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Agent-based dynamic spatial simulation of land-use/cover change in the Yucatán peninsula, Mexico

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Abstract

The author presents on-going dissertation research on an "Agent-based Dynamic Spatial Simulation" (ADSS), used in this paper to project short-term forest-regrowth scenarios in the Yucatán Peninsula, Mexico. A conceptual framework based on land manager decision making in relation to socioeconomic institutions and the environment is mapped onto a model composed of an agent-based model and generalized cellular automata. The ADSS is calibrated and validated with household surveys, archival research, and spatial data including imagery and maps of land-use/cover and biophysical characteristics.

Keywords

Global environmental change, land-use, land-cover, projection, dynamic spatial simulation, GIS, cellular automata, agent-based model

Introduction

This paper introduces a novel "Agent-based Dynamic Spatial Simulation" (ADSS) as a means of exploring human-environment relations. The ADSS is an integrated assessment model that aids policy development and advances understanding of human decision-making in environmental contexts through identification of interrelationships among socioeconomic and biophysical factors. In creating the ADSS, the author seeks a new means of addressing human-environment relationships, moving away from equilibrium-oriented and deterministic conceptions of these relationships and towards a technique that accommodates their dynamic and cross-scalar nature. The ADSS uses two streams of research, conceptual and methodological, to accomplish this goal. It combines research into decision making, socioeconomic institutions, and ecology to create a conceptual framework. Then, by drawing upon recent methodological advances in geographic information science, the conceptual framework is mapped onto a model composed of an agent-based model and a generalized cellular automata within a geographic information system (GIS) framework.

This paper describes a prototype of the ADSS applied to a regional policy context by projecting short-term land-use/cover change (LUCC) scenarios of cultivation and subsequent forest secondary succession in the southern Yucatán peninsular region (SYPR) of Mexico. Land-use/cover change (LUCC) is a

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major human dimension of global environment change. Human-induced transformations in terrestrial cover significantly change biogeochemical cycles and thereby affect climate, biotic diversity, and livelihoods (Meyer and Turner 1994). Policy responses mandated by the magnitude of these impacts are often frustrated by the inability to project land-use/cover change trajectories due to insufficient understanding of the complex relationships between LUCC and global change and among the forces that induce change in land-use/cover.

The research described here is guided by three themes not well addressed by present land-use/cover research. First, deforestation and cultivation occur incrementally in spatially distinct patterns that have different implications for environmental change, yet most models are aspatial or coarse-grained (Kaimowitz and Angelsen 1998). The ADSS has a regional scale of analysis that allows a fine temporal and spatial grain. Second, current LUCC models do not adequately account for the complexity of, and relationships among, socioeconomic and environmental factors (Turner et al. 1995). The ADSS places human-environment relations such as LUCC at the intersection of theories of land manager decision making, the environment, and socioeconomic institutions. Third, this research addresses uncertainty as a factor that plays a large role in understanding human-environment interaction but that is largely ignored in regional-scale models.

The "actor-institution-environment" conceptual framework that underlies the ADSS is described in the next section. Section 3 follows with an overview of methods to model LUCC and how they relate to the ADSS. Section 4 describes the ADSS structure as applied to LUCC in Mexico. Section 5 concludes with future research directions and an exploration of the significance of the research presented here.

Conceptual framework

One major vein of human-environment research lies in global environmental change (GEC). Within the GEC research community there is general consensus on how to conceive of human-environment issues by considering how environmental change results from infrastructure development, population pressure, market opportunities, resource institutions, and environmental or resource policies (Stern et al. 1992). The international LUCC Science/Research Plan partitions these causes (and their effects) among the conceptual foci of social systems, ecological systems, and land managers (Turner et al. 1995).

The ADSS recasts these foci as a three component "actor-institution-environment" conceptual framework (Figure 1). The first part focuses on the decision making of households and other actors. In the context of SYPR, the chief actors are farming households, or smallholders. The actor component draws on research in decision making, bounded rationality, and the effect of actor resources on decision making. The second component concerns socioeconomic institutions that affect actor decision making. Simultaneously artifacts and dynamic processes, institutions constitute, and are constituted by, regularized behavior. Institutions channel the external large-scale political economy and internal power relations. Both actors and institutions interact with the third component of the conceptual framework, the biophysical environment. Complex relationships result when biophysical forces are affected by production strategies that lead to environmental changes such as cover conversion, soil erosion, or nutrient depletion.[1]

While the example explored in this paper concerns deforestation and cultivation, the actor-institution-environment framework, as it is derived from the larger body of GEC research, offers a general view on human-environment situations. The iterative nature of human-environment interaction highlights the need for all three components of the actor-institution-environment conceptual framework. Actor decision making impacts, and is affected by, the environment and is subject to institutions that modify actor resource profiles and decision variables. Actor-institution relationships are the means by which institutions impact the environment. Finally, actors are not merely beholden to institutions, but are active participants that form much of what makes institutions.

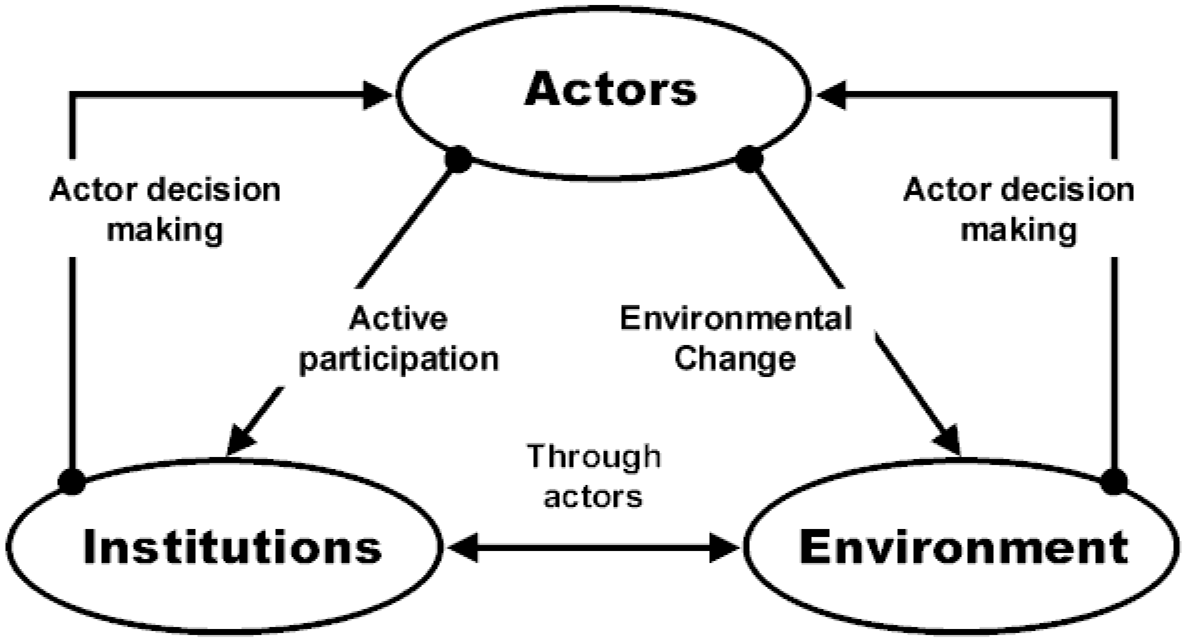


Figure 1. The actor-institution-environment conceptual framework

Approaches to projecting LUCC and the ADSS framework

There are few spatiotemporally explicit LUCC modeling techniques and none suit implementation of the actor-institution-environment framework. Common approaches, including cellular automata, spatial statistical techniques, and Markov models, downplay decision making and institutions (e.g., Li and Reynolds 1997; Ludeke et al. 1990). Spatial econometrics is a good technique but not amenable to the conceptual framework used here (e.g., Geoghegan et al. 1998). Dynamic spatial simulation (DSS) portrays the landscape as a two-dimensional grid where rules based on factors such as agricultural suitability determine how cells change (e.g., Gilruth et al. 1995; Southworth et al. 1991). DSS typically lack heterogeneous actors, institution-actor relations, and multiple production activities. In an exhaustive review of deforestation models, however, DSS is recommended by Lambin as the "most advanced modelling approach for a complex, dynamic and spatial problem such as tropical deforestation" (1994: 92).

The research described in this paper builds on DSS models and addresses their shortcomings by coupling an agent-based model (ABM) and generalized cellular automata (GCA) to create an agent-based DSS, or ADSS. Agent-based approaches are used to combine empirical and theoretical models of actor behavior in resource-use situations (Conte et al. 1997). Here they embody the actor and institution components of the conceptual framework. The use of cellular automata in ecological models suggests the use of generalized cellular automata to represent the environment (Smith and Bull 1997). GCA models offer greater realism through rules independent of adjacency (Takeyama and Couclelis 1997). By coupling generalized cellular automata and agent-based models, the ADSS is a novel means of operationalizing the actor-institution-environment framework and offers a powerful approach to understanding and projecting environmental change.

In summary, this research implements the actor-institution-environment conceptual framework by coupling an agent-based model and generalized cellular automata (Figure 2). Actor decision making is represented by smallholder-agent processes that choose production strategies based on resource profiles, environmental information from GCA cells, and other decision variables. Agent behavior feeds back on GCA cells through non-adjacent rules, allowing continual interaction that simulates actor-environment relationships. Institution-agents modify smallholder-agent resource profiles and decision variables to affect actor decision making. This is also the means by which institution-agents impact the environment.

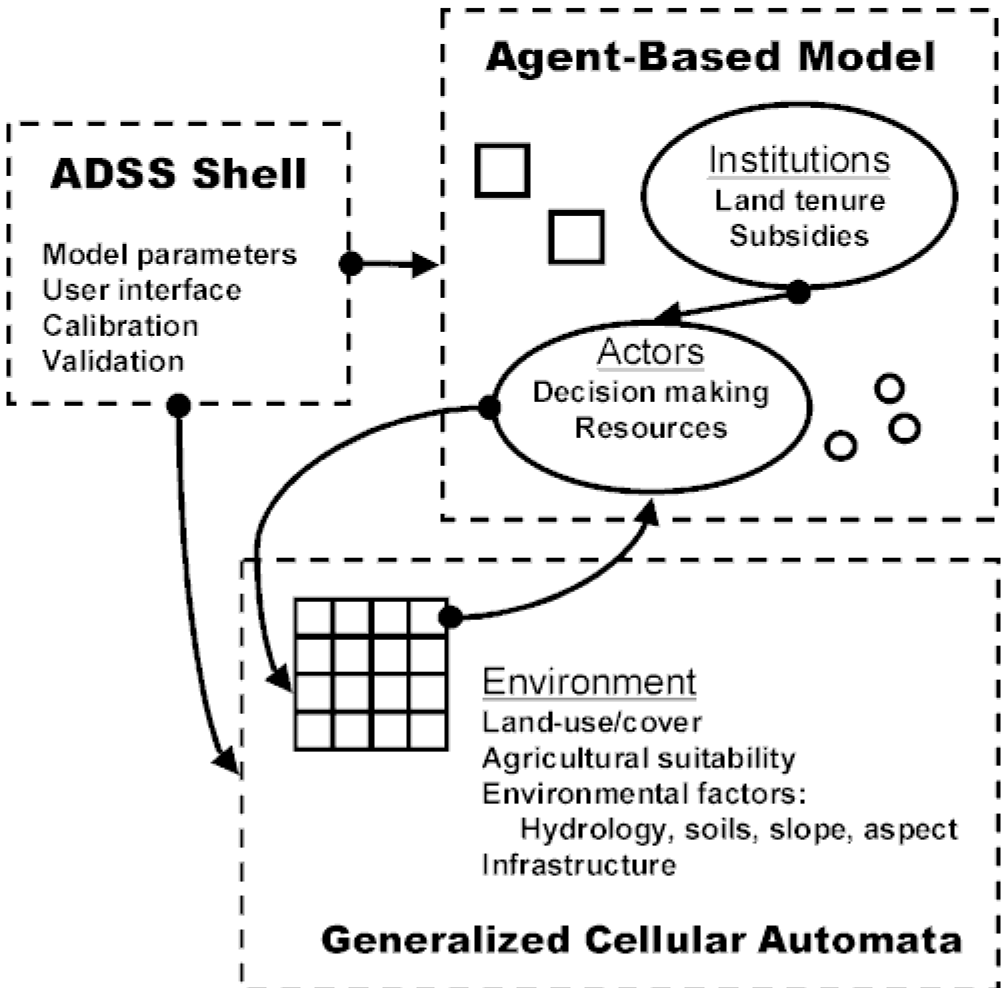


Figure 2. ADSS model structure.

Implementation and example

Prototype framework

The ADSS is a C++ language program consisting of the ABM and GCA bound together by a program shell. The shell's graphical user interface is used to specify exogenous parameters, establish model configurations, and examine model output. The ADSS is an example of "close-coupling" (Goodchild et al. 1992) because the ADSS offers the user a script language, compete with control structures and variables, with which to specify agents, specify GCA grids, enact calibration/validation routines, make general operating system calls, and make direct calls to the Idrisi32 raster GIS and Microsoft Access databases.

The ADSS shell uses a Monte Carlo strategy whereby it conducts many runs with identical parameters, extracts the simulated environment from each run, and combines the results for a probabilistic measure of land-use/cover change. A single simulation run iterates through four stages once a year for time intervals ranging up to forty model 'years' (1970-2010). First, the shell updates exogenous parameters. Second, institution-agents change smallholder-agent resource profiles. Third, each smallholder-agent chooses production activities with a decision making model that combines its resource profile, exogenous parameters, and environmental characteristics. The result is registered in the agent's resource profile and as a land-use/cover impact on a GCA grid. Finally, the shell updates the GCA environment.

Calibration of smallholder-agent decision making, institution-agent processes, and GCA operations is considered below. The author is fortunate to be part of a larger research project, Land-Cover/Land-Use Change in SYPR (LCLUC-SYPR), which provides spatial data such as imagery, LUCC, aerial photography, elevation, topography, climate, soils, precipitation, and hydrology. The project also provides an actor survey of 188 households that details an extensive set of socioeconomic characteristics and spatiotemporally explicit land-use histories. Finally, the author conducts archival research and interviews researchers to gather information on several aspects of the conceptual framework and model calibration.

Generalized Cellular Automata

The environmental component of the model is specified and calibrated as seven sets of GCA grids, denoted E_x, that encompass the study area. Grids update through endogenous transitions and non-adjacent transitions that result from actor behavior. The author derives GCA rules from ecological theory and field work and tests them with repeated runs. A simple set of rules, for example, can correlate forest cover in a cell with the state of its neighbors to represent secondary succession. The GCA is also the repository for relatively unchanging model components such as environmental attributes.

The GCA grids are as follows:

1. E_{USE} - A repository for simulated land-use by actors.
2. E_{COVER} - State of land cover as a function of land-use and extant cover.
3. E_{SOIL} - Stores soil fertility as a function cover, past soil fertility, and duration of the cell's present land-use.
4. E_{ENV} - Environmental attributes: hydrology, soil type, slope, and aspect.
5. E_{SUIT} - Suitability for three production activities: agriculture, forestry, and nontimber forest products. Based on land use, land-cover, soil quality and biophysical attributes.
6. E_{ECON} - Distance to market and transportation infrastructure.
7. E_{LUCC} - Actual land-use and land-cover for model verification and calibration (1970-1996).

Agent-Based Model

The ABM is composed of smallholder and institution agents. The latter communicate institutional rules to smallholder-agents, specifically land tenure and market characteristics such as crop and fuel prices or governmental subsidies. The ADSS converts these characteristics into: 1) GIS layers of spatial extent over time for use by institution-agent processes in directing the focus of institutions towards particular smallholder-agents; 2) institution-agent processes for land tenure rules; and 3) exogenous shell production functions that incorporate subsidies.

The agents that represent smallholder actors are invested with one of three different decision making models. The first is a set of heuristic processes similar to those used by other dynamic spatial simulations (e.g., Gilruth et al. 1995). An example rule set is would have the agent use land near roads, use a field for three years and then return it to fallow, and use recent secondary regrowth with an age of 4-7 years. While simple, in many respects these rules can capture more complex relationships or practices when they reflect key aspects of smallholder behavior without recourse to complex combinations of data. As such, they are applicable to data-poor situations, such as when the sole source of spatial data is remotely sensed imagery that provides only information on land-cover and infrastructure (e.g., roads, settlements).

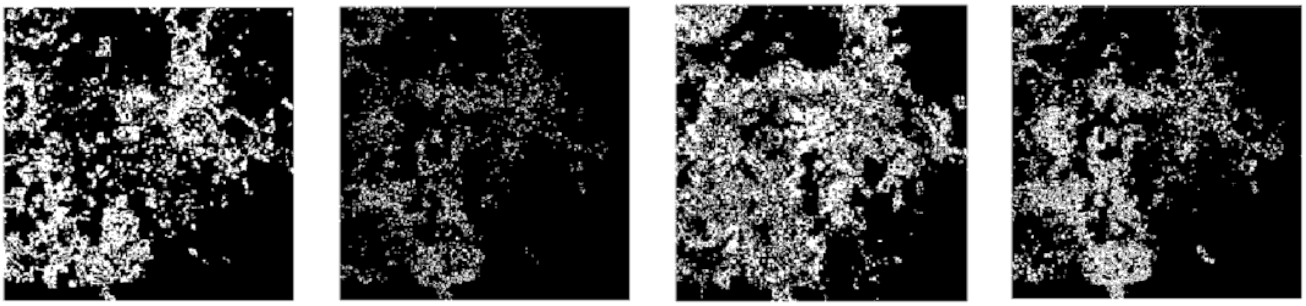
The second decision making model is subsistence orientation, as explored above in the discussion of the conceptual framework. It is implemented as a multicriteria evaluation that uses household variables, agricultural suitability (E_{SUIT}), and accessibility measures (E_{ECON}), to determine the location and kind of production necessary to feed the household. This is a basic model with a number of restrictive assumptions, such as risk taking behavior and lack of labor market participation. It demonstrates how a theory-led model may be incorporated into the ADSS, however, and later can be empirically specified and expanded. This model is implemented as a weighted linear average of the form where suitability is a function of factor weights, criterion scores, and constraints.

The third form of decision making invested in agents is provided by sets of genetic programs (GP) calibrated by matching actor land-use histories to an array of decision variables from the smallholder survey and GCA grids. GP may be treated as inductive black-boxes for use in projection of land-use change by selecting GP strategies that are best able to match actual land-use histories to projected land-use change. When applied to decision making, GP are bounded-rationality representations of decision making models (Edmonds 1999). As such, GPs offer insight into actor decision making when their internal structure is examined. Frequency counts of spatial and aspatial factors and their branching points in GP, for instance, can indicate the relative importance of factors.

ADSS Validation

The ADSS validation suite measures the difference in accuracy between high probability projected LUCC and observed land-use/cover change. The complexity inherent to spatial simulation demands several different approaches to validating the model. The ADSS therefore uses a set of five different tests to measure projection accuracy: Kappa Index of Agreement (KIA) coefficients; differences in land-use/cover fragmentation in fractal dimension (D) and contagion; multi-resolution goodness of fit (F) (Costanza 1989); and a Monte Carlo Uncertainty (MCU) measure (Ogneva-Himmelberger 1998).

A key aspect of all model validation is that the balance between model specification and prediction almost invariably causes support to vary across the test suite (Alonso 1968). Consider, for instance, the difference in output between the different models of smallholder decision making in projecting the location of secondary succession of forest for a sub-section of the study area (Figure 3). Although each of the three models use the same underlying data, agreement varies among them. The difference among decision making models across validation metrics is illustrated in Table 1.



Actual succession | All models agree | Two models agree | No agreement

Figure 3. Comparisons of model choice for the example of secondary succession.

Variation across decision making models and tests is potentially quite useful because the differences between the model results provides information. For example, the weighted linear average models is interesting in its ability to replicate regional parcel structure, as indicated by its contagion index. For applications where this measure is important, such as assessing the effects of ecological structure on biodiversity (Skole and Tucker 1993), a weighted linear average model may be a good choice even if its overall predictive power does not match that of other models.

Model	**Heuristic**		**WLA**		**Genetic Program**	
Test	Metric	Rank	Metric	Rank	Metric	Rank
KIA	0.173	3	0.194	2	0.223	1
Fractal Dimension (D)	0.024	3	0.0106	2	0.008	1
Contagion Index	0.00149	2	0.0002	1	0.00306	3
MRGF (F) (1 = perfect)	0.770	2	0.767	3	0.783	1
MCU (0 = perfect)	0.8772	1	0.9039	2	0.9116	3

Table 1. ADSS validation metrics.

Conclusion

The ADSS is a general means of modeling the complexity of human-environment relationships. By facilitating the management of complex information and relationships, the ADSS improves understanding of environmental change, especially in light of decision making theory and conceptualization of institutions. It also allows examination of the impacts of policy alternatives that often cannot be easily explored in reality. The ADSS is also an example of "computational human geography" that bridges theoretical and empirical conceptions of what constitutes geographical information science and geography in general. This research speaks to actor-structure debates by explicitly combining micro-scale phenomena (ABM actors and GCA neighborhood transition functions) with those at larger scales (ABM institutions and GCA non-contiguous transition functions). As such, and in conjunction with the ADSS's explicit embodiment of the conceptual framework, the research serves as a point of communication between GIS and its critics. Finally, ABM and GCA combined address the problem of surface/entity integration in GIS, answer the call for artificial intelligence in GIS-based modeling, and further the use of GIS for dynamic environmental modeling.

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End Notes

1. Portions of this paper, including an extended description of the conceptual framework, were presented at the UCGIS 2000 Summer Assembly, Portland OR, June 23, 2000. See http://www.ucgis.org/oregon/papers/manson.htm.

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