Chapter 19

Integration of Geographic Information Systems and Agent-Based Models of Land Use: Prospects and Challenges

DAWN C. PARKER
GEORGE MASON UNIVERSITY
FAIRFAX, VIRGINIA

ABSTRACT

INTEREST IS GROWING IN AGENT-BASED MODELS of land-use and land-cover change (ABM/LUCC). Such models combine agent-based representations of the decision makers influencing a land-use system with a cellular landscape and are appropriate when complex dynamics are present in the system under study. This chapter reviews conceptual challenges related to integrating ABM/LUCC and geographic information systems (GIS) and progress to date in meeting those challenges. Since the design of a model must take into account how it is likely to be used, the needs and possible activities of two hypothetical ABM/LUCC users, an end user and a researcher, are discussed. Three levels of possible integration of ABM/LUCC and GIS—no integration, initialization with real-world data, and full integration—are presented, and key ongoing research projects using each approach are reviewed. The review reveals a large number of ongoing projects and promise for continued rapid development of integrated ABM/LUCC GIS, especially given recent development of tools that integrate vector-based GIS with ABM. Drawing on input from the modeling community, functionality desired in an integrated ABM/LUCC-GIS model is discussed, including tools for programming, modeling, mathematical operations, verification and validation, and use of standard algorithms. Options for software implementation of such a model in terms of user interface, component integration, and software licensing are presented. Finally, a call for development of a standardized, component-based conceptual framework for ABM/LUCC is made. Such a framework would serve to facilitate communication of model mechanisms, comparisons across models, and derivation of standard results for ABM/LUCC models and would help ABM/LUCC transition to a mature scientific discipline.

INTRODUCTION

Interest in agent-based models of land-use and land-cover change (ABM/LUCC) is growing, and many researchers are choosing to adopt such models for the study of coupled human-biophysical interactions related to land-use change. Agent-based models (ABMs) are micro-level simulation models that directly represent decision-making entities and their interactions with their social and physical environment. ABMs have been applied in a variety of social science domains, including economics, sociology, political science, and geography (Berry, Kiel, and Elliot 2002). Closely related individual-based models focus on nonhuman entities and their behavior (Grimm and Railsback forthcoming). ABM/LUCC combine agent-based representations of the key decision-making entities in the land-use system with a spatial model of the landscape under study. Decision-making agents can represent stakeholders at multiple scales, from individual parcel managers to village households to local planning boards. Interaction environments can include social networks, markets, and political institutions. Examples of feedbacks between agents and their environment include hydrologic balance, soil fertility and erosion, changes in species abundance, and spread of invasive species.

In contrast to techniques traditionally used in social science modeling, such as microeconomic, game-theoretic, and system dynamics models, ABM/LUCC are simulation-based, not equilibrium-based. Although models may reach an equilibrium, that equilibrium is the result of interactions among lower-level entities. As well, like cellular automaton models, ABM/LUCC may not reach an equilibrium. For the interested reader, many other works focus on potential roles for, applications of, and conceptual challenges related to development of ABM models of human-environment interactions (Bousquet and Le Page 2004; Janssen 2003; Janssen and Ostrom forthcoming; Parker, Berger, and Manson 2002b; Parker et al. 2003; Verburg et al. forthcoming).

One important challenge for the development of ABM/LUCC models is integration of geographic information systems (GIS) functionality with ABMs. This challenge was first discussed by Gimblett (2002a), following a 1998 workshop, and was also identified by participants at the 2001 Special Workshop on ABM/LUCC models (Parker, Berger, and Manson 2002a, b). This chapter again focuses on needs for integration of ABM/LUCC models with GIS, the current state of integration, additional functionality desired by the user community, and various options for accomplishing integration. The goal of the chapter is both to report on current activities and to serve as a point of departure for continuing dialog within the community. While the chapter focuses most closely on development of agent-based land-use models, it draws on examples of other spatially explicit models, both agent-based and land-use, which face similar concerns and challenges. This chapter summarizes the activities, concerns, and challenges of developers and end users of ABM/LUCC. Readers are directed to other works for discussions of conceptual and technical integration of ABM and GIS (Brown et al. forthcoming-a; Torrens and Benenson forthcoming; Westervelt 2002).

NEEDS AND ACTIVITIES OF ABM/LUCC MODELERS

While users of ABM/LUCC are a diverse group, for purposes of illustration, this section outlines the needs of two hypothetical representative users of ABM/LUCC. The first is an end user of an existing ABM/LUCC model. He or she may be a student in a modeling class or a policy maker interested in conducting scenario analysis. The end user may possess limited knowledge of programming but is likely to be comfortable with a wide variety of software applications, including GIS. The second is a researcher developing an ABM/LUCC from scratch, potentially as part of a larger research team or project. He or she is likely to have a moderate level of programming expertise, often linked to a particular programming language. The project's goals may include theoretical exploration, hypothesis generation and testing, developing land-use projections, and scenario analysis. Results are likely to be published in peer-reviewed academic literature. Often, individuals will progress from the first role to the second, as their knowledge of and interest in ABM/LUCC increases.

End Users. The end user will most likely begin by running a demo version of a simple model in order to become familiar with the basic model mechanisms and their results. As part of this process, he or she may find graphical documentation of the model helpful. He or she may then experiment by changing model parameters and observing how this leads to changes in outcomes, may also want to compare the results of different assumptions regarding agent decision-making mechanisms, and may then wish to develop a simple model of his or her own, using existing model components. He or she will likely want to view spatial model outcomes, as well as graphs and statistics generated from model output.

Researchers. An ABM/LUCC researcher embarking on a new modeling project will undertake a more complex series of tasks. First, a conceptual model will be specified that elucidates the component parts of the ABM and potential interactions between the parts. The set of software tools most useful for the particular project will be identified. This decision may be driven by the role of the model (Berger and Parker 2002), the available input data, the need for advanced mathematical functionality, the decision to use a vector or raster landscape representation, and the need for GIS functionality. The researcher will design agent decision modules, potentially choosing from a wide variety of decision algorithms, and will build spatial and temporal interactions among agents and between agents and their environment. He or she may input real-world data from GIS, surveys, and statistical models in order to parameterize his or her model. While initial model verification and exploratory analysis may be conducted through manually changing parameter settings and re-running output, at some point the researcher is likely to conduct multiple model runs by incrementally sweeping the parameter space for purposes of model calibration, hypothesis generation, or model validation. Data from these multiple runs would be saved in a database for subsequent optimization or statistical analysis. Both spatial and a-spatial outcomes are likely to be of interest. Finally, the researcher will likely want to compare generated and real-world outcomes, again focusing on both spatial and a-spatial outcomes. To facilitate communication with other researchers and review of his or her work, the researcher may need to provide detailed model metadata, potentially including graphical descriptions of model structure and mechanisms.

CURRENT LEVELS OF INTEGRATION WITH GIS

Several different levels of integration of ABM/LUCC with GIS are possible. Models may run on abstract cellular landscapes, implementing simple spatial functionality within the ABM. Models may read in real-world spatial data from a GIS and also potentially write output into a format readable by GIS. When significant GIS functionality is required at run time, integrated models—those that implement both ABM and GIS functionality dynamically—may be constructed. Three approaches to such models are identified here: models that use separate GIS and ABM programs/libraries and communicate via files written to disk, models that use separate programs but communicate via a shared database or virtual memory, and stand-alone models that implement GIS functionality within the ABM model. (These definitions are related to, but do not exactly parallel, characterizations of model coupling discussed by Westervelt 2002, and Brown et al., forthcoming-a.)

Abstract Cellular Landscapes. Many ABM/LUCC researchers begin by developing models that operate over an abstract landscape, even when their longer-term goals include application to real-world landscapes. Roles for abstract ABM/LUCC models are discussed by Parker and colleagues (Parker, Berger, and Manson 2002 a,b; Parker, Manson, and Berger 2002; Parker et al. 2003), and the advantages of a progression from abstract to empirical are discussed by Berger and Parker (2002). Balmann and colleagues (Balmann 1997; Balmann et al. 2003) have developed spatially explicit models of structural change in agriculture. The Repast-based (repast.sourceforge.net) SLUDGE model (Parker and Meretsky 2004) examines the relationship between negative spatial externalities, landscape fragmentation, and economic efficiency. The Swarm-based (www.swarm.org) FEARLUS model explores the evolution of cropping patterns and land holdings in an agrarian setting (Gotts, Polhill, and Law 2003).

GIS Initialization /Output Display. Many currently developed ABM/LUCC models input either abstract or real-world raster landscapes and export output to files suitable for viewing in raster GIS. Berger (2001) models the influence of information networks and resource markets on adoption of new efficient irrigation technologies in Chile. The LUCIM model (Evans and Kelley 2004) focuses on the relationship between land-owner decision making, landscape heterogeneity, and the process of deforestation and reforestation. Landscape statistics similar to those produced by FRAGSTATS (McGarigal and Marks 1994) are calculated for the raster-based model output. The Repast-based LUCITA model (Deadman et al. forthcoming) focuses on the behavior of heterogeneous agricultural land owners in the Brazilian Amazon. The Swarm- and

Repast-based SLUCE model focuses on the influence of landscape amenities on development on the ex-urban fringe (Brown et al. forthcoming-b). Caruso, Rounsevell, and Cojocaru (forthcoming) have developed a related model that focuses on the impact of both positive and negative local spatial influences on the expansion of the ex-urban fringe. The Swarm-based VILLAGE project models migration and settlement patterns of Anasazi populations in the U.S. Southwest. In addition to initializing the model with GIS landscapes, the model also uses GIS at the validation stage (Kohler et al. 2000; Reynolds, Kohler, and Kobti 2003).

A large number of ABM/LUCC applications has been developed using the Cormas platform (Bousquet et al. 2003). These applications are often designed through stakeholder participation, and are used for role-playing games with stakeholders to develop strategies for sustainable resource use. Cormas allows users to import existing vector and raster GIS layers and create layers interactively. Abstract landscape-based applications include comparison of multi-scaled agent representations (Bousquet and Gautier 1998); fuel wood management and deforestation in Burundi (Bousquet et al. 2000); negotiations between foresters and herdsmen over forest and pasture management in the French Mediterranean forest (Etienne 2003a); and land and water management in a periurban water catchment (Ducrot et al. 2004). Raster applications include land-use conflicts between fishers, hunters, herdsmen, and farmers in Senegal (d'Aquino et al. 2003); use of common groundwater in Tunisia (Feuillette, Bousquet, and Le Goulven 2003); the impacts of institutional change on mountain agrarian systems in Vietnam (Boissau and Castella 2003); multiple land-use interactions in the Rhone delta (Mathevet et al. 2003); water management in Northern Thailand (Becu et al. 2003); and wild game hunting in Cameroon (Bousquet et al. 2001). Vector applications include soil erosion risk in Thailand (Trébuil et al. 2002). Cormas can create composite objects, facilitating potential implementation of agents at differing spatial scales and cross-scale feedbacks.

Integration via Files Written to Disk. Westervelt and colleagues have developed a series of integrated agent and individual based models that explore interactions between mobile human and endangered animal species (Harper, Westervelt, and Trame 2002; Westervelt 2002; Westervelt and Hopkins 1999). Their modeling framework integrates SME (Chapter 7, this volume) and Swarm with GRASS GIS (grass.itc.it) via files written to disk at run time. Gonçalves, Rodrigues, and Correia (2004) simulate the spatial distribution of residues from stone-cutting operations, using a Java-based model coupled with Geotools open-source GIS (http://www.geotools.org/). Etienne, Le Page, and Cohen (2003b) use a simplified Cormas-based ABM to support a role-playing game focused on the problem of pine invasion into open space in the south of France. Their model uses MapInfo to initialize the raster-based model and to display updated landscapes every five time steps.

Run-Time Communication. Manson has developed the C++ DS3 system that integrates IDRISI GIS (http://www.clarklabs.org), SQL database functionality, embedded agent-based models, Monte-Carlo tools for uncertainty analysis, and spatial validation tools into a dynamic modeling system. The SYPR model (Manson 2000, 2002; Manson forthcoming), which focuses on smallholder agricultural decision-making in the southern Yucatán peninsula, is implemented in DS3.

Several fully integrated ABM-GIS models utilize the Java-based Repast programming libraries (http://repast.sourceforge.net/). GeoGraphs (Dibble and Feldman 2004), a set of software libraries for use with Repast, initializes model landscapes through GIS input, including DEM and network layers. Modeling capabilities allow agents to move and interact via rugged 2- and 3-D networks and include run-time 3-D visualization capabilities. Applications include epidemiology, civil violence, and hierarchical social networks. The vector-based Tactical Sensor and Ubiquitous Network Agent-Modeling Initiative (TSUNAMI) (Brown et al. forthcoming-a; Najlis 2004; North, Rimmer, and Macal 2003) of peer-to-peer communication networks between mobile objects facilitates agent movement, sensing of surroundings, and communication using Openmap GIS (www.openmap.net). The Infrastructure SimSuite (Brown et al. forthcoming-a; Thomas et al. 2003) represents interactions between independent public utility infrastructure units. The model uses ArcGIS to initialize topological information and update feature attributes. Two recent extensions to the Repast libraries facilitate integration with ArcGIS through the Agent Analyst extension and with Openmap (Brown et al. 2004; Najlis and North 2004).

Internal GIS Functionality in ABM. The Recreation Behavior Simulator (RBSIM) models simulate the movement of recreational users in outdoor environments (Itami et al. 2004). The Visual Basic models import GIS layers from MapInfo and ESRI GIS, but also embed GIS functionality through a topological database structure, a network object model, and a terrain model. Mobile agents possess both line-of-sight and ability to calculate distances (Gimblett, Richards, and Itami 2002; Gimblett et al. 2002; Itami 2002; Itami et al. 2000).

Torrens and Benenson have developed an abstract geographic automata system (GAS), a conceptual framework for linking automaton-based urban models to geographic information systems (Torrens 2003; Torrens and Benenson forthcoming). The framework has been implemented in a variety of languages, including Starlogo, Java, and C++. The Object-Based Environment for Urban Systems (OBEUS) model (Benenson, Aronovich, and Noam forthcoming), written in C++, inputs MapInfo GIS files and implements a wide range of GIS functionality, including networks, georeferencing, and neighborhood relationships. Software implementation is discussed by Benenson and Torrens (2004).

The above examples and additional feedback from the modeling community indicate that a broad range of GIS functions are useful with ABM/LUCC models. These include topological functions such as neighborhood calculations, buffering, and spatial connectivity; complex network representations and travel-cost calculations; terrain functions such as DEMs, viewsheds, and line-of-sight calculations; and calculation of landscape-based spatial statistics. As well, although the majority of models are now implemented as rasters or other regular tesselations, many researchers have emphasized the need to create vector-based models, which may require the topological data structure provided in a GIS.

A WISH LIST FOR MODEL INTEGRATION

As seen in Section 2, a researcher developing an ABM/LUCC model will engage in a wide variety of tasks, which may require extensive mathematical and software functionality. In an informal poll by the author of researchers developing a diverse set of fine-scale models of natural resource use, researchers expressed desire for a wide range of functionality within an ideal coupled ABM/GIS modeling environment (Maspace mailing list, Sept. 2003, csiss.ncgia.ucsb.edu/mailman/listinfo/maspace).

Programming/Modeling Functionality. From a programming standpoint, researchers expressed a preference for an object-oriented structure that allows a range of event sequencing mechanisms, including synchronous, asynchronous, and event-driven (Brown et al. forthcoming-a; Najlis, Janssen, and Parker 2002; Torrens and Benenson forthcoming). Researchers have noted that ABMs are by their nature dynamic models, whereas GIS's traditional database structure does not facilitate dynamic modeling and generation of output statistics related to time as well as space (Brown et al. forthcoming-a; Gimblett 2002b; Manson 2002; Torrens and Benenson forthcoming). Researchers expressed a desire to interface with other temporally and spatially dynamic models, such as hydrology, transport cost, and erosion models. Modeling of mobile objects (see Chapters 8, 12, and 17) was desired, as was the ability to model and visualize in 3-D.

Mathematical Functionality. Researchers expressed a desire for a high degree of advanced mathematical functionality. This functionality is potentially needed for constructing agent decision-making algorithms, especially those based on optimizing behavior, for model calibration, and for coupling ABMs with environmental process models. Specific functions desired include finite-element modeling, and complex and robust optimization algorithms such as spatial integer programming, genetic algorithms, and simulated annealing.

Verification and Validation Tools. Researchers expressed the need for tools to support model verification and validation: "the correctness of model construction and the truthfulness of a model with respect to its problem domain" (Parker et al. 2003). Requests for verification tools included real-time visualization, the ability to conduct "on the fly" sensitivity analysis by changing model parameters, generation of good quality temporal and spatial output graphics, and the ability to save and export animations in standard formats. Requests for validation tools included the ability to call individual functions and components in batch mode, potentially for multiple runs that do Monte-Carlo-style sweeps of the model parameter space; the ability to store model parameters and output for any execution; and the ability to analyze generated output using standard statistical models.

Built-in Standard Functions. Related to these needs, researchers expressed a desire for a wide range of built-in standard functions, including transparent and well-documented algorithms for agent behavior, spatial processes, calibration, verification, and validation; process-based models including flows, fluxes, transport, and reactivity; and spatial and landscape statistics functions, including standard land-use modeling validation statistics and non-parametric statistics.

POSSIBLE PATHWAYS FOR SOFTWARE DEVELOPMENT

As in Sections 2 and 4, this section takes the perspective of the individual or team responsible for instantiating a conceptual ABM/LUCC model in computer code through development of a project-specific software model. There are many possible paths through which development of this software model (hereafter "model") could proceed. Here, the main choices are broken down into three relevant dimensions: single program vs. hybrid, graphical user interface (GUI) vs. scripted, and commercial vs. open source. Any single solution would utilize at least one option in each dimension. Each option within these dimensions has advantages and disadvantages, some specific to the type of model user, as discussed in Section 2.

Single Program vs. Hybrid. Single-program options range from a model created entirely within a stand-alone application using the application's own scripting language, such as ArcInfo's AML (Irwin and Bockstael 2002), to development of a project-specific stand-alone application in a lower-level language such as C++ (Berger 2001). The potential advantages of a single-program approach include reduced complexity of model development and decreased run time (Itami 2002). Hybrid program options range from instantiation in a single programming language, utilizing specialized ABM and GIS libraries (Najlis and North 2004; North, Rimmer, and Macal 2003) to the use of a lower-level language to integrate functionality from a series of applications (Manson 2002). The strongest advantage of the hybrid approach is the ability to use optimized and well-verified specialized mathematical, statistical, and GIS functions. The disadvantages lie in increased model complexity, which may include increased development time required to program in and integrate multiple applications, the need to update the model as individual application elements are updated, and increased run time. Brown et al. (forthcoming-a) note, however, that the increased efficiency offered by previously optimized GIS algorithms may compensate for the increased complexity due to calling multiple applications.)

GUI vs. Scripted. While most higher-level applications designed for ABM can run in both GUI and scripted mode, a discussion of the role played by each could be helpful to developers with limited resources. GUIs are especially useful for the end users described in Section 2, as their major advantage is that they do not require specialized programming ability. Such an interface can also be quite useful for advanced researchers for model verification and exploratory analysis. GUI systems that record user commands in a format that can be examined, saved, edited, and re-run are particularly useful. Graphical modeling languages such as Simile (www.simulistics.com) provide additional utility by facilitating a direct connection between the underlying conceptual model and its instantiation in programming code, enhancing model communication and replicability.

"Scripted" models can include those written in noncompiled scripting languages such as Python and compiled languages such as C++ and Java. For research and documentation purposes, there are many advantages to scripted models. Large numbers of model runs can be completed with little initial effort by the modeler, creating a database of model output for scenario analysis and validation. Such models create exact records of the research conducted and allow for replication of model-based experiments. Scripted models can facilitate communication of model mechanisms between researchers sharing a proficiency in that language and, when code is made available, create building blocks that can then be adopted and customized by other researchers.

Commercial vs. Open-Source. Integrated ABM/LUCC models can be developed as stand-alone commercial packages (Kwartler and Bernard 2001) or make use of commercial software (Brown et al. forthcoming-a; Thomas et al. 2003). Use of commercial software can have some advantages, especially for the end user. Commercial software is often widely available via site license agreements and can be easily installed by a system administrator or end user. Such software often contains extensive on-line help facilities, and training in the base software is often available to end users, reducing start-up time for researchers interested in investigating ABM/LUCC models. Because of the software's wide use, its available functions and algorithms may be well understood. Finally, when development of a model requires a large up-front investment of time and money beyond what is generally provided through research and educational funding, commercial development may be a practical alternative (Westervelt 2002).

Models can also be developed using only open-source licensed software (Itami et al. 2004), or developers may choose to provide newly developed code under an open-source license (Brown et al. forthcoming-b). Open-source licensing of land-use models has many potential advantages (Agarwal et al. 2002). The greatest advantage is that any modeler or end user can access and modify the model's source code. This facilitates transparency and replicability of models used for research and policy purposes. It also means that modelers can build on the previous work of other researchers, thus substantially shortening model development time and cost. A large and active user community can further speed software development and debugging time. These reduced development costs can potentially facilitate a high degree of individual customization by individual researchers that would not be profitable for commercial software developers (Westervelt 2002). The low cost of open-source models could potentially lead to wider model dissemination and use, particularly for users in developing countries. Research models possess important characteristics of what are referred to in economics as public goods—the benefits generated through their use are potentially nonrival, meaning that one user's benefits from the model are not diminished if others are concurrently using the model (Perman et al. 2003).[1] These public good characteristics may justify public investments in the often substantial start-up costs required to develop the basic infrastructure needed for a new modeling environment.

A CALL FOR A STANDARD BASE MODELING FRAMEWORK FOR ABM/LUCC

As seen from Sections 3 and 5, a wide variety of ABM/LUCC models has been developed, using a mix of software options. In this sense, substantial progress is occurring in the development of integrated ABM/LUCC and GIS models. Yet substantial challenges remain with respect to developing a shared modeling vocabulary and understanding of the theoretical effects of various assumptions. In traditional analytical mathematical modeling, this shared vocabulary and understanding is provided through the language of mathematics. In statistical land-use modeling, it is provided through standard statistical regression models, including limited dependent variable models (Long 1997), spatial econometrics models (Anselin 1988), and combinations of both (Fleming 2004).

One pathway towards this shared vocabulary and understanding is development of a standard generic ABM/LUCC modeling framework that could be implemented in a variety of software environments. Such a framework would form a “conceptual design pattern” that might nest a number of representative project-specific models. A large number of specialized models could be implemented within this framework through invoking particular modeling components and parameter settings. The framework could serve as a point of reference for comparison of alternative modeling platforms and could also be used to develop a set of standard results for ABM/LUCC models, including the effects of alternative agent decision-making algorithms and the qualitative influence of changes in drivers of land-use change on land-use composition, pattern, and location. Finally, it would serve as a valuable resource for teaching and as a start-off point for new modeling projects. A similar role is served by the Sugarscape model (Epstein and Axtell 1996), originally implemented in Ascape (Parker 2001), and subsequently implemented in Swarm, Repast, and Cormas, with planned implementation in MASON (Luke et al. 2003). Jackson (1994) proposes a similar integrative framework for regional science.

An ideal version of such a generic framework would strike a balance between simplicity and realism sufficient to incorporate the major drivers of land-use change identified by the LUCC research community (Anas, Arnott, and Small 1998; Angelsen and Kaimowitz 1998; Briassoulis 1999; Geist and Lambin 2002; Irwin and Bockstael forthcoming; Kaimowitz and Angelsen 1998; Lambin, Geist, and Lepers 2003). These drivers include agent behavior and preferences; parcel accessibility and transportation costs; positive and negative local spatial externalities; biophysical properties of the parcel, such as slope, elevation, and soil quality; social relationships and norms, information availability, population growth and other demographic changes; and external institutional factors such as market prices, taxes and subsidies, land-tenure regimes, and zoning constraints. In order to represent these potential influences, the generic model requires a minimum set of ABM and GIS functionality:

- an agent decision model capable of implementing optimizing, boundedly rational, and rule-based decision models for a heterogeneous group of agents;
- a network model capable of representing both social and transport networks;
- a model that expresses both positive and negative local spatial influences, flexible with respect to the impact radius and the functional form of diffusion;
- the ability to input spatial layers representing institutional, socioeconomic, and biophysical data and constraints;
- the ability to input relevant global socioeconomic and biophysical parameters; and
- the ability to link to separately developed biophysical process models.

In principle such a framework should be inclusive of the major concerns of a diverse set of researchers, and a determination of whether this list of features is sufficient should be made in collaboration with the research community. It should be sufficiently well documented and specific to be replicable in a variety of software models. Since a one-size-fits-all generic model is not likely to be a good fit for any individual empirical research project, the model should be customizable and extensible, arguing in favor of an object-oriented representation (Gimblett 2002b; Jackson 1994; Najlis, Janssen, and Parker 2002). Specific options for representation might include the Discrete Event System Specification (DEVS) formalism and/or Unified Modeling Language (UML) (Fowler and Scott 2000; Gimblett 2002b; Gonçalves, Rodrigues, and Correia 2004). At least one software implementation of the framework should use open-source tools that are available across computing platforms at low or no cost. This implementation should have the ability to call basic GIS functions in a loosely coupled way that allows for integration with a number of GIS packages. Ideally, the implementation would also include a graphical modeling environment, facilitating use by nonprogrammers and seamless model replication.

Development of such a generic framework could provide a needed research and teaching infrastructure item for the ABM/LUCC community. Because of the lack of a shared mathematical or statistical language for ABM modeling discussed above, a coordinated effort to develop such infrastructure may be especially critical to help ABM/LUCC develop into a mature scientific discipline. (Grimm and Railsback, forthcoming, cite difficulties in model communication as a factor that has inhibited development of the related field of individual-based modeling.) Support for such infrastructure development is often difficult to obtain through traditional grant programs. Two relevant models for support for such infrastructure development exist, however. The LUCC (Land-Use and land-Cover Change) project (www.geo.ucl.ac.be/LUCC/lucc.html), a program element of the IGBP and IHDP programs, has supported specialist workshops, related publications, learning workshops, and large conferences related to land-use change analysis and modeling. A variety of development activities for spatial statistical modeling has been supported by CSISS (the Center for Spatially Integrated Social Science) at UC Santa Barbara, including summer workshops, specialist meetings, and development of open-source tools for spatial data analysis. (See Chapter 5 in this volume.) This effort has been supported by a series of general overview publications (for example, Anselin, 2002) and learning workshops at professional meetings. The ABM/LUCC community has itself benefited from support from both organizations for specialist meetings, publication, and educational activities and development of communication infrastructure (for more details, see www.csiss.org/resources/maslucc).

CONCLUSIONS

The ABM/LUCC modeling field is young but rapidly developing, given increased interest in modeling human-environment interactions, increased computing power and availability of specialized programming tools, critical support from several senior researchers, and development of an enthusiastic cadre of young researchers. Much progress has already been made in terms of identifying key challenges and research priorities for the field. As well, as evidenced by the large number of well-developed projects cited here, substantial development of software infrastructure is occurring. A lens through which to focus this development, in terms of development of a generic integrated ABM/LUCC and GIS modeling framework, could ensure continued coordination between researchers and could contribute to the integration of new researchers into the ABM/LUCC community.

ACKNOWLEDGMENTS

The author acknowledges useful input from Maspace list members, fellow participants at the 2003 ESRI Modeling and GIS workshop, and student participants in the author's land-use and spatial agent-based modeling classes. Section 5 draws on white papers developed with Robert Najlis for NSF Biocomplexity in the Environment grant SES008351. Helpful comments on the first draft from Robert Muetzelfeld, Francois Bousquet, Derek Robinson, Gary Polhill, and the volume editors are also acknowledged. Thanks to Julie Witcover for excellent technical editing. All errors, misrepresentations, and omissions are the author's responsibility.

REFERENCES

Agarwal, C., G. M. Green, J. M. Grove, T. Evans, and C. Schweik. 2002. A review and assessment of land-use change models: Dynamics of space, time, and human choice. Publication NE-297. Burlington, VT: USDA Forest Service Northeastern Forest Research Station. www.fs.fed.us/ne/newtown_square/publications/technical_reports/pdfs/2002/gtrne297.pdf.

Anas, A., R. Arnott, and K. A. Small. 1998. Urban spatial structure. Journal of Economic Literature 36 (3): 1426–64.

Angelsen, A., and D. Kaimowitz. 1998. Rethinking the causes of tropical –-98. www.worldbank.org/research/journals/wbro/obsfeb99/pdf/article4.pdf.

Anselin, L. 1988. Spatial econometrics: Methods and models. Studies in Operational Regional Science series. Norwell, Mass.: Kluwer Academic.

Anselin, L. 2002. Under the hood: Issues in the specification and interpretation of spatial regression models. Agricultural Economics 27 (3): 247–67.

d'Aquino, P., C. Le Page, F. Bousquet, and A. Bah. 2003. Using self-designed role-playing games and a multi-agent system to empower a local decision-making process for land use management: The selfcormas experiment in Senegal. Journal of Artificial Societies and Social Simulation 6 (3). jasss.soc.surrey.ac.uk/6/3/5.html.

Balmann, A. 1997. Farm-based modelling of regional structural change. European Review of Agricultural Economics 25 (1): 85–108.

Balmann, A., K. Happe, K. Kellermann, and A. Kleingarn. 2003. Adjustment costs of agri-environmental policy switchings: A multi-agent approach. In Complexity and ecosystem management: The theory and practice of multi-agent approaches, ed. M. A. Janssen. Northampton, Mass.: Edward Elgar Publishers.

Becu, N., P. Perez, B. Walker, O. Barreteau, and C. Le Page. 2003. Agent-based simulation of a small catchment water management in northern Thailand: Description of the catchscape model. Ecological Modelling 170 (2-3): 319–31.

Benenson, I., S. Aronovich, and S. Noam. Forthcoming. Let's talk objects: Generic methodology for urban high-resolution simulation. Computers, Environment and Urban Systems.

Benenson, I., and P. Torrens. 2004. Geosimulation: Automata-based modeling of urban phenomena. London: John Wiley and Sons.

Berger, T. 2001. Agent-based spatial models applied to agriculture: A simulation tool for technology diffusion, resource use changes, and policy analysis. Agricultural Economics 25 (2-3): 245–60.

Berger, T., and D. C. Parker. 2002. Introduction to specific examples of research. Meeting the Challenge of Complexity: Proceedings of the Special Workshop on Agent-Based Models of Land-Use/Land-Cover Change. Santa Barbara, Calif.: CIPEC/CSISS. www.csiss.org/maslucc/ABM-LUCC.htm.

Berry, B. J. L., L. D. Kiel, and E. Elliot. 2002. Adaptive agents, intelligence, and emergent human organization: Capturing complexity through agent-based modeling. Proceedings of the National Academy of Sciences 99 (Supplement 3): 7178–88.

Boissau, S., and J. C. Castella. 2003. Constructing a common representation of local institutions and land use systems through simulation-gaming and multi-agent modeling in rural areas of northern Vietnam: The SAMBA-Week methodology. Simulations and Gaming 34 (3): 342–7

Bousquet, F., F. O. Barreteau, P. d'Aquino, M. Etienne, S. Boissau, S. Auber, C. L. Page, D. Babin, and J. C. Castella. 2003. Multi-agent systems and role games: An approach for ecosystem co-management. In Multi-agent approaches for ecosystem management, ed. M. A. Janssen.Northampton, Mass.: Edward Elgar Publishers.

Bousquet, F., and D. Gautier. 1998. Comparaison de deux approches de modélisation des dynamiques spatiales par simulation multi-agents : Les approches spatiales et acteurs. CyberGéo 89. 193.55.107.45/modelis/bousquet/bousquet.htm.

Bousquet, F., and C. Le Page. 2004. Multi-agent simulations and ecosystem management: A review. Ecological Modelling 76 (3-4): 313–32.

Bousquet, F., C. Le Page, M. Antona, and P. Guizol. 2000. Ecological scales and use rights: The use of multiagent systems. Paper presented in the session-Forest and Society : The Role of Research. Sub-plenary session XXI. IUFRO World Congress 2000, Kuala Lumpur.

Bousquet, F., C. LePage, I. Bakam, and A. Takforyan. 2001. Multi-agent simulations of hunting wild meat in a village in eastern Cameroon. Ecological Modelling 138 (1-3): 331–46.

Briassoulis, H. 1999. Analysis of land use change: Theoretical and modeling approaches. Morgantown, W.V.: Regional Research Institute, West Virginia University. www.rri.wvu.edu/WebBook/Briassoulis/contents.htm.

Brown, D., M. North, D. Robinson, R. Riolo, and W. Rand. Forthcoming-a. Spatial process and data models: Toward integration of agent-based models and GIS. Journal of Geographic Systems.

Brown, D., R. Riolo, D. Robinson, W. Rand, M. North, and K. Johnston. 2004. Toward integration of spatial data models and agent-based process models. Paper presented at GIScience 2004: Third International Conference on Geographic Information Science, University of Maryland.

Brown, D. G., S. E. Page, R. Riolo, M. Zellner, and R. W. Forthcoming-b. Path dependence and the validation of agent-based spatial models of land use. International Journal of Geographic Information Science.

Caruso, G., M. Rounsevell, and G. Cojocaru. Forthcoming. Exploring a spatio-dynamic neighbourhood-based model of residential behaviour in the Brussels periurban area. International Journal of Geographical Information Science

Deadman, P., D. Robinson, E. Moran, and E. Brondizio. Forthcoming. Effects of colonist household structure on land-use change in the Amazon rainforest: An agent-based simulation approach. Environment and Planning B.

Dibble, C., and P. G. Feldman. 2004. The GeoGraph 3D Computational Laboratory: Network and terrain landscapes for RePast. Journal of Artificial Societies and Social Simulation 7 (1). jasss.soc.surrey.ac.uk/7/1/7.html.

Ducrot, R., C. Le Page, P. Bommel, and M. Kuper. 2004. Articulating land and water dynamics with urbanization:an attempt to model natural resources management at the urban edge. Computers, Environment and Urban Systems 28 (1-2): 85–106.

Epstein, J. M., and R. Axtell. 1996. Growing artificial societies: Social science from the ground up. Washington, D.C.: Brookings Institution Press.

Etienne, M. 2003a. Sylvopast: A multiple target role-playing game to assess negotiation processes in sylvopastoral management planning. Journal of Artificial Societies and Social Simulation 6 (2). jasss.soc.surrey.ac.uk/6/2/5.html.

Etienne, M., C. Le Page, and M. Cohen. 2003b. A step-by-step approach to building land management scenarios based on multiple viewpoints on multi-agent system simulations. Journal of Artificial Societies and Social Simulation 6 (2). jasss.soc.surrey.ac.uk/6/2/2.html.

Evans, T. P., and H. Kelley. 2004. Multi-scale analysis of a household level agent-based model of landcover change. Journal of Environmental Management 72 (1-2): 57–72.

Feuillette, S., F. Bousquet, and P. Le Goulven. 2003. Sinuse: A multi-agent model to negotiate water demand management on a free access water table. Environmental Modelling and Software 18 (5): 413–27.

Fleming, M. 2004. Techniques for estimating spatially dependent discrete choice models. In Advances in spatial econometrics, ed. L. Anselin and R. J. G. M. Florax. New York: Springer.

Fowler, M., and K. Scott. 2000. UML distilled: A brief guide to the standard object modeling language. Reading, Mass.: Addison Wesley Longman.

Geist, H., and E. F. Lambin. 2002. Proximate causes and underlying driving forces of tropical deforestation. Bioscience 52 (2): 143–50.

Gimblett, H. R., ed. 2002a. Integrating geographic information systems and agent-based modeling techniques for simulating social and ecological processes. Oxford: Oxford University Press.

Gimblett, H.R.. 2002b. Integrating geographic information systems and agent-based technologies for modeling and simulating social and ecological phenomena. In Integrating geographic information systems and agent-based modeling techniques for simulating social and ecological processes, ed. H. R. Gimblett, 1–20. Oxford: Oxford University Press.

Gimblett, H. R., M. T. Richards, and R. Itami. 2002. Simulating wildland recreation use and conflicting spatial interactions using rule-driven agents. In Integrating geographic information systems and agent-based modeling techniques for simulating social and ecological processes, ed. H. R. Gimblett, 211–44. Oxford: Oxford University Press.

Gimblett, H. R., C. A. Roberts, T. C. Daniel, M. Ratcliff, M. Meitner, S. Cherry, D. Stallman, R. Bogle, D. K. Allerd, and J. Bieri. 2002. An intelligent agent model for simulating and evaluating river trip scenarios along the Colorado River in Grand Canyon National Park. In Integrating geographic information systems and agent-based modeling techniques for simulating social and ecological processes, ed. H. R. Gimblett, 245–76. Oxford: Oxford University Press.

Gonçalves, A. S., A. Rodrigues, and L. Correia. 2004. Multi-agent simulation within geographic information systems. Paper presented in the 5th Workshop on Agent-Based Simulation, ABS04, Lisbon, Portugal.

Gotts, N. M. G., J. G. Polhill, and A. N. R. Law. 2003. Aspiration levels in a land use simulation. Cybernetics and Systems 34 (8): 663–83.

Grimm, V., and S. F. Railsback. Forthcoming. Chapter 1: Introduction. In Individual-based modeling and ecology, ed. V. Grimm and S. F. Railsback. Princeton, N.J.: Princeton University Press.

Harper, S. J., J. D. Westervelt, and A.-M. Trame. 2002. Management application of an agent-based model: Control of cowbirds at the landscape scale. In Integrating geographic information systems and agent-based modeling techniques for simulating social and ecological processes, ed. H. R. Gimblett. Oxford: Oxford University Press.

Irwin, E., and N. Bockstael. 2002. Interacting agents, spatial externalities, and the evolution of residential land use patterns. Journal of Economic Geography 2 (1): 31–54.

—. Forthcoming. The spatial pattern of land use in the U.S. In A companion to urban economics, ed. R. Arnott and D. McMillen. .

Itami, R. 2002. Mobile agents with spatial intelligence. In Integrating geographic information systems and agent-based modeling techniques for simulating social and ecological processes, ed. H. R. Gimblett, 191–210. Oxford: Oxford University Press.

Itami, R., R. Raulings, G. MacLaren, K. Hirst, R. Gimblett, D. Zanon, and P. Chladek. 2004. Simulating the complex interactions between human movement and the outdoor recreation environment. Journal of Nature Conservation 11 (4): 278–86.

Itami, R. M., G. S. MacLaren, K. M. Hirst, R. J. Raulings, and H. R. Gimblett. 2000. RBSIM 2: Simulating human behavior in National Parks in Australia: Integrating GIS and Intelligent Agents to predict recreation conflicts in high use natural environments. Paper presented in the 4th International Conference on Integrating GIS and Environmental Modeling (GIS/EM4). Banff, Alberta, Canada. www.colorado.edu/research/cires/banff/pubpapers/57.

Jackson, R. W. 1994. Object-oriented modeling in regional science: An advocacy view. Papers in Regional Science 73 (4): 347–67.

Janssen, M. A., ed. 2003. Complexity and ecosystem management: The theory and practice of multi-agent approaches. Northampton, Mass.: Edward Elgar Publishers.

Janssen, M. A., and E. Ostrom. Forthcoming. Governing social-ecological systems. In Handbook of computational economics II: Agent-based computational economics, ed. K. Judd and L. Tesfatsion. North-Holland.

Kaimowitz, D., and A. Angelsen. 1998. Economic models of tropical deforestation: A review. Jakarta, Indonesia: Centre for International Forestry Research.

Kohler, T. A., J. Kresl, C. V. West, E. Carr, and R. H. Wilshusen. 2000. Be there then: A modeling approach to settlement determinants and spatial efficiency among late ancestral pueblo populations of the Mesa Verde region, U.S. Southwest. In Dynamics in human and primate societies, ed. T. A. Kohler and G. J. Gumerman, 145-178 New York: Oxford University Press.

Kwartler, M., and R. N. Bernard. 2001. CommunityViz: An integrated planning support system. In Planning support systems integrating geographic systems, models, and visualization tools, ed. R. K. Brail and R. E. Klosterman. Redlands, Calif.: ESRI Press.

Lambin, E. F., H. Geist, and E. Lepers. 2003. Dynamics of land-use and land-cover change in tropical regions. Annual Review of Environmental Resources 28: 205–41.

Long, J. S. 1997. Regression models for categorical and limited dependent variables. Thousand Oaks, Calif.: Sage Publications.

Luke, S., G. C. Balan, L. Panait, C. Cioffi-Revilla, and S. Paus. 2003. MASON: A Java multi-agent simulation library. Paper presented in the Agent 2003 conference: Challenges in Social Simulation, Chicago, IL. agent2003.anl.gov/proc.html.

Manson, S. M. 2000. Agent-based dynamic spatial simulation of land-use/cover change in the Yucatán peninsula, Mexico. Paper presented in the Fourth International Conference on Integrating GIS and Environmental Modeling (GIS/EM4). Banff, Canada. www.tc.umn.edu/~manson/Resources/Manson_2000_GISEM4_ADSS_www.pdf.

—. 2002. Integrated assessment and projection of land-use and land-cover change in the Southern Yucatán Peninsular Region of Mexico. Ph D. diss. Clark University.

—. Forthcoming. The SYPR integrative assessment model: Complexity in development. In Final frontiers: Understanding land change in the Southern Yucatán Peninsular Region, ed. B. L. Turner II, D. Foster, and J. Geoghegan. Oxford: Claredon Oxford University Press.

Mathevet, R., F. Bousquet, C. Le Page, and M. Antona. 2003. Agent-based simulations of interactions between duck populations, farming decisions and leasing of hunting rights in the Camargue (Southern France). Ecological Modelling 165 (2-3): 107–26.

McGarigal, K., and B. J. Marks. 1994. FRAGSTATS: Spatial Pattern Analysis Program for Quantifying Landscape Structure. General Technical Report PNW-GTR-351. Portland, OR: U.S. Dept. of Agriculture, Forest Service, Pacific Northwest Research Station.

Najlis, R. 2004. Personal Communication: Technical specifications for the TSUNAMI and Agent Analyst models.

Najlis, R., and M. North. 2004. Repast for GIS. Paper presented in the Agent 2004 Conference on Social Dynamics: Interaction, Reflexivity, and Emergence, Chicago, IL. agent2004.anl.gov/proc.html.

Najlis, R. I., M. A. Janssen, and D. C. Parker. 2002. Software tools and communication issues. Meeting the Challenge of Complexity: Proceedings of the Special Workshop on Agent-Based Models of Land-Use/Land-Cover Change. Santa Barbara, Calif.: CIPEC/CSISS. www.csiss.org/maslucc/ABM-LUCC.htm.

North, M., M. Rimmer, and C. M. Macal. 2003. Why the Navy needs TSUNAMI. Paper presented in the Swarmfest, South Bend, Ind.

Parker, D. C., T. Berger, and S. M. Manson. 2002a. Meeting the Challenge of Complexity: Proceedings of the Special Workshop on Agent-Based Models of Land-Use/Land-Cover Change. Santa Barbara, CA: CIPEC/CSISS Publication CCR-3. www.csiss.org/maslucc/ABM-LUCC.htm.

Parker, D. C., T. Berger, and S. M. Manson. 2002b. Agent-Based Models of Land-Use/Land-Cover Change: Report and Review of an International Workshop. Bloomington, IN: LUCC Focus 1 Publication 6. www.indiana.edu/~act/focus1/FinalABM11.7.02.pdf.

Parker, D. C., S. M. Manson, and T. Berger. 2002. Potential strengths and appropriate roles for ABM/LUCC. Meeting the Challenge of Complexity: Proceedings of the Special Workshop on Agent-Based Models of Land-Use/Land-Cover Change. Santa Barbara, CA: CIPEC/CSISS. www.csiss.org/maslucc/ABM-LUCC.htm.

Parker, D. C., S. M. Manson, M. A. Janssen, M. Hoffmann, and P. Deadman. 2003. Multi-agent systems for the simulation of land-use and land-cover change: A review. Annals of the Association of American Geographers 93 (2): 314–37.

Parker, D. C., and V. Meretsky. 2004. Measuring pattern outcomes in an agent-based model of edge-effect externalities using spatial metrics. Agriculture, Ecosystems and Environment 101 (2-3): 233–50.

Parker, M. T. 2001. What is Ascape and why should you care? Journal of Artificial Societies and Social Simulation 4 (1). jasss.soc.surrey.ac.uk/4/1/5.html.

Perman, R., Y. Ma, J. McGilvray, and M. Common. 2003. Natural Resource and Environmental Economics. New York: Pearson Addison Wesley.

Reynolds, R., T. A. Kohler, and Z. Kobti. 2003. The effects of generalized reciprocal exchange on the resilience of social networks: An example from the Prehispanic Mesa Verde region. Computational & Mathematical Organization Theory 9 (3): 227–54.

Thomas, W. H., M. North, C. M. Macal, and J. P. Peerenboom. 2003. From physics to finances: Complex adaptive systems representation of infrastructure interdependencies. Dahlgren, V.A.: Naval Surface Warfare Center Publication.

Torrens, P. 2003. Automata-based models of urban systems. In Advanced spatial analysis, ed. P. A. Longley and M. Batty, 61-81. Redlands, Calif.: ESRI Press.

Torrens, P., and I. Benenson. Forthcoming. Geographic automata systems. International Journal of Geographic Information Science.

Trébuil, G., F. Shinawtra-Ekasingh, F. Bousquet, and C. Thong-Ngam. 2002. Multi-agent systems companion modeling for integrated watershed management: A Northern Thailand experience. Paper presented in the 3rd International Conference on Montane Mainland Southeast Asia (MMSEA 3), Lijiang, Yunnan, China.

Verburg, P. H., P. Schot, M. Dijst, and A. Velkamp. Forthcoming. Land-use change modeling: Current practice and research priorities. GeoJournal.

Westervelt, J. 2002. Geographic information systems and agent-based modeling. In Integrating geographic information systems and agent-based modeling techniques for simulating social and ecological processes, ed. H. R. Gimblett. Oxford: Oxford University Press.

Westervelt, J. D., and L. D. Hopkins. 1999. Modeling mobile individuals in dynamic landscapes. International Journal of Geographic Information Science 13 (3): 191–208

FOOTNOTES

[1] The public good characteristics of open-source software imply that the success of many open-source projects contradicts the standard, static theoretical prediction that public goods will be underprovided in the marketplace. Thus, open-source licensing regimes are a potentially exciting area for research in public economics.