

Guest editorial

Space, complexity, and agent-based modeling

There is considerable interest in agent-based modeling as a tool to understand better the dynamics of complex systems. Particular attention has been focused by the land-change science community, but there has also been a good deal of effort in fields including epidemiology (Teweldemedhin et al, 2004), finance (LeBaron, 2000), computational sociology (Macy and Willer, 2002), ecology (Grimm et al, 2005), and computational economics (Tesfatsion, 2002). There are several notable prior syntheses and collections of agent-based modeling work. Gimblett (2002) and Janssen (2003) edited two early collections of agent-based model (ABM) research centered on complex human–environment systems. Parker et al (2003) summarized applications of ABMs to land-use and land-cover change, including how the field transitioned from abstract ‘toy’ models to those more directly tied to real-world applications. Brown and Xie (2006) organized an issue of the *International Journal of Geographic Information Science* that included a number of agent-based applications with a particular emphasis on the spatial dynamics within the models. And, as evidence of the evolution in the application of agent-based approaches from abstract systems to real-world ones, Janssen and Ostrom (2006) collected a series of works of ABMs in the journal *Ecology and Society* that were directly supported by different types of empirical data.

There are at least two fundamental reasons why ABMs are appealing tools for studying complex systems. First, ABMs explicitly incorporate agent interactions and the properties that emerge at higher levels of observation from these interactions. The importance of these agent interactions varies from system to system, but in many cases these relationships provide key insight into the behavior of complex systems. Second, ABMs enable modelers to represent agents with heterogeneous properties. Instead of every cell in an urban growth model being governed by the same land-change dynamics, the fitting process of an ABM can enable diverse spatial dynamics to be discovered through modeling. For example, landowners in south-central Indiana have varying responses to the same land-use decision-making context (Evans and Kelley, 2004).

Recent innovations in agent-based modeling have produced yet more sophisticated representations of complex systems. A large body of work, particularly in land-change science, has focused on households as the primary agent of study. Now we see more diverse types of agents being portrayed, such as individuals (human and otherwise), villages, viruses, or voters. As we learn more about the kinds of modeling possible with agent-based approaches, we will likely incorporate a greater variety of agents in our models. And with this evolution will hopefully come a greater understanding not only of village-to-village interactions or landowner-to-landowner interactions, but also of interactions that go up and down across scales and representational levels (eg landowner to village, village to landowner).

While there has been great progress in the agent-based modeling community (see, for example, the manuscripts here and those in the special issues and edited collections noted above), there remain a number of key challenges that point to reasonable next steps in the research enterprise. Researchers have made greater efforts to validate ABMs than was the case during the inception of ABM applications (Janssen and Ostrom, 2006). However, we should continue to consider the types of validation being

implemented and whether they are appropriate for an assessment of ABMs. For example, it is common for ABMs of land-cover change to be validated by matching the landscapes produced from the model to observed data. This same approach is used to validate cellular automata and spatial regression models. Yet, if we are to assess what we gain by using ABM approaches over others, there perhaps should be greater attention focused on validating the spatial interactions inherent in the model (eg communication, positive or negative spatial externalities, diffusion). A particular spatial pattern observed in a system may be the result of spatial interactions, but it may also be the result of relatively simple factors such as distance or accessibility.

With this greater attention being paid to agent dynamics comes a greater understanding of the role of agents in complex systems. A perpetual tension in modeling complex social–ecological systems lies in the decision to simplify various parts of the system being examined. The decision of where to aggregate or simplify a system is often made on a seemingly ad hoc basis, and, although there are more strategic means of making this decision (Manson, 2001), we face particular challenges when developing a model with complex dynamics requiring the expertise from multiple fields of research (eg land change requires an understanding of fields including hydrology, ecology, and economics). The increasing availability and ease of use found in tools such as Netlogo, Repast, and the Agent Analyst extension to ArcGIS have lowered the barriers to entry in agent-based modeling. This should enable ABMs to be coupled with established models of forest, hydrological, or wildlife dynamics.

Perhaps the greatest challenge in the development of ABMs is to determine how to package the insight gained from these models for policy makers so that more effective management decisions can be implemented in real-world situations. Of course, this is not a challenge unique to the agent-based modeling community. Models that lack a user-oriented interface, or that have a high degree of complexity, may produce impressive results, but the utility of these results may remain elusive for policy makers. There are notable exceptions. Work from the companion modeling (CORMAS) approach by Bousquet and others (2003) and the development and application of UrbanSim, led by Waddell (2002), has been particularly successful in connecting with stakeholders and/or policy makers. Yet the complexity that is often inherent in agent-based approaches presents challenging obstacles in the translation of science to policy for many agent-based modeling projects.

This theme issue brings together a subset of papers from a set of organized sessions at the 2004 meeting of the Association of American Geographers that in various ways address some of the challenges raised above. These sessions were broadly focused on an exploration of complexity, and many presentations included the use of agent-based models. The papers presented in this issue are notable for their richness and breadth across topics including model evaluation, residential mobility, land use, and land ownership.

A conceptual model of residential mobility is presented by Paul Torrens that he instantiates in an ABM. This work exemplifies the advantages of agent-based modeling because it achieves the difficult goal of simultaneously representing individual households, their perception of social conditions, their reactions to their environment, and their movements in the physical and socioeconomic housing landscape. Of particular interest to the residential mobility research community is the manner in which individual agents interact with one another and larger housing markets while also creating synthetic submarkets. The model extends Torrens's research in geographical automata, an approach that represents individual entities such as households and their interactions with other social entities and the environment more broadly.

Konstantinos Alexandridis and Bryan Pijanowski describe their work dealing with parcels in an ABM, the Multi Agent-based Behavioral Economic Landscape (MABEL). They respond to a key need in the agent-based modeling of land change—the use of vector polygons to represent discrete parcels. Many land-change models treat the environment as a regular grid from which agents choose cells of land for production activities, such as agriculture or home building. Challenges in using parcel data center on the need to replicate convincingly real processes such as parcel subdivision, land transactions, and the creation of new parcel boundaries. The authors implement agent rules in MABEL via a Monte Carlo simulation approach to model land change from 1970 to 1990 in two regions of Michigan, USA. They compare their simulated parcels against actual land-change histories with landscape metrics, the use of which in assessing model performance is an area of great interest to the agent-based modeling community.

Steven Manson examines methodological, conceptual, and policy challenges of geographic complexity through the lens of model evaluation. He describes how important methodological issues are raised by sensitivity in complex systems and the challenges of modeling systems at multiple spatial, temporal, and organizational scales. Significant conceptual challenges lie in the conflation of pattern and process in geographic complexity and in the related issue of creating models that must reconcile simplicity and complexity. In terms of the policy issues of complex systems, he argues that geographic complexity is particularly susceptible to the science – policy gap (differences among scientific, policy, and public communities) and challenges of postnormal science, which deals with problems of great uncertainty, large decision stakes, or disputed values.

An ABM of shifting cultivation in Luangprabang, Laos is presented by Yumiko Wada, Krishnan Rajan, and Ryosuke Shibasaki. These researchers offer a dynamic model of agriculture as a function of demand and supply of crops. Perhaps more notably, the authors also treat villages as decision-making entities in their own right, a formulation that differs from many ABMs of land change that treat households or individuals as the unit of analysis. They also advance the cause of evaluation in ABMs by using a scale-sensitive evaluation procedure, which validates the model across differing spatial resolutions when measuring areas of shifting cultivation areas.

Li Yin and Brian Muller use an ABM to examine the relationship between residential location and the environment, specifically through the example of exurban development in Colorado, USA. This work focuses much of its attention on the effects of heterogeneity in both the environment and agents whose decision making drives residential development. The authors tie this decision making to factors that influence exurban growth. Particularly important is how the model captures the effect of demographic factors on the attractiveness of locations as a function of natural amenities, such as the proximity of natural features in two dimensions and scenic views in three dimensions. As the authors note, many existing models of exurban growth do not fully incorporate how the locational decision making of exurban residents is sensitive to heterogeneity in the biophysical environment.

We wish to thank the editors of *Environment and Planning B: Planning and Design* for enabling the collection of these papers in this special issue. We hope that this collection not only builds on the strong existing foundation of agent-based modeling research but also demonstrates the breadth of applications being explored with these methods.

Acknowledgements. This work was supported by NSF funding for research at the Department of Geography and Center for the Study of Institutions, Population and Environmental Change at Indiana University through grants SES0083511 and SES0232072. It was also supported by the National Aeronautics and Space Administration New Investigator Program in Earth-Sun System Science (NNX06AE85G) and the University of Minnesota McKnight Land-Grant Professorship Program.

Tom P Evans, Department of Geography and Center for the Study of Institutions, Population and Environmental Change, Indiana University
Steven Manson, Department of Geography, University of Minnesota

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