Agent-Based Modeling of Land-Use Change

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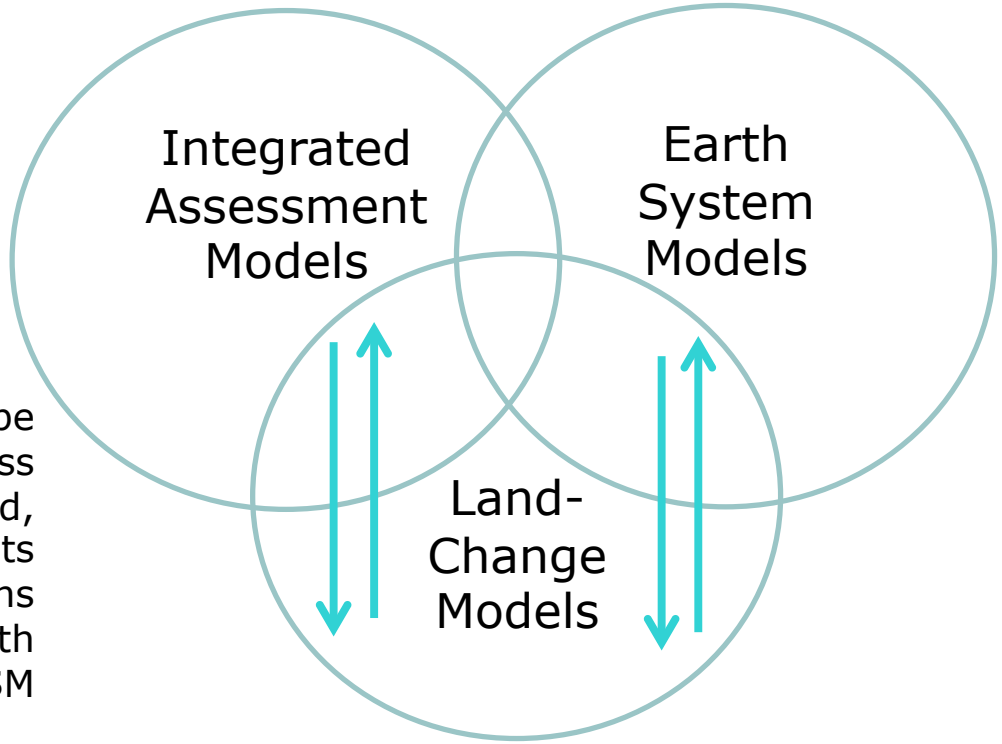
Land Use in Carbon Modeling



Global scope
Economic Process
Trade, Demand, Representative Agents
15-150 regions
Weak Integration with ESM

Global scope
Natural land process (DGVM)
No human decision making
Spatially explicit
Weak Integration with IAM

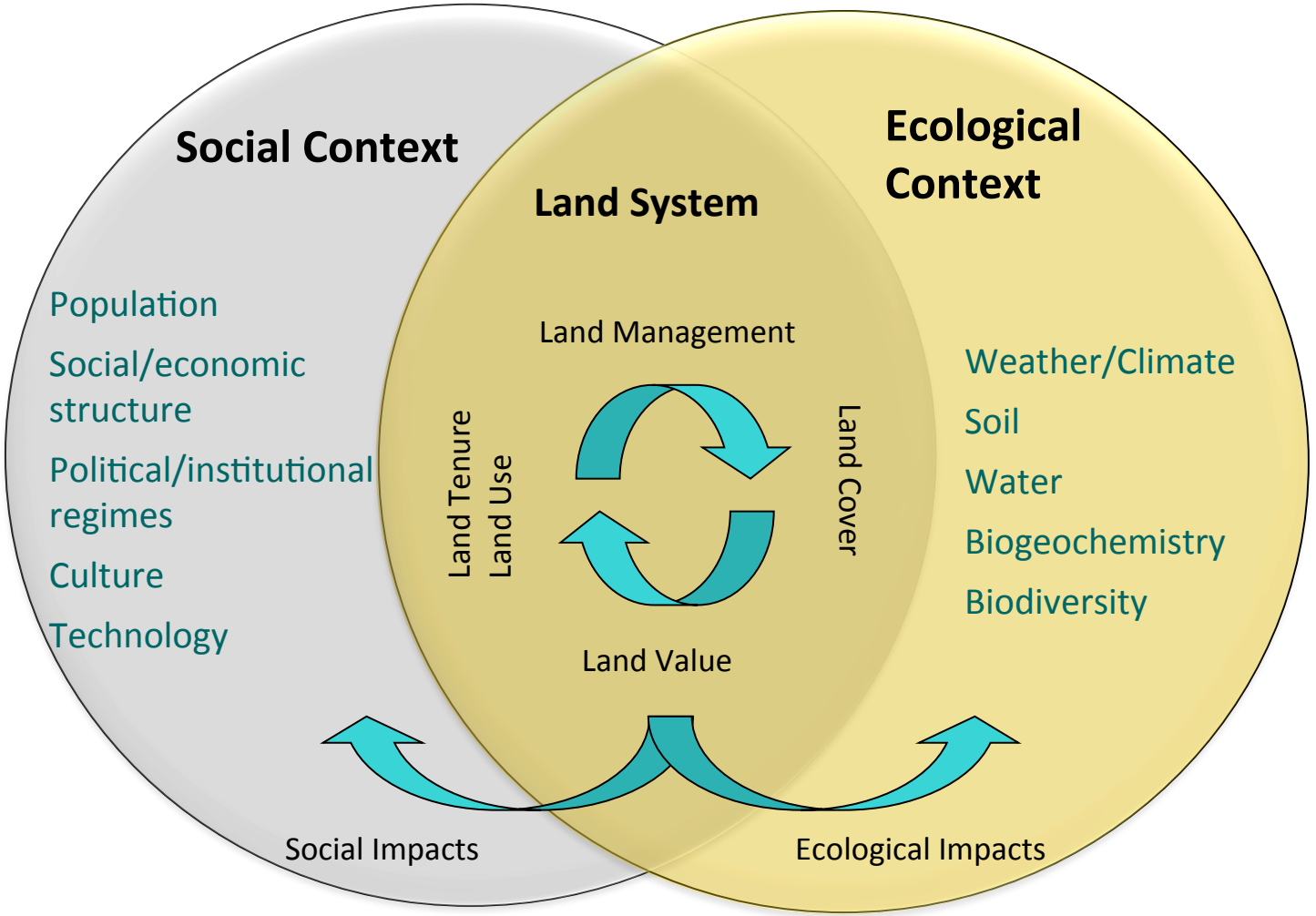
Local/Regional scope
Little Integration with global models
Integration with spatial/regional ESM
Can include heterogeneous, interacting agents
Spatially detailed
Can include representation of institutions

Why Land-Change Modeling?

Need for process-level understanding to answer key questions.

- Attribution question
  - What land-use processes and drivers produce how much emissions and sequestration?
- Carbon supply curve
  - How much carbon storage is available at what price?
- Impact, vulnerability, adaptation
  - How do or can land processes interact with climate change to exacerbate or ameliorate climate impacts?
- Effectiveness of mitigation program/policies
  - How well do REDD+ and market mechanisms deliver carbon mitigation?

Land Systems



Spatial Land-Change Models

- Encode our knowledge of process
  - Integrate findings across case studies
- Help test pattern-process links
  - Can help us examine feedbacks between ecosystem structure/function and human actions
- Provide dynamic and spatially explicit information for input to ecosystem process models
- Test alternative futures under various hypotheses, policies, practices, and incentives
- Make projections of future landscape patterns

Dimensions of Land-Change Models

Key

A-Time series statistical models, STELLA models with no human dimension

B- Time-series models with human decision-making explicitly modeled

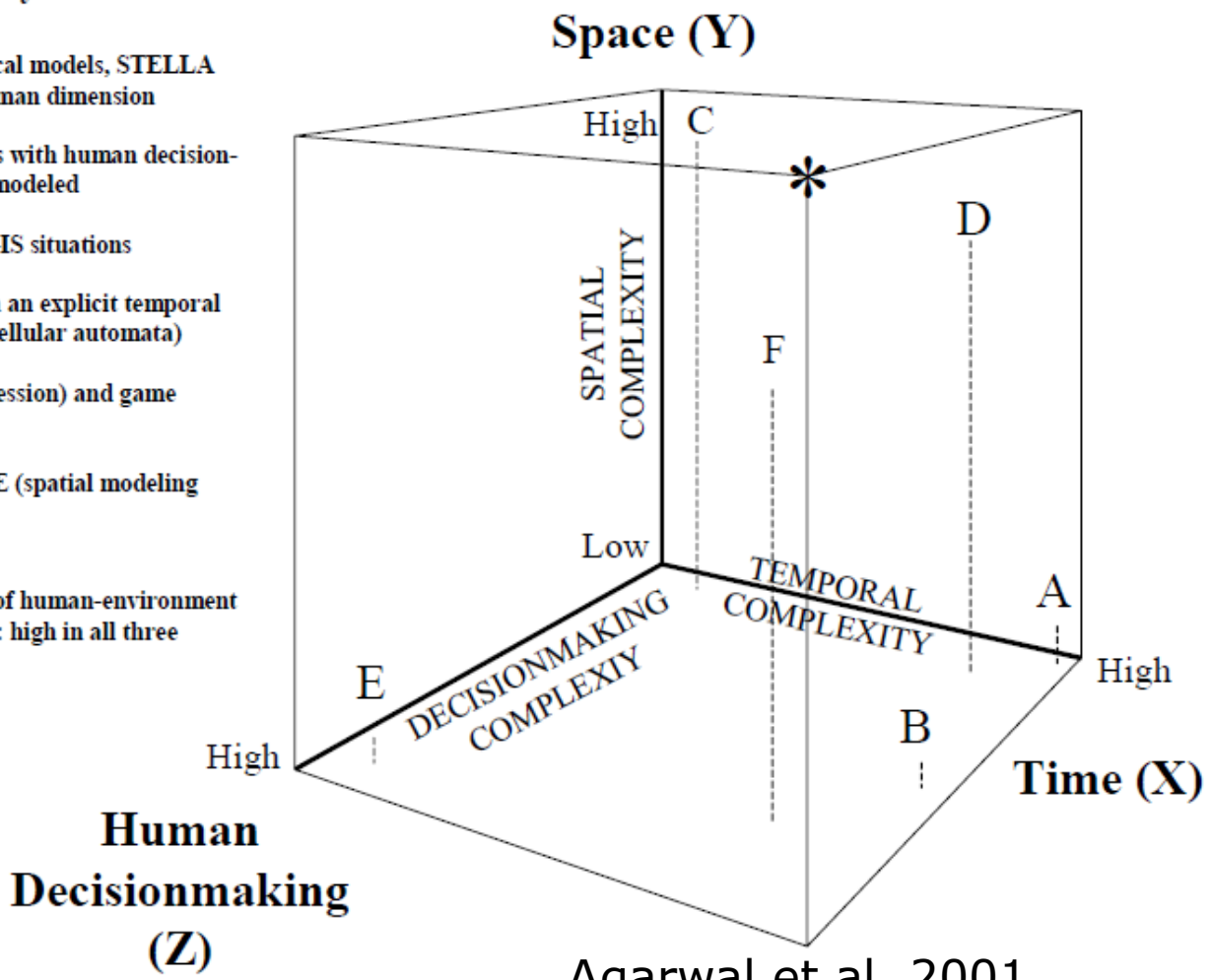
C- Most traditional GIS situations

D- GIS modeling with an explicit temporal component (e.g., cellular automata)

E- Econometric (regression) and game theoretic models

F- SWARM and SME (spatial modeling environment)

*** The ultimate goal of human-environment dynamic modeling: high in all three dimensions**



Agarwal et al. 2001

Representing Decision Making

- Various decision-making strategies
  - Rational actors, Bounded rationality, Satisficing
- Heterogeneity – not all people are alike (e.g., risk tolerance)
- Adaptability – people respond to changing contexts
- Interaction – people learn from each other
- Time and space scales – multiple processes acting at multiple scales
- Stochasticity – we don’t know everything deterministically

Agent-Based Modeling

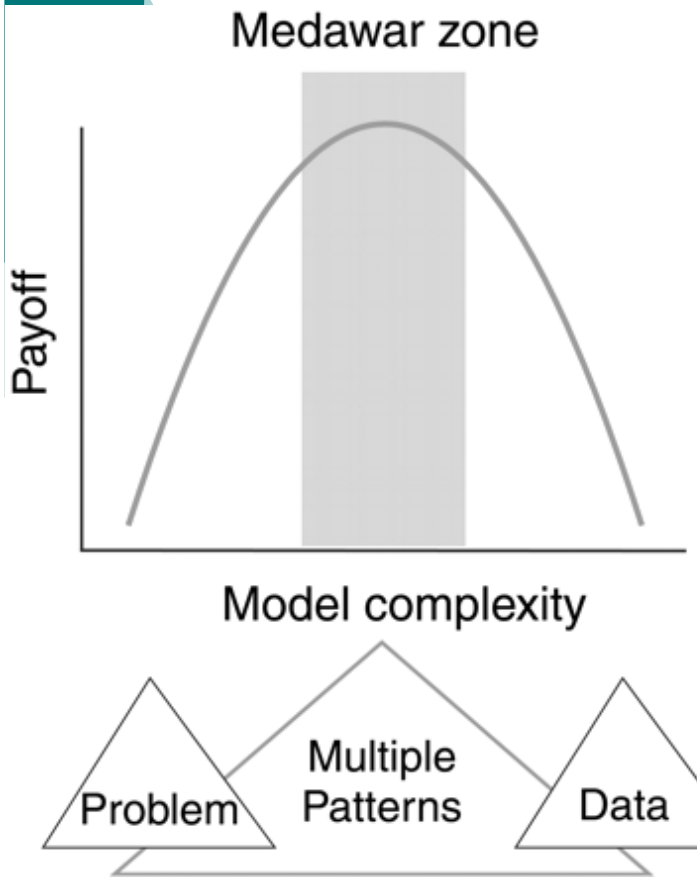
- Uses object-oriented programming …
- to represent and simulate the attributes, decisions, and behaviors of multiple interacting actors…
- and their collective impacts on landscape condition and pattern.

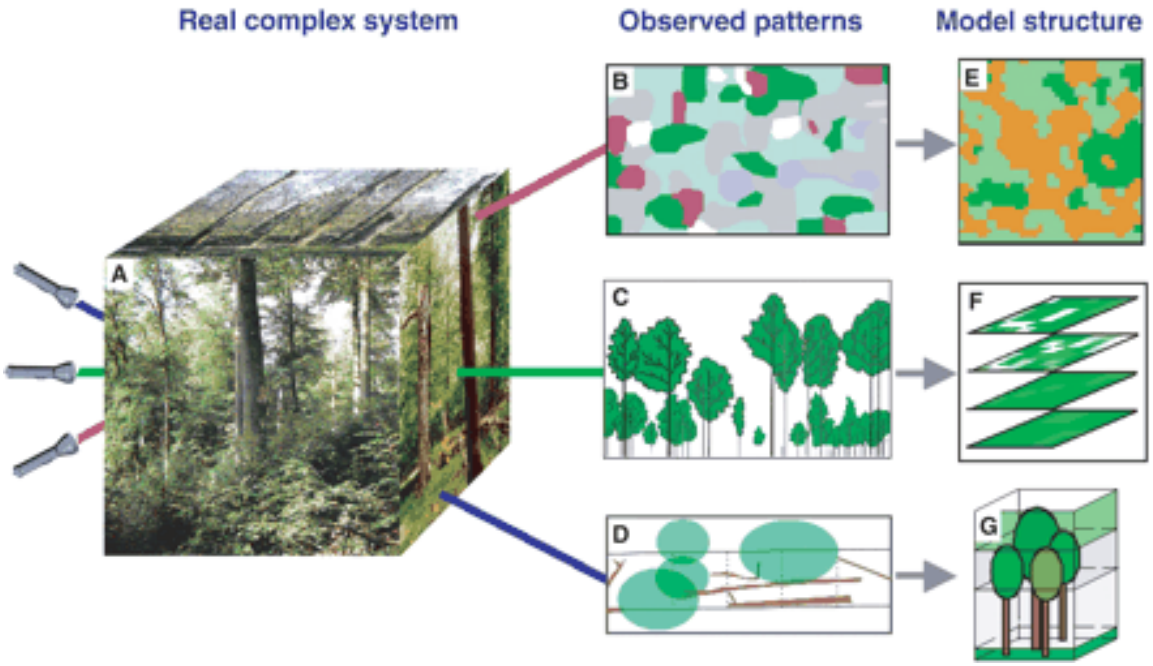
- We apply this tool through iteration with data collection, and starting with simple models
- Micro-processes, macro-patterns

Experimental Approach

- Develop conceptual model of system
  - This is effectively a hypothesis about how a particular outcome (e.g., spatial or temporal pattern) comes about.
- Encode that model in software
  - Collect empirical observations to support qualitative and quantitative decisions as much as possible.
- Vary some aspect of the model
  - Relevant to some question about system sensitivity
- Measure outcomes of interest and assess differences across varied aspects of the model relative to hypotheses
  - Could be spatial or temporal patterns of interest

Pattern-Oriented Modeling





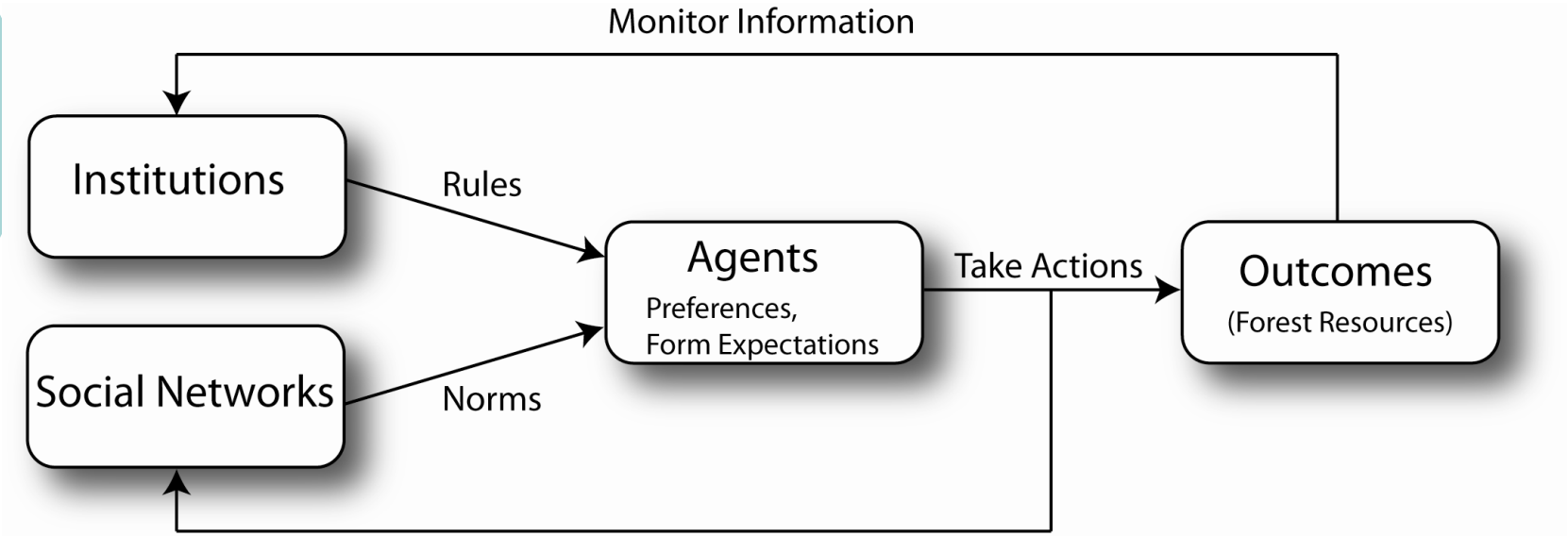
Grimm et al. 2005

Example 1: Research Question

- How are resource behaviors and outcomes affected by governance rules imposed by formal institutions and network norms as generated through informal social interactions?

Agrawal et al. (In Revision)

Rural Forest Resource Use in India



Agents decide how much of the resource to use based on:

a. preference for following rules or their neighbors
b. the payoff from consumption
c. a payoff from not working too hard to consume (i.e., leisure)

Some model parameters calibrated with data from forest users in India

Computational Experiments

Evaluate how resource outcomes in the model varied with

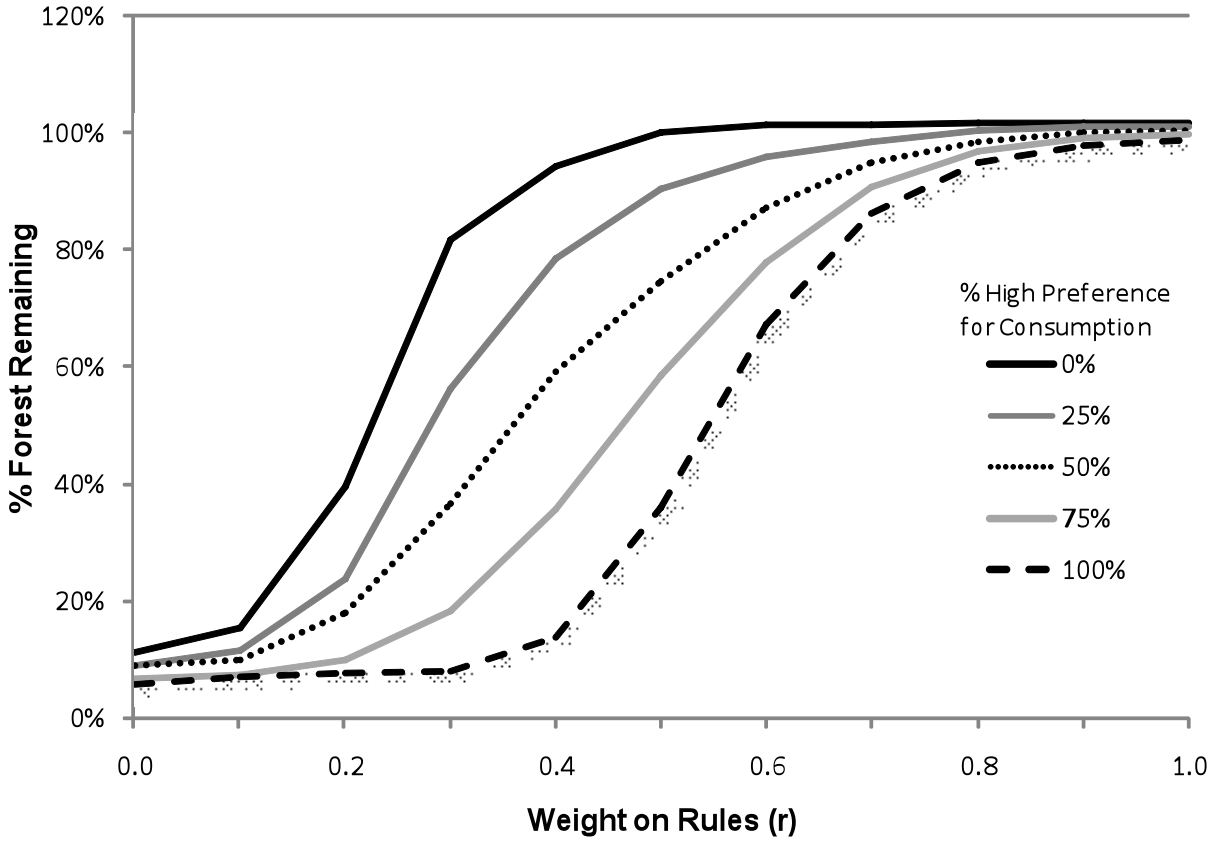
1. Importance of rules versus norms
2. Proportion of pop. with high preference for consumption
3. Social network structure
4. Proportion of pop. with high preference for adherence to rules

Results

- **Experiments: Weight on rules versus norms & Agents with high preference for consumption.**
  - Resource remaining increases non-linearly with greater weight on the preference to adhere to institutional rules; Evidence of non-linear response to level of rule adherence
  - Increasing proportion of agents with high preference for consumption requires higher level of adherence to rules before improvement in forest resources.

Results

Experiments 1 & 2

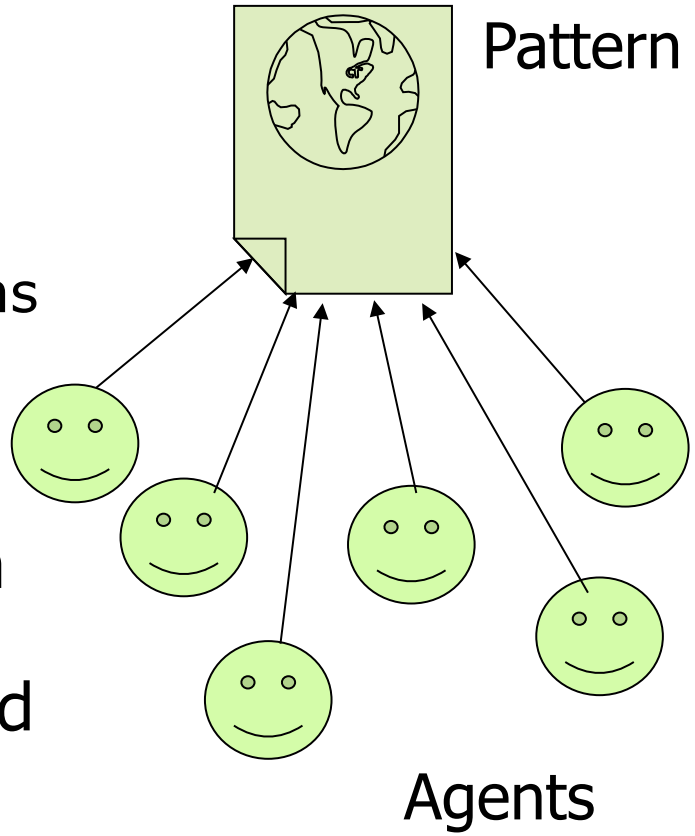


Lessons from India Example

- We learn that elements missing from models with aggregate populations matter in determining land-use outcomes:
  - Interactions between formal and informal institutions in affecting behavior
  - Diversity in preferences of agents
  - Structure of interactions
  - Feedbacks between outcomes and agent behavior (e.g., imitation)

Empirical Data in ABMs

- Agent actions aggregate to produce patterns.
- Goal:
  - Data on agents support building the model.
  - Data on aggregate patterns can then be reserved for validation.
- Contrasts with approaches that perform calibration within the model based on observed patterns.

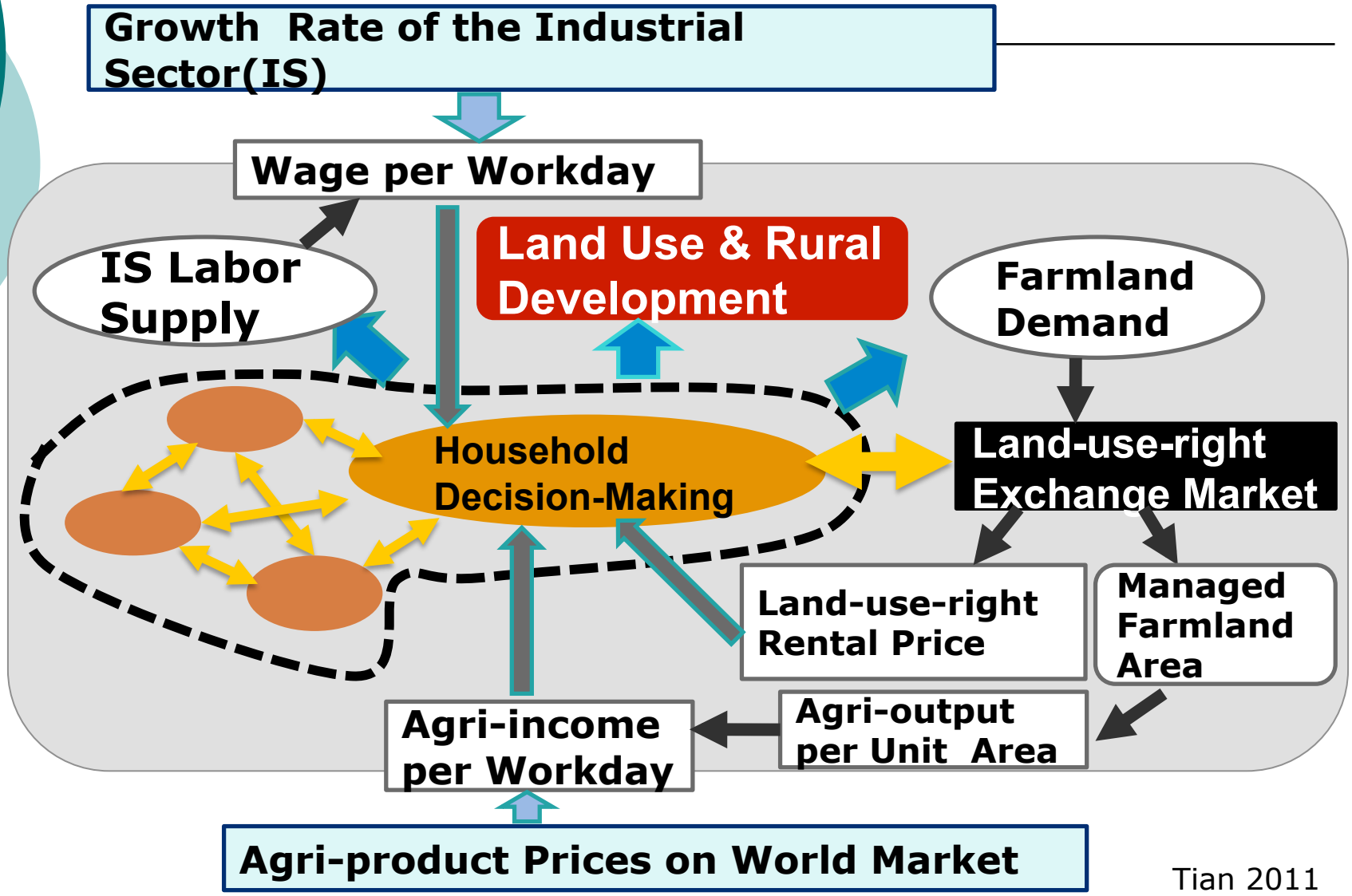


Empirical Support of Agents

- Social surveys
- Participant observation
- Field/lab experiments
- Companion (participatory) modeling
- Spatial/statistical inference

Robinson et al. 2007. *Journal of Land Use Science.*

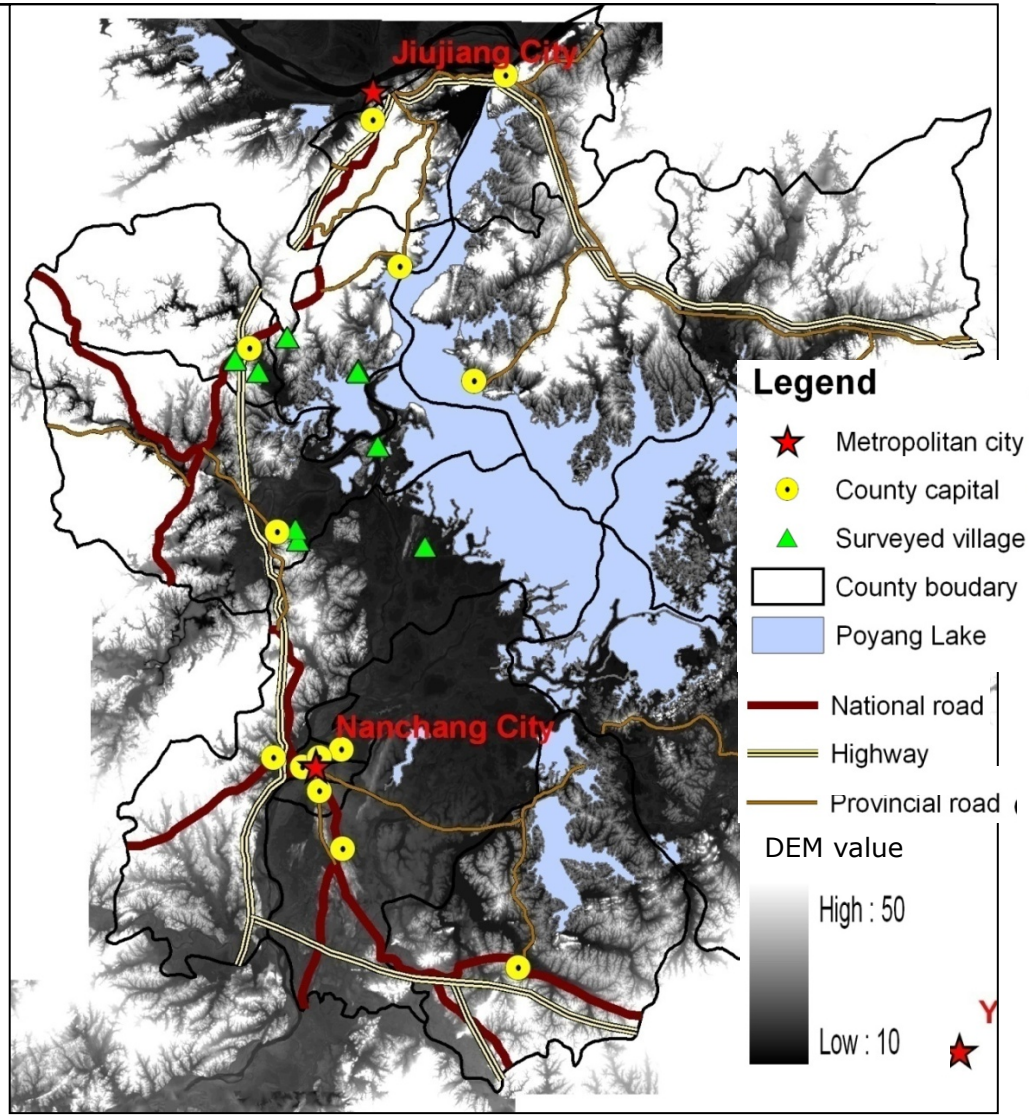
Example 2: Agricultural land change in China



Tian 2011

Empirical support

- Eight villages selected from west side of lake
- Stratified by (a) exposure to flooding and (b) distance from towns.
- Survey and interviews conducted Feb 2007-June 2008.



Experiment: Effect of land scarcity

Village	Farmland Resources	Scenario	Cultivation Rate	Pct. Off-farm Income	Avg. Income	Pct. Labor on Migration Work
V1	Poor (small area, fragmented & low fertility)	Current	64.9%	96.5%	22300YUAN	92.9%
		Hypo-scenario	166.4	90.7	22900	89.6
V2	Average	Current	94.6	84.3	22200	75.5
		Hypo-scenario	264.4	59.8	25800	60.8
V3	Good (large Area & fertile)	Current	98.3	51.9	26100	49.9
		Hypo-scenario	233.8	16.7	36100	20.5

Note: Compare the choices of households with their optimal choices in an idealistic scenario in which they can acquire whatever amount of farmland they intend to manage at no cost.

Poyang Experiment Results

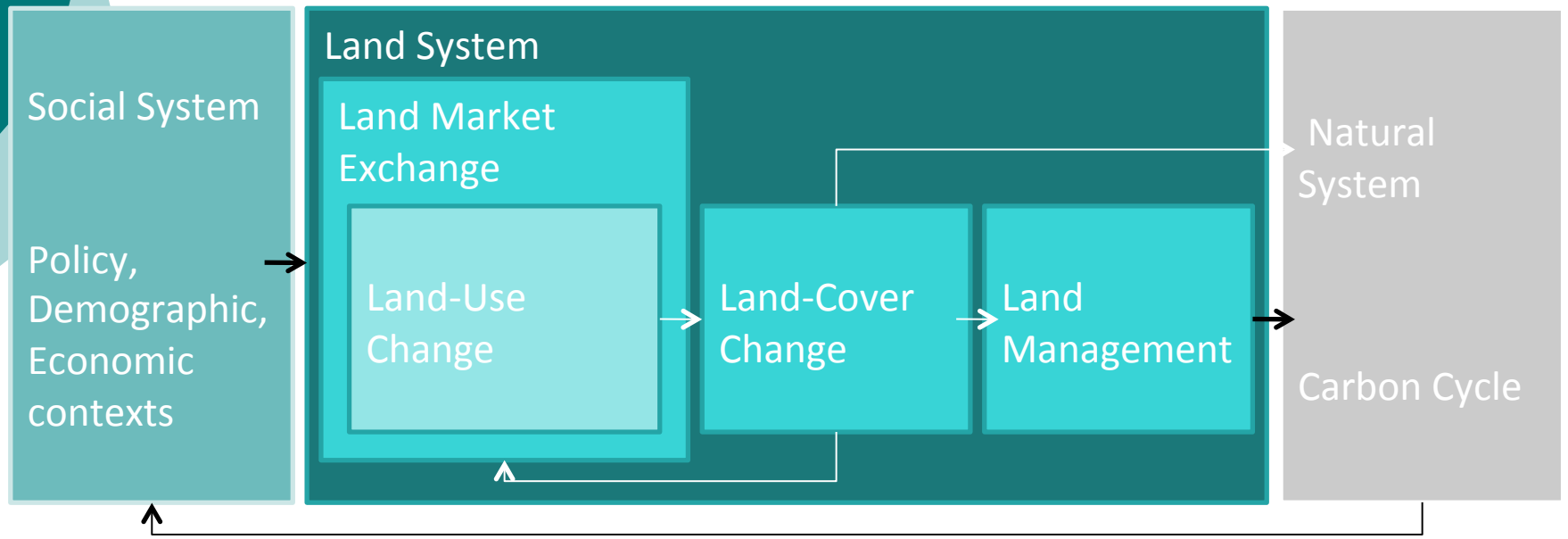
- **Limited farmland resources are an important constraint on land-use decisions**

- Further experiments explore effects of policies related to agricultural subsidies and land exchange on patterns of household choices and well being.

Lessons from Poyang Example

- Example illustrates:
  - How different institutional frameworks affect overall well-being as well as levels of inequality, by constraining or enabling land-use decisions.
  - Empirical support can combine both quantitative and qualitative information about agent attributes and behaviors.

Example 3: SLUCE II



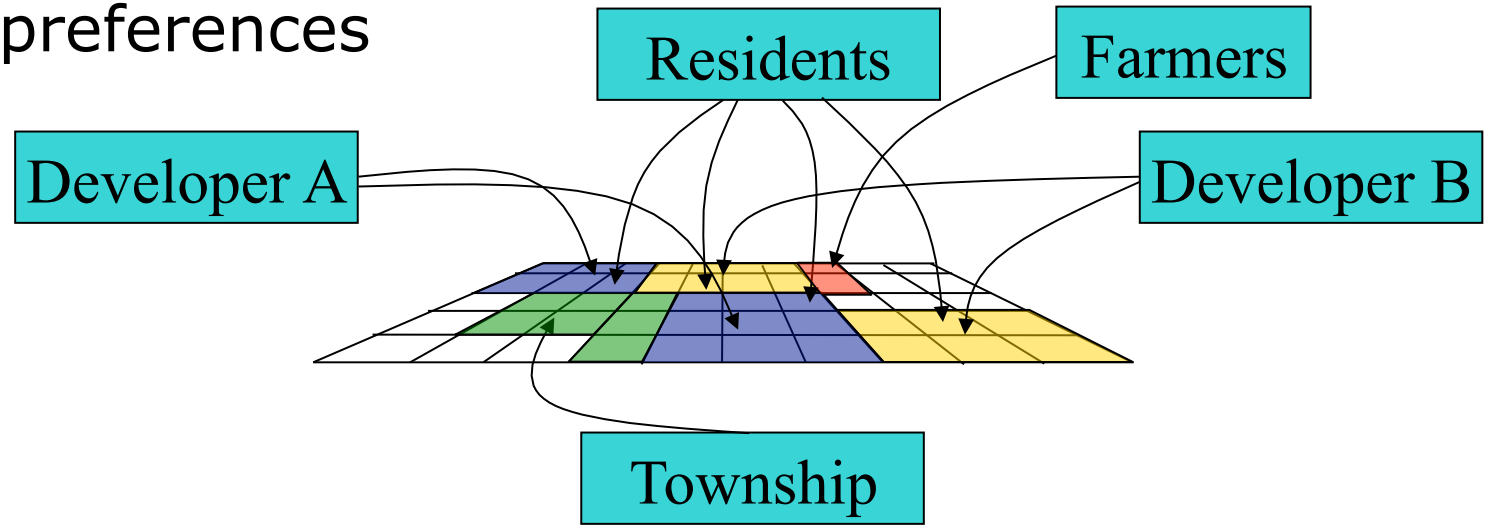
Scenarios

Agent-Based Model

Biome-BGC

Dynamic Ecological Exurban Development (DEED) Model

- *Municipalities* – purchase land to **preserve**
- *Farmers* – can sell **rural lot** from part of farm field
- *Developers* – convert farms to **subdivisions** of different types
- *Residents* – select residential lots based on preferences

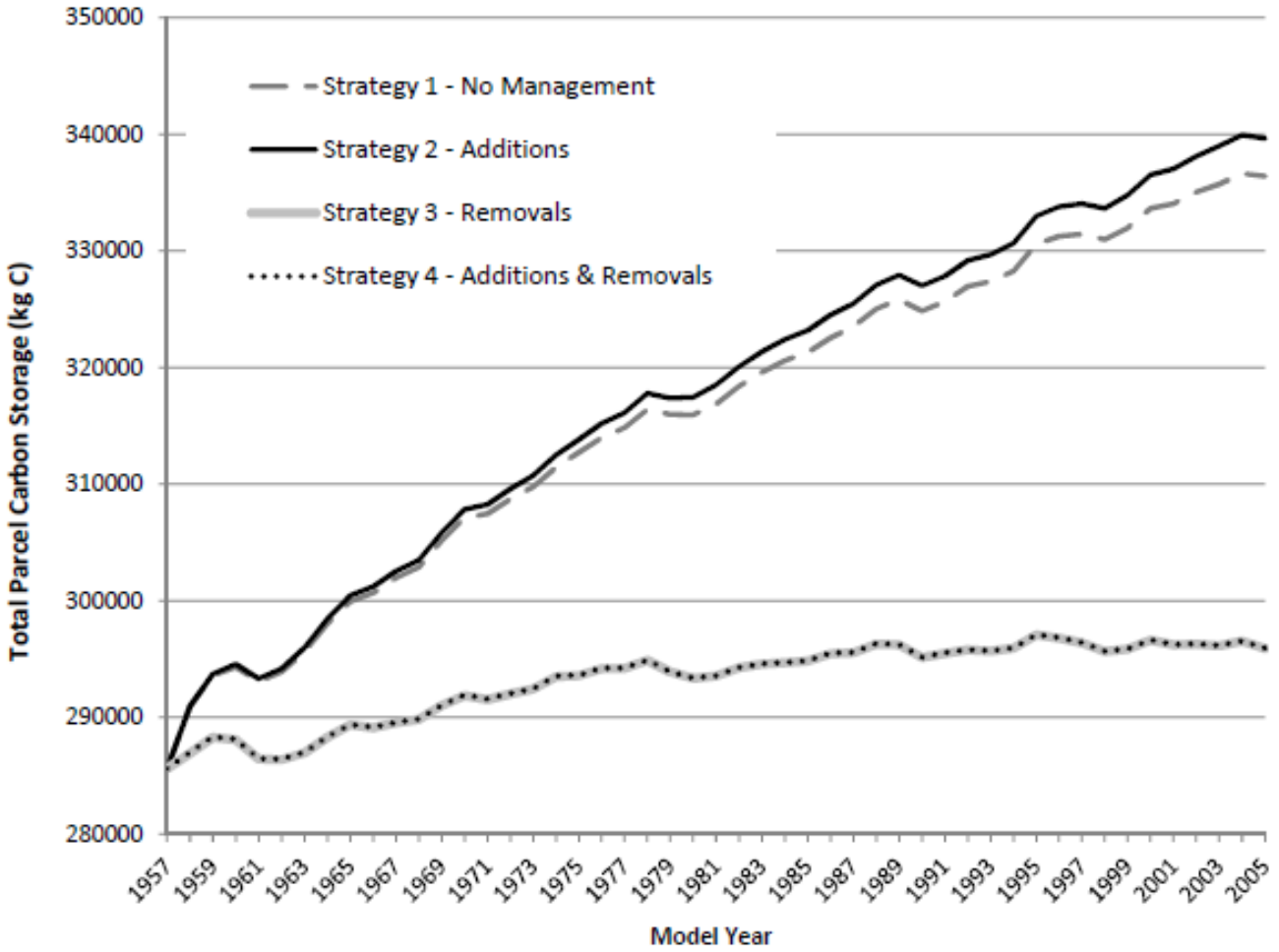


Details: Brown et al. 2008. *Geoforum*. 39(2):805-818. Robinson and Brown 2009. *IJGIS* , 23(9): 1211-1232.

Land Management & Carbon Experiments

Removals	Additions: No	Additions: Yes
No	**Strategy 1** No land management Baseline strategy for comparison. Model conforms to non-managed applications of BIOME-BGC	**Strategy 2** Fertilize and irrigate Hypothesis: upper boundary, expecting highest level of C storage and NPP
Yes	**Strategy 3** Remove litter from turfgrass and CWD from DTC Hypothesis: lower boundary, expecting lowest level of C storage and NPP	**Strategy 4** Fertilize, irrigate, and remove litter from turfgrass and CWD from DTC Hypothesis: expect levels of C storage and NPP between Strategies 2 and 3

Effects of Management on Carbon



Lessons From SLUCE Example

- Fine scale of ABM facilitates linkage of specific land-change processes (land development, management behaviors) with biogeochemical processes.
- Experiments with specific constraints and incentives can be used to evaluate effects of policy and market changes on carbon.

Challenges of ABMs

- Matching conceptual and computer models to questions takes time
  - …and to be effective it needs to be done again and again.
- Scaling up is a challenge, computationally expensive
- Bottom-up models are notoriously difficult to calibrate, in the sense that we do for empirically fitted models.
- Land-change community still has work to do on expressing standards of evidence for land-change models.

A Possible Next Step

- Model experiments that can identify how scale of representation affects interaction of LCMs, ISMs, and ESMs.
  - When does heterogeneity, interaction, and boundedly rational behavior among land-use actors affect outcomes within IAM regions?
  - When do feedbacks between environmental processes in ESMs and social processes in LCMs drive system dynamics?
  - Are there instances/questions for which we need to couple LCMs and IAMs across scales?
  - Are there specific non-linearities in the way land-use dynamics scale up, or environmental changes downscale to affect land use?

Conclusions

- Agent-based models are useful for representing the influence of human agency spatial landscape dynamics.
- Such models can link landscape patterns, policy, and ecosystem processes at the level of individual decision makers.
- How much detail about local- to regional-scale dynamics is needed at the global scale?
  - We may need a "scaffolding," that allows us to incorporate our understanding of process from ABMs into broader global models.

References

- Agarwal et al. 2001. A review and assessment of land-use change models: dynamics of space, time, and human choice. Gen. Tech. Rep. NE-297. Newton Square, PA: USDA, Forest Service, Northeastern Research Station. 61 p.
- Agrawal et al. In Revision. Interaction between organizations and networks in common-pool resource governance. For *Environmental Science and Policy*.
- Brown and Robinson 2006. Effects of heterogeneity in residential preferences on an agent-based model of urban sprawl. *Ecology and Society*, 11(1): 46.
- Brown et al. 2008. Exurbia from the bottom-up: Confronting empirical challenges to characterizing complex systems. *GeoForum*, 39(2):805-818
- Fernandez et al. 2005. Characterizing location preferences in an exurban population: Implications for agent based modeling. *Env Plan B*, 32(6): 799-820.
- Grimm et al. 2005. Pattern-oriented modeling of agent-based complex systems: Lessons from Ecology. *Science* 310, 987-991
- Nassauer et al. 2009. What will the neighbors think? Cultural norms and ecological design. *Landscape and Urban Planning*, 92: 282-292 .
- Robinson and Brown 2009. Evaluating the effects of land-use development policies on ex-urban forest cover: An integrated agent-based GIS approach. *Int J Geographical Information Science*, 23(9): 1211-1232.
- Robinson et al. 2007. Comparison of empirical methods for building agent-based models of land and resource use. *J Land Use Science,* 2(1):31-55.
- Tian, Q. 2011. From Vulnerability to Sustainability: Rural Development in the Poyang Lake Region of China amid Institutional Changes and Flood Hazards. PhD Dissertation, University of Michigan, Ann Arbor.