Land use in the southern Yucatán peninsular region of Mexico: Scenarios of population and institutional change

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Received 9 June 2004; accepted 25 January 2005

Abstract

Land-use and land-cover change, human activity that results in altered land-use systems and surface features, defines the environmental and socioeconomic sustainability of communities around the globe. It is a key response to global environmental change in addition to being both a key cause and medium of this change. This article examines an application of the Southern Yucatán Peninsular Region Integrated Assessment (SYPRIA), a scenario-based spatially explicit model designed to examine and project land use in Mexico. SYPRIA combines Geographic Information Systems (GIS) with agent-based modeling, cellular modeling, and genetic programming. The application examined here explores the effects on land-use and land-cover projections of scenarios that rely on varying assumptions pertaining to population growth, land-use trends, role of agrarian technology, and effects of resource institutions. This work also highlights the importance of understanding the many factors influencing land use, particularly population, different production systems, and the contextual nature of resource institutions in determining the nature of land use.

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doi:10.1016/j.compenvurbsys.2005.01.009

Keywords: Agent-based model; Genetic program; Land-use and land-cover change; Multicriteria evaluation; Symbolic regression

1. Modeling land-use and land-cover change

A unifying theme in understanding many dimensions of global environmental change is land-use and land-cover change (LUCC), human activity that results in altered land-use systems and surface features. This change contributes roughly a quarter of anthropogenic atmospheric carbon dioxide, a greenhouse gas, and has ancillary effects such as biotic diversity impacts and desertification (Steffen et al., 2003). LUCC is also essential to the environmental and socioeconomic sustainability of communities around the globe because it is both a key cause and medium of change impacts (Kates et al., 2001).

Interdisciplinary research and use of computational models are both increasingly important to understanding LUCC. Researchers ask, and answer to varying degrees, three questions: (1) what are the rates and spatial patterns of LUCC; (2) where does LUCC occur now and where will it occur in the future; and (3) which human and environmental factors explain it? (IGBP-IHDP, 1995) Given the complexity of LUCC processes and the difficulty of answering all three questions simultaneously, full assessments tend toward interdisciplinary initiatives that blend an array of data, methods, and theories. A valuable tool in this integration is the use of spatially explicit, dynamic LUCC models that examine land-manager decision making in the context of social and ecological systems (Veldkamp & Lambin, 2001; IGBP-IHDP, 1999). Modeling methodologies range from simple mathematic formulas to intricate spatiotemporal simulations (see for reviews Agarwal, Green, Grove, Evans, & Schweik, 2002; Brown, Walker, Manson, & Seto, 2004; Kaimowitz & Angelsen, 1998; Lambin, 1997; Manson, Geoghegan, & Turner, forthcoming; Verburg, Schota, Dijkstra, & Veldkamp, forthcoming).

Using models to link data and theory is a continuing challenge. Models can help provide the conceptual and methodological integration necessary for interdisciplinary research (Nicolson, Starfield, Kofinas, & Kruse, 2002). A variety of potentially conflicting conceptual frameworks can be applied to understanding LUCC, however, and the manner in which individual theories are best applied remains unclear (Lambin et al., 2001). Irwin and Geoghegan (2001) note that LUCC models tend to rely on implicit theoretical frameworks that can lead to ad hoc results; they argue for the need to better incorporate economic theory into models of decision making as it relates to LUCC. While economics offers a theoretically robust entry point into LUCC, it is also just one of several routes that could be explored, given the host of theories that relate to land-use decision making and the variety of settings in which LUCC is influenced by non-market factors (Geist & Lambin, 2001).

One broad heuristic for considering the role of socioeconomic factors in LUCC is the driving forces and proximate causes conceptualization of global change, whereby driving forces (population; economic growth; technological change; political and
economic institutions; and culture) are channeled into proximate causes, activities such as LUCC that impinge on the environment (Stern, Young, & Drukman, 1992). The LUCC research community has recast these driving forces and proximate causes and broadened their engagement with the biogeophysical environment by advocating simultaneous consideration of social systems, ecological systems, and land managers (IGBP-IHDP, 1995). Of particular interest is the use of models to understand the dynamic relationships among household decision making, population, resource institutions, agrarian technology, and land use (Bouman et al., 2000; Fox, Rindfuss, Walsh, & Mishra, 2003; Walker, Perz, Caldas, & Guilherme Teixeria Silva, 2002). When considering LUCC, for example, “neither population nor poverty alone constitute the sole and major underlying causes of land-cover change worldwide. Rather, peoples’ responses to economic opportunities, as mediated by institutional factors, drive land-cover changes” (Lambin, Geist, & Lepers, 2003, p. 261). The capacity to model complex relationships among multiple factors is important to critically assessing popular conceptions of LUCC that in turn support potentially simplistic policies designed to ameliorate LUCC impacts, such as introducing technical fixes or reducing population growth, that fail to address the complexity of the problem.

The need to articulate and understand the complex relationships among driving forces and proximate causes is particularly pressing in the southern Yucatán peninsular region of Mexico. The region is a 22,000 km² expanse just north of Mexico’s border with Guatemala and Belize (Fig. 1). It was the heartland of the classic Maya civilization from BC 500 to AD 900, and during this period, it was subject

[Image of a map of the southern Yucatán peninsular region]
to significant deforestation and then subsequent reforestation (Rosenmeier, Hodell, Brenner, Curtis, & Guilderson, 2002). The region remained sparsely populated until Highway 186 was built in 1967, which opened the region to immigration from the rest of the country that continues to today. In 1992, the federal government established the Calakmul Biosphere Reserve (CBR) in the center of the study region. The CBR is the centerpiece of conservation and ecoarcheological tourism programs intended to diversify the economic base of the region. Overall, the population of the region increased from approximately 2500 in 1960 to over 30,000 today (Klepeis, 2003). While long the site of human–environment interaction, the region is now home to deforestation of a magnitude that threatens its forests and their associated socioeconomic and biogeochemical systems (Achard et al., 1998).

The Southern Yucatán Peninsular Region Integrated Assessment (SYPRIA) is a scenario-based spatially explicit model designed to examine and project land use in the study region. This article examines an application of SYPRIA that explores the effects on LUCC projections of scenarios that rely on varying assumptions pertaining to population growth, land-use trends, role of agrarian technology, and effects of resource institutions. SYPRIA combines Geographic Information Systems (GIS) with methods originating from the so-called complexity sciences, namely agent-based modeling (ABM), cellular modeling, and genetic programming. These methods and others—such as genetic algorithms, classifier systems, cellular automata, neural networks, and multi-agent systems—are finding increased use in representing the dynamic, feedback-laden nature of complex human–environment systems (e.g., Clarke & Gaydos, 1998; Deadman & Lim, 2000; Gimblett, 2002; Janssen, 2003; Parker, Manson, Janssen, Hoffmann, & Deadman, 2003; Shellito & Pijanowski, 2003; Wu & Webster, 1998).

2. SYPRIA: actors, environment, and institutions

SYPRIA serves several roles as part of a larger LUCC research enterprise, Land-Cover and Land-Use Change in the Southern Yucatán Peninsular Region (SYPR or “the SYPR project”) (Turner, Geoghegan, & Foster, 2004). The current version of SYPRIA was designed to accomplish three goals: (1) to demonstrate how complexity-based methods can be joined to examine the effects of different kinds of computational decision-making analogs (Manson, 2004b); (2) to test how land manager decision-making strategies take into account environmental and institutional factors (Brown et al., 2004; Manson, 2004a); and (3) to explore a number of scenarios that relate to land use, population growth, agricultural systems, and institutional influences on household decision making. The SYPRIA application designed to fulfill this final goal is described here.

In conceptual terms, SYPRIA considers LUCC through the driving forces and proximate causes conceptualization as reinterpreted by the LUCC research community—social systems, ecological systems, and land managers (IGBP-IHDP, 1995). To provide analytical tractability without loss of conceptual coherence, SYPRIA recasts these foci as an actor–institution–environment conceptual model, whereby
institutions and the environment are the context for land-manager decision making. The chief actors in the study region are smallholder agriculturalists whose choices are seen through the lens of spatial decision-making theory. These choices are subject to environmental considerations, such as soil characteristics or precipitation. Institutions also influence actor decision making by channeling the effects of driving forces, with special consideration accorded to the market, conservation programs, population, and agricultural communities.

In methodological terms, SYPRIA is a freestanding model written in C++ and loosely coupled to the Idrisi GIS. Actors and institutions are represented by an ABM, which is a software system composed of software objects—or agents—that represent adaptive, semiautonomous entities that draw information from their surroundings and apply it to perception, planning, learning, and behavior (Conte, Hegselmann, & Terna, 1997). The environment is represented by a separate submodel, a cellular model patterned after a generalized cellular automata, a set of two-dimensional grids where cell states are modified dynamically according to rules based on the value of adjacent cells, previous cell states, and external inputs (Takeyama & Couclelis, 1997). SYPRIA agents are capable of movement across spatial layers, communication with other agents, and decision making. Both institutions and actors in their respective ABMs can modify environmental layers, such as land use and land cover, in the cellular model, although actor-agents in this application are more robust than the institutions in their decision making and behavior. The relationship between institutions and actors as agents, however, is useful as both a computational and conceptual organizing rubric. This general model formulation—agents in an ABM moving in a cellular modeling environment or landscape—has a number of advantages in separating out the influence of actors, institutions, and the environment (see Parker et al., 2003).

The joining of the methodological and conceptual facets of SYPRIA is considered below with respect to four pairs of scenarios that relate to population, land use, agricultural technology, and institutions. SYPRIA components—the cellular model environment and agent-based model actors and institutions—are calibrated with data for the years 1987–1992 and then used to project land use for the year 1995 that is validated against actual land-use data for 1995. To produce each individual run, SYPRIA iterates through single model ‘years’ during which three processes take place: (1) institutions change decision variables related to actor decision making; (2) the environment is modified according to the effects of actor and institution behavior; (3) actors engage in production activities influenced by institutional and environmental factors. The four scenario pairs contribute to 16 pair-wise combinations that each produce a series of 100 simulation runs (for a total of 1600 runs), the outcome of which are spatial layers of projected land-use that are considered in Section 3.

2.1. Actors

The chief actors in the region are smallholder households with diversified production activities that include subsistence-oriented milpa cultivation (i.e., extensive or
“slash and burn” agriculture), agroforestry, some logging, and market-oriented cultivation (Abizaid & Coomes, 2004; Vance, Klepeis, Schmook, & Keys, 2004). While extensive agriculture is the most common production activity and has the greatest LUCC impact at present, market-oriented cultivation is becoming increasingly important to households and the region’s LUCC trajectories (Keys, 2004). SYPRIA focuses on how households locate production activities spatially, such as milpa or market-oriented agriculture, as a function of environmental and institutional considerations. Theories of relative space treat distance between locations as key to individual decision making, which gives rise to bid-rent Alonso or Von Thünen circles that consider the returns to land as a function of distance to market or in terms of Christaller and Lösch models of hierarchically ordered locations based on gravity or entropy maximizing principles. Theories of absolute space consider how locational decision making is affected by heterogeneous in situ landscape characteristics (e.g., the Ricardian view) or by economies of scale and agglomeration (Bockstael, 1996; Nijkamp & Reggiani, 1998). Under these two bodies of theory, an agent accounts for the importance of environmental or institutional factors to the suitability for production of a given location as a function of both the characteristics of its absolute location in space (e.g., soil quality) and its location relative to other locations (e.g., distance to market). The absolute and relative characteristics of institutions and the environment with respect to actor decision making are considered below.

In methodological terms, actors are represented by agents in an ABM. Actor-agent behavior centers on how they make their locational decisions in the landscape by selecting cells for production in a GIS raster layer representing land-use in the study region. They draw spatial information necessary for this locational choice, such as soil quality or distance to roads, from raster layers pertaining to environmental and institutional factors that are controlled by the cellular-model environment and ABM institutions (i.e., institution-agents). The amount of information that each agent can perceive is a function of the scenarios considered below (e.g., do they know of land-use opportunities beyond their own surroundings?) as is their ability to move freely about and cultivate crops. Agents are instantiated by a population institution-agent (below) and once in the simulation do not leave.

Each household, represented by an actor-agent in the ABM, faces an individual multicriteria evaluation problem, where it must assess the suitability ($S$) of a set of grid cells for a given production activity:

$$S = \sum_{i=1}^{m} w_i v_i \prod_{j=1}^{n} b_j$$

as a function of spatial factors $V = \{v_1, \ldots, v_m\}$, their weights $W = \{w_1, \ldots, w_m\}$, and a set of Boolean constraints $B = \{b_1, \ldots, b_n\}$ (after Eastman, Jin, Kyem, & Toledano, 1995). Each agent determines $W$ in order to create a continuous surface that indicates suitability for agriculture as a function of the environmental and institutional factors that constitute $V$ and the limits represented by $B$. Each agent then chooses a set of cells, equal in area to acreage limits imposed by institutions (below), that
maximizes aggregate suitability. Spatial limits to this choice are explicit in the holdings of other agents—two agents cannot share the same cells—and implicit in both constraints \( B \), which represent areas like the Calakmul Biosphere Reserve (CBR) that are closed to agriculture, and the limits in range imposed by institutions.

Agents in SYPRIA treat Eq. (1) as an instance of symbolic regression, an inductive alternative-oriented problem that uses response-variable observations to estimate parameters of independent predictor variables (Manson, 2004b). An ideal function \( f(x) \) is known through observations \( X = \{x_1, \ldots, x_n\} \). Its observed value at data point \( x_i \), or \( f(x_i) \), is denoted \( \tilde{f}_i \) and is related to the true value \( f_i \) through error \( (e_i = f_i - \tilde{f}_i) \). Symbolic regression gives an approximation of \( f(x) \)

\[
\hat{f}(x) \approx \sum_{j=1}^{n} a_j \phi_j(x)
\]

where \( \hat{f}(x) \) is a combination of functions \( \phi_j(x) \) with coefficients \( a_j \) estimated in a manner that minimizes \( e_i \) over \( X \) (Ralston & Rabinowitz, 2001).

Actors estimate \( \hat{f}(x) \) through genetic programming, a form of evolutionary computing that uses a computational analog to Darwinian selection (Eiben & Schoenauer, 2002). A genetic program is a software decision tree comprised of mathematical functions (branches) and their numeric arguments (leaves) (Banzhaf, Nordin, Keller, & Francone, 1998; Koza, 1992). Each actor-agent is equipped with a population of genetic programs where each program serves as a freestanding symbolic regression solution to the agent’s multicriteria evaluation problem. Each program is composed of functions drawn from set \( (F) \) of arithmetic operators \((+ - \div \times)\) and terminals drawn from set \( (T) \) defined by \( V \) and \( B \) in Eq. (1).

Use of genetic programming is useful for two reasons. First, in addition to its use by actors to conduct multicriteria evaluations in SYPRIA (Manson, 2004a, 2004b), genetic programming has been applied to a variety of symbolic regression problems in pattern recognition, classification, and modeling (Banzhaf et al., 1998; Krzanowski & Raper, 2001). It is a directed search method that takes advantage of the implicit parallelism of a population-based search process and simultaneous evolution of program structure and parameters, which makes it suitable for finding solutions in highly dimensional stochastic environments (Kaboudan, 2003). Second, genetic programming and similar evolutionary methods (e.g., genetic algorithms, classifier systems) are one approach to forming a cognitive model of decision making in actors that contribute to human–environment interactions and other complex systems (Parker et al., 2003). An agent in an ABM with a population of genetic programs, as modeled here, has many strategies to address changes in the environment (Edmonds, 1999). This formulation encompasses issues of memory, learning and innovation (through evolution of a pool of programs) in addition to a means by which actors share strategies through imitation and communication (Brenner, 1998; Dawid, 1999). Memory is implicit in offspring programs, for example, and both it and computational resources can be bounded by limiting population size, number of generations over which strategies evolve, and the complexity that programs can achieve (Dosi, Marengo, Bassanini, & Valente, 1999). Using computational intelligence
approaches to represent human decision making and learning is an ongoing area of research (Aler, Borrajo, & Isasi, 2001; Chen, 2003).

For the scenario-based application considered here, actor genetic programs are locational strategies that are calibrated against data for the period 1987–1992 and then used to project 1995 land use. Observations $X$ in Eq. (2) are the values of cells sampled by the actor-agent from spatial layers that correspond to the response variable and the predictor variables. As suitability ($S$) is not directly observed, the response variable is land use observed in 1992 as derived from Thematic Mapper (TM) remotely sensed imagery (Roy Chowdhury et al., 2004). Predictor variables, which correspond to $V$ and $B$ in Eq. (1), are environmental and institutional spatial factors, observed in 1987, that are controlled by the cellular-model environment and ABM institutions. These factors in turn map onto the genetic program terminal set ($T$) and are considered in detail below.

Every actor-agent is invested with a population of 300 genetic programs, each of which represents a multicriteria evaluation strategy for siting land use. Each program is a member of a single cohort or generation, and through a computational process analogous to Darwinian evolution, individual programs compete to propagate themselves by creating offspring programs in the following generation through mutation (a random change in a parent alone), reproduction (cloning of a parent into the child), or crossover (breeding of two parents). Successive generations (typically 50 or fewer) of genetic programs evolve to become increasingly fit—better at determining suitability as a function of environmental and institutional factors—because the parents for crossover and reproduction are selected probabilistically in proportion to their fitness as determined by a fitness function $f(k_j)$ that minimizes squared error over observations $X$ for $\hat{f}(x)$. Genetic program settings were chosen to be in line with the lowest bound to computing resources (such as population size, number of generations, and program length) that produced stable results (after Banzhaf et al., 1998). By the end of the calibration period, each actor-agent has an individualized population of genetic programs that serve as a collection of strategies for choosing the most suitable cells for agriculture. At the beginning of the projection period, each actor uses its most fit genetic program strategy to determine the cells most suitable for cultivation. Importantly, each agent conducts its own multicriteria evaluation procedure—there is no global procedure at work, just localized evolution of strategies and their outcomes for individual agents.

2.2. Environment

The environment influences actor spatial decision making through absolute (in situ) characteristics such as soil quality and relative characteristics such as distance to water, while actor choices affect the environment through activities such as cover conversion and fallow cycling. The region as a whole is composed of seasonal tropical forests, including lowland forest, upland forest, savanna, agricultural land, secondary succession, and bracken fern (Table 1). Another SYRIA application (Manson, 2004a) has identified key relationships between actor production choices and environmental factors that are in keeping with other investigations.
In general, actor production strategies favor siting agriculture in areas previously in agriculture, secondary succession, or upland forests. The chiefly rain fed agriculture favors areas with greater precipitation, which varies north to south in the region from 900 mm to 1400 mm. The region sits on a limestone plateau with elevation ranging from 200 m to 300 m amsl while the surrounding lowlands descend to less than 100 m. Agriculture is less likely at higher elevations due to increased rockiness and steeper slopes. Elevation also plays a part in the varying importance of soils that range from thin rocky soils (lithosols) at higher elevations to clays (gleysols and vertisols) found in depressions to productive clay loams (rendzinas) found elsewhere that are more associated with agriculture.

While actor choice centers on siting production activities in locations with suitable environmental characteristics, the environment also indirectly affects the amount of land placed in production through fallow-cycle dynamics that dictate the nature of weed competition, pests, disease, and soil fertility. Time in agriculture of 2 to 3 years and a fallow of 20–30 years is seen as optimal, while 10 years is seen as the shortest tenable fallow if herbicides and fertilizer are used to counter soil fertility declines and invasive species (Lawrence & Foster, 2003). The repercussions of fallow cycling are taken into account by institution-agents (below) that control the amount of land put into cultivation by actors.

SYPRIA represents the environment with a cellular model that implements many aspects of a generalized cellular automata (Takeyama & Couclelis, 1997). A two-dimensional grid is comprised of cells in a regular square tessellation, the states of which are endogenously modified according to rules based on the value of adjacent cells and exogenously modified by the actions of agents that represent actors and institutions. Cellular model grids are functionally identical to the Idrisi raster layers used to store spatial data; SYPRIA therefore uses these layers as a base for the cellular model.

The influence of the environment is held constant in this application in order to focus on the effects of the scenarios—expanded use of the cellular model

### Table 1
Regional land-use and land-cover change (1987–1995)

<table>
<thead>
<tr>
<th>Land state</th>
<th>Year</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ha</td>
<td>%</td>
</tr>
<tr>
<td>Lowland forest</td>
<td>306,685</td>
<td>17.8</td>
</tr>
<tr>
<td>Upland forest</td>
<td>1,201,979</td>
<td>69.8</td>
</tr>
<tr>
<td>Secondary succession</td>
<td>121,247</td>
<td>7.0</td>
</tr>
<tr>
<td>Agriculture</td>
<td>85,864</td>
<td>5.0</td>
</tr>
<tr>
<td>Bracken fern</td>
<td>458</td>
<td>0.0</td>
</tr>
<tr>
<td>Savanna</td>
<td>3590</td>
<td>0.2</td>
</tr>
<tr>
<td>Water</td>
<td>2049</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Source: SYPR project.
environment is considered elsewhere (Manson, 2004a, 2004b). The cellular model in this application is used to represent relatively stable environmental factors such as elevation, slope, aspect, precipitation, soil type, and land cover classes (Table 1) and derived variables including distance to a class, time in current state, and fragmentation. At the same time, the joint ABM-cellular model formulation is a useful organizing framework in addition to being the SYPRIA computational implementation. Factors are derived from SYPR project data that include land-cover maps from Thematic Mapper (TM) remotely sensed imagery for 1987, 1992, and 1995; elevation, slope, and aspect calculated from a 1:50,000 digital elevation model; soil categories at 1:250,000 from the Mexican National Institute for Statistics, Geography, and Information (INEGI, Instituto Nacional de Estadística, Geografía e Informática); precipitation interpolated from 21 climate stations; and surface hydrology from INEGI 1:50,000 topographic sheets (Turner et al., 2004).

2.3. Institutions

Institutions influence household decision making. The Institutional Analysis and Development (IAD) framework can be used to understand institutions as the “shared concepts used by humans in repetitive situations organized by rules, norms, and strategies” (Ostrom, 1999, p. 37). Strategies are plans that individuals make given institutional constraints, namely rules (predictably enforced shared prescriptions) and norms (enforced by less formal costs and inducements). Using institutions as proxies for social systems is useful because they act as conduits for driving forces such as population, the market, and resource institutions. SYPRIA uses the IAD formulation to model how institutions influence actors through institution-agents equipped with rules to model this influence on actor-agents (Manson, 2004b).

Institutions important to the regional nature of LUCC in the southern Yucatán are ejidos, the market, and conservation programs. Ejidos are communal land management councils defined by an area with a collective tenure system and the community that legally administers and owns it. Ejidos are of two types, being either agricultural ejidos belonging to the region’s ejidatarios (members of an ejido) or ejidos dedicated to forest reserves, national lands, or to uses determined by ejidatarios outside of the region (Fig. 2). Data on the relationship between households and ejidos comes from a survey conducted in 1997 and 1998 via a spatially stratified random sample of eleven ejidos and within them 188 households. Data are on household characteristics, production activities, labor, institutional ties, and land use in distinct plots over time (Klepeis & Vance, 2003). For the scenarios considered here, agents representing agricultural ejidos assign to each household (actor-agent) an average annual acreage of 5 ha for milpa (4.6–5.4 ha/household) and 2 ha for market-oriented agriculture (1.5–2.5 ha/household). This allotment is consistent with responses given by the household survey and is in line with fallow cycling for milpa and application of inputs to maintain constant market-oriented acreage. These values are also stationary over the study period, as land under cultivation per family
on the whole has remained relatively stable for decades for the households surveyed (Klepeis & Vance, 2003).

Until recently, households could not spatially allocate their allotted production outside of their own ejidos. This situation is changing, however, as the federal government undertakes a neoliberal shift towards loosening ejidal restrictions. During the mid to late 1990s, ejidos were allowed to move away from communal ownership of lands and toward individuals owning their own land outright, with attendant rights of use and selling it to outsiders (Zendejas & Mummert, 1998). Two scenarios are considered below with respect to this changing ejidal situation.

In terms of siting cultivation, federal and state governments limit access to non-agricultural ejidos, forest reserves, national lands, and the CBR. Agents within the ABM represent these institutions by making the pertinent areas off-limits to actor production through spatial layers corresponding to Boolean constraints B in Eq. (1). Within these limits, the choice of where to situate production is also a function of market considerations, per theories of relative spatial decision making. A market institution-agent makes available to all actors travel-cost surfaces for markets, population centers, and roads. These features are derived from expert interpretation of land-use maps classified from Thematic Mapper (TM) remotely sensed imagery (1987, 1992, and 1995), a road network digitized from INEGI 1:50,000 topographic sheets, and anecdotal information produced by the SYPR project (Turner et al., 2004).
3. Scenario results

SYPRIA is based on scenarios designed to elicit the influence of varying configurations of land managers, ecological conditions, and institutional characteristics. Four pairs of scenarios are outlined in Table 2. Two pairs of scenarios pertain to the quantity of land change projected to occur as driven by population (P1 and P2) and land-use (L1 and L2). The two remaining scenario pairs consider how the location of LUCC is influenced by market-oriented agriculture (A1 and A2) and ejidal institutional limits on the spatial range of households (E1 and E2). The scenarios are used to produce a 1600-run simulation series that is considered in terms of region-wide impacts and location-specific spatial residuals.

It is important to note that validating agent-based models is complicated given the often complex and dynamic nature of the systems modeled and the use of relatively new methods for modeling. These characteristics are true for much of LUCC modeling: “the lack of validation of most current land use models makes it impossible to properly assess the performance of these models” (Verburg et al., forthcoming). This paper offers several different strategies to evaluate the outcomes of the SYRPIA model with respect to the scenarios and thereby highlights the usefulness of validation in understanding the effects of various drivers of LUCC. It is also important to note that the use of scenario in land-use planning, and modeling more generally, is the subject of ongoing research and the scenarios presented here could be examined in number of different ways, such as their plausibility or the emotional interest they invoke (Xiang & Clarke, 2003).

Table 2
SYPRIA scenario description

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
<th>Agriculture (Ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Actual (P1)</td>
<td>Actual 1995 population per ejido</td>
<td>83,552</td>
</tr>
<tr>
<td></td>
<td>Land use ≈ 17 ha/household over 3 years</td>
<td></td>
</tr>
<tr>
<td>Trend (P2)</td>
<td>Estimated 1995 population per ejido</td>
<td>81,632</td>
</tr>
<tr>
<td></td>
<td>Δ = 3.8%/year, base = 1990 population per ejido</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Land use ≈ 17 ha/household over 3 years</td>
<td></td>
</tr>
<tr>
<td>Land use</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Actual (L1)</td>
<td>Actual 1995 land use per ejido</td>
<td>80,112</td>
</tr>
<tr>
<td>Trend (L2)</td>
<td>Estimated 1995 land use per ejido</td>
<td>111,466</td>
</tr>
<tr>
<td></td>
<td>Δ = 3.8%/year, base = 1992 land use per ejido</td>
<td></td>
</tr>
<tr>
<td>Agriculture</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base (A1)</td>
<td>Balance between shifting and persistent agriculture</td>
<td>n/a</td>
</tr>
<tr>
<td>Persistent (A2)</td>
<td>Higher probability of persistent agriculture</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>Persistence = p(0.52), base = 1992 land use</td>
<td></td>
</tr>
<tr>
<td>Spatial bounding</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Region (E1)</td>
<td>Households limited to region</td>
<td>n/a</td>
</tr>
<tr>
<td>Ejido (E2)</td>
<td>Households limited to ejido</td>
<td>n/a</td>
</tr>
</tbody>
</table>
3.1. Scenarios

Two population scenarios influence the quantity of land use at the ejidal level. In order to control for the effects of local population on land use, an institution-agent representing “population” instantiates actor-agents according to ejidal population densities over the period 1987–1995. The first population scenario (P1) uses the actual ejidal population for both the calibration and projection periods, given by census data (INEGI, 1985, 1990, 1995), to interpolate population between 1990 (24,084) and 1995 (32,092). The second scenario (P2) estimates ejidal population for the projection period by extrapolating population from the calibration period 1987–1992 to estimate a 1995 population of 30,926 (an annual growth rate of 3.8%). These values are then used to instantiate household actor-agents, assuming an average household size of 6.4 people; both this and the overall population figures are in keeping with other estimates (cf. Ericson, Freudenberg, & Boege, 1999; Goujon, Kohler, & Lutz, 2000). As scenarios P1 and P2 determine the number of agents instantiated in the model, actor-driven land use translates into roughly 84,000 ha for P1 and 82,000 ha for P2 (Table 2). Note that the acreage under agriculture given by Table 2 differs from the amount in the region as a whole given by Table 1 because the latter includes areas controlled from outside of the region.

Two land-use scenarios also influence quantity of land use projected for 1995. The first (L1) is analogous to P1 because it uses the actual amount of agricultural land use, per ejido for the projection period. The second land-use scenario (L2) simulates per-ejido agricultural land use for the projection period as a function of P2 and independently of the default land allocation of ejido institution-agents. Scenario L2 directly applies the 3.8% population growth rate of P2 directly to a base defined by agricultural land use in each ejido for 1992 (ranges = 2–13,005 ha, median = 439 ha). In effect, L2 ties land use directly to population-growth by bypassing the normal functioning of both the population and ejido institution-agents by having projected amount of land use per ejido divided among households by the ejidal-agent. Scenario L2 yields overall land use of over 111,000 ha vs. roughly 80,000 ha for actual land use in scenario L1 (Table 2).

Two persistent agriculture scenarios influence land-use location by addressing the divide between shifting cultivation and persistent, intensive market-oriented cultivation such as chile or pasture. Under scenario A1, households make decisions in accordance with the initial ejidal allotments, while under scenario A2, any cell that remained under agriculture for the five-year calibration stage (1987–1992) is re-classed as persistent market-oriented cultivation. Of the 64,162 ha under agriculture in 1987, 33,584 ha remained in 1992 in the same location, or approximately 52%. This figure is used by actor-agents to calculate the probability of persistence for market-oriented cultivation in the projection period. Scenarios A1 and A2 are first-order approximations of a complicated decision-making process that is part of the changing nature of agriculture in the region.

Finally, two ejidal scenarios consider the extent to which the spatial decision making households are limited by ejido controls. Under the first (E1), ejido-agents allow households to move freely across ejido boundaries, while under the second scenario
households are not allowed to leave the ejido in which they are instantiated. The second scenario is analogous to the institutional situation as it was for much of the twentieth century, while the first scenario is more in keeping with Mexico’s neoliberal movement towards expanded private property rights. As with the agricultural scenarios, the ejidal scenarios are designed to provide simple analogs to, and shed light on, the potentially complex factors that influence the location of LUCC.

3.2. Scenario tests

Of the four pairs of scenarios, two influence quantity of land change—population (P1 and P2) and land-use (L1 and L2)—and two influence its location—persistent agriculture (A1 and A2) and ejidal range (E1 and E2). There are therefore 16 possible combinations of scenarios that jointly affect quality and location. Each of these produces 100 unique simulations runs, for 1600 runs. Each run produces a binary map of agriculture projected for 1995 due to actor-agent production choices. In addition, a composite land-use layer is created by overlaying each of these 100 Boolean layers and rescaling the result from zero to one, which gives 16 spatial layers that denote the probability of agricultural land use for each of the scenario combinations. Each of these composite layers is a probabilistic assessment of regional agricultural land use under a given scenario. A cell value of zero indicates that none of the Boolean masks contributing to the composite map has agriculture in that location while a cell value of one indicates the agreement among all 100 layers on whether the cell in question is under cultivation. Each of the 16 scenario combinations therefore produces 100 individual layers and a single probabilistic composite layer can be compared to actual 1995 land use to assess scenario performance.

As noted above, greater attention must be paid to validating both models of LUCC and agent-based models. When model outcomes are validated, several different kinds of tests should be used to examine how spatial outcomes vary according to changes in model structure (Manson, 2003; Parker et al., 2003). To assess the effects of model scenarios, this paper uses several methods that have been recognized as appropriate for the validation of spatial models of LUCC, namely measures of agreement between projected and actual land use and, in the next section, examination of spatial residuals (Gardner & Urban, 2003).

The Kappa Index of Agreement (KIA or Kappa) calculates how each of the 100 binary layers for each scenario combination compares to actual agriculture in 1995. The general Kappa statistic (Kappa Standard or Kstd) is joined by measures, designed to evaluate spatial models, of how well the model predicts quantity (Kquant) and location (Kloc), all of which range from –1.0 to 1.0 to denote complete disagreement through complete agreement (Pontius, 2000; Walker, 2003). The Relative Operating Characteristic (ROC) compares the likelihood of a given class occurring in a given location, per the composite scenario layers, to a reference Boolean layer that denotes where the class exists in reality. ROC ranges from 0.0 to 1.0, where a value of 1.0 indicates greatest agreement and 0.5 indicates agreement due to chance (Gardner & Urban, 2003; Pontius & Schneider, 2001). The reference layer for both
the Kappa and ROC procedures is actual agricultural land use in 1995 within agricultural ejidos.

The performance of each of the 16 different scenario combinations is assessed through a comparison of mean Kappa scores across runs and the ROC for the composite layer (Table 3). Overall, the ROC scores range from 0.841 to 0.911 and the Kstd score ranges from 0.38 to 0.58. Table 4 provides a closer examination of the Kappa scores across scenario combinations by giving the results of a one-way analysis of variance (ANOVA). For comparison purposes, only pair-wise comparisons with the baseline land-use scenario (L1) are considered when calculating Kappa for the persistent agriculture (A1, A2) and ejidal range (E1, E2) scenarios because they modify the location of land use irrespective of quantity.

The first pair of scenarios considers the actual (L1) and projected (L2) land use for 1995. There are significant differences between them in terms of ability to project quantity of land use (Table 4). Scenario L1 predicts quantity perfectly because it represents the actual quantity of change in 1995, or 80,112 ha (Kquant = 1.0). Scenario L2 does less well because it overestimates the amount of land use at 111,466 ha (Kquant = 0.907). This overestimation is exacerbated by the fact that agricultural land use declined during the projection period; land under agriculture increased from about 48,000 ha in 1987 to just over 100,000 ha in 1992 and then dropped to about 80,000 ha in 1995. Scenario L2 cannot readily address the decline in land use during the projection stage because it is based on extrapolating agriculture from the 1987–1992 calibration period. It is important to note that Kloc is inflated by the overestimated quantity, which in turn inflates the apparent value of Kstd and ensures that there is no significant difference between L1 and L2 in terms of their mean Kstd scores. For this reason, it is useful to assess Kstd, Kloc, and Kquant separately.

The second pair of scenarios considers actual (P1) and projected (P2) population and its effect on projected land use. Scenarios P1 and P2 are just significantly different in terms of Kquant largely because the latter, at 81,632 ha, is closer in value than the former, 83,552 ha, to the 80,012 ha of actual agricultural land use in 1995 (Kquant = 0.992 vs. 0.995). In terms of quantity, the relative success of P1 and P2

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Table 3
SYPRIA scenario ROC and Kappa scores

<table>
<thead>
<tr>
<th>Population</th>
<th>Land use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual (P1)</td>
<td>Trend (P2)</td>
</tr>
<tr>
<td><strong>Baseline agriculture (A1)</strong></td>
<td></td>
</tr>
<tr>
<td>Region (E1)</td>
<td>ROC</td>
</tr>
<tr>
<td></td>
<td>Kstd</td>
</tr>
<tr>
<td>Ejido (E2)</td>
<td>ROC</td>
</tr>
<tr>
<td></td>
<td>Kstd</td>
</tr>
<tr>
<td><strong>Persistent agriculture (A2)</strong></td>
<td></td>
</tr>
<tr>
<td>Region (E1)</td>
<td>ROC</td>
</tr>
<tr>
<td></td>
<td>Kstd</td>
</tr>
<tr>
<td>Ejido (E2)</td>
<td>ROC</td>
</tr>
<tr>
<td></td>
<td>Kstd</td>
</tr>
</tbody>
</table>
with respect to extrapolated land use (L2) speaks to the utility of including driving forces such as population in a LUCC model, with the key caveat that it must be considered in conjunction with land manager and institutional information because P1 and P2 benefit from land use declining during the 1992–1995. In this sense, scenarios P1 and P2 are less incorrect than L2 with respect to quantity for the projection period. As discussed below, further analysis of spatial outcomes demonstrates that ejidal institutions determine in part how well the population scenarios fare.

A strictly interpreted land-use trend would have fared more poorly than any of the scenarios considered. Agricultural land use in 1995, extrapolated from the calibration period 1987–1992, would have projected land use of about 160,000 ha due to an annualized growth rate of 16.06%. This effect further demonstrates the value of linking quantity of change to interrelated driving forces and proximate causes, such as the population, resource institutions, and land managers. The population (P1, P2) and land-use (L1, L2) scenarios act as proxies for driving forces because

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Mean</th>
<th>Diff.</th>
<th>F</th>
<th>p</th>
<th>df</th>
</tr>
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<tr>
<td><strong>Land use</strong></td>
<td></td>
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<tr>
<td>Kstd</td>
<td>0.471</td>
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<td>0.010</td>
<td>0.932</td>
<td>1599</td>
</tr>
<tr>
<td>Trend (L2)</td>
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<tr>
<td>Kloc</td>
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<td>224.820</td>
<td>0.001</td>
<td>1599</td>
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<tr>
<td>Kquant</td>
<td>1.000</td>
<td>-0.093</td>
<td>6.3 \times 10^7</td>
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<td>1599</td>
</tr>
<tr>
<td>Trend (L2)</td>
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<td><strong>Population</strong></td>
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<tr>
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<td>2.300</td>
<td>0.130</td>
<td>1599</td>
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<td>-0.003</td>
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<td>0.001</td>
<td>1599</td>
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<tr>
<td>Trend (P2)</td>
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<td><strong>Persistent agriculture</strong></td>
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<tr>
<td>Kstd</td>
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<td>-0.091</td>
<td>104.160</td>
<td>0.001</td>
<td>399</td>
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<tr>
<td>Persistent (A2)</td>
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</tr>
<tr>
<td>Kloc</td>
<td>0.426</td>
<td>-0.091</td>
<td>104.000</td>
<td>0.001</td>
<td>399</td>
</tr>
<tr>
<td>Persistent (A2)</td>
<td>0.517</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Spatial extent</strong></td>
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<tr>
<td>Kstd</td>
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<td>-0.102</td>
<td>140.180</td>
<td>0.001</td>
<td>399</td>
</tr>
<tr>
<td>Region (E1)</td>
<td>0.420</td>
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<tr>
<td>Region (E1)</td>
<td>0.522</td>
<td>-0.102</td>
<td>141.000</td>
<td>0.001</td>
<td>399</td>
</tr>
<tr>
<td>Ejidos (E2)</td>
<td>0.522</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ejidos (E2)</td>
<td>0.522</td>
<td></td>
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</tr>
</tbody>
</table>
they influence the raw amounts of LUCC in conjunction with institutional, environmental, and actor characteristics. Similarly, determining future growth rates is complicated by the fact that much population growth in the past has been driven by migration, while now natural fertility and out-migration are playing a larger role in the region. These issues are the subject of ongoing research.

While population (P1, P2) and land-use (L1, L2) scenarios are critical to determining the quantity of LUCC projected, its location is influenced by scenarios for persistent agriculture and ejidal controls. Table 4 shows a difference of means in Kloc of 0.091 between baseline agricultural scenario (A1) and persistent market-oriented agriculture scenario (A2). This difference is somewhat expected given that market-oriented activities are increasingly common in the region and it highlights the importance of moving beyond characterizing LUCC in frontier regions as the sole realm of small-scale shifting agriculturalists. It also speaks to the importance of place—while LUCC is per se defined by change, past land use is a key contributor to present and future land use.

The fourth scenario pair concerns the effect of ejidal institutions on the location of LUCC. There is a clear difference in model outcomes between whether households can roam freely in the southern Yucatán peninsular region (E1) or must remain in their initially assigned ejido (E2). Under scenario E2, Kstd is 0.522 while under E1 it is only 0.420, a net difference-of-means of 0.102 and the largest over all scenarios. The relative success of E2 underscores the importance of institutions, such as ejidos, in understanding the nature of land-use and land-cover change and the merit of including an institutional component in the SYPRIA actor–institution–environment conceptual framework. As Mexico moves towards a neoliberal land market, the power of ejidos to spatially bound households is beginning to wane, as is the case in many areas of Mexico where ejidatarios are embracing privatization (although initial anecdotal evidence points to solidarity on the part of ejidatarios in the study region due to an unwillingness to forgo perceived communal benefits of the ejido combined with a lack of capital). Scenario E1 can offer insight into the potential effects of land-manager decision making with the move toward privatization.

3.3. Spatial residual analysis

In addition to examining global spatial validation metrics, it is useful to examine spatial residuals in order to understand how well scenarios account for the where and why of LUCC. Fig. 3 portrays how well combinations of ejidal (E1, E2) and the baseline population (P1) scenarios perform relative to actual agriculture in 1995. The figure gives four categories: (1) correctly predicted non-agriculture is denoted by white cells; (2) correctly projected agriculture is denoted in light gray; (3) incorrectly projected non-agriculture is denoted by dark gray (i.e., areas in 1995 under agriculture in actuality not modeled as agriculture); and (4) incorrectly projected agriculture is denoted by black cells. The dark gray and black cells demonstrate where the model performs poorly against agriculture in 1995.

Fig. 3 highlights important interactions between models of location and quantity of change by examining two maps of residuals for scenarios of household movements.
across ejidal boundaries (E1, E2) combined with the population scenario P1. Overall, E2 performs better than E1 in terms of locational accuracy, as per the Kappa scores noted in Table 4, because agents are limited to their ejidos, as is the case for households in reality. For several ejidos in the north west of the study site, however, the combination of the baseline population scenario P1 and ejidal scenario E2 leads to the situation, highlighted by the difference between Fig. 3a (P1/E1) and Fig. 3b (P1/E2), where several ejidos with high population densities are incorrectly projected as being dominated by agriculture (again, denoted by black cells). In reality, agriculture in these ejidos has shifted towards less land-intensive market-oriented agriculture and other activities (such as labor market participation) that leave proportionally fewer individuals in agriculture when compared to other ejidos. This trend is also reflected in the Kappa and ROC scores in Table 3, where population scenarios perform less well with respect to the land-use scenarios when combined with ejidal limits because agents are constrained to their native ejidos, which differs from the conclusions supported by the Kloc tests given in Table 4. Examination of the spatial patterning of residuals amplifies the need to contextualize the linkage between driving-force proxies and actual agricultural decision making as a function of scale.

The manner in which both ejidal and agricultural scenarios affect location are also better understood at the local scale. Fig. 4 portrays how well scenarios perform relative to the actual location of agriculture in 1995 for a subregion of the study site. These scenarios include: (1) free-ranging households with no market-oriented
agricultural persistence (E1/A1, Fig. 4a); (2) free-ranging households with agricultural persistence (E1/A2, Fig. 4b); (3) households limited to ejidos with no agricultural persistence (E2/A1, Fig. 4c); and (4) households limited to ejidos with agricultural persistence (E2/A2, Fig. 4d). The area chosen for residual analysis includes portions of several ejidos and lies along the main east-west highway and several other roads (Fig. 4).

In terms of fine-scale spatial outcomes, two factors seem to influence the location of incorrectly identified forest cells (dark-gray cells in Fig. 4). First, there are a large number of small cell collections such as those identified by Point A in Fig. 4a (E1/A1) that are due to small-scale processes that may forever elude models like SYPRIA. Second, there is infilling in several locations due to incorrectly projected forest, where too few agents are interested in a given set of cells under A1 (Point A).
B in Fig. 4a, E1/A1). The persistent agriculture scenario A2 has fewer projection errors in the corresponding location (Fig. 4b, E1/A2). These small-scale differences demonstrate that while scenarios can be assessed and understood at a regional scale, it is also necessary to assess them at a small scale and a fine resolution. At a regional scale, for example, ejidal-range scenario E2 is better than regional-range scenario E1 in terms of location (Table 4), but the fine-scaled consideration the subregion in Fig. 4 demonstrates that the reverse can be true in some areas, which mirrors the overt overprojection highlighted by Fig. 3 due to ejidal restrictions combined with the population scenario P1.

Error due to incorrect projection of agriculture appears to be of two kinds (black cells in Fig. 4). The first is an over-emphasis in agent strategies on the influence of roads, which manifests in incorrectly projected agriculture running along roads (Point C in Fig. 4b). The second error occurs when agents grant too much importance to fragmentation of, and proximity to, current land use (Point D Fig. 4c) and (Point E in Fig. 4d). The importance of these factors is the subject of much LUCC research (IGBP-IHDP, 1999) and is considered in detail for the study region with respect to agent strategies elsewhere (Manson, 2004b). Fig. 4 demonstrates that scenario assumptions can attenuate or amplify these features of actor decision making.

4. Discussion and conclusion

SYPRIA draws on the driving-forces conceptualization of global change in order to elucidate the relationships between environment, institutions, and land use. It combines genetic programming, cellular models, and agent-based models in a GIS framework to explore the relationships between human decision making and ecological and social systems. SYPRIA also highlights the importance of modeling, and model validation, in examining the many factors in influencing land use, particularly in terms of exploring the role of population, understanding the impacts of different production systems, and the contextual nature of institutions such as ejidos and the market in determining the spatial nature of land use.

More broadly, SYPRIA is one of a growing class of models that assess the relationships between driving forces and proximate causes of LUCC. As demonstrated by the scenarios, it is necessary to explore how assumptions about driving forces determine both the quantity and location of change, which are essential to applying LUCC models to larger aspects of global environmental change such as biodiversity and carbon sequestration. LUCC models can also be designed to elucidate the structural and theoretical dimensions of land-use and land-cover change, such as the role of institutions or decision making. Theory-lead, empirically calibrated projections arguably deal with stationarity of processes in a manner that other investigations may not because they go beyond inductive model fitting.

The LUCC scenarios presented here point the way to areas of further exploration, particularly the need to better model the effects of production technologies and the relationship between decision making and household characteristics. Many
environmental and institutional dynamics are either not represented in this application or minimized by the short temporal periods examined. SYPRIA development continues within the larger ongoing efforts of the SYPR project to develop multiple approaches to specify household decision making, better incorporate the influence of ecological systems, and increase the temporal extent of the data set. The next stage of SYPRIA development is oriented towards developing SYPRIA as a collaborative research tool to sponsor interdisciplinary research within the SYPR project and to explore community stakeholder involvement in modeling (after Bousquet, Bakam, Proton, & Le Page, 1998).

Acknowledgements

This work is supported in part by the National Aeronautics and Space Administration (NASA) Earth System Science Fellowship program (ESS 99-0000-0008) and a National Science Foundation Doctoral Dissertation Improvement grant (NSF 99-07952). It is also supported by NASA’s Land-Cover and Land-Use Change program through the Southern Yucatán Peninsular Region project (NAG 56406 and NAG 511134) and the Center for Integrated Studies of Global Environmental Change, Carnegie Mellon University (NSF-SBR 95-21914). The author gratefully acknowledges the assistance of the SYPR project, the editor, and three anonymous reviewers. Responsibility for the opinions expressed herein is solely that of the author.

References


Lambin, E. F., Geist, H., Agbola, S., Angelsen, A., Bruce, J. W., Coomes, O., et al. (2001). The causes of land-use and land-cover change: Moving beyond the myths. Global Environmental Change, 11, 5–13.


