Title
Agent-based Models of Land Use / Land Cover Change

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Agent-based Models of Land Use / Land Cover Change

October 4, 2001, Santa Barbara CA

Workshop Sponsors

Center for Spatially Integrated Social Science (CSISS), University of California, Santa Barbara

The Land Use and Land Cover Change (LUCC) Project, Center for the Study of Institutions, Population, and Environmental Change, Indiana University

Workshop Coordinators
Dawn Cassandra Parker
Michael F. Goodchild
B.L. Turner II
Bill McConnell

The workshop in Santa Barbara (hosted by CSISS) took place prior to and in conjunction with the **National Academy of Sciences Arthur M. Sackler Colloquium on**

Adaptive Agents, Intelligence and Emergent Human Organization: Capturing Complexity through Agent-Based Modeling

Beckman Center, Irvine, California, 6-7 October 2001.

A schedule, summary of proceedings, and Position Papers by workshop participants follow

Agent-based Models of Land Use / Land Cover Change—Schedule

Thursday, 4 October 2001, 3:00-6:00 Santa Barbara
Short presentations

- Jim Opaluch presenting Linking Agent Models and Controlled Laboratory Experiments for Managing Community Growth
- Alfons Balmann presenting Adjustment Costs of Agri- Environmental Policy Switchings A Multi-Agent-Approach
- Thomas Berger presenting Multiple-Agent Modeling Applied to Agro-Ecological Development]
- Peter Deadman presenting Agent Based Simulations of the Effects of Household Structure on Patterns of Land Use Change in the Brazilian Amazon
- Daniel G. Brown presenting Project SLUCE: Spatial Land Use Change and Ecological Effects

- [Gary Polhill presenting FEARLUS: An Agent-Based Model of Land Use
- Patrick D'Aquino presenting Linking Role-playing Games, GIS and MAS to Accompany Governing Processes in Land Use Management: The SelfCormas Experiment in the Senegal River Valley Accompanying Paper

- Steve Manson presenting Agent Based Approaches to Land-Use and Land-Cover Change in the Southern Yucatan Peninsular Region of Mexico

- Dawn Parker presenting Biocomplexity Project Overview

National Academy of Sciences Arthur M. Sackler Colloquium on

Adaptive Agents, Intelligence and Emergent Human Organization: Capturing Complexity through Agent-Based Modeling

Saturday, 2:45-4:30 at the Beckman center, UC Irvine

Break-out session followed by group discussion

- Introductory Remarks, Michael Goodchild

- Issues in Spatially Explicit Modeling by Michael F. Goodchild

- What are important methodological questions related to space?

- What lessons have we learned for MAS/LUCC models from the NAS sessions?

Sunday, 8:30-10:00 at the Hyatt
Goals and Models

Break-out groups followed by summaries and discussion

- Introductory Remarks

- What are our goals for the workshop?

LUCC working paper goals
Potential follow-up activities:
- CSISS expert meeting?
- NAS Colloquium?
- Special journal issue?
- Listserve and enhanced web site

- What are the potential strengths of MAS/LUCC models? What is the most appropriate role for such models?

  Dealing with space and time
  Process discovery vs. policy analysis
  Levels of abstraction

10:15-Noon—Linking models to data

Break-out groups followed by summaries and discussion

- How can models be parameterized?

  Data from outside the system: surveys, experiments, statistical models, GIS coverages

  Data gathered within the system: same sources

- What are the compatibilities and synergies of alternative modeling techniques?

- What are the special challenges for model verification for MAS/LUCC models?

  Understanding systems that can't be analytically explored

  Understanding systems with non-linearities, complex feedbacks, and multiple equilibria

  Identifying problems of parameter identification (i.e., an outcome may have several observationally equivalent possible causes)

- What are possible techniques for model validation (i.e., comparing generated and actual landscapes and behavior)?

Landscape comparisons -- existing techniques and possible innovations

Behavioral comparisons

- What are important issues with respect to spatial and temporal scale that must be considered in model parameterization, verification, and validation?

- What empirical challenges are unique to MAS/LUCC models?

1:00-3:00 Infrastructure Development

New break-out groups followed by summaries and discussion

- What tools have researchers used and explored?
- What are the strengths and weaknesses of these tools?
- What enhancements are needed?
- What coordination or investments would be helpful?

3:15-5:00 Open Questions

Full group discussion

- Modeling human decision making (discussed)
- Modeling socio-political phenomena (institutions, group decision making, etc.) (discussed)
- Modeling land markets and alternative land allocation strategies (discussed)
- Modeling interactions
- Modeling endogenous rule formation
- What can't we use ABM models for?
- What non-human entities can be represented as agents?
- What should be endogenous and exogenous to our models?

5:00-5:30—Closing discussion

- Potential publication outlets
- Development of enhanced web site
- Possible future workshops, conference venues and communication strategies

Summary of Proceedings

Dawn Cassandra Parker, Postdoctoral Fellow
CIPEC, Indiana University

An increasing number of scholars are exploring the potential of agent-based or multi-agent system tools for modeling human land-use decisions and subsequent land-cover change. In an agent-based model, individual agents (representing, for example, migrant populations, land-owner households, or local governments) autonomously make decisions based on internal rules and local information. While agent interactions may lead to recognizably structured outcomes, a set of equilibrium conditions is not imposed on these models, in contrast to modeling techniques such as mathematical programming or econometrics. Thus, these models potentially offer a high degree of flexibility for accounting for heterogeneity and interdependencies among agents and their environment. Further, when coupled with a cellular model representing the landscape on which agents act, these models are well suited for explicit representation of spatial processes, spatial interactions, and multi-scale phenomena. In order to bring together scholars with interests in this area for an in-depth discussion of goals, methodological challenges, and needs for research infrastructure, Focus 1 of LUCC (http://www.indiana.edu/~act/focus1/), the Center for Spatially Integrated Social Science (http://www.csiss.org/), and the Center for the Study of Institutions, Population, and Environmental Change (http://www.cipec.org/) jointly sponsored a special workshop on agent-based models of land use, held Oct. 4 in Santa Barbara and 6-7 Oct. in Irvine, CA.

The workshop was organized by Michael Goodchild (CSISS), William McConnell (LUCC Focus 1), Dawn Parker (CIPEC), and B. L. Turner (Clark University). This workshop occurred in tandem with the **U.S. National Academy of Sciences Arthur M. Sackler Colloquium on Adaptive Agents, Intelligence and Emergent Human Organization: Capturing Complexity through Agent-Based Modeling.** A participants list, meeting agenda, abstracts describing participants' research activities, and copies of participant presentations, are available at http://www.csiss.org/events/other/agent-based/. Position papers for participants are attached following this summary.

An overview paper, "Multi-Agent Systems for the Simulation of Land-Use and Land-Cover Change: A Review," by Dawn C. Parker, Steven M. Manson, Marco A. Janssen, Matthew Hoffmann, and Peter Deadman provided background reading for the workshop. In this paper, we review existing techniques for LUCC modeling, briefly discussing the strengths and limitations of each approach. We define a multi-agent system model of land-use/land-cover change as a union of agent-based and cellular models that incorporates endogenous links between agent decisions and their environment. We discuss several potential advantages of MAS/LUCC models. First, these models can incorporate mechanisms that generate complexity (heterogeneity and interdependencies) and illustrate complex outcomes (nested hierarchical structures and potentially related "emergent" properties). Second, these models allow the user to examine the path of land-use change dynamics, rather than only examining an equilibrium outcome. Third, these models can interface with geographic information systems models to represent space and link anthropogenic and biophysical processes. We discuss alternative roles for MAS/LUCC models, from generative (exploratory) to fitting (descriptive). We discuss the many challenges of verification and validation in these models, including understanding the behavior of non-linear models, parameterizing models, and comparing model outcomes to real-world data. Finally, we review current applications of MAS/LUCC models, and offer our perspective on ongoing challenges and opportunities in this research area.

The workshop opened with presentations of on-going projects by Jim Opaluch, Alfons Balmann, Thomas Berger, Peter Deadman, Dan Brown, Gary Polhill, Patrick d'Aquino, Steven Manson, and Dawn Parker. Following the NAS colloquium sessions, Michael Goodchild gave a presentation on issues in spatially explicit modeling, and participants discussed lessons from the NAS sessions. Discussion focused on the concept of emergence and its definition and relevance for LUCC phenomena.

The remainder of the workshop consisted of structured discussions among participants, using a combination of break-out groups and full group discussion. Opening discussions focused on the potential strengths of MAS/LUCC models and what roles these models may play in research. The group identified a range of possible roles, from exploratory to predictive, and agreed that the entire range potentially represented appropriate applications of such models. Continuing discussions focused on issues related to data acquisition, model parameterization, and model verification and validation. Several issues received substantial attention. First, the group agreed that a clear definition of validation was needed. Second, both comparisons with results from alternative modeling strategies and application of existing validation techniques for LUCC models could be useful. Finally, the high degree of complexity in MAS/LUCC models implies special challenges for verification and validation.

The group then moved on to consider infrastructure needs for the MAS/LUCC modeling community, discussing available software tools and communication challenges. While development of a single standard modeling platform was not supported, participants suggested two strategies for more effective communication of model function: meta-data descriptions of model mechanisms, and provision of a pseudo-code version of the programming code used for specific model implementations. The need for integration of ABM, GIS, and validation software tools also was recognized. The group then created a distilled list of open questions that our discussion had not yet touched on. Challenges of modeling individual and group decision making, modeling institutions, and creating land allocation mechanisms were discussed. Additional questions are listed on the conference web site.

Several follow-up activities are planned. A LUCC working paper summarizing the conference discussions will be published through the Focus 1 office. Please contact Focus 1 if you would like to receive a copy upon publication (focus1@indiana.edu). A listserve or bulletin board to enhance communication between scholars in this area will be created, as well as an advanced web site containing background information on spatial modeling, a glossary, links to ongoing projects, model links and meta-data, and a bibliography. The group also discussed possible future conference venues and appropriate publication targets for work in this area across multiple disciplines. Further follow-up activities, including a special journal issue, a hands-on modeling workshop, and a future National Academy of Science colloquium are also being discussed.

The Background Reading for this workshop, was modified and accepted for publication in the *Annals of the Association of American Geographers* "Multi-Agent Systems for the Simulation of Land-Use and Land-Cover Change: A Review" by Dawn C. Parker, Steven M. Manson, Marco A. Janssen, Matthew J. Hoffmann, and Peter Deadman.

The original background paper appeared in 2001 as a CIPEC Working Paper CW-01-05. Bloomington: Center for the Study of Institutions, Population, and Environmental Change, Indiana University.

Position Papers from workshop participants follow:

Modeling the Interactions Among Urban Development, Land Cover Change, and Bird Diversity - NSF Biocomplexity Program

Marina Alberti (PI), Paul Waddell, Mark Handcock, and John Marzluff

Abstract

The interactions between urban development and ecological processes are extraordinarily complex. Urban development evolves over time and space as the outcome of microscopic interactions of individual choices and actions taken by multiple agents. These decisions affect ecosystem structures and functions through the conversion of land, fragmentation of natural habitat use, disruption of hydrological systems, and modification of energy flow and nutrient cycles. Environmental changes at local and regional scales affect human well-being and preferences as well as the decisions people make. This project will develop an integrated model of urban development and land-cover change in the central Puget Sound region that can interface with models representing a large set of ecosystem processes. The focus of this project will be on linking urban development to bird diversity as a test case for an integrated modeling approach. This approach builds on model traditions in urban economics, landscape ecology, bird population dynamics, and complex system science, each of which offers different perspectives on modeling urban ecological interactions. The project will apply Bayesian networks and a multi-agent microsimulation approach because of the potential for those approaches to support complex inference modeling in problem domains with inherent uncertainty. Instead of separately simulating urban growth and its impacts on birds habitats, this project will develop a framework to simulate metropolitan areas as they evolve through the dynamic interactions between urban development and ecological processes and link them through a spatially explicit representation of the urban landscape.

Assessments of ecological impacts of urban growth that are timely, accurate, and transparent are crucial to sound policy and management decisions. Although extensive urban research has focused on the dynamics of urban systems and their ecological interactions, these diverse urban processes have yet to be synthesized into one coherent modeling framework. Simulation models of urban and ecological dynamics have evolved in separate knowledge domains. While both of these research areas deal with human-environmental interactions, they do so with very different emphases, scale, methodology and objectives. This research will investigate how best to model complexity and uncertainty of coupled socioeconomic and biophysical processes in metropolitan regions and their interactions with the policy domain. This project will emphasize the importance of explicitly representing human and ecological processes in modeling urban systems, including patterns, processes, and impacts. Ultimately, this project will assist in identifying answers to questions related to the potential use of public policy to intervene in urban ecological systems in ways that may reduce ecological damage from urban processes while sustaining economically and socially viable urban communities for people. The project therefore should help in the development of tools for policy makers to explore the links between human behaviors and environmental change.

CURRENT RESEARCH RELATED TO AGENT-BASED MODELING AND LAND-USE / LAND COVER CHANGE

by
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My relation with agent-based modeling started with a spatial-dynamic model of structural change in agriculture that I have developed during my dissertation research in the early nineties at the Department of Agricultural Economics in Göttingen. In the meantime the modeling approach has been used in subsequent studies with respect to manifold research fields, such as policy analysis, structural change, and land use. In the remainder, I will illustrate the idea of the approach. I continue with present extensions as well as with related research.

Introduction: The Idea

The original inspiration arose from the question whether and under which conditions structural change in agriculture may be path dependent (cf. Balmann 1995, 1999). The idea was to model and to simulate agricultural regions "from the bottom up" by considering a multitude of individually behaving farms that interact on certain product and factor markets. For instance, it is obvious that farms can increase their acreage only if there is land available in the farms' neighborhood - probably because neighboring farms reduce their acreage. Moreover, if a farm invests, this often has an impact on the farm's production capacities for the lifetime of the asset. The same holds for the capital stock that depends on previous investments as well as on previously gained profits. In such a model, the evolution of every farm depends on its own state and history as well as on the evolution of other farms, particularly the evolution of its neighbors. Once a simulation is started, the evolution of the region and thereby structural change would occur endogenously. Hence, such a model should allow the study of the impacts of sunk costs, factor mobility, and returns to scale on the direction and speed of structural adjustment.

To realize this idea, a spatial model was developed where farms are located at certain points on a chessboard-like spatial grid. The fields within the grid represent land plots that can be used for agricultural production. The farms compete for the land in repeated iterative auctions where every farm bids according to its marginal land productivity and its distance to the next available plot. Figure 1 gives a snapshot of a selected simulation run by showing how the land is distributed to different farms after a number of periods. Plots marked with an X represent locations of farms. Plots with the same color belong to the same farm.

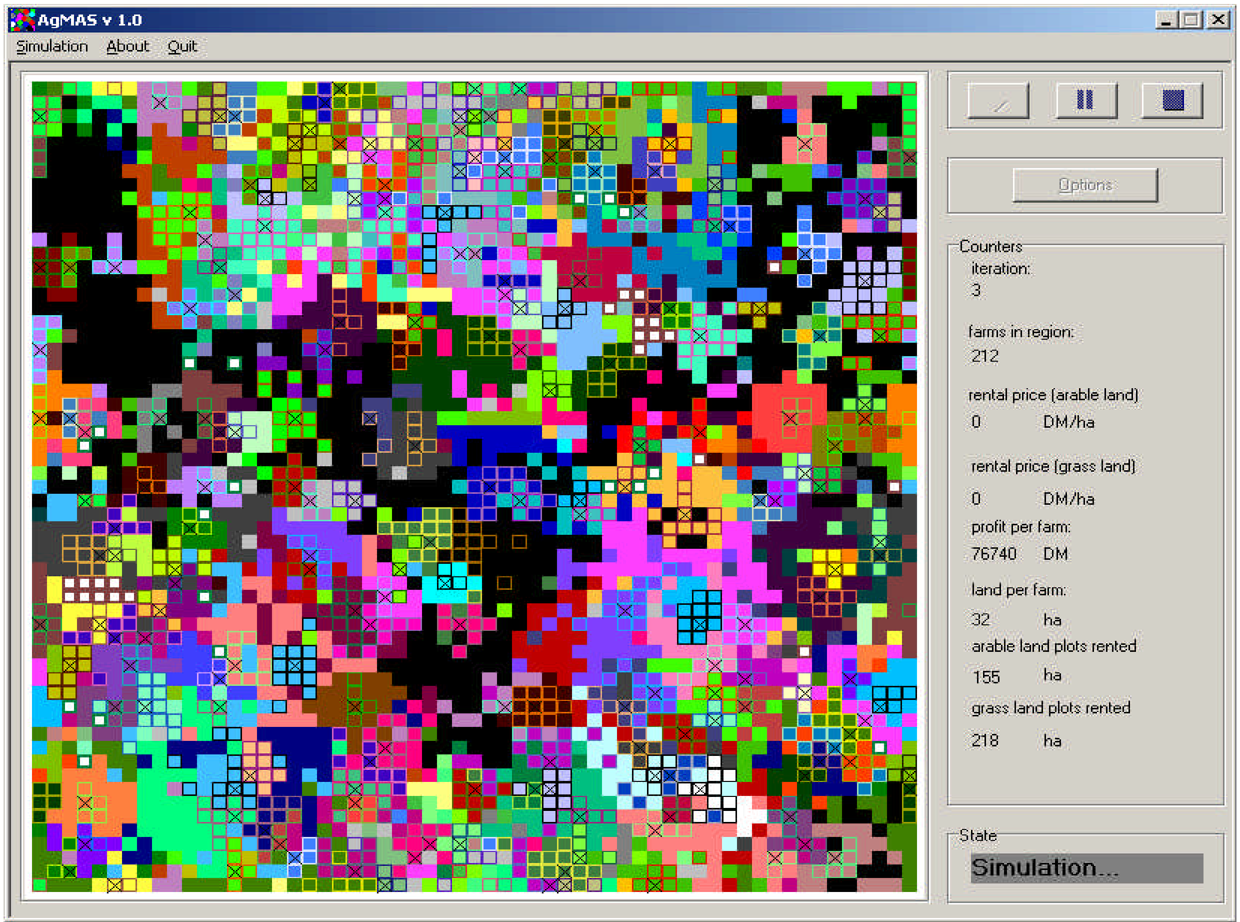

Figure 1: Land distribution in a simulation with 1600 plots and 110 farms.

Apart from renting and disposing land, the farms can engage in different agricultural production activities (e.g. dairy, cattle, hogs, sows, arable farming, pasture land) and they can invest in different assets (differently sized buildings for various activities, machinery of different sizes). In addition to the different production and investment activities, the farms can use their labor and capital for off-farm employment as well as to hire additional labor and to make debts. Moreover, farms can give up farming and new farms can be founded. Each of the farms can be understood as an agent that acts autonomously in trying to maximize the individual household income in response to expected market prices and the availability of land. All decision-making routines are based on adaptive expectations. Mixed Integer Linear Programming is used to optimize production activities and investment.

Extensions and Related Research

The application of the model led to interesting results and insights regarding the question of path dependent structural change (Balmann 1995, 1999). This encouraged several subsequent studies:

a) Thomas Berger (1999, 2000) extended and refined the original modeling idea in several significant respects. Berger enabled the farms to follow heterogeneous decision rules, to communicate in information networks and to exchange land bilaterally. Further particular extensions were the introduction of heterogeneous land qualities and the integration of regional water resource systems that allow considering tradable water rights. Berger completely reprogrammed the model and applied it to a comparatively large agricultural region (with 5400 farms in a region of 667 km^2) in Chile to study the dynamic impacts of free trade-oriented policy options with regard to the diffusion of specific innovations and the resulting resource use change.

b) Balmann (2000) presents applications of the original model that focus on the dynamical impacts of selected agricultural policies on structural change, efficiency, land use, and farmers' incomes. The rather explorative simulations show the interrelation of these terms. Particularly, they show how subsidies like direct payments - which are often considered as non-distorting - may affect the speed and direction of structural change and thus they may also affect production and land use. In cooperation with Kathrin Happe (University of Hohenheim) these studies are enhanced and applied to selected regions in the German federal state of Baden-Württemberg. For instance, Balmann, Happe, Kellermann, Kleingarn (2001) analyze the adjustment costs of a policy switching that aims to reduce per farm animal density in the highly intensive agricultural area of Hohenlohe. The model considers explicitly some 2500 farms that are derived from a set of 12 real farms that are considered to be typical for the region.

c) A substantial part of the last mentioned project with Kathrin Happe is to develop the models to a well documented, basic model. This is done for two reasons. Firstly, a basic version shall allow third persons in a comparatively easy way to understand its structure and to adapt it for own projects as well as to extend it by additional features. Therefore, the actual programming exploits more consequently the object-orientation of C++ (cf. Happe 2000). The second reason for a basic, properly documented version may be paraphrased by the term "frankness". For instance, the model developed by Berger (1999) contains a source code of 17000 lines, corresponding to more than 300 pages of text (cf. Berger 1999, p. 5-39). Such a complexity means that the model is a black box for almost every addressee of the results and the mediation particularly of controversial simulation results is hardly possible. Standardization and frankness are seen as means to overcome such problems.

d) An obvious and straightforward extension is the integration of human decision making into such models. Real persons may replace the normative decision routines of individual farmers or of 'policy makers'. This idea is taken up in a joint project with Konrad Kellermann that develops the model's version discussed in c) towards an interactive computer game. The realization of this idea offers several perspectives for future use. The first is to use it for teaching. Students can apply textbook knowledge and can experience the often complex dynamic consequences of strategies. They may either take the role of a farmer who competes with other farms in the region or of a politician who tries to improve efficiency and/or the farmers' incomes. It will even be possible to link different 'regions' via a common market, so that 'politicians' of different regions can interact. A second perspective of the game is to study experimentally the behavior of players that take the role of farmers. It gives for instance a kind of benchmark to evaluate how 'smart' a particular computational decision making-routine is. Moreover, it is proposed to identify cognitive deficits of the present computational agents. A third, more visionary perspective is using the interactive model for planning purposes, like the analysis of local policies and dispute resolution, e.g., to manage conflicts between farmers and environmental interests. It is quite clear that this needs to adjust the model to the considered region.

e) Balmann (1998) and Balmann and Happe (2000) investigate whether economic models that are based on artificial adaptive learning may become a useful alternative to a normative behavioral foundation of the agents' behavior. The studies are based on a simplified comparative-static version of the model, presented above. Again, a number of agents (farms) that are spatially ordered on a grid compete for renting land. But in this model a genetic algorithm (GA) is applied to an agent specific population of genes representing particular bidding strategies in order to determine the agent's behavior. GA can be understood as a heuristic optimization technique that breeds solutions by applying operators known from natural evolution, such as selection, recombination (crossover) and mutation. Two principal market constellations are simulated for a variety of parameter constellations. First, a situation of limited market access is defined. A series of simulation experiments shows that for this scenario the model generates results that fit comparative static equilibrium conditions like allocative efficiency and zero-profits. Second, a limited market access scenario shows that only under very special conditions the distributed GA-model generates results that indicate oligopolistic behavior. Summarizing, nature related artificial intelligence methods like GA (and probably artificial neural networks too) seem to be promising alternatives for studying complex spatial processes. These positive experiences with using GA for analyzing complex microeconomic problems induced further work. In joint work with Oliver Mußhoff, GA are used to analyze real options problems of single firms as well as of competing firms.

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Multiple Agent Modeling Applied to Agro-Ecological Development

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Summary:

The application of adaptive agents methods has a long history in agricultural and resource economics. Beginning in the mid 1960s, a series of empirical computer models was developed and directly applied to policy-related research questions. While the early results were highly encouraging, the further refinement of the adaptive economics approach was hampered by the very limited computation power. Equipped with inexpensive computers, object-orientated programming languages and conceptual advances in complexity theory, new efforts are now being made to revive the tradition of applied agent-based modeling in agricultural and natural resource issues. The Center for Development Research (ZEF) has gained experience with the multiple-agent modeling approach in studying technology diffusion and resource use change in the farm sector in Chile. The applicability to other areas of research and the use of multi-agent modeling for methodological integration of different disciplinary approaches and data sets is currently being tested.

Mathematical programming, i.e. the maximization of objective functions constrained by inequalities or equalities, has been used in agricultural and resource economics for almost half a century. Organizing data and processes in input and output vectors has proven to be the appropriate format for merging rather multidisciplinary information from farmers, agronomists and agricultural engineers. In combination with a properly defined objective function, mathematical programming provides a way of integrating/including human decision-making into agricultural production and resource use models.

However, if the portrayed real-world situations are characterized by spatial and behavioral heterogeneity together with economic-ecological instability, such models are often poor predictors of human behavior and might therefore fail to provide reliable information for policy analysis. Since they largely neglect the complexity of human interactions, spatial relations and feedback effects with biophysical processes, they are especially weak in analyzing the role of technological change and human organization.

A recent attempt to overcome these weaknesses was made in Berger (2001) by applying an integrated multiple-agent approach. The spatially explicit, interacting farm-household model was successfully tested in Chile and used for empirical policy analysis. Mathematical programming models for each actor represent the individual choice of a farm-household among available land and water use, consumption, investment and marketing alternatives.

Key behavioral responses and constraints of the heterogeneous farm-households are explicitly considered, as are their social and spatial interactions. These inter-household linkages include communication concerning the adoption of technical innovations, allocation of water return-flows and land/water markets. The model's economic and hydrologic components are tightly connected into a spatial grid-based framework. Each cell or pixel has several attributes associated with it: soil quality, water supply, land cover/land use, and financial returns to land. The model agents, i.e. the farm-households and non-farm owners, largely determine these attributes over time. For example, water supply depends on the amount of individual water user rights traded on markets. Land cover/land use is derived from the farm's land-use decision problem taking into account the price expectations, the technical and financial constraints.

Further testing of this model class and the incorporation of integrated ecological and economic modeling approaches is called for. ZEF's research portfolio on multiple agents modeling includes the following research activities:

Technical and structural change in agriculture
(University of Göttingen and Talca, completed in 1999)

- Study area: Melado River Catchment (Chile) of about 670 km^2 and 5,400 farm-households
- Temporal period: 19 years sectoral adjustment in agriculture (starting in 1997)
- Spatial and temporal resolution: 158 * 158 m (size of one grid cell is 2.5 ha), monthly time interval
- Types of land use and/or land cover modifications: very disaggregated land use types in agriculture and forestry (5 soil types, 3 technological levels, 160 cropping and livestock systems), investment in water-saving irrigation methods
- Specific agents: farm-household agents and non-farm land owners who engage in land and water markets and whose plots belong to different hydrological units
- Factors included for agent decision-making: agents seek to maximize expected family incomes without exhausting their land and water assets. Adoption of innovations is conceptualized as a farm investment problem under uncertainty. Several types of interactions such as contagion of information, exchange of land and water resources, return-flows of irrigation water.
- Research questions: diffusion of water-saving irrigation methods in a watershed; structural effects of a 'treadmill' innovation process in agriculture; impact assessment of government intervention.

Policies for improved land management
(jointly with IFPRI, Washington)

- Study area: 2 selected landscapes in Eastern Highlands of Uganda
- Temporal period: 15 – 20 years
- Spatial and temporal resolution: (see above)
- Types of land use and/or land cover modifications: very disaggregated land use types in agriculture and forestry, investment in soil conservation methods
- Specific agents: farm-household agents and non-farm land owners who engage in land and water markets and whose plots belong to different nutrient response units
- Factors included for agent decision making: (see above)
- Research questions: introduction of sustainable land-use practices as a farm investment decision; identification of suitable policy incentives to enhance the adoption of such practices

Interrelated water and land use changes in the context of global change (LUCC endorsed project)
• Study area: Volta River Basin (mainly Ghana and Burkina Faso), about 400,000 km^2 • Temporal period: 20 years • Spatial and temporal resolution: meteorological and hydrological modeling will take place at a very coarse and socio-economic modeling at a very fine resolution. Multiscale results will be down- and up-scaled to a basin wide $9km^2$ multi-agent land use grid. • Types of land use and/or land cover modifications: aggregated and disaggregated land use types including “natural” vegetation, depending on specific research question • Factors included for agent decision making: (see above) • Research questions: human responses to policy and environmental changes

Community-based management of natural resources (Robert-Bosch-Foundation)
• Study area: selected communities in Ghana • Temporal period: several years • Spatial and temporal resolution: (still not defined) • Types of land use and/or land cover modifications: (still not defined) • Factors included for agent decision making: (see above) • Research questions: collective action and environmental externalities; dynamic evolution of property rights institutions

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- German Federal Ministry of Economic Co-operation and Development

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Website featuring all these projects: http://www.zef.de/zef_englisch/f_mas.htm

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Reference: Berger, T., 2001. Agent-based Spatial Models Applied to Agriculture: A Simulation Tool for Technology Diffusion, Resource Use Changes and Policy Analysis. Agricultural Economics Volume 25, Issue 2, p 1-16.

Project SLUCE: Spatial Land Use Change and Ecological Effects

Daniel G. Brown, Joan I. Nassauer, and Scott E. Page
The University of Michigan - Ann Arbor

Project SLUCE (Spatial Land Use Change and Ecological Effects), a new 4.5-year effort (2001-2006) funded under the NSF Biocomplexity and the Environment program, will investigate the dynamics of land use changes at the urban-rural fringe and their interactions with the natural environment and ecosystem function. The project builds on our separate, on-going projects on land use and land cover change, landscape scenario design and testing, and development and analysis of agent-based and other complex systems models. The model development and data collection efforts will be designed simultaneously to address specific questions about the interactions between land use decisions, social, cultural, political and economic structures, specific policy and design interventions, and impacts on ecological landscape patterns and function. Our initial focus will be on the interactions between agricultural and developed land uses. We expect to iteratively develop multiple agent-based models in the course of the project, working initially with Objective C and the Swarm libraries, and to develop several hooks that will link the models with empirical observations. Identification of specific agent types and behaviors is currently underway and will likely continue for the duration of the project, responding to the needs of the various questions posed.

The empirical focus of the project is the Detroit metropolitan area (~5.5 million people). Empirical data will link to the models for the purposes of (a) evaluating model behavior through back-casting exercises, (b) endowing agents with behaviors that are based, to the extent possible, on surveys of actual people, and (c) evaluating historical impacts of land use change on ecosystem structure through remote sensing. Most work will be done within specific townships, which are selected through stratification of the region according to demographic, economic, and land-use planning characteristics. We are focusing on observations of actual land use changes that have occurred from approximately 1950 to the present. Data, which include mapped parcel boundaries and owner identifiers together with aerial photography for interpretation of land use, are available on temporal resolutions of about decades. The model will likely have a finer temporal resolution and we expect matching model and data resolutions to be an on-going challenge. Surveys of land owners, home buyers, developers, and land use regulators are designed to evaluate the factors that affect residential location decisions, as well as the factors that restrict or affect the supply of land for development. We expect that the surveys will provide information about the relative importance of environmental and social factors for the location decisions. Historical time series of remotely sensed data on landscape structure will be compiled and compared with historical land use dynamics to begin the process of linking land use and land cover dynamics within the modeling framework. These landscape structure descriptions, and their relative degree of ecological impact, are important emergent properties of interest from land use change dynamics.

One of our goals is to use the models we develop to evaluate the potential for specific interventions in the land use change processes that might lead to more ecological benign and/or beneficial configurations. The kinds of interventions that can be tested include regulation or restriction by governing bodies, incentives of various kinds, educational initiatives, and widespread introduction of alternative landscaping approaches. We intend to use the working models of land use change to evaluate both the historical dynamics of the region, but also alternative possible futures that might come about under various scenarios.

Why I no longer work with Agents

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My work with ABS dates from the mid-1980s when I published two papers exploring the possibilities of agents in spatial modeling. The first paper developed a formal model of a way-finding agent operating within a complex building where other similar agents were also present. The objective there was to express a sequence of models of human decision of increasing complexity in terms of the formal hierarchy of systems specifications developed by Zeigler (1976). This helped clarify the nature of the relationship between these different models, ranging from elementary stimulus-response to rational decision to reactive and intelligent agents (Couclelis 1986). The second paper described a CA model of urban development in which developers were making investment decisions based on complex rules expressed in predicate calculus (Couclelis 1989). Since that time I have not done any research involving agents even though I have followed with interest the rapid growth of the field. In this note I explain briefly why I became skeptical of the whole paradigm following that early enthusiasm. At the same time I wish to express my willingness, if not hope, to change my mind regarding the relevance of ABS to spatial modeling following this workshop.

As a former engineer turned scientist I am acutely aware of the subtle but profound differences, practical as well as conceptual, between the synthetic stance of the design disciplines and the analytic stance of the sciences. One major difference in practical terms is that when you design something you have direct (partial or total) control on the outcome, whereas when you analyze something that's "out there" you can only hope that you guessed correctly. That distinction is also discussed at length in the Parker et al. review paper under the rubrics of 'generative' vs. 'fitting' (or fitted) models.

My view of how that distinction impacts ABS modeling of land use and land cover change is as follows. ABS models fundamentally involve one or several *agents* interacting with an *environment.* Combined with the 'generative' vs. 'fitted' models distinction (or: designed vs. analyzed) this gives four cases:

1 *Agents and environment both designed*. This describes the 'social laboratories', the self-contained microworlds (such as Sugarscape) that researchers build from scratch. These models can achieve complete validity within the artificial microworlds they set up but outside of these they serve as abstract thought experiments at best (Axelrod).

2 *Agents designed, environment analyzed.* This describes the engineering applications of the ABS paradigm whereby software or hardware robots are designed to operate within pre-existing environments. These are problem-solving applications where

the agents' behavior rules may or may not be anthropomorphic. These kinds of agent models clearly can be extremely effective in practice though they can be often be defeated by the complexity of the real environments within which they operate.

3 *Agents analyzed, environment designed.* This is the case of behavioral experiments where natural subjects (human or animal) are observed within controlled laboratory conditions. Reasonably reliable behavioral and decision rules may be inferred under these circumstances (notably, through the methods of experimental psychology) but it is always questionable whether the rules thus derived will also be valid 'out there' in the real world.

4 *Agents and environment both analyzed*. This is the only one of the four cases that directly concerns land use/ land cover modeling. Here the relevant kinds of models are the traditional types recognized in the philosophy of science: descriptive, predictive or explanatory models. Building a *descriptive* model (i.e., one that fits observations) is technically no trivial task but in principle it can always be done given enough free parameters. Such models can be very useful as data summaries but beyond that their utility is limited. They may sometimes be used as *predictive* models to the extent that trend extrapolation is warranted but true predictive models must be structurally appropriate, i.e., they need to correspond to the mechanisms operating in the real system(s) under study. This requires the existence of formal process theory, which simply is not available in the land use/ land cover field (with or without agents). Predictive models based on theory are by that token also *explanatory* models, though not all explanatory models are also predictive (e.g., the causal relations identified may change over time in unpredictable ways). Reasonably reliable predictive and explanatory models of land use change would be of tremendous value to planning and policymaking but after forty years of efforts in that area the success stories are still quite limited.

ABS modeling meets an intuitive desire to explicitly represent human decision making when modeling systems where we know for a fact that human decision making plays a major role. However by doing so the well-known problems of modeling a highly complex, dynamic spatial environment are compounded by the problems of modeling highly complex, dynamic decision making units interacting with that environment and among themselves in highly complex, dynamic ways. The question is whether the benefits of that approach to spatial modeling exceed the considerable costs of the added dimensions of complexity introduced into the modeling effort. The answer is far from clear and in my mind it is in the negative. But then I am open to being persuaded otherwise.

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Support continuous collective processes in resources management: The linked uses of Multi-agent simulations, GIS, and role-play to improve collective decisions.

P.d'Aquino, C. Lepage, F.Bousquet

1. Multi-Agent Systems for land use management

For several years Multi-Agent Systems have been used in the field of natural and renewable resource management. Rapidly, the researchers in Mas and resource management have raised the issue of the interactions between agents and their environment. Cormas is a multi-agent simulation platform specially designed for renewable resource management. The authors consider that in complex agrarian situations, decisions on land management changes should be based on a common understanding of the interactions between ecological/bio-physical and socio/economic dynamics that are at work. As agricultural and environmental issues are more and more inter-linked, the increasing multiplicity of stakeholders, with differing and often conflicting land use representations and strategies, underlines the need for innovative methods and tools to support their coordination, mediation and negotiation processes aiming at an improved, more decentralized and integrated natural resources management (INRM). Cormas gives the possibility to manipulate and to incorporate into the same model spatial entities defined at different hierarchical levels. Involved in applied research on land and resource management we have tried to go beyond the classical laboratory experiments. During the past ten years, very significant advances in the simulation of societies in interaction with their environment have been achieved. More and more powerful and user-friendly computer modelling tools facilitate the understanding and simulation of such complex interactions. The main objective of this research is to study the use of MAS models and cartographic tools, associated with role games, for knowledge integration in collective learning processes focusing on key local INRM issues. How can these kind of tools be involved in such a processes, i.e., how can they help actors to govern the land? We are seeking to develop a companionable modelling use of multi-agent systems. We conducted participatory modelling experiments through the joint use of MAS models, others modelling tools (GIS for instance) and role-play. We will present some results or lessons drawn from these experiments with a special emphasis on respective positions of the different methodological steps and their effects to improve the collective process.

2. Some first experiments

Several experiments have been conduct in Europe, Africa and South Eastern Asia, specially about scheme irrigated management, natural resources and land use management. One of the main experiment, called "SelfCormas", has been under way since 1997 at the POAS (Plan d'Occupation et d'Affectation des Sols) experimental unit in northern Senegal. In support of a local decentralization policy, the aim is to test tools (maps, GIS, simulations, role-play,...) that will help local rural authorities and the people under their jurisdiction to improve their empowerment on planning decisions about sustainable land use management (agriculture, animal production, the environment, etc). The management scale considered is around 2 500 km² and 40 000 people. The simulation developed needs to help to stakeholders at every stage of the decision-making process: when zoning the area, identifying rules of access to a given type of area, and evaluating possible social and environmental impacts. It should also make it possible to forecast the different possible options, and therefore needs to be flexible. Two precise objectives were set right at the start of the experiment. The first was to test direct design of the MAS model by the stakeholders right from the initial stages, with as little prior design work by the modeller as possible, hence the “self” added to the CORMAS name. This means that upstream modelling work had to concentrate on producing an environment enabling the stakeholders to express themselves in designing their model. The second objective was to test the use of a geographical information system (GIS) managed by the region’s public development company[1], to sustain the decision-making process and modelling work regularly if necessary. The modellers used this blueprint, not to develop a specific model, but to develop tools within and around CORMAS (cf. role game, GIS, etc), so as to formalize as accurately as possible the knowledge and views expressed by the stakeholders (including the GIS) during the continuous, collective decision-making process. This "self-design" experiment was organized in the form of discussion workshops. The use of these three linked tools (Cormas x GIS x role-play) lead on discussions, appraisals, and even decisions, about definition of possible futures (scenarios) in the form of either trends (for instance population growth) or events (for instance the digging of new canals).

3. Some first conclusions

This operation provided us with confirmation of the feasibility of using computers in such socio-cultural situations. Thus, developing a role game in conjunction with stakeholders seems to be an interesting way of enabling stakeholders to play an active part in design a multi-agent model. The role game serves in this case as a sort of dialogue interface between computer modelling, the “machine”, and stakeholders. The stakeholders who developed and played the game were fully capable of interpreting the results of the model. As they were themselves the initial designers of the simulations carried out, they were also entirely aware of the distance between the model and reality, and of the way in which simulation results should be used. Moreover, simulation made it possible to go much further than the role game. For one thing, it would have been physically impossible without computer simulation to “play” the different scenarios selected by the stakeholders and to observe their multiple impacts over sufficiently long time lapses. Furthermore, a sufficiently flexible modelling platform offers many more possibilities of modifying the rules on request than cumbersome game sessions. Simulation thus multiplies the effectiveness of the role game and can take the decision-making process much further, be it by taking account of the long-term future or through the feasibility of the decisions made.

Lastly, in line with the option of supportive modelling, in this case, it is not up to the model to provide solutions to problems, but to encourage discussion of the different alternatives, to improve the effectiveness of a collective decision-making process and even to change the behaviour of local stakeholders with respect to their technical partners. In our approach, recourse to technical expertise is the stage that follows, and not that which precedes, the collective choice of scenarios that can “reasonably” be envisaged by the community. From this initial discussion, which supportive modelling made both endogenous and technically valuable, it was the representatives of local populations who themselves identified the priority types of support they required within their decision-making process and who contacted the services capable of satisfying their needs directly. Decision-making processes are about that too.

[1] SAED, Société d’Aménagement et d’Exploitation des terres du Delta du Sénégal et des vallées du fleuve Sénégal et de la Falémé (a public regional development company)

Exploring Colonist Household Structure and Land Use Change in the Amazon Rainforest

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This research effort represents a collaboration between people at the University of Waterloo and the Center for the Study of Institutions, Population, and Environmental Change at Indiana University. To date, work has focused on the development of a pilot simulation system called LUCITA (Land Use Change In The Amazon) designed to explore the factors influencing land use decisions made by individual households in the Altamira region of the Brazilian amazon.

While it has been assumed that deforestation rates in the Amazon are directly tied to population changes, resulting from high rates of in-migration and subsequent high natural increase, these general observations do not explain the spatial variation that can occur in colonized regions, such as that near Altamira. Neighboring farms in the Altamira region can have very different patterns of land use. This observation has raised research questions related to the relative importance of family and market factors in shaping land use decisions. One approach to this problem has been to study the individual cohorts who arrived on the Altamira frontier at different times, along with age and period effects. Utilizing this approach, an analysis of data collected in Altamira has led to the development of a model which proposes that land use changes in the region should be understood as a product of the age and gender characteristics of farm households. This conceptual model maps out a trajectory for families, which relates the type of agricultural practices pursued to the available capital resources and labor pool within each household. Five temporal stages of household composition are proposed by the conceptual model, with each stage of development characterized by increasing levels of capital and available family and male labour. This conceptual trajectory inspired the development of LUCITA.

LUCITA is a spatially referenced simulation, comprised of 2 sub-models that interact with one another through a raster landscape. These 2 sub-models are designed to capture the actions and interactions of the ecological and human systems characteristic of the study region. LUCITA can be configured to run simulations on one individual household, or on a landscape comprised of 236 properties. The raster landscape is an abstraction of the intensive study area described during field studies by Fearnside (1986). The landscape is representative of the Agrovila (village) Grande Esperança area, located in the municipality of Prainha in the state of Pará, approximately 50 km west of Altamira. Each cell in the raster grid is representative of an area of 1 hectare. Each cell in the grid references an object data structure, which is used to store soil properties including pH, phosphorus, aluminum, nitrogen, and carbon.

During the simulation, the soil object of each grid cell is linked to the environment object so that the soil properties of that cell, as well as crop yields, can be calculated based on the events that have occurred on that cell during the previous round of the simulation run. The environment object sub-model of LUCITA calculates these changes with the use a set of multiple regression equations developed for the KPROG2 model by Phillip Fearnside. Within LUCITA, a household agent may clear three types of land covers; virgin forest, secondary forest, and weed covered areas. The environment object also simulates the processes of secondary succession on the raster landscape.

In LUCITA, frontier colonists are modeled as a collection of intelligent agents, where each agent represents the actions of one household. The model of the environment contained by each household agent includes information on which cells constitute that agent's property, and the land cover on each of those cells. The architecture of an agent also specifies the agent's model of itself. This model includes a set of parameters describing the demographic composition of the household, the monthly available family and male labour, available capital, and a rule base where alternate land use strategies are contained. Eight possible land use strategies can be considered by the agent including; the production of rice, beans, manioc, maize, black pepper, and cacao, pasture development, and cattle grazing. A classifier system is used for agent decision making in each round of the simulation. The agent utilizes this classifier system to determine which land uses to implement on a given cell, given the resources of the agent and the previous experiences, expressed as crop yields, with that particular land use.

In each round of a simulation, the household agents execute a series of actions governing how the individual cells within their 100 hectare property will be managed. These actions include: maintaining existing pasturelands or perennial crops, clearing and burning land, and planting and harvesting crops. The agent determines which crops to plant by using the classifier system to compare its own capital and family labour resources with the labor and capital requirements for each of the available land use strategies. The agent has a predefined set of clearing preferences for determining which currently unused cells are to be converted to crops. For the simulations described here, the agents clearing preferences are set to place the highest priority on cells with advanced secondary succession, followed by cells with progressively younger secondary succession, then bare land, and finally virgin forest.

The pilot version of the simulation, while limited in scope, has allowed researchers at Waterloo evaluate an architecture for the development of additional simulations. Future goals are focussed on exploring alternate decision making architectures for the household agents and the effects of outside factors such as credit rates and commodity prices on household behaviour.

Do cities learn from getting burned?

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Abstract

Human settlements have always been effected by natural disasters. Our awareness of these events is usually that of something "happening" to the city. The fact that the city is changing the *agent* of disaster is left out of that awareness. I argue that many disasters, fire in particular, have co-evolved with cities over time. The perspective I am taking is that the city is an organism that can grow in ideal situations and can shrink in a disaster. Wildfire too can be viewed as an organism, one that usually lies in stasis until the ideal conditions, then quickly grows and dies. Both entities compete for space and resources. One entities' behavior will impact the other, and over time the systems co-evolve. This co-evolution beckons the question, what observable emergent properties emerge from this co-evolution? Does the city learn from the wildfires, and does the fire-adapted landscape change its behavior as a result of city growth? Through the use of modeling we can gain a better understanding of these disasters and the process of urban growth. I propose to examine the use of a coupled urban-wildfire cellular automaton (CA) based model to examine the emergent behavior of the two-process system. Questions of the appropriateness of modeling are explored as well as the possible conclusions that could be drawn from these experiments.

Introduction

Humans are so well adapted to Earth that not only can we live in any ecological niche on (and off) the planet, but we can modify the environment to the extent that we make our own niche. We, as a species, are quite adept at this, exhibiting our dominance over the landscape by literally flattening mountains and creating lakes from rivers, not to mention coating much of the natural landscape with a gray skin of concrete. It is in the city, where we think we can exist uninhibited or unharmed from nature's wrath, and build our habitat as we se fit. But as the adage goes, "never turn your back on the ocean." We forget that cities are perennially vulnerable to disaster, and that many natural disasters are in fact, normal. But does the city, as an organism, forget?

As cities have grown, each has had some sort of natural disaster that has destroyed part or all of it. Some of these disasters are one-time human-induced events, like Nagasaki's atomic destruction or the impending displacement of 2 to 4 million people's homes as a result of China's Three Gorges Dam. The human-induced destruction of urban dwellings will not occur again and those cities can't (and don't need to) plan for another disaster on that temporal and physical scale (especially since the dwellings along the Yellow River will be underwater).

Most cities that have survived one natural disaster can do little to prevent the next disaster, usually by the same agent, from hitting again. In some cases this is due to a missing feedback between then city and the disaster, tsunamis and earthquakes being two pathological cases. However, it can also be because the engine of the disaster, and the city are in fact, co-evolving. Both are changing their behavior as they respond to each other.

I have been focusing my efforts on the co-evolution of wildfires and the cities that they burn. Co-evolution can occur when two entities compete in some way for resources. A brief example of co-evolution is in the relationship between plants and herbivores. Some plants develop toxins in order to discourage their leaves and stems from being eaten. At the same time, herbivores have developed ways of metabolizing the toxins, in order to not go hungry.

Each year, wildfires cause hundreds of millions of dollars of damage in property and infrastructure, in addition to incalculable expenses and losses of the misplaced and newly homeless. The threat of fire is on the increase as cities encroach on natural areas. (Jehl, 2000). Also, each year, millions of acres of fire-adapted landscapes are paved, built on, and destructively managed. Acre for acre, the city is winning the battle with the natural landscape. In this study, the city is viewed as a spatial organism, one that has shape and behavior. I take the perspective that the human dimension of the city is manifested in the size and behavior of the urban area. The city emerges as an object from humans building communities, infrastructure, and homes. The ecological dimensions of wildfire are manifested by fire frequency, behavior and size. The next section will examine some of the dynamics of this two-process system.

The City-Wildfire Relationship

Many of the natural landscapes of the American West, South-West, and Florida include fire as an emergent property of ecological self-organization at many spatial and temporal scales. Fire promotes succession by triggering the seed germination of some species, and clearing the land for pioneer annual plants. The scorching of a forest and chaparral leave some dead wood standing, making new habitat for raptors and small mammals. Historically these fires were triggered by lightning and would burn until they ran out of fuel or they became extinguished by the accompanied rains. Typically each region has a fire regime which operates on a cycle, dependent on the dominant habitat type. The cycle is generally different for the size of the fire as well. For example, large fires in chaparral, the dominant vegetation type of Santa Barbara, California, occur every 10 – 25 years, while small fires (< 1 acre) can occur frequently during the dry months of the year. When a large fire burns, its movement is determined by the winds, fuel load and slope of the surroundings. If the winds are strong enough, spotting, can occur. Fire spotting is the process of an ember, blown by the wind, starting a new fire up to a kilometer away from the "mother" fire.

Humans have changed the natural fire regime. Since we view the natural landscape as an economic resource, our shepherding of nature has been paramount to fire policy. The buildup of kindling and fuel has led to an altered fire regime for most areas. The result of this is a stochastic periodicity and a better fueled fire, with a behavior no less predictive. The prescribed burn policy of government agencies has possibly done some good in re-establishing the natural fire regimes, although there is clearly a lack of deep understanding of the system. This is evidenced by the ignition of fires in weather where they never catch hold, or of the wrong scale (possibly too small). The lack of understanding is further evidenced by the recent fire started in the Bandelier National Monument in New Mexico, which burned hundreds of homes in Los Alamos, including some structures of the Los Alamos National Laboratory (luckily, no buildings where fire is modeled were burned.)

Urbanization is a complex process as well. Urban areas grow in many ways as they age, such as economically, socially and spatially. Spatial urban growth occurs by the construction of urban structures in commercial and residential zones. The spatial distribution of new zones is dependent on the distribution of the existing zones, the economic and social drivers of the region, the geography of the region, as well as the area's topography.

As the acres of the natural landscape become urbanized, there are some neutral and positive feedbacks that create better fire conditions. As cities grow, pockets of non-urbanization remain. Examples include parks, nature preserves, and conservation easements. Urban areas are usually not built on steep slopes, due to building and insurance costs. These small refugia of native habitats are becoming increasingly biologically valuable and the need of fire is retained along with the biota.

The development of infrastructure to support the city can lead to wildfires. Simple observations of ignition points of wildfires correlate to road proximity. A cigarette, a spark from metal-on-concrete, or a forgotten campfire ember can be effective in starting a fire in ideal wildfire conditions. An arsonist from the nearby city can do similar damage. Another example of activities which can promote wildfires is the use of fire-prone landscaping near the urban fringe. The use of these plants (usually non-native) allow a wildfire to easily spread into an urban area.

Most of the behavior change of the urban areas occurs after a fire. The learning comes in the form of human behavior change. This includes the system of fire-fighting, often consisting of volunteers, who gain respect in the community for their actions. As a way of dealing with family separation as a result of the recent Los Alamos fire, a volunteer website was developed which retained a database of rescue shelters and their temporary inhabitants. In the Santa Monica Mountains of California, Los Angeles Department of Fire has started a nursery of fire-resistant and drought-tolerant native plants, handed out free to county residents. There are changes in building and landscaping code and pre-fire "management" techniques put in place. Rarely does the burnt city opt to not rebuild the burnt dwellings and build somewhere else, however. Private landowners' desires and insurance companies' deep pockets facilitate the re-building.

Other disasters can force cities to adapt the behavior of re-building. In coastal areas, insurance companies and federal agencies refuse to pay for building sea walls for cliffside homes. As a result, the houses fall into the sea, or in Isla Vista, California, the houses are destroyed and the cliff is turned into a park. Elsewhere in California, a landslide in La Conchita entombed a handful of homes. The area is condemned and will not be restored.

Modeling the co-evolution

One way of examining the spatial interaction of these two phenomena is through temporal modeling in a Geographic Information System (GIS). The relationship can be better understood through simulating the competing processes of these phenomena. For the urban modeling a CA-based model is employed. The Urban Growth Model (UGM) (Clarke, Hoppen, and Gaydos 1997) calibrates the historical behavior of a city and applies the parameters of calibration to four growth rules which affect the city's response to slope, roads, dispersion, creation of new spreading centers and edge growth.

A CA-based fire model is used to model wildfires as well (Clarke, Brass, and Riggan 1995). This model operates on a different time scale (hourly instead of yearly) and takes wind, slope, soil moisture and vegetation type into account. Fires are started from user-defined ignition points and then allowed to burn until they extinguish themselves. The fire organism is generated by the ecological processes which promote fire. Other parameters, fire regime and successional stage for example, are important properties of the ecology and contribute to the expression of wildfire.

Santa Barbara, California , was used as a study site due to its rich historical fire and urban datasets and large amounts of wildfire damage in its history. The infamous Painted Cave fire burned many homes and caused millions of dollars of damage in 1990. The Painted Cave fire was notable for burning lemon groves and jumping US-101, a four-lane highway and a major transportation artery for the South Coast.

In order to examine the relationship of the dynamics of wildfire and urban growth, the systems will be coupled in a number of ways.

1. The first method does not use the fire model. It relies on the urban growth model to fill in the missing temporal urban data with output from the model's calibration stage. These "backcasted" timesteps will be intersected with the historical fire extents, producing the fire-urban spatial intersection from 1929 to 1997. This method will produce the spatial extent and frequency of the urban-wildfire competition. Urban areas which were burned more than once will be identified as well.
2. The second method of linking the two models will be in running UGM in calibration mode, but allowing the historical fires to remove the urban pixels as they are burned. Those pixels will be allowed to re-urbanize, but the effect on the model parameters will be taken into account. The urban predictions can then be run and the difference between the fire-calibrated run and the non-calibrated run can be observed as Santa Barbara grows into the future.
3. In a "alternate future" modeling scenario, the Urban Growth Model can be calibrated with the fires burning Santa Barbara as they occur, but this time, the city will be forced to "learn" - it cannot grow back where it has been burned. The difference between the "intelligent growth" and the present day urban extent can be explored as well as the differences in predictions. In examining an alternate present of Santa Barbara, one that has learned from wildfires, the differences in city shape and behavior can lead to different implications about how cities can behave.
4. Using the fire-calibrated urban parameters, Santa Barbara growth is simulated into the future. In-between each annual time step, the fire model can be applied to the landscape, using the historical ignition points for starting fires. The fire model does not force all fires to start, but is dependant on the environmental conditions. Since climatic conditions and fuel load vary throughout the year, choosing the time of year to seed the ignition points will be an issue. At first, it might be best to use the historical ignition points for dates in the Julian calendar to ignite fires.
5. Currently there is research on developing good fuel models for fire models and fire hazard assessments (Regelbrugge and Conard 1996). Most of this effort has been in determining the differences in fuel loads and moisture contents of different types of plants, native as well as non-native. Little of this effort has included modeling the fuel load of human dwellings. After running a simulation of Santa Barbara urban growth, the new and existing urban areas could be tested for fire danger. The urban pixels could be given surrogates for fuel load and fires could be ignited near the homes. Scenarios could be run with high urban fuel loads - reflecting poor management, or low fuel loads - reflecting intelligent choices of material and landscaping were used. In addition, fires could be started inside the urban boundary, employing the model as an urban fire model as well. The expense of fire would be calculated from the 1997 property values associated in the urban database.

This study in modeling may lead to some insight into the following questions:

1. Can urban-wildfire co-evolution be observed and tested in a spatial setting?
2. Fires change a city's behavior by establishing zoning and building codes, as well as rules for landscaping. Which new emergent properties be detected in the urban-wildfire system? At what spatial and temporal scales is it visible? Is there "collective intelligence" in this co-evolved system?
3. From the use of a coupled urban-wildfire model: Is there a distance effect? Do burned pixels in one area affect the behavior of another urban area in the same city?
4. Can the study of this coupled system lead to observations about each system that are non-observable on their own?
5. How do cities organize themselves in a disaster, with respect to information and disaster management? Which forms of mitigation are effective?

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Research Abstract
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My broad interest in complexity theory and agent-based modeling arose in response to a growing dissatisfaction with the traditional tools of international relations and political science--especially in how my discipline deals with change and evolution. Thus, in graduate school I embarked on a broad research project (one on which I am still working) that explores ways in which the insights and tools of complexity theory can improve upon and complement examinations of world politics.

This broad research interest sparked the specific work of my dissertation--"Going Global: The Complexity of Constructing Global Governance in Environmental Politics." In it, I applied the insights of complex adaptive systems research to the evolution of international negotiations surrounding the ozone depletion and climate change issues. I utilized complexity theory to construct an analytic framework useful for structuring case studies in addition to two agent-based models. One of the agent-based models explored the emergence of norms and the other was a more detailed model that examined bargaining between 'Northern' and 'Southern' agents over environmental issues.

In my more recent work, I have concentrated on the model of norm emergence and evolution. I've improved and extended this model in an attempt to address some fundamental questions about norms that have puzzled both economic and sociological approaches--namely, how do specific norms arise and how do norms change over time.

The other aspect of my modeling work arises from my association with the Center for the Study of Institutions, Population, and Environmental Change (CIPEC). I began working there in fall of 1998 as a visiting scholar. I worked on developing our prototype model and with the team that put together the National Science Foundation grant proposal that was eventually funded under the ``Biocomplexity in the Environment" initiative:``Biocomplexity in Linked Bioecological-Human Systems: Agent-Based Models of Land-Use Decisions and Emergent Land Use Patterns in Forested Regions of the American Midwest and the Brazilian Amazon." (A participants list is available at http://www.cipec.org/research/biocomplexity/participants.html.) In Spring of 2000 I continued work on the project as a post doctoral research fellow and since January of 2001, I have been a participating scientist on the project. The first paper to detail the prototype model and its results is: Matthew Hoffmann, Hugh Kelley, Tom Evans "Simulating Land Cover Change in South-Central Indiana: An Agent-Based Model of Deforestation and Afforestion." It is currently being considered as a chapter for a volume being edited by Marco Janssen.

For more information on this project see Dawn Parker's research abstract.

Spatially Explicit Multi-Agent Modelling of Land Use Change in the Sierra Madre, Philippines

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Introduction

Land use in tropical regions such as the Sierra Madre in the Philippines is influenced not only by proximate actors such as farmers or loggers but also by many others such as government agencies, NGOs, absentee landlords, banks and politicians, who exert many influences on the proximate actors and on each other. In order to "socialize the pixel", i.e. to make the connection between social science and the "GIS-based" land use models of geography, the ensemble of these actors can be represented in a multi-agent model. This project aims to do so in an empirically and theoretically valid manner, following the basic structure of the 'Action-in-Context' framework (De Groot 1992).

The goal of the PhD is the design and implementation of a computerized structure that catches the basic causality of land use change in the Sierra Madre in a spatially explicit manner, while yet remaining sufficiently connected to real-world phenomena and social science theory. This implies that the gap has to be bridged between, on the one hand, the great modeling power (but weak validity) of present-day computer science and, on the other hand, the theoretically sound, quantitative models from social sciences such as micro-economics and social psychology that are as yet not spatially explicit and do not contain the many types of actors interacting in actual land use changes.

Region

The region of focus will be the Sierra Madre in the Philippines, characterized by a high diversity in land use types and processes of change. The project will use an "available" multi-agent modeling platform, adapt this so that it comes closer to social-scientific theory of agency and inter-agent connectivity, and validate the model through field work. The modelled structure of the environment will be put to work in a number of small areas of 1 to 25 square kilometres.

Agents

The agents are the Farmers and loggers, the direct ('proximate') actors in tropical land use change. Focusing on these actors only, however, does not give insight in the crucial role of numerous other actors that co-determine what farmers and loggers do, such as government agencies, traders, landlords etc. that are causally linked to each other and to a next ('tertiary') layer of actors that may in fact be even more responsible for what in fact happens in the forest lands, such as the legislature, manufacturers or consumers of forest land products.

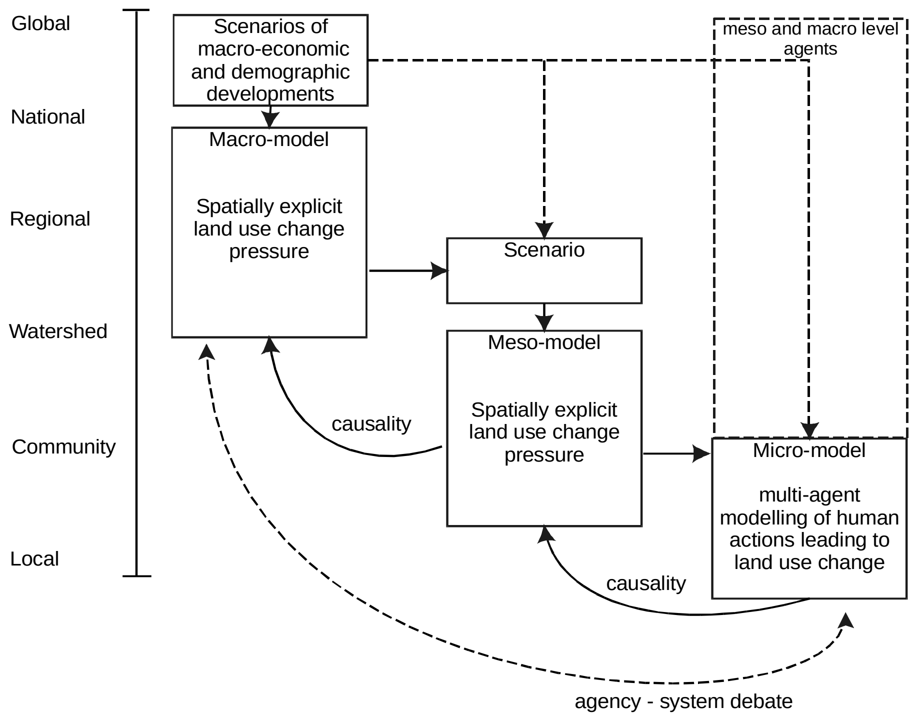
Based on previous research in the area (e.g. Van den Top 1998), candidates for primary and secondary actors are, for instance, maize traders, logging crews, Agta hunter-gatherers, furniture industrialists, the ministry of the environment and forest (DENR), the ministry of agriculture (DA), local and supra-local politicians. All in all, then, there will be a maximum of approximately 16 agents connected to each pixel, part of which will represent generalized actor categories.

The most pertinent type of interaction between agents in the model will follow the principle of the 'actors field' in the Action-in-Context framework. This type of connection is that the options, outcome or weights on criteria (hence the choices) of the proximate agents (in this case, the farmers) are influenced by the choices of secondary agents, e.g. the DENR field officials who may choose to fine small-scale logging activities and confiscate their illegal logs, or traders who may decide to accept a promise to plant maize as a collateral for credit. Next are the tertiary agents such as the local politicians who influence the DENR field officials and so on; such an actors field may include agents up to the national and international level. Thus, the land use actions of the farmers become actions-in-context. Besides these 'vertical' interconnections that express the lines of power surrounding local land use, there exists a class of 'horizontal' interconnections between agents of largely the same level (primary, secondary etc.). Farmer agents, for instance, may learn from each other, imitate each other or coordinate actions. This is the type of interconnections that gets most attention in the majority of current multi-agent models, that are usually interested in game theory or the emergence of collective action. The model of the present project will put the 'vertical' interconnections first, however, for reasons of scientific innovation but also of empirical relevance. It is felt that the power field surrounding the land use choices is more salient in the actual land use decisions. They are also more policy relevant, for obvious reasons.

The research program

Being embedded in the program (http://gissrv.iend.wau.nl/~clue/philippines/intro.htm) as a whole is of great value to this project, and in return the project adds to the program as a whole. One aspect of this concerns the upscaling steps of the model; The project will receive important information from the meso and macro-scale projects (CLUE) ‘downward’ in terms of the various driving factors that are important for the options and/or motivations (hence the choices) of actors in the multi-agent model. Examples of this are shifts in demand and prices, shifts in logging policies, the construction of rural roads, tenure policies that change the motivation of actors to invest in the land they work, etc.; the information may represent actual or predicted developments, or policy scenarios. From the project ‘upward’ into the meso and macro-scale projects, the causal structure of the model (both the way the agents are modelled and the way they are interconnected) will support the quality of the causal structures as that are modelled at the meso and macro scales, for instance in the regression analyses. The same bottom-up interaction concerns the possibility to assess the causal status of statistical relationships found at these scales.

Being actor-oriented throughout, the ‘micro-project’ is truly micro in that it conceptualizes the world as an assembly of actors, but not truly micro in terms of spatial scale, because some of its actors are ‘macro-actors’. The programme thus yields a fairly unique opportunity to compare the ‘system’ and the ‘actors’ conceptualisations of the world at work on the same scale connected to the same problem. The figure below, representing the program and the multi-agent project embedded in it, shows the most important of these interactions.


Global
National
Regional
Watershed
Community
Local
Scenarios of macro-economic and demographic developments
Macro-model
Spatially explicit land use change pressure
Scenario
Meso-model
Spatially explicit land use change pressure
meso and macro level agents
Micro-model
multi-agent modelling of human actions leading to land use change
causality
causality
agency - system debate

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Research on Agent-Based Interactions

My research focuses on spatially disaggregate, economic models of land use conversion and household location patterns. My main research interest with respect to agent-based interactions has been on the empirical identification of interactions among landowners who convert their land to development and the role of these spillovers in generating "sprawl" patterns of development. A secondary research focus has been on the development of a cellular automaton that simulates the net effect of negative endogenous interactions among developed land parcels and the positive, attracting effects of a city center and built infrastructure (e.g. roads). My current research interests include the development of an agent-based model of urbanization in which environmental amenities (such as open space and water quality) are endogenous to household location. In what follows, I elaborate on each of these research areas.

Identification of Interaction Effects Among Agents

Manski (1993, 1995), Brock and Durlauf (2001), and Moffitt (1998) have given serious attention to the challenges involved in identifying interaction effects among agents within a regression context. This work discusses three major identification problems that arise in testing for the presence of interactions among agents: the simultaneity problem, the endogenous group formation problem, and the correlated unobservables problem. My research on identifying the spillover effects among developed land parcels has focused on the problem of unobserved spatial correlation in a discrete choice, duration modeling framework. An identification problem arises here because omitted spatial variation leads to correlation between the error and interaction terms, which biases the interaction estimate upwards if uncontrolled.[1] As a result, a positive interaction effect may be estimated even in the absence of such any interaction. Solving this problem for cross-sectional models and discrete choice models is difficult. Solutions that have been proposed in the literature include assigning an upper bound to the interaction effect, using instrumental variables or related approach called a partial population identifier, and conditioning out the unobserved component using an analog of a fixed effects approach for discrete choice models. Irwin and Bockstael (2001a) use the strategy of bounding the interaction effect to identify negative interactions among developed parcels, which offers one explanation for sprawl development. In related research, Irwin and Bockstael (2001b) and Irwin (2001) use an instrumental variables and partial population identifier respectively to identify the effects of open space spillovers in a hedonic model of residential property values.

Cellular Automaton Model of Development

Irwin (1998) employs cellular automaton to explore the evolution of regional patterns of development with a negative interaction effect among developed parcels and offsetting positive spillovers from a city center and other built infrastructure, all of which decay over distance. Parcels are represented by cells arranged on a two-dimensional square lattice and each parcel

[1] This same problem arises in the literature on own-state dependence over time, which seeks to separate "true" temporal state dependence (e.g. habitual effects) from "spurious" state dependence (Heckman, 1978, 1981).

takes on only one of two states, undeveloped and developed. The growth parameter and unit of time are defined such that one parcel is developed in each time period. Agents form expectations over the returns to converting by considering the location of the parcel relative to exogenous features and the amount of development that surrounds the parcel in the current period. Agents are assumed to be myopic in the sense that they do not attempt to forecast future changes in their neighboring land use patterns. Once converted, the expected costs from re-converting a parcel back to an undeveloped state are assumed always to exceed the returns of re-conversion, so that development is effectively irreversible. Multiple simulations are performed by altering the distance decay parameters that govern the relative strength of the negative and positive effects. The results demonstrate that varying degrees of clustering and fragmentation emerge, depending on the relative values of the neighborhood interaction and other parameters. In particular, they identify the minimum threshold value required for the negative interactions to generate a sprawl pattern of development.

Irwin and Bockstael (2001a) use a cellular automaton to predict patterns of land use change using estimated parameters from an empirical model of land use conversion to calculate the transition probabilities for yet undeveloped parcels. Because the development spillover is endogenous, these probabilities are then updated with each round of development.

Agent-Based Model of Urbanization with Endogenous Environmental Amenities

The development of this model is still in the very formative stages and is joint work with several others. Initially we are developing a simple model of household location within a region with a given distribution of employment, infrastructure, and environmental resources. Households are differentiated by income and preferences over access to employment and environmental quality. The system evolves with new population being added in each time period and the relocation of existing households, based on utility-maximizing behavior. Environmental quality, which is specified as water quality and surrounding open space, is endogenous and acts as an attractor. A primary goal of this modeling effort is to work with biological and physical modelers to develop an integrated and dynamic model of the human/biological/physical systems associated with Lake Erie. Extensions of this model will include making roads, employment, and public services endogenous to household location, so that the entire urban spatial structure of the region can be modeled in a dynamic framework. Ultimately this modeling effort will seek to explain the endogenous interactions between household location and environmental quality, redistribution of population from a city center to suburbs and exurbs, the formation of edge cities, and the fragmented pattern of exurban residential development within a region.

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Current research related to agent-based modeling of land-use/land cover change

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My research in this area mainly focuses on methodological aspects on how to model the interactions between people and nature. These methodology studies are not restricted to LUCC but cover ecosystem management in general. A common element in the ecosystems of interest is the possibility of abrupt shifts among a multiplicity of very different stable domains. Multiple states have been observed in fresh water systems, forests, fisheries, semi-arid grasslands, and interacting populations in nature. Whether and when an ecosystem suddenly flip from a productive and sustainable state to an unproductive state depends on ecosystem management. Ideally resource managers strive to maintain the resilience of the system, that is they minimize the probability that the system flips to another state due to a perturbation (for example, fires and weather extremes). Most of the research is inspired by my participation in the Resilience Alliance (http://www.resalliance.org). I will briefly discuss three topics. For publications on the various topics I refer to my website.

Management of Ecosystems

Within the context of the Resilience Alliance I developed with others various stylized models on the interactions between resource managers and ecosystems like lakes and rangelands. The questions is how resource managers can learn to maintain the resilience of the system, or which type of resource managers are most likely to maintain resilience. One of the key-papers was a study where a number of properties (100) of rangelands were managed by particular types of pastoralists. The ecosystem characteristics were equal for all properties as well as the rainfall and the wool prices. But the characteristics of the pastoralists differ (lifestyle, knowledge, management style). When pastoralists do not earn enough income, they leave the system and one of the other pastoralists or a random new pastoralist starts to use that property. The question was what type of pastoralists would evolve for different types of governmental regulations (drought relief/conservation).
In current experiments we use genetic algorithms to find robust management strategies for rangelands, and explore the impact of spatial heterogeneity (leaving the mean-field assumption behind by simulating moving sheep) on the resilience of the system.

Cognitive strategies

Together with Wander Jager, social psychologist from the University of Groningen in the Netherlands, the consumat approach is developed (http://go.to/consumats). This is a multi-agent approach of individual decision-making based on a multi-theoretical framework of psychology. One of the main points is the distinction of different types of cognitive processes based on whether the agent is satisfied or not and whether the agent feels uncertain or not. We distinguish four types of cognitive processes: repetition, deliberation, imitation and social comparison. One of the current activities

is the development of a simple artificial world where agents with different cognitive strategies can live, die and reproduce. The question is to understand in which conditions agents use different types of cognitive strategies. Since cognition is limited, we can not deliberate for each decision, so it is economically rational from a cognition point of view to use other cognitive strategies like imitation and repetition. But differences in cognitive strategies can have important consequences for the type of resource use. In various papers we analyzed the different consequences of assuming Homo Economicus (only deliberation) and Homo Psychologicus (four different strategies).
In a recent study we use data from laboratory experiments on common pool resources from Indiana University. The predicted Nash equilibrium was not found in the experiments with real people, but economic models can not explain the experimental data. We use the consumats to understand what assumptions do we have to make to replicate the statistics of the experimental findings. The assumptions relate to the importance of the cognitive strategies, social orientation (cooperative and competitive attitudes) and the need for experimentation.

Institutions
A recent interest is the development of rules between people. I had for a long time problems to capture this topic, but I came across with the research on artificial immune systems and came to the conclusion that an immune system perspective might be a helpful metaphor. Together with PhD student Daniel Stow a conceptual model is developed to study the evolution of rules. How are they coded, created, get selected and be remembered. The next step will be the developments of a stylized model to study self-organization of rules. This might be based on the model I am developing with Elinor Ostrom from Indiana University. This model simulates a population that build up mutual trust relationships and may accept the implementation of a candidate set of rules. Furthermore, once the rule is implemented the agents can break rules, monitor and sanction. This model version only looks at the selection of a candidate rule set, and we want to understand the critical factors that foster self-governance of common pool resources. Maybe we will do an implementation of this model for the Pacific islands Mangaia and Tikopia, who have an interesting archeological record.

As one recognized my works is very methodological. I think that we need still to do a lot of work on the development of simple models of agents that are acceptable for behavioral scientists. Most of the agents in multi-agent models are rather simplistic and not very well based on theories in social science. The challenge will be to develop simple stylized models, to test hypothesis with them in the laboratory and to test the consequences of different assumptions with real field data.

What phenomenon can be addressed by agent-based models that cannot easily be addressed in other LUCC modeling frameworks?

Heterogeneity of the agent population leads to very different types of dynamics compared with the representative agent model. Sometimes we can mimic observed patterns by the representative agent, but we often have to make strict assumptions related to homogeneity and mean field equations. But, when agents differ, imitate each other, interact, have complex social relationships by social networks than the results of social processes can be very different than ordinary models.

How can cellular automata and agent-based models be combined to explicitly represent the complex dynamics of landscape systems?

Some, not all, models are developed in Cormas (http://cormas.cirad.fr). The cells represent the environment, often based on differential equations. The agents are the topic of research, and are represented as mobile agents. Agents can move and eat. How and when they move and eat relates to the decision process implemented for the agents, and to which rules affect the behavior of the agents.
The interaction between agents and the environment related with the energy/nutrition agents derive from the ecosystem.

How might we parameterize models and understand model behavior?

Since my models are often very stylized, I tend to define a default case and perform a lot of sensitivity tests. The default case can be, for example, lead to cooperation of the agents, and with sensitivity tests we want to understand for which parameter changes the agents will not be willing to cooperate anymore. Obviously, each experiment contains many runs due to stochastic elements of the model. It is also helpful to use an analytical version of the model using a representative agent to put the results in context with traditional models.

Validating model outcomes – How can we construct and carry out empirical tests of model hypothesis?

One of the items high on my wish list is to use agent models to formulate a number of hypotheses and test these in the laboratory. A problem with human agents is that there are no general well-accepted agent models. So, tuning an agent model to data is not enough. But, like classical laboratory experiments try to falsify theories, we may try to falsify the agent models. Of course, when the agent model pass the test it is not valid, but at least not falsified.

Infrastructure development – What is available in terms of research tools, infrastructure for sharing scripts, techniques, and learning resources, and opportunities for collaboration? What enhancements are needed?

Currently I use the Cormas software (based on Smalltalk). Cormas is very easy to use for little models with CA and MAS. But it is slow when you want to do many experiments. Probably I will explore Java too, especially since the new version of Java is not purely an interpreter anymore.

Integrated Assessment and Projection of Land-Use/Cover Change in the Southern Yucatán Peninsular Region of Mexico

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Associated with the NASA funded LCLUC-SYPR project (http://earth.clarku.edu).

Keywords: ADSS, agent-based dynamic spatial simulation, cellular automata, deforestation, cultivation, agriculture, geographic information science

Broad research goals: This research develops a scenario-driven integrated model to project trends of tropical deforestation and cultivation and their effect on carbon sequestration in the southern Yucatán peninsular region of Mexico. The study is conducted as an integrated assessment: it is policy relevant global change research that addresses the complex interactions among socioeconomic and biophysical systems. The research addresses three themes: 1) the distinct temporal and spatial patterns of deforestation and cultivation; 2) the complexity of, and relationships among, socioeconomic and environmental factors and 3) the value of information and the role of uncertainty.

Geographical area: the southern Yucatan peninsular region in Mexico. The study site is roughly 18000 km^2 with about 30 000 inhabitants in over two hundred settlements.

Temporal period: 1970 to 2010.

Spatiotemporal resolution: varies, most typical simulation runs are at a spatial resolution of 900 m^2, 10000 m^2, or 1 km^2. Temporal resolution is generally a one model year iteration, although longer intervals are modeled to reduce computational periods and shorter periods are possible.

Agent decision making factors: broadly speaking, the model draws together several bodies of theory to create a conceptual framework from different disciplines by considering land-use/cover change as the result of land manager decision making in the context of the biophysical environment and socioeconomic institutions. Decision making is largely within a rational actor framework with bounded rationality extensions. While many institutions are at work in the southern Yucatan peninsular region, the model focuses on large scale land tenure, subsidies, and the market. Ecological modeling focuses on secondary succession, pest invasion, and changes in agricultural suitability. Other, more static, factors include slope, aspect, precipitation, hydrology, and infrastructure.

Actors and types of land-use/cover change modeled: largely deforestation and attendant cultivation. In addition to the institutions mentioned above, the model focus on land-managers, generally small holder farming household, with some exploratory extensions to rancher and intermediaries seeking to facilitate new kinds of production.

Methods: The prototype simulation model couples an agent-based model and generalized cellular automata to create an agent-based DSS, or ADSS. Agent-based approaches are used to combine empirical and theoretical models of actor behavior in resource-use situations and are used here to embody the actor and institution components of the conceptual framework. Decision making analogs include simple heuristics, estimated parameter models, and genetic program approximations of bounded rationality. The use of cellular automata in ecological models suggests the use of generalized cellular automata to represent the environment. By coupling generalized cellular automata and agent-based models, the ADSS is a good means of operationalizing the actor-institution-environment framework and offers a powerful approach to understanding and projecting environmental change.

Calibration/Validation: The model is calibrated and validated with remotely sensed imagery and socioeconomic data, namely household surveys, archival research, and geographic information system layers of land-use/cover and biophysical characteristics derived from satellite imagery and other spatial data. The bulk of this data is from the larger LCLUC-SYPR project of which the PI is part. A suite of validation techniques is employed, including Kappa Index of Agreement, fractal dimension, contagion , a multi-resolution goodness of fit metric, and a Monte Carlo uncertainty analysis.

Linking Agent Models and Controlled Laboratory Experiments for Managing Community Growth

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The increasing concentration of human activity has led to significant impacts to the ecological health, quality of life and economic vitality of communities. Indeed, in many cases growth threatens the very amenities that attract people to an area in the first place. The rapid pace of growth is the result of numerous, often small scale land use changes occurring over time. The *cumulative* impact of these diffuse land-use changes can be extremely high when one considers a watershed or landscape scale.

Agent models provide an excellent organizing framework for modeling decisions that determine land use change in the community. The results of computational models provide insights into the underlying structure of systems, and models are often validated by comparing outcomes of simulated systems to actual outcomes. However, empirical validation of agent models faces the considerable challenge of separating the multitude of endogenous interactions among agents from observationally equivalent exogenous landscape and ecological features that influence development decisions. So there are profound limitations to the use of field data as a basis for analysis and validation of agent models.

Experimental methods are a promising avenue for augmenting field data in validating agent models. In the laboratory one can combine a known structure with interactions among actual decision makers brought into the lab. In this sense the experimental environment represents a middle ground between pure computer simulation models and analyses based on field data. Indeed, use of a controlled laboratory environment allows an entire spectrum of analyses, from fully specified computer-generated structure and parameters, to an indirectly observed structure of endogenous interactions among participants, similar to those faced in analyses based on field data. Therefore, augmenting analyses of field data with analyses of data generated under controlled laboratory conditions allows us to better understand the structures underlying decision making processes and the effectiveness of computational tools to identify underlying structures at varying levels of complexity.

This projects links computer simulations of agent behavior with behavior of agents in controlled laboratory experiments. We use CommunityViz® software (WWW.Orton.Org/CommunityViz), to simulate development under different policy scenarios. CommunityViz is an extension to ArcView® GIS (WWW.ESRI.Com), and is made up of three components: Scenario Constructor, Town Builder and Policy Simulator. Scenario Constructor extends the capability of standard GIS software. Town Builder creates 3D renditions that allow interested parties to better visualize growth scenarios. Policy Simulator uses an agent-based model to forecast growth community growth under alternative policy scenarios.

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We propose to augment and calibrate agent models using a controlled laboratory environment using the new Policy Simulation Laboratory (SimLab) developed by the Department of Environmental and Natural Resource Economics at the University of Rhode Island (www.uri.edu/cels/enre/preview/SimLab). The SimLab is a world class facility for research that integrates science and decision making. It is comprised of computer systems and audio-visual equipment housed in a group of electronically networked rooms. The facility includes a Policy Simulation room, a Presentation Hall, two Group Decision rooms and a Geographic Information System (GIS) laboratory. The core of the facility is the Policy Simulation room, which contains a network of 26 computer workstations and advanced audio-visual capabilities used to create simulated decision environments. The Presentation Hall is a 125-seat auditorium with in-seat voting capabilities and advanced audio-visual aids. The two Group Decision rooms are conference rooms where participants make decisions while interacting face-to-face, and with notebook computers that are networked with the other facilities. The existing University of Rhode Island Environmental Data Center (EDC), an advanced GIS laboratory, is also networked into the system with a gigabit Ethernet connection.

What makes this facility unique is the close interconnection of the system components, which together comprise an integrated decision research tool. For instance, the group decision rooms might each house a team of policymakers designing proposals for community development. The SimLab and GIS computer systems translate the development plans into resultant impacts to the natural and human environment, and create GIS maps indicating consequences of each proposal for water quality and for fragmentation of natural ecosystems. Simultaneously, audio-visual systems are used to present these management plans and their consequences to “voters” in the Presentation Hall, who then vote on the proposals. Policy makers in the group decision rooms could then obtain real time feedback regarding fiscal, social and environmental implications, as well as voting results, and revise their plans in response.

In the SimLab, real people play the roles of agents by being placed in simulated decision environments, with actual rewards and penalties assessed just as they are in real decision environments. This simulated decision environment represents a middle ground between studies of decision makers in uncontrolled field conditions, and computer simulations that provide complete control over system structure and response. As such, it will provide insights into decision processes whose structure is too complex for estimation with field data, while still including *real* decision makers making choices in response to incentives and constraints. The system also allows one to assess the performance of institutions that may not exist in the real world, to observe and/or control factors in ways not possible in field analyses and to test the effectiveness of estimation techniques designed for use with field data.

Research Activities Related to Multi-Agent Systems Models of Land Use/Land Cover Change[1]

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http://php.indiana.edu/~dawparke/

My interest in spatially explicit agent-based modeling developed as a result of a specific research interest in distance-dependent spatial externalities. An ``externality" in the economic jargon is a positive or negative economic impact 1) that results from the actions of a particular economic actor; 2) that has economic impacts on someone other than the actor instigating the impact; and 3) whose ``external" costs are not taken into consideration when the instigating actor makes the decision about the generating activity. My research specifically focused on negative externalities whose impacts decay and may become negligible with distance, such as pesticide drift. Drawing on parallels with ecological edge effects in landscape ecology, I quickly realized that when these externalities are present, some configurations of land use may be more efficient from an economic perspective than others. Further thinking quickly suggested that initial conditions of land use may impact whether an unregulated economy would develop an arrangement of land uses that was economically efficient.

It became apparent that analytical techniques were not well-suited to examine this particular research question, due to the high degree of spatial interdependencies and induced spatial heterogeneity that these externalities imply. As a complement to an initial analytical model, I developed a cellular automaton, agent-based model to represent the key components of the system. This model meets the definition of a cellular automaton in the sense that each cells contains a single, identical, immobile decision maker, and the rules available to decision makers are identical. Each agent/cell is potentially impacted by a spatial externality generated by only immediately neighboring cells. However, the model meets the definition of an agent-based model in the sense that the decision rules used by each agent consist of an intelligent decision-making process, whereby agents use a traditional profit maximization algorithm to choose between two possible land uses. A key feature of this model is an endogenous price for the outpur from one land use (designed to represent a niche market). This endogeneity provides sufficient structure to the model so that both land uses are represented in any economic equilibrium, and the assumption was appropriate for the particular case study for which the model was designed. I have used this model to demonstrate that stable inefficient patterns of land use are possible in an unregulated free-market setting, and that initial conditions influence the final outcome. Further, I have used the model to demonstrate key interactions between transportation costs (an agglomeration mechanism) and negative spatial externalities (a dispersal mechanism). The model and results are described in Parker 1999. The model was create in Mathematica, and the code is available on request. A slightly refined version of this paper, and a discussion of empirical analysis on the locations and patterns of production of certified organic farming operations, are presented in Parker 2000.

Recently, I have used an expanded version of the same model to explore the relationship between economic processes and landscape pattern, with the goal of identifying landscape pattern as a possible emergent outcome in explicitly spatial models of landscape processes. The model has been expanded to include representation of a more flexible range of spatial externalities. In its current form, either of two possible land uses can generate both positive and negative externalities to either or both uses. I have also updated the model to produce a set of landscape metrics that measure pattern outcomes. A paper based on this model [Parker et al. 2001] was presented at this year's Society for Computational Economics annual meetings.

Since January, 2001, I have been involved as a Participating Scientist in a National Science Foundation grant funded under the ``Biocomplexity in the Environment'' initiative: ``Biocomplexity in Linked Bioecological-Human Systems: Agent-Based Models of Land-Use Decisions and Emergent Land Use Patterns in Forested Regions of the American Midwest and the Brazilian Amazon.'' (A participants list is available at http://www.cipec.org/research/biocomplexity/participants.html.) The goal of this project is to create an integrated socioeconomic and biophysical model of rural land use in South-Central Indiana. An agent-based model is being developed to represent the land-use decisions of rural land-owner households. Through a geographic information system, this decision-making model will be linked to a biophysical forest growth model, information on topography, hydrology, transportation network, soil conditions, and other relevant biophysical and infrastructure factors. Thus, interactions between the socioeconomic and biophysical systems will be endogenized. We are developing historical GIS layers that will be used to validate model performance. Concurrently to developing the agent-based model, an econometric model of the region is being developed. This model will both inform development of the agent-based model and allow for a comparison between the two modeling techniques. Further, we also plan a series of related economic experiments, which will test our assumptions regarding agents' decision-making processes and further inform model development.

Our agent-based model is designed to compare a series of preference specifications, information processing abilities, decision-making strategies, and learning models. A preference specification will be used to evaluate agent well-being for any decision-making strategy. This specification is based on a modified economic household decision framework, and consists of a definition of goods (for our model: intertemporal leisure, consumption, residential housing, aesthetic and recreational benefits from land use); a particular mathematical functional form that may reflect risk preferences; constraints on available labor, land, and the household's budget; influences of other agents (ie, altruism, spatial spillovers, etc); and exogenous factors such as production and price parameters. Agents will vary in their ability to process information in two dimensions. Their time horizon may vary from completely myopic to infinitely forward looking. They may also vary in their ability to discern information, from receiving a very noisy signal to perfectly receiving information signals. Agents may use a variety of decision strategies: the pure mathematical optimization of Homo Economicus, boundedly rational optimizing search strategies, and heuristic rule-based decision strategies. We also plan to compare a variety of learning models, including Bayesian learning, neural network models, reinforcement learning, and genetic algorithm models

While substantial endogeneity will be build into our model, certain factors, such as climate, will always be taken as exogenous. Initially, political factors and demographic influences may be exogenous. However, we are exploring possible approaches to modeling the endogenous development of institutions. Within the economic module, prices and wages will be modeled as exogenous. However, modeling of endogenous land markets is a high priority. A vegetation growth model will reflect interactions between agent decision making and the biophysical state of the landscape.

We have developed a list of key questions that our modeling efforts will address:

1. How do individuals make labor allocation, production, consumption, and investment decisions in risky, multi-asset environments?
2. What factors affect individual preferences and actions related to land use?
3. What is the impact of landowner actions on the landscape?
4. How do socioeconomic landscape patterns and ecological landscape patterns interact?
5. How does a change in land use in one location influence the probability of a change in land use at a neighboring location?
6. What is the role of scale in the observed changes in land use in southern Indiana?
7. What are some key ways of testing our theoretical models? How do initial assumptions impact model outcomes? Can differing assumptions lead to observationally equivalent outcomes?

We plan to focus empirical evaluation of the model on comparison of landscape composition and pattern between generated and actual landscapes, as argued for in . We also plan substantial comparisons between our MAS models and spatial econometrics models.

Questions of model platform, accessability, and software remain open at this writing.

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Footnotes:

[1]Preparted for the Special Workshop on Agent-Based Models of LUCC, Oct. 4-7, 2001, Irvine, CA.

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FEARLUS: An Agent-Based Model of Land Use Change

Abstract

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The FEARLUS (Framework for the Evaluation and Assessment of Regional Land Use Scenarios) project started in April 1998, to run initially for five years. It is one of three main approaches to the study of land use change being conducted at the Macaulay Institute, the other two being analytical and empirical. The FEARLUS approach is to use agent-based simulation modelling, with the intention of eventually being able to provide advice to policymakers in the Scottish Executive on the possible effects of such things as regulation, climate change, and globalisation on land use change.

At the moment, FEARLUS is mainly involved in proof-of-concept work, trying to establish the advantages and disadvantages of agent-based modelling, and the kinds of problem it can be used to address. Thus, whilst FEARLUS is ostensibly focused on land use issues in Scotland (population ~5M, area ~8Mha) or particular subregions or catchments therein, at present the model itself is too abstract to be regarded as representing any particular area or time period.

The main reason for retaining as abstract as possible a model, which underpins the core methodology in the FEARLUS project, is the idea that explanations of emergent phenomena should be based on the simplest possible models. Two main approaches to agent-based modelling are emerging in the literature, one deriving from complex systems and cellular automata research, the other from distributed artificial intelligence — with the interaction between them focused on debate about realism versus tractability (Goldspink, 2000). Whilst the appropriate level of realism to use may in the end depend on the purpose of the model, the attitude within FEARLUS is that extra realism should only be built in on the basis of a thorough understanding of the dynamics of the interactions and the kinds of emergent phenomena that are generated by simpler models.

As it stands, the FEARLUS model is implemented in Objective-C using the Swarm simulation libraries. The agents are land managers, who have to decide each year which land uses they will use on the one or more land parcels they own. The decision is made using a decision algorithm, which is applied to each land parcel owned individually, rather than for the farm as a whole (if the land manager owns more than one land parcel, for example). The decision algorithm consists of three possibly different strategies, which reflect the context and behavioural aspects of the land manager. The first strategy is the contentment strategy. This strategy is used to determine the land use for a land parcel whose yield exceeds the land manager's individual contentment threshold (for example, a habit strategy might be used in this case, which just applies the same land use as the previous year). If the yield is less than the contentment threshold, then the land manager has an individual propensity to either imitate or innovate. The decision algorithm therefore specifies an innovative and an imitative strategy for the land manager to use when the yield is unsatisfactory, together with a probability to determine which of these will be used each time.

Imitative strategies use exclusively information from neighbouring land managers' land parcels and the land managers themselves when determining land uses — meaning that the set of land uses available for selection consists only of those that appear in the neighbourhood. For the purposes of imitation, a distinction is made between the social and physical neighbourhoods. The physical neighbourhood reflects the topological layout of the environment — which land parcels neighbour which other land parcels. Land

managers, however, are simulated as exchanging information socially — thus the information drawn on when using an imitative strategy includes all land parcels owned by land managers with neighbouring land parcels to those owned by the land manager making the decision. An example of an imitative strategy might be to apply the land use that the majority of the land manager's neighbours are using.

Innovative strategies make no use of neighbouring information, but may choose from any of the land uses. An example of an innovative strategy might be to choose a new land use at random — "innovative" for our purposes meaning that a land use may be introduced that is not currently being applied by any land manager in the neighbourhood.

Land managers may be grouped into sub-populations according to the decision algorithm they use. This is used to compare various decision algorithms for their competitive advantage in different environments. This competitive advantage is usually assessed on the basis of which sub-population owns the greatest number of land parcels at a predetermined time after the beginning of the simulation.

The environment consists of a uniform 2D grid of cells, each cell representing a land parcel — meaning land parcels all have the same area. Facilities are provided for simulating hexagonal and triangular cells, as well as squares with von Neumann or Moore neighbourhoods. The grid may be bounded, with edge and corner cells having fewer neighbours than the other cells, or toroidal ("wrap-around") in which edge cells have neighbours on the opposite edge. Each land parcel has individual biophysical properties, simulated using a string of binary digits ("bitstring" henceforth). These spatially varying biophysical properties remain constant during the course of the simulation — they are not affected by the land uses or climate. Temporal variation is introduced by the spatially homogenous climate and economy, also simulated using bitstrings. Since there is no difference between their function in the simulation, these may be referred to generically as "external conditions". A fixed set of land uses is determined at the start of the simulation, and all land uses are available for selection by land managers at all times (at least, by those using innovative strategies). Land uses are also simulated using bitstrings. The yield from a particular land use is determined by how well its bitstring matches with a concatenation of those of the external conditions and the biophysical properties of the land parcel.

Land managers accumulate wealth from the yield generated by their land parcels, less a constant break-even threshold, applied equally to the yield from all land parcels. Land managers with negative accumulated wealth must sell off their land parcels at a fixed, constant price, until their wealth is zero or above. If they lose all of their land parcels in this way, then they are removed from the simulation. Land parcels put up for sale are transferred to other land managers by choosing at random from the set of land managers with sufficient wealth owning neighbouring land parcels to the one that is for sale, and one new land manager. A land manager chosen to have the land parcel transferred to them will have their wealth deducted by the land parcel price. Land managers have no option to refuse this transfer.

The focus of work in FEARLUS so far has been on the competitive hierarchy of decision algorithms, and in particular, on purely imitative decision algorithms versus those with an innovative component (Polhill, Gotts, & Law, 2001). These studies have found that whilst the competitive advantage of various decision algorithms depends on the physical and social context, purely imitative strategies tend not to perform so well as those with an innovative component. A followup paper, currently under way, will look at aspiration level (another way of looking at the contentment threshold) and look for cases when imitation has an advantage over decision algorithms that make no use of imitation.

In the near future, the FEARLUS project will be starting work studying common-pool resource dilemmas, with a particular focus on the EU Water Framework Directive. This work will explore the use of multi-dimensional utility functions in land managers — separating the financial gains from using over-exploitative strategies from the social costs that might be applied by land managers who are affected in response. We also hope to introduce policy into the model, to see what kinds of regulation can be used to prevent over-exploitation of common-pool resources, and to look at possible warning signs by looking for the kinds of environment that promote over-exploitative strategies. A forthcoming review paper (currently being refereed) contains a survey of agent-based research in common-pool resource dilemmas (Gotts, Polhill, & Law).

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PROJECT SLUCE: Spatial Land Use Change and Ecological Effects at the Rural-Urban Interface: Agent-Based Modeling and Evaluation of Alternative Policies and Interventions

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Project Summary

The complex interaction among current landscape conditions, cultural values and norms, policy prescriptions, and markets dramatically limits the usefulness of linear models of the interaction between the human systems that lead to land use/cover change and their effects on landscape ecological systems. For this reason, positing policy and other solutions to minimize negative ecological effects and introduce possible positive ecological effects of land use change requires tools for anticipating and evaluating the complex interactions between humans and ecological systems. To have some predictive power these tools should characterize the nature of land use decision making on an individual household, firm and local government unit basis and permit evaluation of the ecological effects of various decisions. Such tools should recognize both economic, political, and psychological motivations for land use and management decisions on the urban fringe (demand), as well as utilities for sale of undeveloped land (supply).

This project focuses a multidisciplinary team on developing, evaluating and applying agent based models of land use and cover change processes and assessing the interactions with ecosystem structure and function. Models and tools resulting from this proposed work will have direct implications for understanding both social and landscape dynamics within an urban system as well as projecting patterns of ecological change at the urban-rural fringe. They will also have a direct impact on the graduate and undergraduate education through their incorporation in a broad range of courses at the University of Michigan and their dissemination to the broader research and education communities. Our project seeks to understand the individual decision-making that drives land use decisions and to formulate and test alternative policies and interventions that could reduce environmental costs and enhance environmental benefits. Further, we will focus deliberately on the model development and application process and develop innovative approaches to integrating agent based models of the land use change process with empirical observations of land purchaser, seller, developer, and agency attitudes and land use, cover, and ecosystem change.

The two-fold educational objectives of the project will be implemented immediately and will continue to develop through the course of the project. The first component of the educational initiative involves formal incorporation of the models into a multitude of both "content" classes, which will look at the environmental economics, sociology, and policy implications of the project results and models, and the "methods" classes (e.g., complex systems modeling, GIS, spatial analysis, remote sensing), which will use the model system represented through this project as an example for presentation, discussion, and projects around analytical and modeling methodologies. The second educational component involves the dissemination of various versions of the models and data we create to communities outside the University of Michigan, through the internet and various user communities (e.g., Swarm and GIS). Our models will be well suited to wide dissemination and will be packaged with data collected through this project.

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The Intersection of Agent-Based Models, Land Use and Community Mental Health

I am probably unique among participants in the workshop on agent-based models of land use/land cover change in that my primary research interest lies in community mental health. Thus, my deepest interest is not so much land use itself as the effects of that use on the human psyche. I am particularly interested in individuals who suffer from chemical dependency and severe and persistent mental illnesses such as schizophrenia and bipolar disorder. However, it is not unreasonable to think that different types of land use might affect the stress level and therefore the mental health of individuals who carry no actual psychiatric diagnosis (Halpern, 1995; Ulrich, 1993). This abstract will therefore discuss research that would touch on the needs of considerably divergent populations. I should add that I am only in the beginning stages of planning these lines of research.

There is a rich and varied literature that addresses the effect of the built environment of buildings, streets and landscaped parks on human behavior and mental health (Bechtel, 1997; Gifford, 1997; Halpern, 1995). There is a parallel, and sometimes overlapping, literature that addresses the effect of the unbuilt, "natural" environment on human mental health (Kahn, 1999; Kellert, 1997; Kellert & Wilson, 1993). Much of this latter literature derives from the "biophilia" hypothesis, first stated by Edward O. Wilson, that human beings have an inbred need to affiliate with life and the broader ecological system. However, the built environment is entirely, and the natural environment is largely, the result of human actions and interactions (Meyer & Turner, 1994). To look deeper, to understand how the landscapes that affect us arise, we need to understand how these interactions occur. Agent-based models constitute a natural framework for thinking about such interactions.

For instance, the Not In My Backyard (NIMBY) phenomenon, in which homeowners oppose the location of residential facilities for individuals with chronic mental illness in their neighborhood, has blocked construction of as many as half of all planned group homes for people with disabilities in the United States (Tse, 1995). NIMBY has probably contributed to the concentration of people with chronic mental illness in relatively impoverished inner-city neighborhoods, whose residents are less likely to be able to organize against residential facilities (Levine & Perkins, 1997). Administrators have attempted to alleviate NIMBY by meeting with prospective neighbors of proposed facilities (Zippay, 1999), but fundamental questions about NIMBY, such as the motivations of homeowners and how far the effect reaches, remain poorly understood (Colon & Marston, 1999; Gilbert, 1993; Mangum, 1988). Agent-based models, incorporating the bounded rationality of homeowners and distance effects, could be useful in generating more precise hypotheses than the ones that currently characterize the literature and in thinking about the implications of the somewhat contradictory empirical findings.

There is evidence from both qualitative and quantitative studies that social support can significantly benefit those who suffer from a variety of mental illnesses (Marsh, 2000; Paykel, 2001). There is also evidence that the built environment heavily influences both the quality and quantity of social support. The conditions for strong social support networks are complex. The opportunity to interact with others is, of course, necessary, but so is the ability to control such interactions. An environment such as a busy street that forces interactions with others actually tends to lead to hostility to neighbors (Halpern, 1995). A particularly unpleasant environment can make social interactions far more difficult, while some level of local social heterogeneity appears to foster social networks (Halpern, 1995). Agent-based models are natural tools both for studying the way in which different built environments arise and for developing a better and deeper understanding of the effects of those environments on social networks.

Agent-based models of land use could also yield considerable insight into the origin and effects of such environmental stressors as weather, air pollution and noise and crowding (Halpern, 1995). There is evidence that cloudy weather has a negative effect on mental health (Halpern, 1995). Cities tend to be more cloudy, more rainy and more foggy than the surrounding countryside (Rogers, 1994), and it is possible that this has an adverse effect on the mental health of some urban residents. Levels of environmental noise and crowding are, to a large extent, the straightforward result of urban and suburban development patterns (Halpern, 1995). In all of these cases ABMs could be of great value in modeling the interactions that lead to changes in land use, as well as the interactions between those who live in urban and suburban areas, their environments and each other.

There is also evidence that exposure to natural environments improves both mental and physical health (Kahn, 1999). Many studies have shown that subjects prefer natural scenes, particularly those that show fairly open landscapes with a scattering of trees and those that include water, to built scenes (Ulrich, 1993). There is substantial evidence that many people find that natural settings, whether they are wilderness areas or urban parks, reduce perceived stress (Ulrich, 1993). There is even evidence that postoperative hospital patients recover more quickly when they have a window that overlooks a natural scene, when compared to those who have a window that overlooks a brick wall (Ulrich, 1993). Human interactions, policies and land use largely determine where natural environments remain and how easily individuals can gain access to them. All of these, of course, can potentially be modeled through ABMs. Moreover, findings of positive effects of natural environments on mental health would have implications for models of the response of land values to natural amenities, such as Irwin & Bockstael, (2001), since they might allow a more accurate quantification of the value of access to those amenities.

There is substantial evidence that both the natural and built environments have significant effects on human mental health. ABMs seem likely to be of considerable value both in developing a more detailed theory of those effects and in understanding the human interactions that give rise to much of the world in which we live.

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