection policies and spatially explicit growth management policies
- This requires a more comprehensive, spatially explicit model

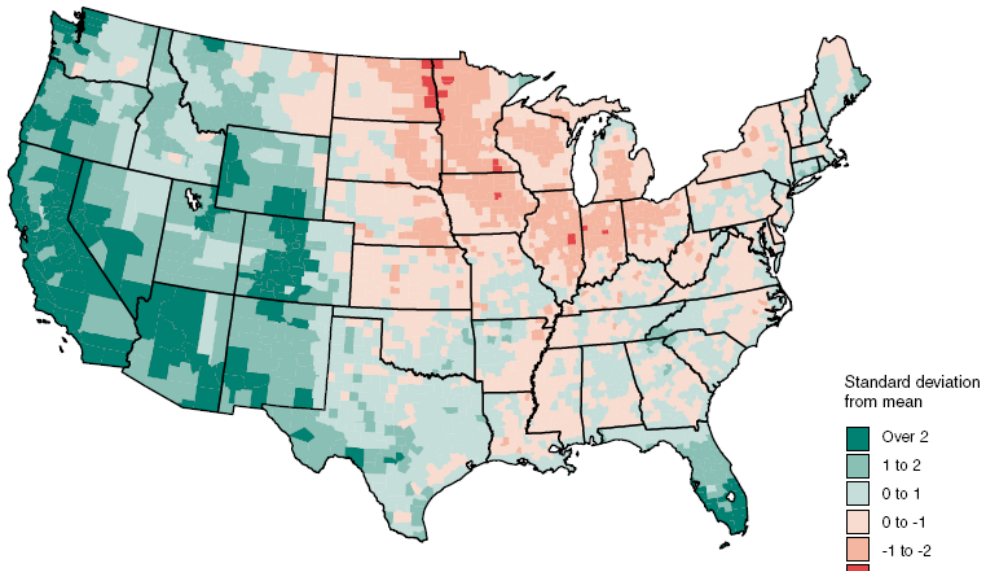
Future directions: modeling

- Spatially explicit model with heterogeneous agents → necessitates a full agent-based approach
  - Spatially explicit residential location, recreational sites, nutrient loadings
  - Heterogeneous expectations
  - Agent interactions, e.g., word-of-mouth influence memory, expectations, recreational choice
- More realistic representation of lake dynamics
  - Consideration of discrete events, e.g., algal blooms, fish kills, and how this influences memory and expectations
- Specification of model parameters using data from large lake regions, including the Lake Erie recreational region

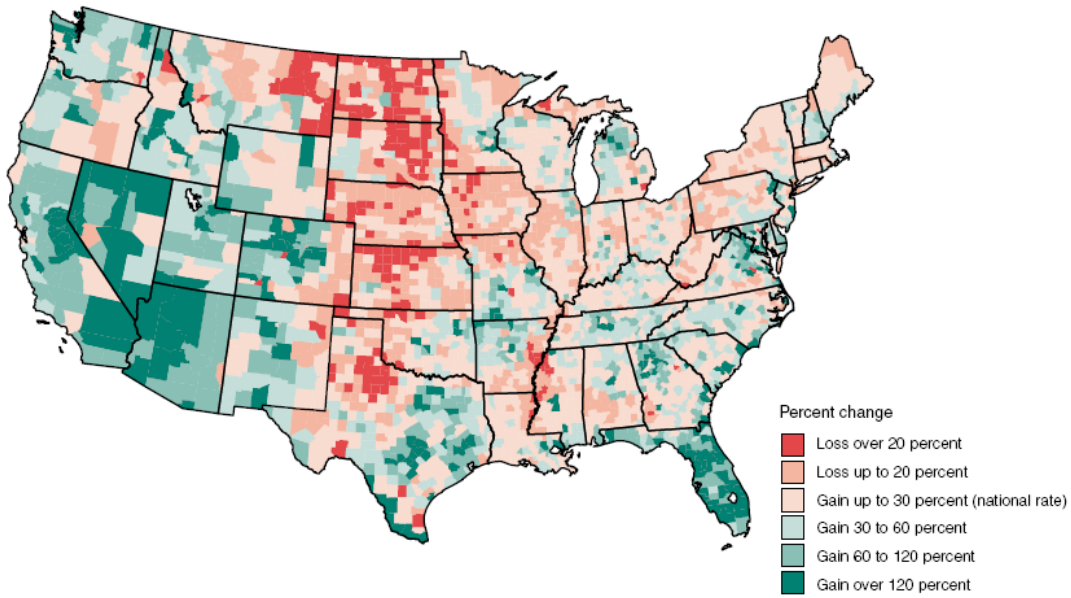
Population change and natural amenities

(McGranahan, 1999, Economic Research Service, USDA)

Natural Amenity Scale, 1970-1996

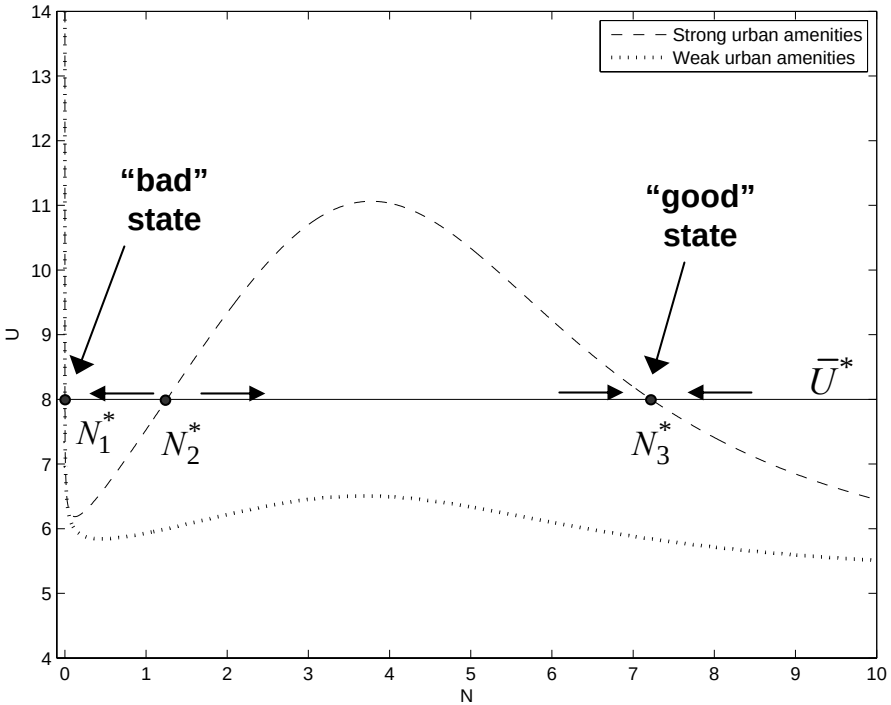


US County Population Change, 1970-1990

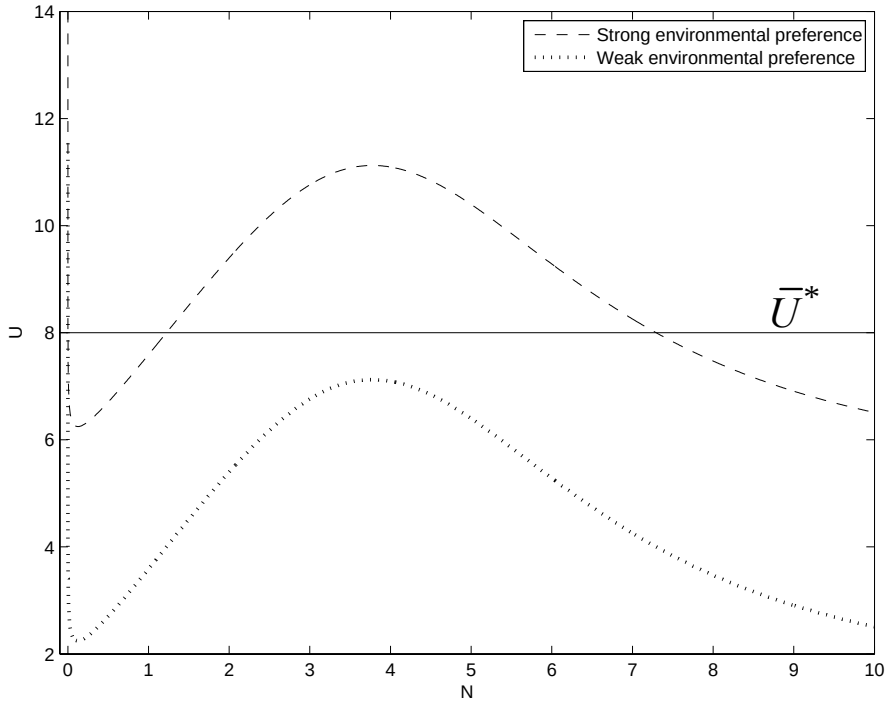


The role of urban and natural amenities

Maximized utility as a function of population



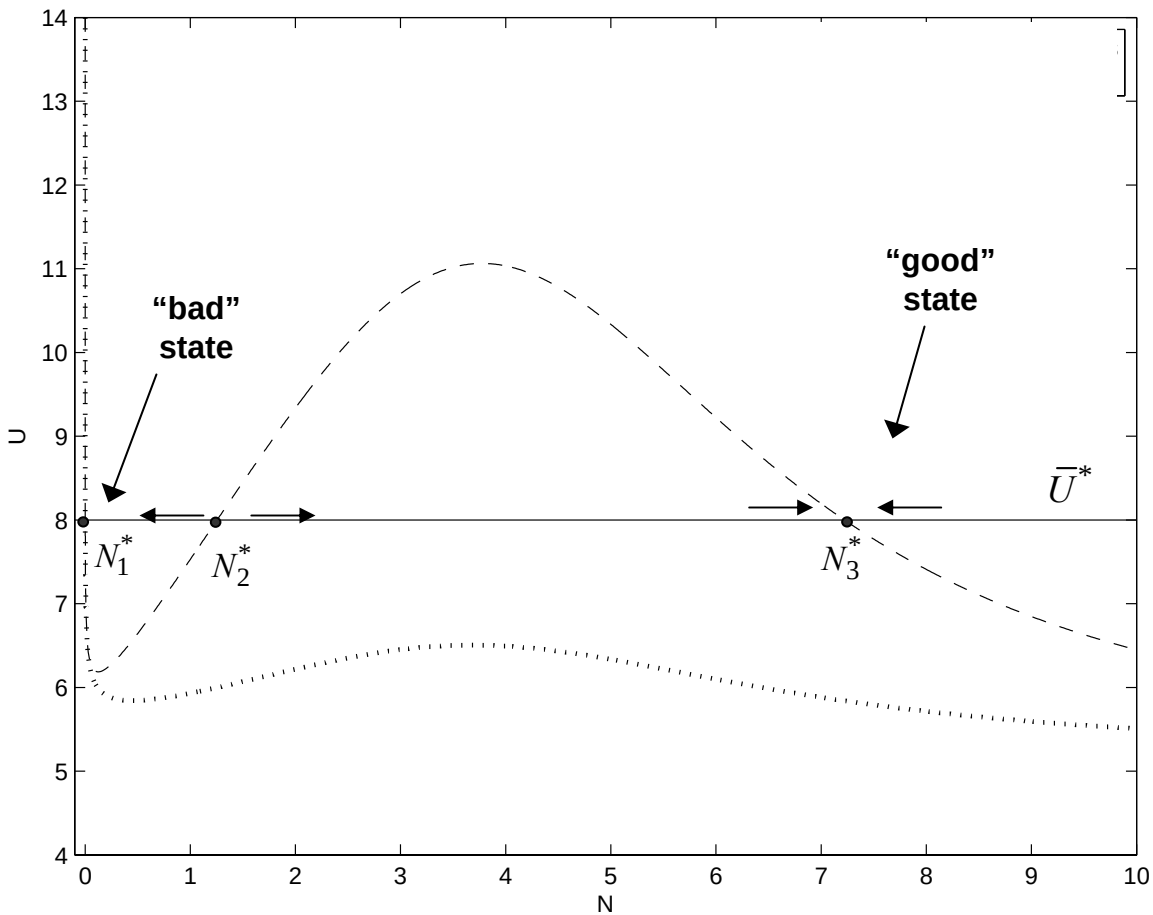
Strong and weak urban amenities for a given and constant level of natural amenities



Strong and weak natural amenity preferences for a constant level of urban amenities

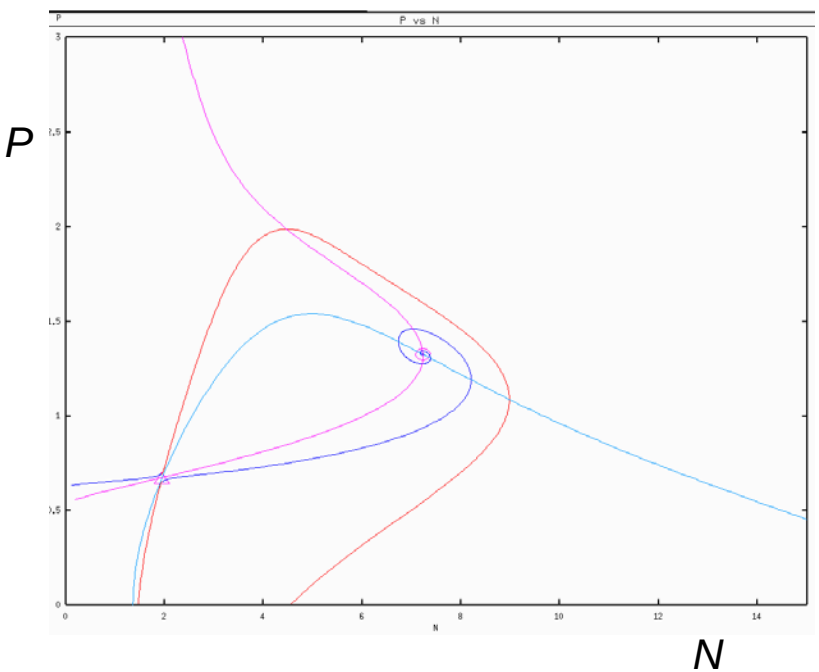
Population dynamics

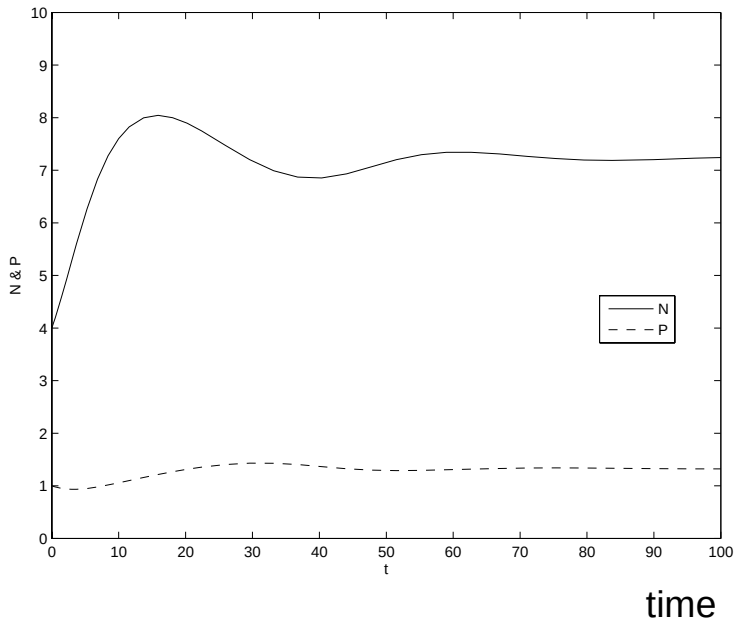
Maximized utility as a function of population



Policy and interaction effects

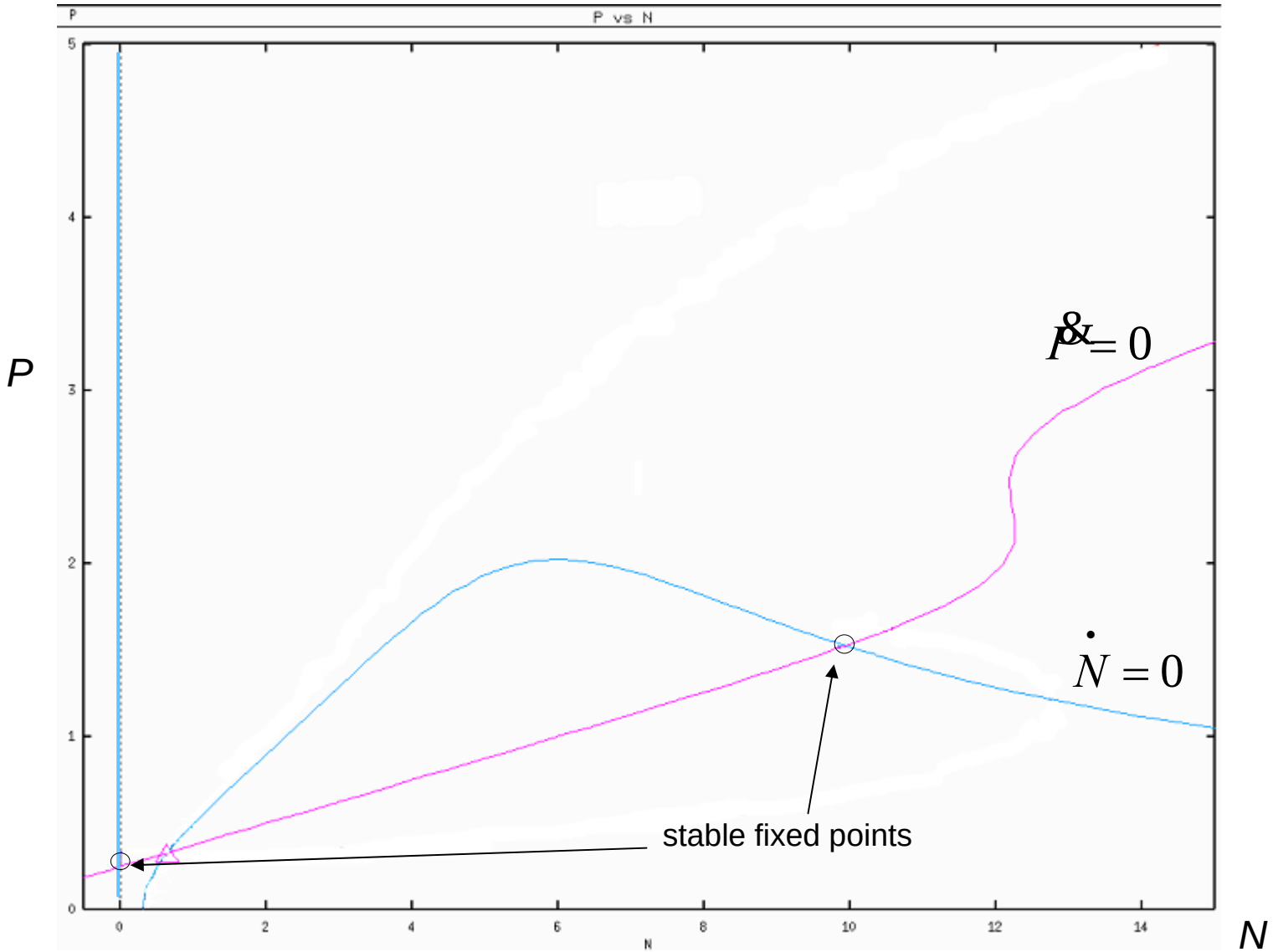
- Reformulate *e(q)* so the *e* is lake recreational visits and *q* is ecosystem services; households pay a per visit site fee.
- Compare effects of a tax on lake visits vs. a tax on residential land



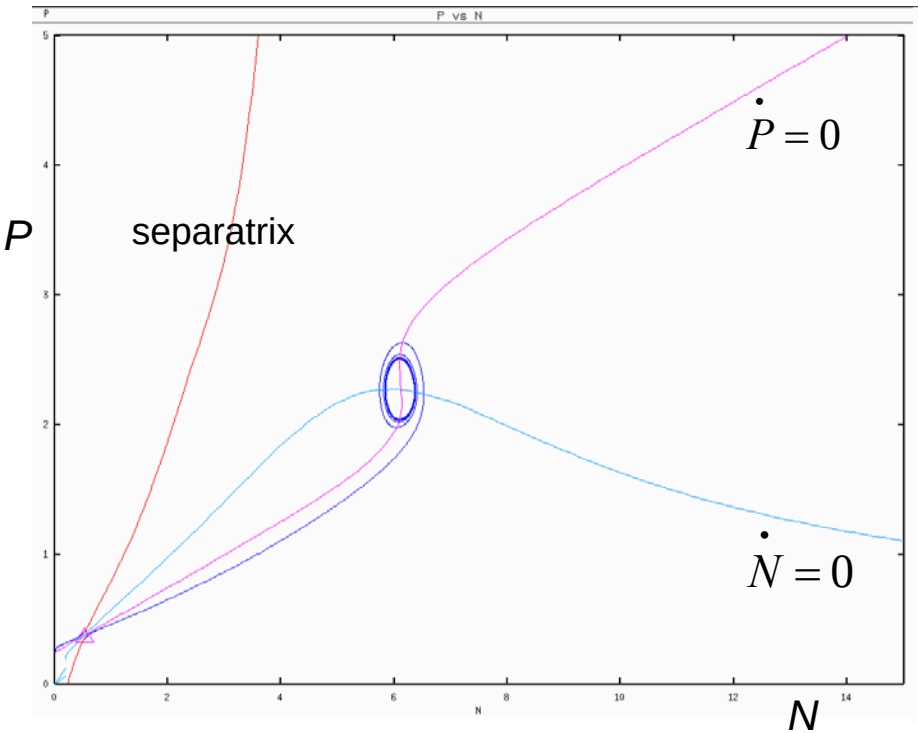


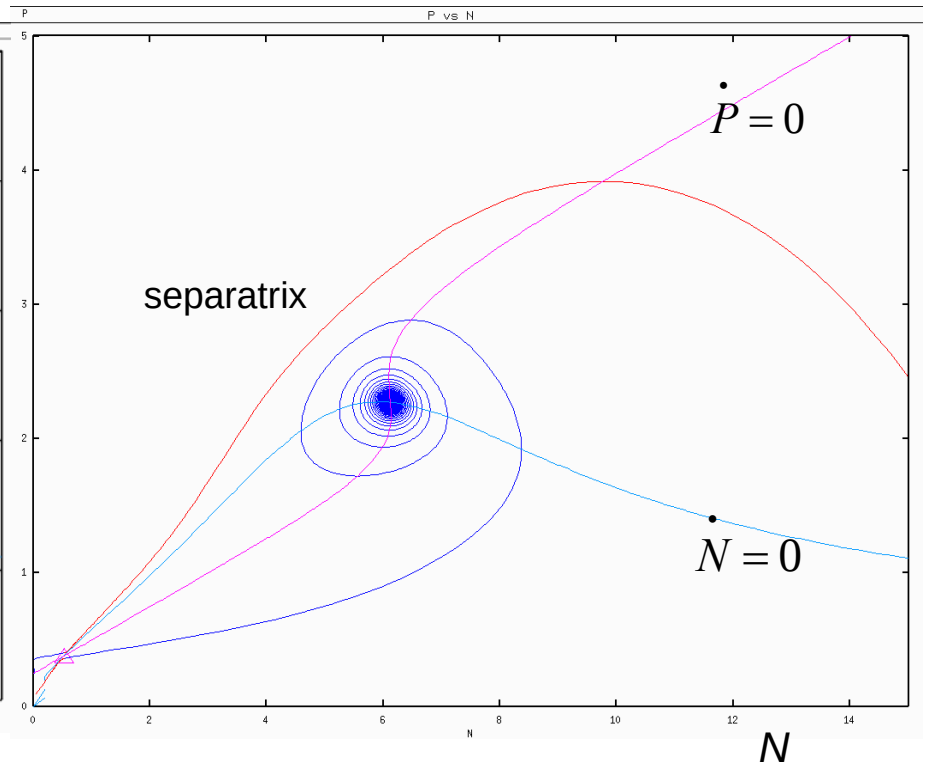
<u>Baseline case</u>: no tax on land, moderate fee assessed for lake visits; system oscillates and then settles down to stable fixed point

Joint population and phosphorus dynamics



Relative time scales of fast and slow processes: making slow variable faster





Baseline case: 10 year migration time scale; moderate oscillations and relative high resilience

Migration time scale is <u>decreased</u> to 5 years; oscillations increase substantially; much lower resilience