ACT Publication No. 08-07

Land Use Change: Complexity and Comparisons

Rindfuss RR, Entwisle B, Walsh SJ, An L, Badenoch N, Brown DG, Deadman P, Evans TP, Fox J, Geoghegan J, Gutmann M, Kelly M, Linderman M, Liu J, Malanson GP, Mena CF, Messina JP, Moran EF, Parker DC, Parton W, Prasartkul P, Robinson DT, Sawangdee Y, Vanwey LK, Verburg PH.

Reprinted from:

Journal of Land Use Science 3(1):1-10.

Anthropological Center for Training and Research on Global Environmental Change
Indiana University, Student Building 331, 701 E. Kirkwood Ave., 47405-7100, U.S.A.
Phone: (812) 855-6181, Fax: (812) 855-3000, Email: act@indiana.edu, internet: www.indiana.edu/~act
ACT Publication No. 08-02

Journal of Land Use Science
Vol. 3, No. 1, March 2008, 1–10

Land use change: complexity and comparisons

Ronald R. Rindfuss[a,b]*, Barbara Entwisle[a], Stephen J. Walsh[a], Li An[c], Nathan Badenoch[d], Daniel G. Brown[d], Peter Deadman[e], Tom P. Evans[f], Jefferson Fox[b], Jacqueline Geoghegan[g], Myron Gutmann[d], Maggi Kelly[h], Marc Linderman[i], Jianguo Liu[j], George P. Malanson[i], Carlos F. Mena[k], Joseph P. Messina[j], Emilio F. Moran[f], Dawn C. Parker[l], William Parton[m], Pramote Prasartkul[n], Derek T. Robinson[d], Yothin Sawangdee[p], Leah K. Vanwey[f] and Peter H. Verburg[o]

[a]*University of North Carolina at Chapel Hill, USA;* [b]*East–West Center, Hawaii, USA;* [c]*San Diego State University, USA;* [d]*National Agricultural and Forestry Research Institute Lao PDR;* [e]*University of Michigan, USA;* [f]*University of Waterloo, Canada;* [g]*Indiana University, USA;* [h]*Clark University, USA;* [i]*University of California-Berkeley, USA;* [j]*University of Iowa, USA;* [k]*Michigan State University, USA;* [l]*Universidad San Francisco de Quito, Ecuador;* [m]*George Mason University USA;* [n]*Colorado State University, USA;* [o]*Institute for Population and Social Research, Mahidol University, Thailand;* [p]*Wageningen University, The Netherlands*

(*Received 17 January 2008*)

1. Introduction

Research on the determinants of land use change and its relationship to vulnerability (broadly defined), biotic diversity and ecosystem services (e.g. Gullison et al. 2007), health (e.g. Patz et al. 2004) and climate change (e.g. van der Werf et al. 2004) has accelerated. Evidence of this increased interest is demonstrated by several examples. Funding agencies in the US (National Institutes of Health, National Science Foundation, National Aeronautics and Space Administration and National Oceanic and Atmospheric Administration) and around the world have increased their support of land use science. In addition to research papers in disciplinary journals, there have been numerous edited volumes and special issues of journals recently (e.g. Gutman et al. 2004; *Environment & Planning B* 2005; *Environment & Planning A* 2006; Lambin and Geist 2006; Kok, Verburg and Veldkamp 2007). And in 2006, the *Journal of Land Use Science* was launched.

Land use science is now at a crucial juncture in its maturation process. Much has been learned, but the array of factors influencing land use change, the diversity of sites chosen for case studies, and the variety of modeling approaches used by the various case study teams have all combined to make two of the hallmarks of science, generalization and validation, difficult within land use science. This introduction and the four papers in this themed issue grew out of two workshops which were part of a US National Institutes of Health (NIH) 'Roadmap' project. The general idea behind the NIH Roadmap initiative was to stimulate scientific advances by bringing together diverse disciplines to tackle a common, multi-disciplinary scientific problem. The specific idea behind our Roadmap project was to bring together seven multi-disciplinary case study teams, working in areas that could be broadly classified as inland frontiers, incorporating social, spatial

*Corresponding author. Email: ron-rindfuss@unc.edu

ISSN 1747-423X print/ISSN 1747-4248 online

DOI: 10.1080/17474230802047955
http://www.informaworld.com

and biophysical sciences, having temporal depth on both the social and biophysical sides, and having had long-term funding. Early in our Roadmap project, the crucial importance of modeling, particularly agent-based modeling, for the next phase of land-use science became apparent and additional modelers not affiliated with any of the seven case studies were brought into the project. Since agent-based simulations attempt to explicitly capture human behavior and interaction, they were of special interest.

At the risk of oversimplification, it is worth briefly reviewing selected key insights in land use science in the past two decades to set the stage for the papers in this themed issue. One of the earliest realizations, and perhaps most fundamental, was accepting the crucial role that humans play in transforming the landscape, and concomitantly the distinction drawn between land cover (which can be seen remotely) and land use (which, in most circumstances, requires in situ observation; e.g. Turner, Meyer and Skole 1994). The complexity of factors influencing land use change became apparent and led to a variety of 'box and arrow' diagrams as conceptual frameworks, frequently put together by committees rarely agreeing with one another on all details, but agreeing among themselves that there were many components (social and biophysical) whose role needed to be measured and understood.

A series of case studies emerged, recognizing the wide array of variables that needed to be incorporated, and typically doing so by assembling a multidisciplinary team (Liverman, Moran, Rindfuss and Stern 1998; Entwisle and Stern 2005). The disciplinary make-up of the team strongly influenced what was measured and how it was measured (see Rindfuss, Walsh, Turner, Fox and Mishra 2004; Overmars and Verburg 2005), with limited, if any, coordination across case studies (see Moran and Ostrom 2005 for an exception). In large part, the focus on case studies reflected the infancy of theory in land use science. Teams combined their own theoretical knowledge of social, spatial and ecological change with an inductive approach to understanding land use change – starting from a kitchen sink of variables and an in-depth knowledge of the site to generate theory on the interrelationships between variables and the importance of contextual effects. This lack of coordination in methods, documentation and theory made it very difficult to conduct meta-analyses of the driving factors of land use change across all the case studies to identify common patterns and processes (Geist and Lambin 2002; Keys and McConnell 2005).

Recognizing that important causative factors were affecting the entire site of a case study (such as a new road which opens an entire area) and that experimentation was not feasible, computational, statistical and spatially explicit modeling emerged as powerful tools to understand the forces of land use change at a host of space–time scales (Veldkamp and Lambin 2001; Parker, Manson, Janssen, Hoffmann, and Deadman 2003; Verburg, Schot, Dijst and Veldkamp 2004). Increasingly, in recognition of the crucial role of humans in land use change, modeling approaches that represent those actors as agents have emerged as an important, and perhaps the dominant, modeling approach at local levels (Matthews, Gilbert, Roach, Polhil and Gotts 2007).

In this introductory paper we briefly discuss some of the major themes that emerged in the workshops that brought together scientists from anthropology, botany, demography, developmental studies, ecology, economics, environmental science, geography, history, hydrology, meteorology, remote sensing, geographic information science, resource management, and sociology. A central theme was the need to measure and model behavior and interactions among actors, as well as between actors and the environment. Many early agent-based models focused on representing individuals and households (e.g. Deadman 1999), but the importance of other types of actors (e.g. governmental units at various levels, businesses, and NGOs) was a persistent theme. 'Complexity' was a term that peppered the conversation, and it was used with multiple meanings. But the dominant topic to emerge was comparison and generalization: with multiple case studies and agent-based models blooming, how do we compare across them and move towards generalization? We return to the generalization issue at the end of this introductory paper after a brief discussion of the other themes.

2. Complexity

A number of theoretical and methodological themes from complexity science and the study of complex adaptive systems inform land-use science (c.f. Manson 2001; Brown et al. 2007). Complexity science, with intellectual roots in general systems theory (von Bertalanffy 1968), has experienced considerable advancement in the last couple of decades with contributions from physics, genetic biology, evolutionary computation and political science (Axelrod and Cohen 2000). Unlike the general systems theory which focuses on order, stability, and rationality, complexity science is more concerned with disorder, instability, and change – usually rapid change (Warren, Franklin and Streeter 1998). The term 'complex adaptive systems' refers to systems that exhibit (a) macro-level outcomes manifested as emergent spatial or temporal regularities, (b) decision-making with specified behaviors, (c) heterogeneity in characteristics or behavior of actors, (d) social or other interactions that affect their attributes or decisions, and (e) feedback mechanisms that can produce nonlinear system behaviors (e.g. Waldrop 1992; Holland 1995; Axelrod and Cohen 2000). These characteristics limit the ability of traditional statistical and dynamical modeling approaches to adequately examine system outcomes. Rather than proposing a set of hypotheses to be tested or making specific ontological claims, complexity science offers a flexible ontology, based on relationships among actors, and makes claims about how we can learn about systems using simulation modeling (Manson and O'Sullivan 2006). However, complexity science offers precious few testable hypotheses related to any specific domain, such as land use science.

Complexity encompasses interactions within and among ecological systems, the physical systems on which they depend, and the human systems with which they interact (Michener et al. 2001; Liu et al. 2007). Complexity is scale sensitive (Phillips 1999; Walsh, Evans, Welsh, Entwisle and Rindfuss 1999). Feedbacks can heighten, constrain or even reverse some of the original changes in land use/land cover (Verburg 2006). Studies of the complex dynamics of land use draw on theories and practices from across the social, natural, and spatial sciences (Parker, Hessl and Davis 2008). For instance, complexity has been applied to the study of tropical deforestation (e.g. Silveira, Coutinho and Lopes 2002; Deadman, Robinson, Moran and Brondizio 2004; Messina and Walsh 2005; Entwisle, Rindfuss, Walsh and Page 2008) and land use/land cover change in coupled human–natural systems (e.g. Messina and Walsh 2001; Lambin, Geist and Lepers 2003; Evans and Kelly 2004; An, Linderman, Qi, Shortridge and Liu 2005; Walsh, Entwisle, Rindfuss and Page 2006; Walsh, Messina, Mena, Malanson and Page 2008). In short, complexity science has established itself as an emerging paradigm for the study of non-linear and dynamic systems that can be applied to understanding pattern-process relations in coupled human–natural systems, and where system dynamics are examined using a variety of methods, including agent-based models (ABMs).

3. Modeling agent interactions

A fundamental feature of complex adaptive systems is considerable interaction among actors, and between actors and the environment. Agent-based modeling is an ideal tool to incorporate such interactions. Indeed, agent interaction is a key characteristic that yields emergent properties within ABMs. Agents can differ in important ways: the characteristics of the agents may change over time as they adapt to their environment, learn from experiences through feedbacks, or 'die' as they fail to alter behavior relative to new conditions and/or factors. ABMs have recently been used, for instance, to explore complex systems in land use/land cover change (Brown, Page, Riolo and Rand 2004; Deadman et al. 2004; Evans and Kelley 2004; An et al. 2005; Brown, Page, Riolo, Zellner and Rand 2005), ecosystem management (Bousquet, Le Page, Bakam and Takforyan 2001;

Bousquet and LePage 2004), and agricultural economics (Berger 2001). Multiple empirical data sources, including cross-sectional and longitudinal surveys, are used to characterize agents and to define their spatial interactions with the environment and other agents (Robinson et al. 2007). Socio-economic and demographic data, possibly linked to the environment through spatial data layers and/or social and spatial networks, are used to address the adaptive behaviors of agents through information sharing, learning through historical events (i.e. a drought), or choosing to act through stochastic processes. Parameters determining the influence of environment (biophysical or social) and history on agents' decision-making in spatial simulation models can be developed through empirical statistical approaches (Evans and Kelly 2004; An et al. 2005).

Interaction among agents can be conceptualized and modeled in a variety of ways. Little, if anything, is known about the consequences of featuring one type of interaction over another in these models. Agents may have a direct influence on each other. For example, neighboring farmers might talk about what works and what does not work on their adjacent lands; each will be influenced by the successes (or failures) of the other. Agents may be influenced by prevailing norms about appropriate land uses, which are enforced through local commentary and gossip. Agents may interact strategically to achieve their own goals within the context of the goals of others (e.g. Ostrom 2002), and their behaviors may be shaped by their perceptions of others, as well as myths. For example, neighboring farmers may need to coordinate the flow of water (Lansing 1991). Agents may also compete in markets. For example, they may compete for off-farm jobs on a seasonal basis; they may try to time the sale of their products to achieve the highest price. These are just a few examples of agent interaction with direct implications for land use. Interestingly, each type is studied within and relates to different disciplinary literatures: social influence and social learning in the social network, anthropological and demography literatures; strategies and outcomes for the use of common resources in the geography, political science and economics literatures; and market behavior in the economics literature. A challenge to the interdisciplinary land use science community is to consider the range of potentially relevant interactions among agents and to develop a strategy for choosing which to emphasize. In addition, new methods and techniques are needed to detect, monitor, measure and translate these interactions from the real world into formal model specifications.

4. Actors other than individuals and households

The land-use science community, especially those who work at the case study level and incorporate the tools of ABMs, has learned more about the effects of individual and household actors' behaviors on land cover and use change than the effects of other types of human actors, such as governmental units, businesses, and non-governmental units (religious groups, volunteer organizations, and various charities). This was the result of a deliberate choice on the part of numerous research teams who felt that, for the areas they studied, individuals and households were the predominant decision-makers. In addition to the theoretical rationale, social science methods for obtaining data on individuals and households are more developed and agreed upon than methods for obtaining data on organizations and institutions. While this was undoubtedly a wise strategy, it seems abundantly clear that the land-use science community needs to be able to move beyond, but not abandon, individuals and households. The reasons are straightforward and examples plentiful. Zoning and other statutes regulate how certain land parcels can be used. Governments provide various incentives and disincentives regarding the use of land parcels (ranging from the building of the Erie Canal to the protection of the Wolong Nature Reserve, China). Businesses and various NGOs own and use land, sometimes in discontinuous parcels. A challenge for the land use modeling community is to bring institutions into ABMs that also include individuals and households. There are also non-human agents operating on the landscape – fire and pathogens, for example, can play an important role in land cover and land use change.

5. Representing uncertainty: model calibration and uncertainty

Fundamental to assessing model performance is determining the general goals of the modeling activity – prediction or explanation/understanding of patterns or processes (Brown, Aspinall and Bennett 2006). If prediction is the intent, then the ability of the model to replicate some measure of reality is an appropriate evaluation metric (e.g. Pontius, Huffaker and Denman 2004). If the goal is explanation, then the outcomes of the model need to be assessed relative to the theoretical and empirical understanding of pattern–process relations.

Whether concerned about prediction or explanation, model parameterization, calibration, and validation are central concerns. In developing rules to assess land cover dynamics, there is the temptation to over-parameterize the model and hence 'over fit', rendering the model deterministic (e.g. Brown et al. 2005; Pijanowski, Alexandridis and Mueller 2006). Calibration of the model is commonly accomplished by comparing the model outcomes to a series of classified satellite images, and fine-tuning the parameter values, rules and relationships to generate improved model fit. The danger is that this approach trades fit for generality and applicability.

6. Comparisons

Complexity implies intrinsic differences across study sites, and, not surprisingly, the word 'complex' was used repeatedly with reference to the difficulty of comparing the data, methods and models used in the various cases. The lack of comparability of data across sites was striking. Perhaps the most common data element was the use of remotely sensed data, but even here there were differences in sensors and the methods used to classify land cover. The diversity of data used to inform agent-based models is widespread throughout the literature (e.g. Robinson et al. 2007), making comparison a complex task. Similar issues have arisen in the literature (Parker et al. 2003; Parker, Brown, Polhill, Manson and Deadman 2008) and at our workshop with respect to the elements incorporated within agent-based models. Another issue that makes comparison difficult is the link between agents and the land. Some agent models represent decision-making at the plot level while others dynamically link people and plots.

7. Towards generalization

Generalization (that is, the ability to move beyond a specific case and a particular model) emerged as the issue of most concern to our diverse interdisciplinary group of case study and modeling specialists. Assuming a model is useful at one location (i.e. one model and one location), modelers often encounter problems when applying a site-specific model to other locations. For example, the same processes may not be occurring at multiple sites, and if so, they may not be occurring at the same scale or resolution.

In the reverse case of many models applied to one site, a number of problems also exist. For example, if the models reproduce an observed result but incorporate different processes then they have only achieved a 'proof of concept,' i.e. that given the incorporated processes it is possible to derive the observed result. Then we are faced with the problem of determining which model best represents what has actually happened on the site. One approach that has been offered to compare models is the pattern-oriented modeling approach (Grimm et al. 2005). By matching model results to additional patterns of observation, we increase our confidence that the processes represented in the model are similar to those in the system being studied.

We might also have different case studies, with different data, sites and ABMs that produce different results; how can we adjudicate among them? In these cases we can only attempt to retrieve common drivers or actors identified in each case study that are important contributors to land-use and land-cover change. Given that models are often written in different programming languages, even if their code is made public, how do we compare them? These are questions that we expect the land use science community will struggle with for quite some time. The four papers in this themed issue do not provide definitive answers, but they help clarify the issues and move the community closer to being able to answer them.

The first paper, 'Complex systems models and the management of error and uncertainty', focuses on sources of error and uncertainty in ABMs, expectations about the match between model results and reality, and methods of assessment. The authors distinguish between uncertainty in the underlying data (i.e. measurement error) and uncertainty due to the model itself. In the case of measurement error, there are well-defined approaches to assessing its nature and extent. Less is known about the consequences of measurement error in complex systems, as it might result not only in divergence between model predictions and reality, but could propagate through the model in unanticipated ways. Uncertainty due to the model itself has several sources. For example, there could be incompleteness in the agent decision-making algorithm. Another source is the fact that at some fundamental level, actor behavior does not follow an algorithm exactly, i.e. the model is a generalization of the process being represented. Even if all influences were explicitly modeled, there would still be uncertainty associated with the exercise of free will. The challenge to researchers is to untangle sources of error and uncertainty, and then develop expectations about the match between model results and 'reality' that reflect this understanding.

The next paper, 'Adding ecosystem function to agent-based land use models', discusses how biogeochemical simulations can be linked to ABMs of land use and the specific challenges of doing so. The particular ecosystem representation addressed in this paper is the Century model, a generalized biogeochemical model that simulates plant production, nutrient cycling, and soil organic matter dynamics in relation to land management practices. The Century model is used to generate information about the potential outcomes of land management decisions that agents might consider in making their actual decisions. Given this objective, the authors examine three ways to accomplish a link between an ABM of land use and the Century model. The approaches vary in terms of the type of information agents receive (e.g. number of options considered) and how they receive it (e.g. directly or through some third party), the time period involved, and their computational demands. Models that incorporate a detailed biogeochemical simulation couple human and natural systems in a more complete way and also make possible a broader range of comparisons to other modeling efforts. However, as the authors document, these gains come at a computational cost.

The third paper, 'Case studies, cross-site comparisons, and the challenges of generalization: comparing agent-based models of land-use change in frontier regions', makes an interesting contrast to the first two papers. In this paper, the tension between parsimony and completeness in the specification of agent behavior arises from the desire of researchers to capture what is most essential about their specific case study. Models are developed in response to a particular set of research questions as they apply in a particular research site, subject to the constraints of data availability (and also the disciplinary expertise of the researchers developing the model). As a consequence, input data and algorithms are both different. While this adds realism in a particular application, such specificity has risks. As Messina and his colleagues point out (in the first paper), it has the potential to relegate specific models to the status of a scientific curiosity. Parker and her colleagues (in the third paper) propose a way forward, based on a disciplined assessment of four ABMs of land use in frontier areas that were developed and implemented independently of one another. They compare these models in terms of how they address agent–parcel relationships, non-spatial social networks, land suitability, multiple agents, land transfer mechanisms, and institutional drivers. The paper takes important steps to identify what processes need to be included in all land change models and to lay the groundwork for a generalized model.

The final paper, 'An agent-based model of household dynamics and land use change', is an illustrative example of how it might be possible to compare models in a more precise, but not necessarily easy, manner. This paper takes a model that is currently under development and describes the variables, relationships among variables and assumptions in a series of mathematical equations. By using mathematics, a common language across numerous disciplines, components and relationships are more precisely defined. The paper also illustrates how ABMs of land use can be linked with formal population projections and social network dynamics. The incorporation of population projections is not new to land use science, although rarely are they fully developed. For example, feedbacks are often underspecified. The incorporation of fully dynamic social networks is more novel. As Parker and her colleagues document in the third paper, the modeling of social interaction is still fairly primitive in ABMs of land use. Elaborating this side of the coupled human–natural system is important, but comes at a cost. Data and computational demands are significant.

8. Conclusion

The papers in this special issue, resulting from two workshops intended to chart the way forward for studies of complex land-use dynamics, suggest that the paradigm of 'complexity', in its multiple meanings, raises both new opportunities and new challenges that require multidisciplinary attention. The opportunities include the potential to explore non-linear interactions between social and environmental processes in a way that represents the richness of human behavior and ecological functioning, and the mutual dependence of these systems. Computer simulations of agent-based systems provide this opportunity. The challenges are both conceptual and methodological. The case studies being conducted and the models being built are sufficiently complex that comparison and generalization are difficult. Nevertheless, comparisons are possible, and it is important for the land use science community to work towards the goals of comparison and generalization.

Acknowledgments

The development of this article was supported in part by a National Institutes of Health (NIH), Roadmap Initiative grant (HD051645-01), and a supplement to a National Science Foundation (NSF), Coupled Natural–Human Systems grant (BCS-0410048) to the Carolina Population Center at the University of North Carolina at Chapel Hill. We are also grateful to the Carolina Population Center and the East–West Center for hosting workshops that facilitated the conceptualization of this paper.

References

An, L., Inderman, M., Qi. J., Shortridge, A., and Liu. J. (2005), "Exploring Complexity in Human-Environment Systems: and Agent-Based Spatial Model for Multidisciplinary and Multiscale Integration," *Annals of the Association of American Geographers*, 95(1), 54–79.

Axelrod, R., and Cohen, M.D. (2000), *Harnessing Complexity: Organizational Implications of a Scientific Frontier*, New York: Free Press.

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), 245–260.

Bousquet, F., Le Page, C., Bakam, I., and Takforyan, A. (2001), "Multi-Agent Simulations of Hunting Wild Meat in a Village in Eastern Cameroon," *Ecological Modelling*, 13, 331–346.

Bousquet, F., and Le Page, C. (2004), "Multi-Agent Simulations and Ecosystem Management: a Review," *Ecological Modeling*, 176(3–4), 313–332.
Brown, D.G., Aspinall, R., and Bennett, D.A. (2006), "Landscape Models and Explanation in Landscape Ecology – a Space for Generative Landscape Science?" *Professional Geographer*, 58(4), 369–382.
Brown, D.G., Page, S.E., Riolo, R.L., and Rand, W. (2004), "Agent Based and Analytical Modeling to Evaluate the Effectiveness of Greenbelts," *Environmental Modelling and Software*, 19(12), 1097–1109.
Brown, D.G., Page, S.E., Riolo, R.L., Zellner, M., and Rand, W. (2005), "Path Dependence and the Validation of Agent-Based Spatial Models of Land-Use," *International Journal of Geographical Information Science*, 19(2), 153–174.
Brown, D.G., Robinson, D.T., An, L., Nassauer, J.I., Zellner, M., Rand, W., Riolo, R., Page, S.E., and Low, B. (2008), "Exurbia From the Bottom-up: Confronting Empirical Challenges to Characterizing Complex Systems," *GeoForum*, 39, 867–878.
Deadman, P. (1999), "Modelling Individual Behavior and Group Performance in an Intelligent Agent-Based Simulation of the Tragedy of the Commons," *Journal of Environmental Management*, 56(3), 159–172.
Deadman, P., Robinson, D., Moran, E., and Brondizio, E. (2004), "Colonist Household Decision-Making and Land Use Change in the Amazon Rainforest: an Agent-Based Simulation," *Environment and Planning B*, 31, 693–709.
Entwisle, B., Rindfuss, R.R., Walsh, S.J., and Page, P.H. (2008), "Modeling Population as a Factor in the Deforestation of Nang Rong, Thailand," *GeoForum*, 39, 879–897.
Entwisle, B., and Stern, P. (2005), *Population, Land Use, and Environment: Research Directions*. Washington, DC: National Academy Press.
Evans, T.P., and Kelly, H. (2004), "Multi-scale Analysis of a Household Level Agent-Based Model of Landcover Change," *Environmental Management*, 72(1–2), 57–72.
Geist, H.J., and Lambin, E.F. (2002), "Proximate Causes and Underlying Driving Forces of Tropical Deforestation," *BioScience*, 52(2), 143–150.
Grimm, V., Revilla, E., Berger, U., Jeltsch, F., Mooij, W.M., Railsback, S.F., Thulke, H.H., Weiner, J., Wiegand, T., and Deangelis, D.L. (2005), "Pattern-Oriented Modeling of Agent-Based Complex Systems: Lessons From Ecology," *Science*, 310, 987–991.
Gullison, R.E., Frumhoff, P.C., Canadell, J.G., Field, C.B., Nepstad, D.C., Hayhoe, K., Avissar, R., Curran, L.M., Friedlingstein, P., Jones, C.D., and Nobre, C. (2007), "Tropical Forests and Climate Policy," *Science*, 316, 985–986.
Gutman, G., Janetos, A., Justice, C., Moran, E., Mustard, J., Rindfuss, R.R., Skole, D., and Turner, B.L. (2004), *Land Change Science: Observing, Monitoring and Understanding Trajectories of Change on the Earth's Surface*, Boston: Kluwer Academic Publishers.
Holland, J.H. (1995), *Hidden Order: How Adaptation Builds Complexity*, Cambridge, MA: Perseus Books.
Keys, E., and McConnell, W.J. (2005), "Global Change and the Intensification of Agriculture in the Tropics," *Global Environmental Change, Part A*, 15(4), 320–337.
Kok, K., Verburg, P.H., and Veldkamp, T. (2007), "Integrated Assessment of the Land System: The Future of Land Use," *Land Use Policy*, 24(3), 517–520.
Lambin, E.F., and Geist, H.J. (eds.) (2006), *Land-Use and Land-Cover Change*, Berlin: Springer.
Lambin, E.F., Geist, H.J., and Lepers, E. (2003), "Dynamics of Land-Use and Land-Cover Change in Tropical Regions," *Annual Review of Environment and Resources*, 28, 205–241.
Lansing, J.S. (1991), *Priests and Programmers: Technologies of Power in the Engineered Landscape of Bali*, Princeton, NJ: Princeton University Press.
Liu, J., Dietz, T., Carpenter, S.R., Alberti, M., Folke, C., Moran, E., Pell, A.N., Deadman, P., Kratz, T., Lubchenco, J., Ostrom, E., Ouyang, Z., Provencher, W., Redman, C.L., Schneider, S.H., and Taylor, W.W. (2007), "Complexity of Coupled Human and Natural Systems," *Science*, 317, 1513–1516.
Liverman, D., Moran, E.F., Rindfuss, R.R., and Stern, P.C. (1998), *People and Pixels*, Washington, DC: National Academy Press.
Manson, S.M. (2001), "Simplifying Complexity: A Review of Complexity Theory," *Geoforum*, 32(3), 405–414.
Manson, S.M., and O'Sullivan, D. (2006), "Complexity Theory in the Study of Space and Place," *Environment and Planning A*, 38, 677–692.
Matthews, R., Gilbert, N., Roach, A., Polhil, J., and Gotts, N. (2007), "Agent-Based Land-Use Models: A Review of Applications," *Landscape Ecology*, 22, 1447–1459.
Messina, J.P., and Walsh, S.J. (2001), "2.5D Morphogenesis: Modeling Landuse and Landcover Dynamics in the Ecuadorian Amazon," *Plant Ecology*, 156(1), 75–88.
Messina, J.P., and Walsh, S.J. (2005), "Dynamic Spatial Simulation Modeling of the Population–Environment Matrix in the Ecuadorian Amazon," *Environment and Planning B*, 32(6), 835–856.

Michener, W.K., Baerwald, T.J., Firth, P., Palmer, M.A., Rosenberger, J., Sandlin, E.A., and Zimmerman, H. (2001), "Defining and Unraveling Biocomplexity," *Bioscience*, 51(12), 1018–1023.

Moran, E.F., and Ostrom, E. (eds.) (2005), *Seeing the Forest and the Trees: Human–Environment Interactions in Forest Ecosystems*, Cambridge, MA: MIT Press.

Ostrom, E. (2002), *The Drama or the Commons*, Washington, D.C: National Academies Press.

Overmars, K.P., and Verburg, P.H. (2005), "Analysis of Land Use Drivers at the Watershed and Household Level: Linking Two Paradigms at the Philippine Forest Fringe," *International Journal of Geographical Information Science*, 19(2), 125–152.

Parker, D.S., Manson, S.M., Janssen, M., Hoffmann, M.P., and Deadman, P. (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), 314–337.

Parker, D., Brown, D., Polhill, J.G., Manson, S.M., and Deadman, P. (2008a), "Illustrating a New 'Conceptual Design Pattern' for Agent-Based Models and Land Use via Five Case Studies: The MR POTATOHEAD Framework," in Agent-based Modeling in Natural Resource Management, eds. A. L. Paredes and C. H. Iglesias, Valladolid, Spain.

Parker, D.C., Hessl, A., and Davis, S.C. (2008b), "Complexity, Land-Use Modeling, and the Human Dimension: Fundamental Challenges for Mapping Unknown Outcome Spaces," *Geoforum*, 39, 789–804.

Patz, J.A., Tabor, P.D.G.M., Aguirre, A., Pearl, M., Epstein, J., Wolfe, N.D., Kilpatrick, M., Foufopoulos, J., Molyneux, D., and Bradley, D.J. (2004), "Unhealthy Landscapes: Policy Recommendations on Land Use Change and Infectious Disease Emergence," *Environmental Health Perspectives*, 112(10), 1092–1098.

Phillips, J.D. (1999), "Methodology, Scale, and the Field of Dreams," *Annals of the Association of American Geographers*, 89, 754–760.

Pijanowski, B.C., Alexandridis, K.T., and Mueller, D. (2006), "Modeling Urbanization Patterns in Two Diverse Regions of the World," *Journal of Land Use Studies*, 1(2), 83–108.

Pontius, R.G., Huffaker, D., and Denman, K. (2004), "Useful Techniques of Validation for Spatially Explicit Land-Change Models," *Ecological Modeling*, 179(4), 445–461.

Rindfuss, R.R., Walsh, S.J., Turner II, B.L., Fox, J., and Mishra, V. (2004), "Developing a Science of Land Change: Challenges and Methodological Issues," *Proceedings of the National Academy of Science*, 101(39), 13976–13981.

Robinson, D.T., Brown, D.G., Parker, D.C., Schreinemachers, P., Janssen, M.A., Huigen, M., Wittmer, H., Grotts, N., Promburom, P., Irwin, E., Berger, T., Gatzweiler, F., and Barnaud, C. (2007), "Comparison of Empirical Methods for Building Agent-Based Models in Land Use Science," *Journal of Land Use Science*, 2(1), 31–55.

Silveira, J.J., Coutinho, G., and Lopes, C. (2002), "DINAMICA – a Stochastic Cellular Automata Model Designed to Simulate the Landscape Dynamics in an Amazonian Colonization Frontier," *Ecological Modelling*, 154(3), 217–235.

Turner, I.I.B.L., Meyer, W.B., and Skole, D.L. (1994), "Global Land-Use/Land-Cover Change: Towards an Integrated Program of Study," *Ambio*, 23(1), 91–95.

van der Werf, G.R., Randerson, J.T., Collatz, G.J., Giglio, L., Kasibhatla, P.S., Arellano Jr., A.F., Olsen, S., and Kasischke, E.S. (2004), "Continental-Scale Partitioning of Fire Emissions During the 1997 to 2001 El Nino/La Nina Period," *Science*, 303, 73–76.

Veldkamp, A., and Lambin, E. (eds.) (2001), "Predicting Land Use Change, Special Issue," *Agriculture Ecosystems and Environment*, (85).

Verburg, P. (2006), "Simulating Feedbacks in Land Use and Land Cover Change Models," *Landscape Ecology*, 21(8), 1171–1183.

Verburg, P., Schot, P., Dust, M., and Veldkamp, A. (2004), "Land Use Change Modeling: Current Practice and Research Priorities," *Geojournal*, 61(4), 309–324.

Von Bertalanffy, L. (1968), *General System Theory: Foundations, Development, Applications*, New York: George Braziller.

Waldrop, M.M. (1992), *Complexity: The Emerging Science at the Edge of Order and Chaos.* New York: Simon and Schuster.

Walsh, S.J., Entwisle, B., Rindfuss, R.R., and Page, P.H. (2006), "Spatial Simulation Modeling of Land Use/Land Cover Change Scenarios in Northeastern Thailand: A Cellular Automata Approach," *Journal of Land Science*, 1(1), 5–28.

Walsh, S.J., Evans, T.P., Welsh, W.F., Entwisle, B., and Rindfuss, R.R. (1999), "Scale Dependent Relationships Between Population and Environment in Northeast Thailand," *Photogrammetric Engineering and Remote Sensing*, 65, 97–105.

Walsh, S.J., Messina, J.P., Mena, C.F., Malanson, G.P., and Page, P.H. (2008), "Complexity Theory, Spatial Simulation Models, and Land Use Dynamics in the Northern Ecuadorian Amazon," *GeoForum*, 39, 867–878.

Warren, K., Franklin, C., and Streeter, C.L. (1998), "New Directions in Systems Theory: Chaos and Complexity," *Social Work*, 43(4), 357–372.

ACT Publications 2007

No. 07-01
Lu, D., M. Batistella, P. Mausel and E. Moran. 2007. Mapping and Monitoring Land Degradation Risks in the Western Brazilian Amazon Using Multitemporal Landsat TM/ETM+ Images. *Land Degradation and Development* 18: 41-54.

No. 07-02
Siqueira, A.D., A.O. D'Antona, M.F. D'Antona, and E.F. Moran. 2007. Embodied Decisions: Reversible and Irreversible Contraceptive Methods among Rural Women in the Brazilian Amazon. *Human Organization* 66(2): 185-195.

No. 07-03
Batistella, M. and E. F. Moran. 2007. A Heterogeneidade das Mudanças de Uso e Cobertura das Terras na Amazônia: Em Busca de um Mapa da Estrada. In *Dimensoes Humanas da Biosfera-atmosfera na Amazônia*. W.M. da Costa, B.K. Becker and D.S. Alves (orgs.) São Paulo: Editora da Universidade de São Paulo.

No. 07-04
VanWey, L., A. O. D.Antona, and E.S. Brondizio. 2007. Household Demographic Change and Land Use/Land Cover Change in the Brazilian Amazon. *Population and Environment* 28:163-185.

No. 07-05
Liu, J., T. Dietz, S.R. Carpenter, M. Alberti, C. Folke, E. Moran, A.N. Pell, P. Deadman, T. Kratz, J. Lubchenco, E. Ostrom, Z. Ouyang, W. Provencher, C.L. Redman, S.H. Schneider, and W.W. Taylor. 2007. Complexity of Coupled Human and Natural Systems. *Science* 314:1513-1516.

No. 07-06
Lu, D, M. Batistella, and E. Moran. Land-cover classification in the Brazilian Amazon with the integration of Landsat ETM+ and Radarsat data. *International Journal of Remote Sensing* 28(24):5447-5459.