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Colonist household decisionmaking and land-use change in the Amazon Rainforest: an agent-based simulation

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Abstract. An agent-based model was developed as a tool designed to explore our understanding of spatial, social, and environmental issues related to land-use/cover change. The model focuses on a study site in a region of the Amazon frontier, characterized by the development of family farms on 100-ha lots arranged along the Transamazon highway and a series of side roads, west of Altamira, Brazil. The model simulates the land-use behaviour of farming households on the basis of a heuristic decisionmaking strategy that utilizes burn quality, subsistence requirements, household characteristics, and soil quality as key factors in the decisionmaking process. Farming households interact through a local labour pool. The effects of the land-use decisions made by households affect the land cover of their plots and ultimately that of the region. This paper describes this model, referred to as LUCITA, and presents preliminary results showing land-cover changes that compare well with observed land-use and land-cover changes in the region.

1 Introduction

Managers, policymakers, and academics who have an interest in the management of natural resources, face the ongoing challenge of attempting to understand the complex interactions that occur between the coupled human – environment systems associated with those resources. Complex environmental problems tend to be multidisciplinary, temporally dynamic, and spatially referenced. A system being studied is often comprised recursively of several micro interacting subsystems, each of which is geographically referenced. In addition, these systems and subsystems change over time, thereby adding to the complexity of the problem. The nature of the interactions between these systems often makes it difficult to predict the outcomes that will result from particular management actions, socioeconomic conditions, or environmental processes. In such an environment, policies become experiments. But experiments with real-world systems can have undesirable and damaging outcomes. In response to these risks, researchers have utilized a variety of tools to explore the dynamics of these complex systems and the potential outcomes associated with proposed new policies and/or changes in the human or natural systems in question. Such tools, from statistical and mathematical models to geographic information systems (GIS) and dynamic models, have proven to be helpful in understanding resource-management institutions.

Of these tools, spatially referenced agent-based models (ABM) appear to show particular promise for exploring interactions between coupled human – environment

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systems over time. In particular, simulations utilizing collections of agents to represent the actions of specific human or natural entities have been explored in fields such as anthropology (Doran and Gilbert, 1994; Kohler et al, 1996), resource management (Bousquet et al, 1994; Deadman and Gimblett, 1994; Tillman et al, 1999), and land-use change (see Parker et al, 2002; 2003). Simulation tools, such as Swarm (Minar et al, 1996) and RePast (Collier, 2000), have made dynamic simulation technologies accessible to researchers in a broad range of disciplines, including the social sciences.

In recent years interest in the application of ABM, or multiagent system (MAS) models, to the study of land-use/cover change (LUCC) has grown considerably. These simulations typically couple a human system, represented by a collection of agents making land-use decisions, with an environment system, represented by a raster grid of spatially distributed land uses within the landscape, through agent – agent and agent – landscape interactions that feed back and alter the LUCC in the area of interest (see figure 1). For recent overviews of MAS/LUCC modeling see Parker et al (2002; 2003).

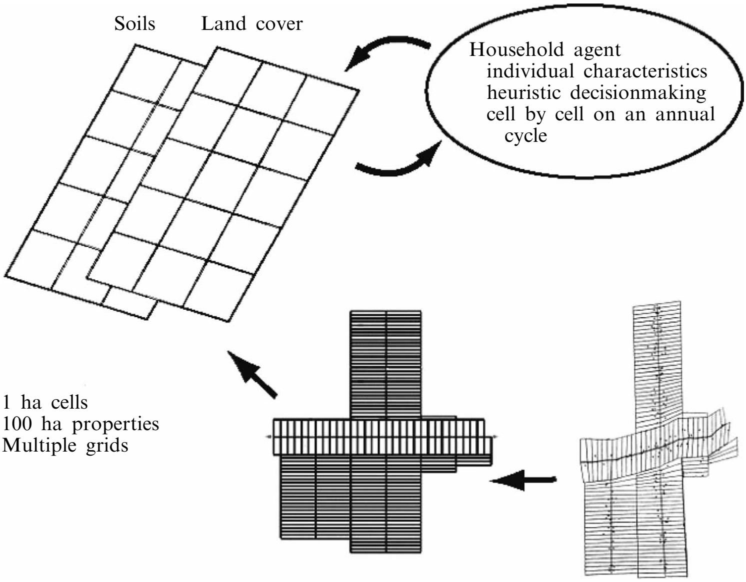

Figure 1. Basic components of the LUCITA simulation system.

The work described here is part of an ongoing effort to develop an ABM, called LUCITA (Land Use Change In The Amazon), to explore the dynamics of land-use decisionmaking behaviour by colonist households in a region of the Amazon rainforest near Altamira, Brazil. The first version of LUCITA (Lim et al, 2002) represented a pilot effort that explored one possible direction for the model and simulation. The pilot version was characterized by homogeneous colonist households designed as distinct decisionmaking entities affecting the land-use/cover on the household's plot. The second version of LUCITA, described here, builds from the pilot model a flexible and modular framework that adds heterogeneity and variability into a dynamic environment more representative of the study area being modeled.

LUCITA v.2.0 explores the interactions between human and environment systems through explicit variations in household composition, household capital endowment levels, soil quality, and burn quality. From previous research in the region, these four primary factors are thought to have an important influence on the land-use decisions of individual farming households. A properly crafted simulation could provide a tool

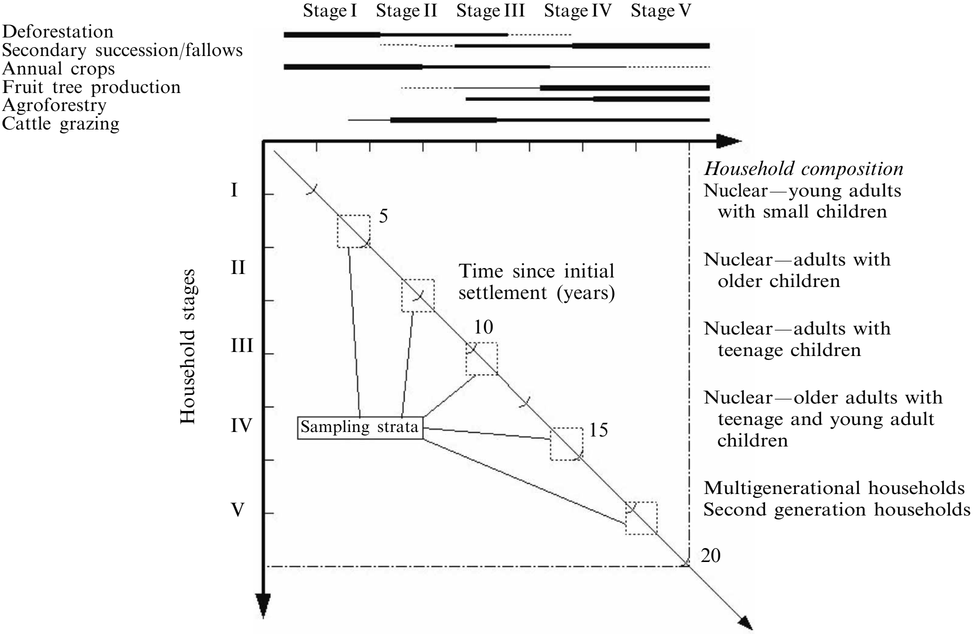

Figure 2. Conceptual model of land-use trajectories defined by stages of the household ageing process (source: Brondizio et al, 2002, McCracken et al, 2002).

for exploring the importance of these factors in the land-use outcomes that are seen in the region. Therefore, the preliminary goal of this study is to determine whether a heuristic household decisionmaking structure based on these four primary factors, and implemented within LUCITA, can produce LUCC trends that mimic quantitative analysis trends measured in the Altamira region by Mausel et al (1993) and Brondizio et al (2002). Here, agents in the model utilize a set of heuristics in which household available labour and capital, soil quality, and burn quality are the primary factors influencing land use. To evaluate the model further, patterns of LUCC observed in LUCITA are compared with the 'conceptual model' of the developmental cycle of households as described in Brondizio et al (2002) and McCracken et al (2002), shown in figure 2, and discussed in the next section. This analysis of the behaviour of the model provides an indication of the overall utility of this modelling approach, while outlining directions for continued development of the model. By reproducing some important fundamental aspects of LUCC in the study site, we ultimately intend to produce a tool to assist researchers in disentangling and better understanding the decisions of agents and the outcomes of their decisions within this region. Although not discussed here, sensitivity analysis on future versions of the model will facilitate an investigation of the relative importance and influence of social and environmental interactions.

In the remainder of this paper, we present some of the history of land-use change in the Altamira region of the Brazilian Amazon, focusing on the colonization activities of farming households over the past thirty years. Efforts by researchers to understand the importance of family size and available family labour on land-use decisionmaking at the individual property level are described. The structure of the current version of LUCITA is described. The results of initial simulation runs are presented, followed by a discussion of the strengths and weaknesses of this simulation and the requirements for future development.

1.1 Land-use change in the Amazon region

Rapid deforestation of the Amazon rainforest since the early 1970s has raised international concern, not only because of the ecological importance of the area with regard to biodiversity and the role the rainforest may play as an important sink in the global carbon budget, but also because of the social and cultural implications. Government desires to develop the Brazilian Amazon have been facilitated both by economic incentives and by the creation of the Transamazon highway. Running from east to west across the Amazon, the highway has been associated with marked changes in the region, such as deforestation, since the early 1970s (Moran and Brondizio, 1998; Wood and Skole, 1998). Although broader causes of deforestation in the Amazon, such as commercial logging, large-scale cattle ranching, mining, road construction, and hydroelectric development, are more obvious, the processes operating at local scales are often less well understood.

One of the predominant local-scale actors found to contribute significantly to the LUCCs occurring in the Amazon are the individual farming households. In areas of the rainforest that are characterized by this type of agricultural colonization, such as the area near Altamira (figure 3), research has begun to reveal how patterns of deforestation are affected by a variety of factors operating locally. At the local scale of analysis, land-use decisions are affected by such factors as household composition, available capital, and soil fertility (McCracken et al, 1999). Simultaneously occurring at the regional scale are a number of socioeconomic factors, including local credit policies, market opportunities, and inflation rates, that can also affect the land-use decisions made by individuals (Moran, 1981). Research conducted at both scales has revealed the existence of complex relationships, feedback, and interactions between human and natural systems.

Questions that have arisen over the last decade address rates and patterns of deforestation (Brondizio et al, 2002), the degree of secondary growth (Lu et al, 2002; Mausel

Figure 3. Location of Altamira, Brazil.

et al, 1993; Moran et al, 2000), radically differing land patterns between neighbouring farms (McCracken et al, 2002), and the influence of soil quality on household success (Moran, 1995; Moran et al, 2000; 2002). Multitemporal analysis of remotely sensed images has revealed that many once-deforested areas are now undergoing secondary succession, indicating that the rainforest ecosystem may be more resilient than was once thought (Moran et al, 1994). Although it has been assumed that deforestation rates in the Amazon are directly tied to population changes, resulting from high rates of in-migration and subsequent population growth and movement, these general observations do not explain the spatial variation that can occur in colonized regions, such as that near Altamira (McCracken et al, 2002). Neighbouring farms in the Altamira region have been observed to have radically different patterns of land use. This observation has raised research questions related to the relative importance of family and market factors in shaping land-use decisions. One approach to this problem has been to study the individual cohorts who arrived on the Altamira frontier at different times, along with age and period effects (see McCracken et al, 2002).

With this approach, an analysis of data collected in Altamira has led to the development of a model which proposes that land-use changes in the region should be understood as a product of the age and gender characteristics of farm households as they interact with local environments and external factors (McCracken et al, 1999). This conceptual model maps out a trajectory for families, which relates the type of agricultural practices pursued to the available capital resources and labour pool within each household (figure 2). Land-use strategies include growing annual cash crops, such as rice, maize, beans, and manioc; perennial crops, such as cacao and black pepper; fruit tree production; agroforestry; and the transformation of land into pasture with or without cattle. For the purpose of sampling households and farm lots across cohort and age differences, five temporal stages of household composition are proposed in the conceptual model, with each stage of development characterized by varying levels of capital and available family and male labour (McCracken et al, 2002).

Stages represented in the conceptual model follow a trajectory of land uses that occur through the evolution of colonist households to inform survey data collection in the region (McCracken et al, 1999; Moran et al, 2002). According to this trajectory, young families who arrive on the frontier typically have limited capital resources and young children. Initially, these young families typically deforest three to five hectares of land a year to plant annual crops such as rice, beans, or manioc. As families age, they continue to deforest their properties to grow annual crops, while turning previously cleared land into pasture or perennial crops, or allowing the land to become fallow or enter secondary succession. McCracken et al (2002) have observed that, although this trajectory can be shaped by outside forces such as credit policies, available household labour plays a significant role in the land-use strategies that are pursued by an individual family. Households with abundant available labour gravitate towards a diversified land use with an emphasis on perennial crops such as fruit trees, coffee, or black pepper, while those with less available labour tend to pursue land-use strategies focused on creating pasture and raising cattle while maintaining small-scale annual crop production (McCracken et al, 2002). Over time, this shift in land-use strategies away from annuals, which require newly cleared land every few years, and towards perennials or pasture results in reduced levels of deforestation and increased secondary succession. The important observation in the context of the development of this simulation is that land-use changes can be associated with the characteristics of individual households. By focusing on the individual household as the decisionmaking unit, we hope to produce a simulation that allows the user to alter the available capital, labour, and composition of a household so as to observe how patterns of land use may change.

2 The model—LUCITA

LUCITA is an abstract representation of our study area, the landscape, the farming households, and processes that link these components. It has been developed at a degree of complexity and scale of representation offering a level of realism that will not inhibit techniques of validation used at a later date. LUCITA is a spatially referenced ABM comprised of two submodels that interact with one another through a raster landscape (figure 1). These two submodels are designed to capture the actions and interactions of the ecological and human systems characteristic of the study region. The current version of LUCITA is written in Java with the RePast MAS toolkit (Collier, 2000). This new version allows the user to alter the demographic composition, as well as the labour and capital resources, of individual households to observe changes in household behaviour and resulting LUCCs within their plot of land (Robinson, 2003). Complementing these household components of heterogeneity are variable ecological aspects related to soil and burn qualities. The degree of heterogeneity introduced through both household and ecological components adds realism and affects the outcome and behaviour of the model.

The remainder of this section describes the framework of LUCITA, including the landscape as defined through land-cover and soil objects and grids, the plot and road infrastructure, household composition and household endowments, household arrival times within the model, assumptions made by LUCITA within the context of knowledge and preferences of households, family subsistence requirements, the heuristic decisionmaking strategy used by each household, and agent interactions in the model.

2.1 The landscape

The raster landscape, a grid of square cells, is an abstraction of the Transamazon highway corridor west of Altamira. LUCITA has been designed such that the size of the study area may be altered by the user in both the vertical (north – south) and horizontal (east – west) directions at the initiation of the simulation. The pattern of road and plot infrastructure is automatically placed into the landscape based on design standards used by the Brazilian Government for colonization of the area in 1971 (Fearnside, 1986). The raster landscape is represented by two grids, one indicating land cover and the other soil quality. The cells within the grids represent 1 ha and are spatially referenced with a common origin such that cells in the same location on each grid are referenced to one another.

Within the soil grid, each cell holds an inert soil object that adjusts nutrient values in response to the land-use activity occurring on the corresponding cell in the land-cover grid. For example, when a cell in the land-cover grid is cleared and burned, nutrient values in the corresponding soil-grid cell are altered to represent nutrient deposition. Similarly, when a crop is planted and harvested on a particular land-cover grid cell, nutrient uptake by the crop depletes the soil-nutrient values in the corresponding soil-grid cell.

Initial values for some soil parameters, soil changes through land-cover clearing and burning practices, and soil-depletion and crop-yield prediction are determined by regression equations developed by Fearnside (1984; 1986; 1988). Some of the parameters, such as those relating to climate or specific soil-distribution levels, are based on documented statistics and fixed or randomly set within observed ranges. As more detailed spatial data on soil quality become available, the data can be added to cells of the soil grid.

The landscape and therefore the model can be configured to run simulations both at the individual household level, or across a region comprised of a community of farmers and their properties. The land-cover grid, which forms the upper layer of this landscape (the soil grid forms the lower), is characterized by a number of objects which inherit from a super '`LandCover`' class designed to provide a general representation of

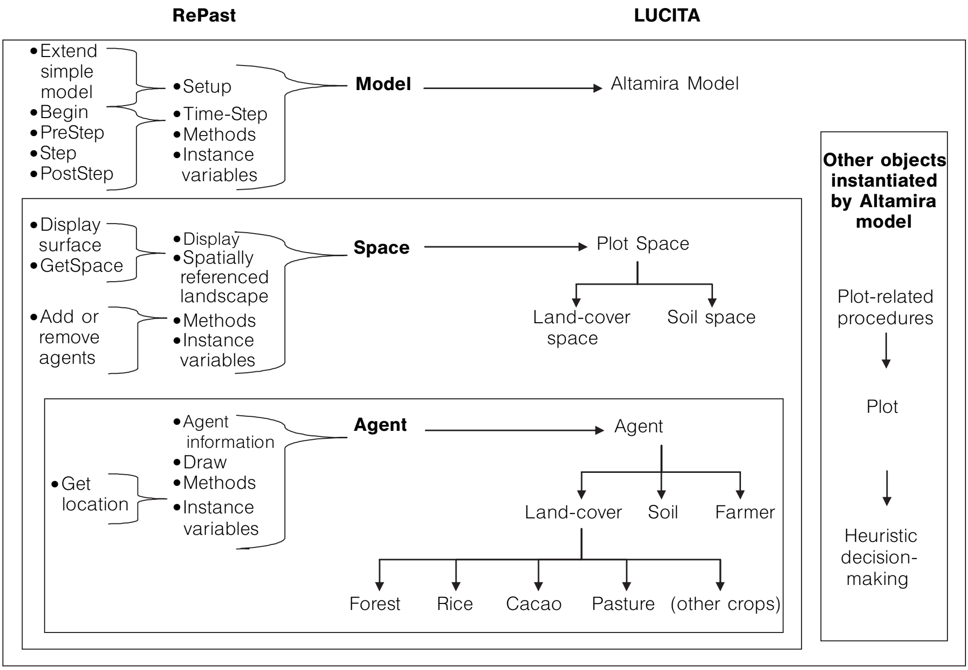

Figure 4. General framework of RePast and LUCITA.

all land-cover types. Figure 4 demonstrates this inheritance as well as the hierarchical structure of LUCITA's objects and agents. The left side of the diagram shows three RePast classes (Model, Space, and Agent) extended by LUCITA. Each RePast class consists of a number of methods (shown in the leftmost column) and a number of instance variables. Between the column listing class methods and the column listing class names is a list of the dominant conceptual tasks completed by the RePast classes. Figure 4 shows that the conceptual task of the Model class is to set up the simulation as well as manage the time-stepping procedure, the Space class is used to display the landscape and provide a spatially referenced environment for objects and agents, and the Agent class is used to draw the agent as well as contain agent-specific information. See Collier (2000) and additional online RePast documentation (http://repast.sourceforge.net/) for a more comprehensive description of the simulation libraries.

The right side of figure 4 shows three classes developed for LUCITA that extend from the RePast classes above. Here the diagram is simplified and shows the direct hierarchy of class inheritance in LUCITA. Additional classes developed for LUCITA, that do not inherit from RePast, are displayed on the right side of the diagram. Boxes are used in figure 4 to delineate where classes are invoked. Therefore figure 4 may be read as: the Altamira Model sets up the simulation and maintains the temporal sequencing of events, the Land Cover Space and Soil Space are invoked during the Altamira Model setup and inherit from the Plot Space class, and agents are invoked or created by either the Altamira Model or the Plot Space classes. The hierarchical structure shown in figure 4 produces a flexible framework, efficient code, and a standard for design for third-party and future creation of additional crop classes.

Currently six annual or biennial crops (maize, rice, bitter manioc, sweet manioc, phaseolus beans, and vigna-cowpeas) and two perennial crops (black pepper and cacao) are represented by LUCITA in addition to pasture. The sale price, yields, soil requirements, and decision strategies for the farming of each crop differ.

2.2 Farm plots

Farm-plot configuration designed by the Brazilian government, prior to colonization of the Transamazon corridor west of Altamira, consists of a rectangular network of plots that run along each side of the main highway, and along the access roads that are set perpendicular to the main highway every 5 km (Fearnside, 1986). Plot sizes along the highway are relatively uniform (Balmann, 1997; Fearnside, 1986; McGrath et al, 2001; Moran, 1981) and abstracted in the model to the designed size of 100 ha (see figure 1).

The narrow side of each plot is situated adjacent to the road. In the simulation, plots along the Transamazon highway measure 500 m by 2000 m, whereas those on the side roads measure 400 m by 2500 m. Plots are virtual and are not explicitly displayed on either of the grids. Each plot records a unique identification, x and y coordinates bounding the plot within the study area, and the side of the plot and road type it is adjacent to. Farmers store a unique plot identification number linking them to the plot they select when entering the study area or ABM.

2.3 Household composition

Initial farming households colonizing the study area were selected by the Brazilian government using a process that favoured families that were both young and large (Moran, 1981). Within the simulation, households amongst the first wave of settlers are composed of a husband (aged 20 – 30 years), wife, and 4 to 10 children; successive families arrive with 0 – 4 children. Based on observations by Moran and Brondizio, children may begin to assist with household tasks as early as 7 years old. However, most children begin to contribute noticeable amounts of farm labour after the age of 10 years (Siqueira et al, 2002). The range of possible labour provided by children is increased in LUCITA to accommodate the small contributions by the very young (7 – 10 years of age) and the increasing contributions by adolescents (11 – 19 years of age).

In the simulation, children are randomly allocated as male or female. It has been documented by Siqueira et al (2002) that even at the age of 10 – 14 years, significant gender differences occur with respect to farm labour. Boys contribute significantly more agricultural labour than girls. In order to accommodate differences in agricultural labour provision, male children have the potential of providing twice the maximum potential amount of labour that a female child may provide.

In each iteration (or year) of the simulation, members of the household age. At an age specified by the user, children leave the house in search of an independent livelihood or other economic opportunities. Although some families acquire additional plots of land for maturing children to manage, this process is not captured in the current version of the simulation. Such processes could be modeled in the future and Moran, Brondizio, and collaborators are currently working on the collection of multigenerational data and linkages within the study area.

Endowments exist in the form of labour and capital. Households utilize both endowments collectively. Each household member produces a specified amount of labour, for the sole purpose of increasing the household's level of farming. Similarly the household head is provided with a constrained range that is defaulted to a maximum of 2250 hours per year (45 hours per week × weeks per year). The random allocation of labour provides for the incorporation of heterogeneous household factors, such as health issues (injuries or sickness), varying cultural norms related to religious activities in some cases, and gender-related norms defining who participates in which farm-related activities (Moran, 1981; Siqueira et al, 2002).

2.4 Household arrival

Starting positions and arrival times of agents affect their outcome and pattern formation within the model (Otter et al, 2001). In this preliminary version of the model, stochastic plot allocation simplifies LUCITA and eliminates factors such as distance to market, and plot preferences based on knowledge of the area, soil quality, topography, road conditions, and aquatic features. Household arrival times are based on a random number, constrained by lower and upper bounds (provided by the user), representing the number of households entering the ABM at a given iteration.

Households are permitted to arrive only if available plots exist. Available plots include those that have yet to be farmed as well as those that have been abandoned by failing households or removed because of the incurrence of massive debt. The configuration of arrival times and method of plot allocation must be coordinated in order to address the effects of each on LUCC. Analysis and comparison of varying arrival times, such as simultaneous or sequential (Dale and Pearson, 1999), and plot allocation will be investigated in future versions of LUCITA.

2.5 Household knowledge/preferences

Moran (1981; 1995) documents the ability of farmers to classify or categorize soil to determine and map areas of soil quality based on existing vegetation, soil colour, and texture. Soil pH influences the ability of specific vegetation to uptake nutrients and impacts soil colour and texture. Based on these findings, LUCITA assumes that all farmers have the ability to detect good or poor soil quality based on pH. In reality, farmers in Altamira were not familiar with the soils of the region at the start, but acquired this knowledge over time. Future versions of LUCITA will explore models of household learning.

Knowledge of crop price influences household selection of annual crops for planting. In this version of LUCITA, households have perfect knowledge of static crop prices (per kg). Although calculated profit returns seem to be the ideal determinant for crop selection, this is typically not done in the Altamira region. Instead farmers use crop prices as a proxy for return revenues such that a crop with a higher price per kg will yield greater returns than crops with a lower price per kg (Moran, 1981). Using this price gradient strictly would create a deterministic selection of crops to farm. To improve variability and avoid unrealistic path dependencies, LUCITA uses crop prices to create a weighted probabilistic form of crop selection.

Although the probabilistic function of crop selection does add variability to the system, initial runs resulted in household bias towards, and near homogeneous planting of, those crops priced highly. To alleviate crop homogeneity and approach realistic and known crop-diversifying schemes by households in the Altamira region, modeled households were assigned a randomly distributed list of preferred crops to farm. From a possible six annual crops, households are assigned a random number of one to six of these crops which are then weighted based on price per kg as noted above. As yet, this method is not wholly validated; however, the framework discussed will ease the incorporation of observed data on crop selection and preferences as they become available.

2.6 Subsistence requirements

The subsistence requirement for a household, in LUCITA, refers to the level of necessities needed to supply adequate food and other essentials to the family over a one-year period. Each year, new requirements are calculated based on household composition. Cash requirements for commodities and services, such as seed, clothing, medicine, transportation, and other necessities, are represented by a fixed price of 1615.30 cruzeiros per person per year (Fearnside, 1986). This subsistence requirement is halved for each child in the household. In the simulation, these values, as well as those for commodity prices, are not adjusted for inflation.

Subsistence food requirements are met through the production of annual crops for household consumption. Each household must produce 1 ha of annual crop for each adult and 0.5 ha of annual crop for each child. Food calculations in number of hectares allow for yield fluctuations and varying requirements of different households. To provide additional variability, households are able to incur debt in their annual production provided that it is met by profit from pasture or perennial production. Therefore it is possible that some farms will refrain from farming annuals.

2.7 Household decisionmaking

Work by Moran (1981; Moran et al, 2002), Brondizio et al (2002), Siqueira et al (2002), and Fearnside (1986) outlines a significant portion of the household decisionmaking process. Figure 5 displays a high-level representation of the decisionmaking structure used in LUCITA which is composed of three basic decisions regarding subsistence requirements, endowments, and soil quality.

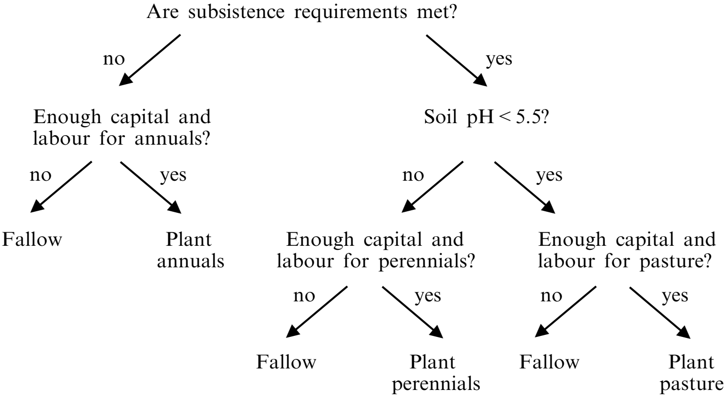

Figure 5. High-level (general) flow of household decisionmaking.

The strategy is applied to individual cells (locations) within a household where the three decisions may be outlined as follows:

(1) Are the households subsistence requirements met?
(2) Does the household have enough resources to farm this cell?
(3) Is soil suitable for the crop the household wishes to farm at a specific location?

A fourth decision occurring only when the household makes decisions related to mature forest, and shown in figure 6, relates to the quality of the burn. If the quality of the burn is poor the household will attempt to reburn the area in the next iteration. If the quality of the burn is good the household will proceed with the strategy outlined above.

The pros and cons of using a heuristic decisionmaking strategy have been discussed by Gigerenzer and Todd (1999). Its usage in LUCITA is to provide a decision structure that accurately represents the majority of households in the study region. Further, whereas other models thrive on black box strategies (genetic algorithms, classifier systems, optimizers, etc), a heuristic decision tree is transparent and may be verified and validated with less confusion compared with these other types of strategies.

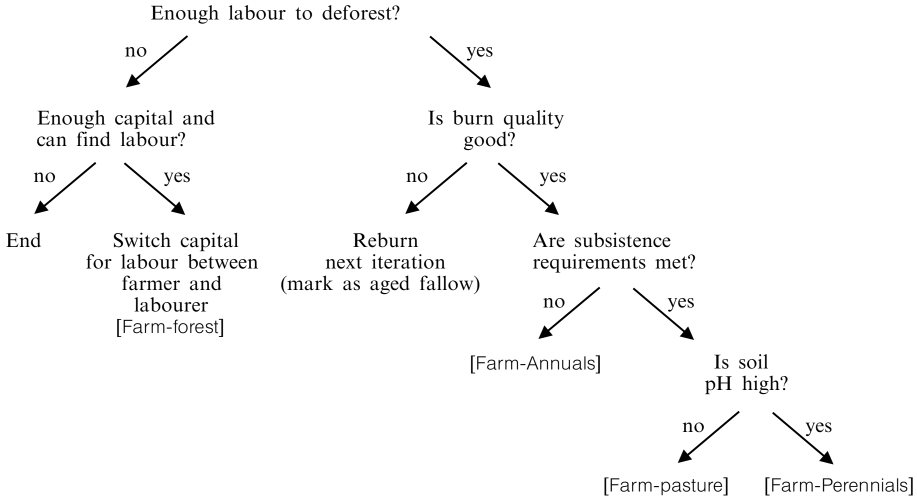

Figure 6. Household heuristic decision tree for cells with mature forest.

2.8 Agent interactions

In the version of LUCITA reported here, agent interaction occurs through a local labour pool. The labour pool is composed of farmers who have failed or have been removed from their plot because of the incurrence of excessive debt. Only labour produced by the household head is available each year and we will refer to this agent herein as a labourer. A household is able to seek out labourers when it has sufficient capital to meet its labour demand. If hired, a labourer's wealth is increased and level of available labour decreased. It is possible that a farmer may attempt to hire a labourer who has no labour available.

The incorporation of a labour pool provides the first of a series of methods for interaction between agents within LUCITA. The current implementation allows the user to alter the price per hour for wage labour—the price is homogeneous for all labourers. Future versions will transform the labour pool into a labour market by allowing for variability in the price and efficiency of labourers as well as providing farmers with aspirations to seek and bid on a labourer who suits household preference. Furthermore, a price market has also been implemented but is pending the retrieval of produce consumption data from Altamira before accurate representation of such processes may occur in the model.

2.9 Simulation runs

Simulation runs in LUCITA are set up to run for 30 iterations, such that the first iteration represents 1971 and the beginning of colonization in the area, iteration 15 corresponds to 1985, and so on. Households are allocated to plots at 0–50 per iteration to a site comprising 234 100-ha plots on a grid representing an area of 15 km by 20 km. The assignment of 50 households per iteration allows all plots to be potentially filled by incoming farmers within 5 years; however, it is most likely that all plots are allocated within the 6–8 year range.

A set of 30 simulations were run in which the parameters were left at a constant setting. Differences between individual simulation runs can be attributed to the stochastic elements of the model, including the timing and location of the introduction of individual households to the simulation run, the individual attributes (family size and capital) of each household agent, and the individual household decisionmaking regarding crop selection that occurs throughout the simulation.

Within the field of MAS/LUCC modeling, a great deal of interest is currently focused on the validation of these models (Manson, 2002). In early MAS/LUCC modeling efforts, validation was not often extensively addressed. In some cases, these early models were highly theoretical in nature, being based on artificial landscapes. However, as the field has expanded, greater attention has been paid to the need to quantify or explain the validity of model output. Model validation should be approached with a view to the overall purpose of the model. Bradbury (2002) argues that, because complex adaptive systems are not, by definition, predictable, then models of these systems should not be validated against real-world outcomes. If we take this view, then models become explanatory tools, designed to explore the relationships between different elements in the study system. The models serve to illustrate and explore particular phenomena, while acting as a tool for generating and testing new theories. However, other researchers view models as predictive tools, and argue in favour of a role for quantitative validation in which simulation output is rigorously compared, by both the quantity and the location of change, with known real-world conditions (Pontius, 2002; Pontius and Schneider, 2001). These approaches to validation typically employ spatial statistical measures to compare binary maps.

LUCITA is viewed as a model whose role is more explanatory than predictive. The model is seen ultimately as a tool for exploring and explaining land-use change phenomena in the Altamira region. Specifically, it is intended that the model will eventually serve as a tool for understanding how the decisions of farmers influence land-use change in the study area. In the face of these alternative validation techniques, the approach taken here has been to compare overall trends in the preliminary output of LUCITA to quantitatively measured trends in land use, and to theoretical models of individual household decisionmaking.

3 Results

In the simulations documented here, all farm properties are typically allocated to farmers within the first 6 to 8 iterations (years) of a run. This pattern is somewhat characteristic of what has been observed. In 1971 in Altamira there were fewer than 500 families, by June of 1972 there were 1834 families, and by June of 1974 there were 3036 (Moran, 1981). Dale and Pearson (1999) also discuss the rapid arrival of colonists in their study (similar to the one presented here) where initial designs for settlement of 500 families in 1971 boomed to 4000 by 1974.

Land-cover trends (represented by the average of thirty runs) are shown in figures 7 and 8. At the commencement of colonization, a significant portion of the land is deforested and put into annual production. Over the first few years colonist agents

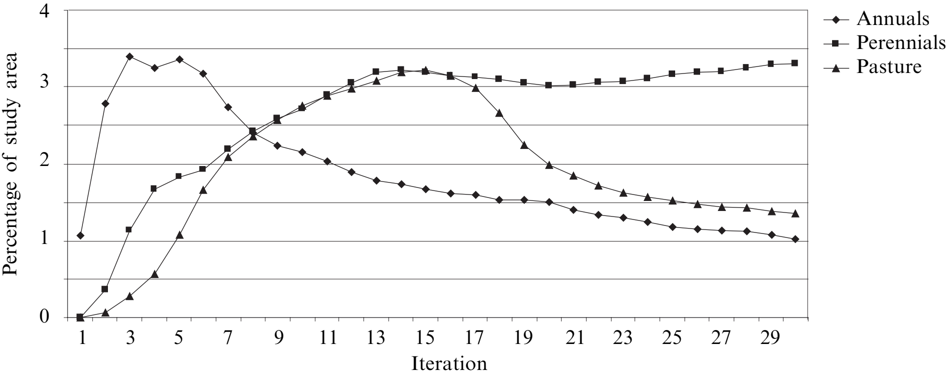

Figure 7. Crop and pasture land-cover trends as a percentage of the study area over time.

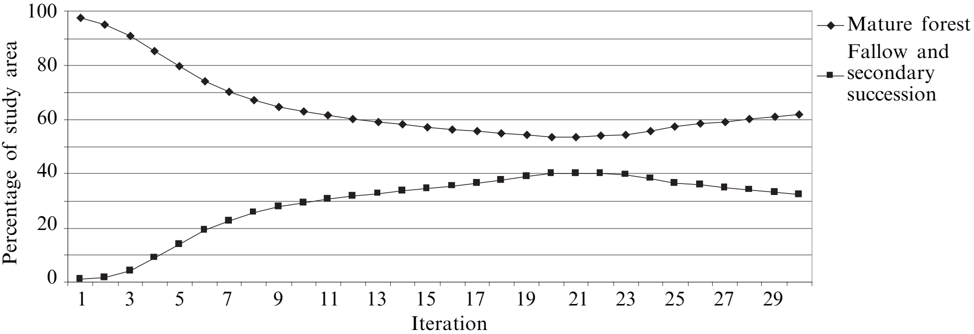

Figure 8. Mature forest and secondary succession and fallow land-cover trends as a percentage of the study area over time.

establish themselves in the frontier accumulating wealth and labour (through aging children) that allow them to increase perennial and pasture production. In a typical simulation run, the total amount of land in perennial and pasture uses surpasses annual production in year 7. After this point the model continues in the expected trajectory in which the next period of cultivation is dominated by perennial crops. In the later iterations of the simulation, decreases in available household labour occur as children begin to leave the household in search of their own economic livelihoods. This constraint on available labour results in a levelling off of perennial production, and a decrease in pasture production. The observed decrease in pasture production in the simulation does not reflect observed trends. At this point in the simulation, successful farmers are those who have accumulated enough capital and are able to hire wage labourers to continue work in cash crops such as black pepper, cacao, or pasture.

Figure 8 displays the trend of mature forest and secondary succession and fallow. These two land-cover types show an inverse relationship such that when mature forest is decreasing, secondary succession and fallow are increasing, and vice versa. Deforestation continues, although at a decreasing rate, until year 20 in which the conversion of mature secondary succession becomes mature forest. It is at this time of conversion (delineated by secondary succession growth time of 17 years) that the level of mature forest in the study area begins to rise while levels of secondary succession and fallow fall.

In table 1 (see over), the percentages of land-cover type found by Mausel et al (1993) are compared with the corresponding percentages, and standard deviations, produced by the simulation. The patterns of deforestation in LUCITA reflect land-use patterns found by Mausel et al (1993) and Brondizio et al (2002). Although an exact numerical match is not found, trends in percentages of land-cover type recorded over time are similar (see table 1). Deforestation results of 43% (shown in figure 8) at iteration 15 approach 1985 observed values by Mausel et al (1993) of approximately 55% in a subset of their study. The higher level of deforestation in the Mausel et al study may be a result of the proximity of their study site to Altamira, and the generally better soils found in the area. Mausel et al (1993) also note that from 1985 to 1988 and from 1988 to 1991 an additional 4% and 1.5% are deforested, respectively. Under iterations 15 – 18 and 18 – 21, LUCITA shows a lower decrease in deforestation with corresponding values of 2% and 1.5%, respectively.

Mausel et al (1993) also measure percentage of additional land-cover types: secondary succession, fallow, crop, water, and wetland. Aggregating fallow and secondary succession recorded by Mausel et al (1993) to match categorization within LUCITA (fallow, secondary succession, and perennials) we find a close similarity in 1985 of

Table 1. Comparison of percentage of land-cover types between results of LUCITA and findings by Mausel et al (1993).

Land cover	Year	Mausel et al (1993) (%)	LUCITA v.2.0	
			%	SD
Mature forest	1985	44.32	57.00	1.06
	1988	40.70	55.00	1.20
	1991	39.21	53.60	1.27
Fallow and secondary succession	1985	33.00	37.70	1.13
	1988	42.00	41.10	1.26
	1991	53.00	43.00	1.31
Crop	1985	2.40	1.70	0.21
	1988	4.80	1.55	0.15
	1991	1.00	1.40	0.13
Pasture	1985	19.00	3.10	0.21
	1988	11.00	2.60	0.16
	1991	6.00	1.80	0.14

33% and 37.7%. The difference is minute in 1988 (42% versus 41.1%) yet increases over time to show similar long-term trends with greater variance (1991 = 53% versus 43%). Despite differences between observations and LUCITA the percentage of secondary succession and fallow show similar increasing trends over periods from 1971 to 1991.

The third category of land-cover type is defined by the ratio of area in annual production over the total study area in crop type. Crop percentages recorded by Mausel et al (1993) and LUCITA demonstrate a higher level of agreement than comparisons made between deforestation or secondary succession and fallow levels. From 1985 to 1991 LUCITA produces a slow decrease in the amount of area in crop production (1.7% – 1.4%).

Throughout this period of decline in annuals, perennial production begins to stabilize. Despite a similar decline in cropping observed by Mausel et al (1993) from 2.4% to 1% over the same period, measurements in 1988 spike to almost 5% of their subsite in crop. It is not unlikely that such spikes occur as they may be attributed to a number of external or stochastic variables, such as droughts, that are not represented within LUCITA.

Last, pasture trends decrease in time from 1985 to 1991. Although values observed by Mausel et al (1993) are markedly higher, with a dramatic decline (19% – 6%) that resulted from a downturn in the Brazilian economy. Such exogenous economic fluctuations are not represented in LUCITA. In the simulations runs, the amount of area in pasture decreases slightly from 3.1% to 1.8%.

4 Discussion

Although the results presented here are preliminary in nature, they are encouraging enough to warrant further exploration of this modeling framework. A modeling approach in which localized decisionmaking based on four primary factors (household composition, household endowment levels, soil quality, and burn quality) is capable of producing encouraging results. The results seen in the thirty runs of the simulation show some similarities with land-use/cover trends observed near Altamira. Aggregate land-cover statistics from LUCITA have shown similar trends and values that approach those observed by Mausel et al (1993) through change detection using remote sensing techniques.

It is important to note that none of the heuristics which are utilized for household decisionmaking has a temporal component. Households do not make land-use decisions on the basis of their length of time on the frontier, but simply on the basis of available household resources, the performance of past crops, and the characteristics of their property. The observed similarities between the temporal patterns of land-use change in the simulation, and those observed in the field are therefore encouraging. Initially households clear their land to plant annual crops. Annual crops provide a method for households to increase their capital slowly and meet subsistence requirements until additional family labour becomes available through ageing children. As these endowments increase over time, the household moves from annuals towards more profitable cultivation such as pasture or perennial crops. Approximately a decade after the household production of annuals drops below that of perennials, the household composition changes again as children begin to leave in search of their own socioeconomic prosperities. When children leave the household, subsistence requirements are reduced and the household becomes capitally dependant. As a result, the amount of annual cropping is reduced and labourers are hired to maintain pasture and perennials.

Extending in temporal distance from the model's point of origin increases the probability of deviating from the observed path because of the infinite number of dynamically adjusting variables in reality. As a result of this we see values approaching those of Mausel et al (1993) very closely at iteration (year) 15 but deviating further in future iterations. This deviation is to be expected. Over time, prices, policies, credits, subsidies, wages, populations, weather, and an infinite number of variables change dynamically and frequently. The incorporation of all possible variables would extend a number of lifetimes and still never approach the complexities inherent in nature. It is our belief that these deviations are the predominant factors in the quantitative differences between values arrived at by LUCITA and observed by Mausel et al (1993).

However, more important than quantitative prediction, replication, and back casting are a solid qualitative understanding of the processes and relationships between human and environment systems. Although the preliminary version of this model provides some encouraging results, a number of future developments with the model will serve to help clarify these qualitative relationships. Sensitivity analysis on the heuristic decisionmaking model will provide a clearer idea of the relative importance of the four primary factors explored here. Further developments with the model could add and explore the role of other factors, such as climate or local credit policies, in influencing patterns of land use. Direct agent communication could be added to explore the diffusion of information across the region. The use of LUCITA, and this approach to its development, outlines a model-making framework that could be implemented within other regions in the Amazon with the addition or extension of additional objects and agents. Therefore the utility of LUCITA is found not only in the relationships and outcomes observed in this study, but also in its flexibility and potential for application to other study sites in the region or beyond.

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