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An agent-based model of agricultural innovation, land-cover change and household inequality: the transition from swidden cultivation to rubber plantations in Laos PDR

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This article examines the transition from shifting cultivation to rubber production for a study area in northern Laos PDR using an agent-based model of land-cover change. A primary objective of the model was to assess changes in household-level inequality with the transition from shifting cultivation to rubber adoption. A secondary objective was to develop explanations for the rate of rubber adoption in the study area. We fit the model to historical land-cover data and land use histories developed from household-level field interviews to reproduce the land use decisions of smallholders over time. The model results indicate an increase in household inequality over time as a function of the variable rate of rubber adoption over time.

Keywords: agent-based model; agricultural innovation; inequality; forest transition

1. Introduction

Montane mainland Southeast Asia (MMSEA) is a large, ecologically vital region comprising approximately half the land area of Cambodia, Laos, Myanmar, Thailand, Vietnam, and China's Yunnan Province (Figure 1). It is a region of great biological and cultural diversity that has come under close scrutiny in the last several decades as a result of both real and perceived deforestation, land degradation, and most recently, the conversion from traditional agricultural systems to more permanent cash crops driven by regional and global markets (Fox and Vogler 2005). Rubber (*Hevea brasiliensis*) is the major commercial crop replacing traditional agriculture and secondary forests in the region (Thongmanivong, Fujita, and Fox 2005; Xu *et al.* 2005), a direct result of strong market demands from China, the world's largest consumer. Forecasts indicate global demand for natural rubber may outpace supply by 1.4 million metric tons by 2020, and there is a growing recognition of the potential impact this demand may have on land cover in areas suitable for rubber production (Mann 2009).

Asia accounts for 97% of the world's natural rubber supply, with most originating from Thailand, Indonesia, and Malaysia. Entrepreneurs from China, Vietnam, Malaysia, and

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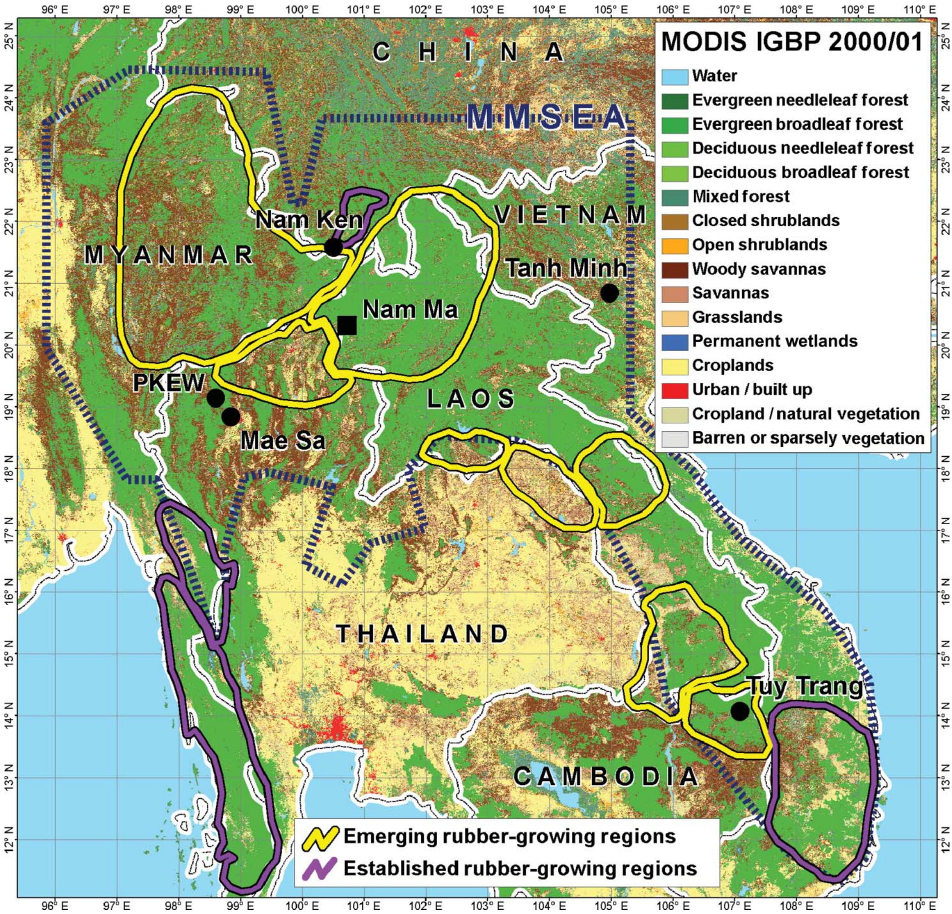

Figure 1. Established and emerging rubber production sites in Southeast Asia. (Available in colour online.)

Thailand are now investing heavily in rubber plantations in the less-developed countries of the region – Laos, Cambodia, and Myanmar. Perhaps even more startling has been the pace at which small farmers have converted from subsistence agriculture to growing rubber for commercial production. Newspaper reports in Laos suggest that over 50,000 ha of rubber had been planted there in 2000. In Cambodia, the Ministry of Agriculture plans to expand the area under rubber cultivation from 50,000 ha to as much as 800,000 ha by 2015. In Myanmar, rubber is expanding into border areas in Kachin and Shan States. In Thailand, rubber has expanded to include over 48,000 ha in the north and 64,000 ha in the northeast. The Thai Rubber Board predicts the total area of rubber in Thailand will increase from 1.9 to 2.4 million ha by 2020. Vietnam currently has approximately 500,000 ha of rubber and little is known about where new rubber trees are being planted or at what rate.

Although the precise magnitude of land-cover change in the MMSEA region is not known, a major land use transition occurring in the MMSEA region is from shifting cultivation, an agricultural system that has been practiced for hundreds of years in the region, to rubber plantations (Guo, Padoch, Coffey, Aiguo, and Yongneng 2002; Padoch *et al.* 2007; Mertz *et al.* 2009). This change in land use has the potential to dramatically impact species diversity (Lawrence, Peart, and Leighton 1998), hydrology (Guardiola-Claramonte *et al.* 2010) and carbon sequestration (Tomich *et al.* 1998; Jepsen 2006) in the region, and the magnitude of this impact is a function of the rate of land use conversion in the context of local-level land suitability.

A key factor in this transition is the linking of smallholder livelihoods to a commodity crop whose price fluctuates according to global market forces (Xu *et al.* 2005). Governments have supported the transition to rubber because of the market opportunities this commodity provides, and the substitution of commercial crops for subsistence crops is a major force in the MMSEA region (Fox and Vogler 2005). The effects of this transition are largely felt at the household level where smallholders must decide whether to convert land from a longstanding traditional production system to a dramatically different land use.

How smallholders evaluate the risk and uncertainty inherent in agricultural innovation plays a key role in the outcome (Mercer 2004). Risk in agent-based models has previously been explored with respect to residential development (Ligmann-Zielinska 2009). Here we explore aspects of risk for smallholder and agricultural innovation. Smallholders must consider the expected utility of a new agricultural production method, one with which they may have little personal experience, with traditional methods where there is less uncertainty. Wealth, income, and capital accumulation are key variables that affect these decisions as well as the vulnerability of farmers to events such as famine, price fluctuations, or climate-related disturbances (Xu *et al.* 2005). Individuals unable to take advantage of new opportunities offered by market integration often suffer a decline in their livelihood (Rigg 2006). The case of rubber (and agroforestry in general) poses particular challenges and risks because of the lag time between planting and harvesting. Prior research has linked gender and demographic characteristics to the likelihood of innovation and risk aversion (Scherr 1995). Access to social networks and agricultural extension services (Wejnert 2002; Mercer 2004) also plays vital roles in places where data are not readily available. Ultimately the reason why a particular smallholder does or does not decide to adopt a new agricultural production method or convert land from one use to another is the product of a complex array of personal and household characteristics and past experiences in the context of various exogenous conditions such as climate and market prices.

Various studies have noted the benefits of using spatial models to study complex systems, including land-change systems (Verburg, Schot, Dijst, and Veldkamp 2004; Grimm *et al.* 2005). Agent-based approaches in particular have received considerable attention within the community of scholars examining human dimensions of global change and land-change science (Janssen 2002; Parker, Manson, Janssen, Hoffmann, and Deadman 2003; Janssen and Ostrom 2006; Evans and Manson 2007; Manson and Evans 2007). Importantly, mixed method approaches have recently been employed to develop empirically grounded agent-based models (Janssen and Ostrom 2006) that include integrating household survey data into the model design, calibration, and validation process (Brown and Robinson 2006; Huigen, Overmars, and de Groot 2006; Pocewicz *et al.* 2007). One advantage of agent-based approaches is the ability to represent agent heterogeneity (Brown and Robinson 2006), which is useful for examining changes in the inequality among agents. For example, an agent-based approach can represent the variability in the willingness (or capacity) of different households to adopt an innovation (Berger 2001). The heterogeneity among agents and the interactions between agents lead to complex aggregated outcomes in the context of agricultural innovation and information diffusion (Berger 2001). These system properties can be examined using a variety of modeling approaches, but agent-based models are effective for examining individual-level agent heterogeneity and agent interactions because of their ability to efficiently handle agents as classes of objects and the ability to examine model performance at both individual and aggregated levels of analysis (Parker *et al.* 2003).

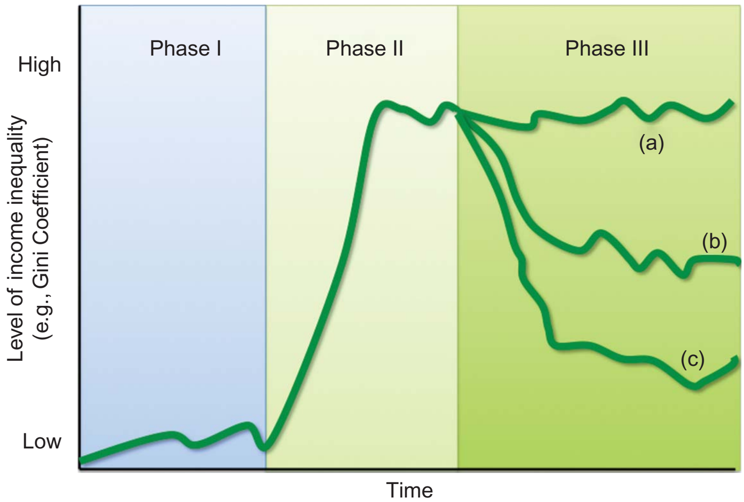

Figure 2. Potential trajectories of inequality resulting from agricultural innovation.

One question regarding agricultural innovation is how the rate of adoption among various smallholders affects the distribution of income, and whether a variable rate of adoption leads to any path-dependent effects (Rigg 1998). Consider the hypothetical trajectories of the inequality presented in Figure 2. In the first phase before innovation, all households have similar land resources and there is little inter-household specialization in crop choice so the distribution of income is relatively even (Phase 1). In Phase 2, a subset of actors decides to convert some of their land resources to a new, more economically advantageous crop. These are the early adopters in the terminology of Rogers' innovation theory (Rogers 1995). The higher relative revenue they receive results in an increase in income inequality. From this point several distinct patterns can emerge. If early adopters gain sufficient economic power to purchase land from other landholders and/or employ them as wage laborers on their high return land holdings, the level of income inequality remains high (Phase 3a). Rigg (2006) warns of this path of agricultural innovation. Alternatively, if the non-early adopters are able to jump on the bandwagon, their incomes begin to approach that of the early adopters and the degree of income inequality begins to decline (Phase 3c). In the middle case (Phase 3b) some landholders are able to belatedly join the early adopters, but others lack the ability or motivation (perhaps due to their aversion to risk) to pursue an alternative mode of agricultural production. In this case, income inequality moves to a moderate level, higher than the original pre-adoption level, but lower than the maximum from Phase 2. This stylized description masks the considerable complexity behind the transition of an area from one agricultural mode to another. And this hypothetical scenario assumes the innovation choice continues to have a higher relative payoff than the traditional alternatives, which of course is not always the case. Real world situations do not follow such clearly distinguishable paths, and issues such as access to credit, the development of cooperatives, and the role of industrial actors complicate these patterns described in these simple scenarios. Still, these hypothetical paths serve as a useful basis to which findings from a case study can be compared.

This article examines the transition from shifting cultivation to rubber production for a study area in northern Laos PDR using an agent-based model of land-cover change. A primary objective of the model was to assess changes in household-level inequalities with the transition from shifting cultivation to rubber adoption. A secondary objective was to identify explanations for the rate of rubber adoption in the study area. We fit the model to historical land-cover data and land use histories developed from field interviews to reproduce the behavior of early adopters versus late adopters. Through the model simulation we calculated a measure of household inequality to determine the impact of the rubber transition on the distribution of income in the village. Section 2 describes the study area and role of rubber in Laos PDR and the MMSEA region. We then describe our agent-based model and results of the model simulations. We close the article with a discussion and interpretation of model results along with implications for land-cover change in the region.

2. Rubber adoption in Laos PDR: Lomue Village

Relative to its neighbors, Laos is a latecomer to rubber. Its first plantations were not established until the mid-1990s. Champassak was the first province in the south to adopt rubber, with 50 ha planted by a state company in 1995 (Manivong and Cramb 2007). In the northern province of Luang Namtha, the Hmong village Ban Had Ngao began planting rubber around 1994. Until the mid-2000s, rubber development remained modest in northern Laos consisting mainly of smallholders and development by individual investors hailing from the immediate borderlands of China and Laos. Beginning in 2004, however, northern Laos saw a rapid influx of Chinese rubber companies, most of which are supported by Chinese government subsidies and enter into contract farming schemes with local farmers. Rubber plantations have also expanded rapidly in recent years in southern Laos, where the model has tended toward large concessions awarded to Vietnamese companies and joint ventures, rather than smallholder contract farming.

As a result of poor governmental regulations, a large range of institutional arrangements for rubber production have emerged in the recent years. These arrangements have been categorized as smallholders, contract farming, and concessions with a number of variations in each type according to who provides the main factors of production, that is, land, labor, capital, market outlet, and technical knowledge. The smallholder scheme is not common but can be found in some villages in northern Laos such as in Had Ngao. The farmers are organized in groups, land is allocated to individual farmers who are members of the association, and labor is shared. Contract farming provides a way for investors to access land and labor without issuing concessions. Under the '2 + 3' model, heavily promoted in northern Laos, an investor supplies capital, technology, and a secure market, whereas the farmer provides land and labor. When the trees begin to produce latex, yields are in theory shared at a ratio generally of 70% for the farmer and 30% for the company. In practice, most farmers receive less than 70% of the profits. Contract farming provides greater ownership and security for farmers; studies in Luang Namtha and other northern provinces, however, have shown that the model is not always successful or stable, and is often converted into a '1 + 4' approach, which gives companies more control over production as well as a higher share of the profits. Under a land concession the investment company is allocated land, and hires labor to help establish, operate, and harvest from the plantation. The company is fully responsible for capital, techniques, planting material, sourcing labor, and marketing its products. Villagers lose access to land during the period of the concession and are instead hired as wage laborers. This production model is prevalent in southern Laos, although further handing out of concessions is technically suspended. Overall there are considerable concerns for food security (Fu *et al.* 2010) and household vulnerability associated with the transition from historical modes of agricultural production to rubber plantations.

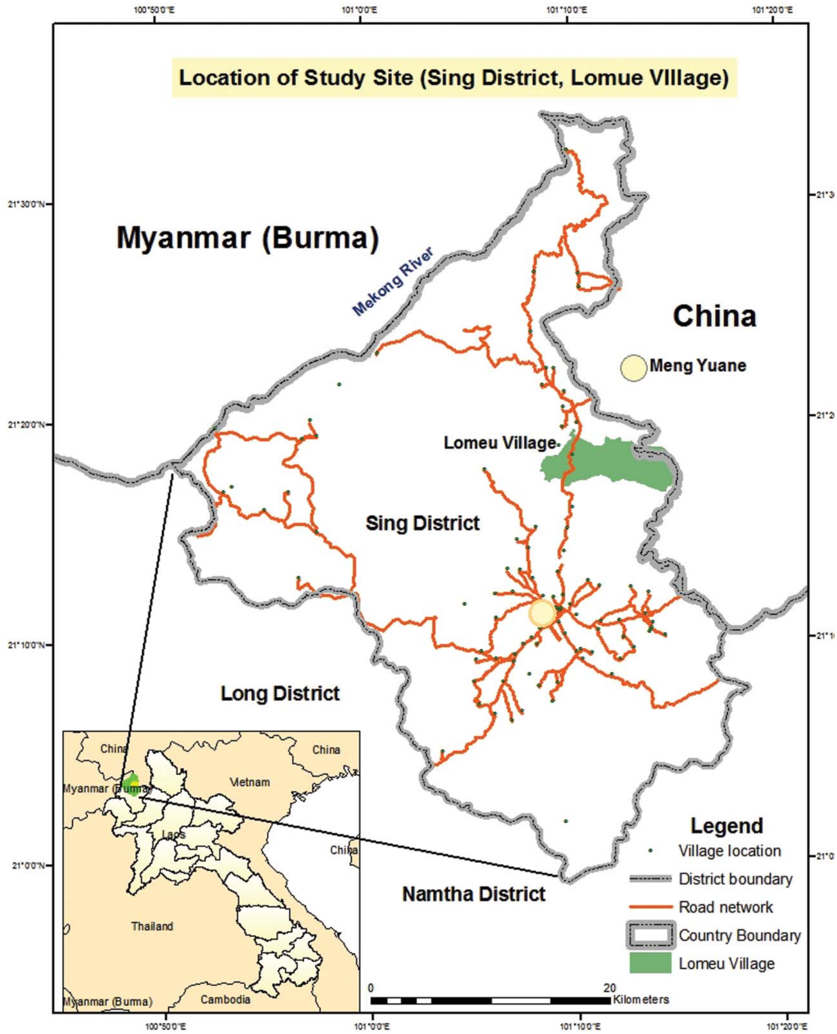

Figure 3. Lomue Village Study Area, Lao PDR. (Available in colour online.)

This research focused on Lomue village located in northwest Laos (Sing district, Luang Namtha province) about 3 km from the Chinese border (Figure 3). Lomue was established in 1984 by migrants of Akha ethnicity who traditionally lived in the Laos, China, Myanmar, Thailand border area, and practiced swidden cultivation in upland areas (Sturgeon 2005); some Akha also practice rice cultivation in lowlands. In the swidden system, agricultural fields are allowed to revert to forest fallow when crop yields decline, which typically occurs after a period of approximately three years. Since Lomue was established there have been three main phases of in-migration. Initial settlement began when a small set of households moved to the area in 1984; the amount of non-forest before this date was relatively small at $<10\%$ of the village area. Between 1994 and 1996, the governments of China and Laos reached an agreement to repatriate Lao refugees that resulted in a second wave of household settlement to Lomue. Then in 2000 and 2004 relatives of existing villagers arrived in the village resulting in a secondary wave of migration. Based on the most recent field data recorded in 2006, the village population is 365 individuals with 85 households (Table 1).

Table 1. Population in Lomue village, 1986–2006.

Year	Total households	Total population
1986	15	70
1995	37	176
2006	85	365

Villagers manage a total area of approximately 3400 ha within the Lomue administrative area.

Rubber seedlings were first planted in the village in 1994–1995 by four pioneer settlers. Data from 2003 to 2006 interviews indicate multiple factors behind the decisions of these early adopters. First they had gained experience in planting and maintaining rubber by working with relatives in China where smallholders began planning rubber in the mid-1980s. Judging from the economic success their Chinese relatives had achieved, these pioneer settlers anticipated that rubber would provide long-term benefits relative to swidden cultivation. Rubber pioneers in Lomue used their own capital to establish rubber plots; whereas in some areas of Laos, villagers received loans from provincial authorities as part of a resettlement support program providing capital to buy rubber seedlings.

Rubber trees require 6–7 years of growth before they can be tapped and latex harvested. This lag period exacerbates the risk farmers face when they decide to take land out of swidden production and plant rubber seedlings. If they have sufficient land resources, those choosing to convert land to rubber may reallocate labor to other activities (e.g., paddy, sugarcane, other upland fields) while they wait for rubber plots to reach maturity. Rubber production in MMSEA is affected by seasonal changes in weather with different cultivars having different tolerances to frost. In the Lomue area, rubber trees die when temperatures drop below 0°C. The winter of 1999 was unusually cold in the MMSEA region and many rubber trees were killed, including up to 50% in some rubber plots in Lomue. Because Southeast Asia is the major supplier of rubber globally, this cold weather event resulted in a large increase in global rubber prices.

The Laos government recently implemented the Land and Forest Allocation (LFA) policy to develop permanent agriculture using conventional production technologies. A key part of this policy converted land that was managed as open access or communal management to a system where individual plots were allocated to specific households. This policy also zoned land in terms of different types of forest protection and areas specifically designated for upland and lowland agricultural production (Sawathvong 2004). Using guidelines from the Ministry of Agriculture and Forestry (1996) and in consultation with the village administrative committee, villagers classified their land into distinct land use zones. A substantial amount of the village area was allocated to conservation or protected forest status, although historical land use has resulted in exceptions to these categorizations in some cases.

Forest land currently is not allocated to individuals or households, but rather to villages as state property but under village management. Only upland, paddy, orchard, gardens and settlement areas can be allocated to individuals and households. Normally a paddy is registered and a land use certificate is issued by the district authority, but for upland fields only a temporary land use agreement and certificate are issued.

As a result of the LFA, Lomue has a relatively large administrative territory compared with other villages in the district. Villagers in Lomue recently indicated that it is becoming difficult to find suitable land for rubber planting given that much of the village territory is set aside for forest protection. An emerging driver is the influence of entrepreneurs from outside the village who are illegally buying land to establish rubber. Unclaimed and unoccupied land can be found on the eastern side of the village bordering China; but under the LFA those areas are zoned for protection, conservation, and the international border zone.

In Xishuangbanna Prefecture in southern Yunnan, the Chinese portion of the MMSEA region, the transition to rubber was particularly dramatic (Xu *et al.* 2005; Mann 2009). The Chinese State introduced rubber in the 1950s as a strategic industrial product for production on large-scale state rubber farms. For over two decades, rubber was cultivated and produced in the planned economy exclusively on these state farms for domestic use. With the dissolution of communes and the transition to a socialist market economy in the mid-1980s, rubber was extended to ethnic minority farmers to plant in their shifting cultivation fields.

In Laos the conversion to rubber has been less extensive but the rate of conversion in rural areas to market-oriented agricultural commodities is growing rapidly (Bouahom, Douangsavanh, and Rigg 2004). Various factors including government policies, agricultural industries, and perhaps most importantly, the social networks of smallholders have affected the rubber transition. Social networks serve multiple purposes. First, they are conduits of information as farmers from China share stories of their economic success with relatives across the border in Laos. More significantly, social networks facilitate the transfer of knowledge for effective production of new agricultural products. Among other factors, Chinese farmers have shared information on the frost tolerance of the various rubber varieties, how to graft rubber seedlings using a side veneer technique, and how to tap rubber so as to avoid injuring the trees in a manner that affects future production levels. The knowledge and techniques used for rubber production are substantially different from the swidden and paddy production methods historically practiced in the village, making technical skill an important enabling factor in the adoption of rubber.

3. Model description

The following summary follows the Overview, Design and Details protocol (Grimm *et al.* 2006; Polhill, Parker, Brown, and Grimm 2008) designed as a standardized method for describing individual-based models and agent-based models.

3.1. Overview

3.1.1. Purpose

We developed an agent-based simulation to explore dynamics between household land use decisions and landscape outcomes in Lomue village with an emphasis on household-level inequality. The model follows a utility-maximizing approach similar to prior research that calculated the potential economic return of different land uses based on cell-based land-suitability measures (topography, accessibility, and neighborhood effects) and market prices for commodity crops (Evans and Kelley 2004, 2008).

3.1.2. State variables and scales

The primary analytical components in the model are actors (households) and cells (land). We used a hybrid design of heuristic rules and utility calculations to generate household-level land use decisions. The model begins with a set of initial conditions drawn from household interviews. Because of the staggered demographic migration events affecting village population over time, the number of household agents and household size are hard-coded in the model based on survey data rather than modeled endogenously (village population for three selected dates shown in Table 1). We extrapolated the distribution of household characteristics for the 33 sampled households to a set of 85 households that gradually populates the village over time. Three key household initial characteristics define agents: (1) household size (number of adult equivalents), (2) year of arrival in village, and (3) area of land holdings (hectares) in different land use categories. A proxy for risk tolerance is the other primary characteristic that differentiates households in the simulation.

Households have the following variables: number of cells managed in each land use, household size (used to calculate labor availability), income, risk, and land use preference parameters for each land use. Cells within the simulated Lomue village area have the following attributes: slope, accessibility, current land use, duration of current land use, household ID (if assigned), and revenue (if harvested).

The model runs on a 1-year time interval from 1984 to 2006, with 1984 being the year that households first migrated to the Lomue area. The Lomue landscape is represented at a 50 m spatial resolution. The estimated Gini coefficient (Sen 1973) and Lorenz curve based on household income are calculated at each time step. Household income is the sum of revenue on each cell managed by a household. We rely on household income rather than wealth because we do not have data on remittances or other sources of income outside the village. In reality households may well accumulate wealth from exogenous sources that may result in a very different picture of disparities between households.

3.1.3. Process overview and scheduling

Land use decisions are modeled as a production function where expected utility is calculated based on exogenous prices and cell-based land suitability. Risk is a parameter that is fit to the rate of rubber adoption measured with the household data. All agents start with the same capital endowments because we have no data to identify actual endowments in 1984. The land use decisions for each agent are governed by a modified utility maximization form (Evans and Kelley 2004) as follows:

$$EU_U = \alpha_U(P_U M_U Y_U - C_U L_U) \tag{1}$$

where α is a preference parameter for each respective land use (*U*), rubber and upland agriculture. *P* is the exogenous revenue (price) for each commodity, *L* is a measure of household labor, *M* is the number of cells in the particular land use, *C* represents initial and annual costs, and *Y* is the productivity of that land use per hectare. Farmers must purchase rubber seedlings from a vendor, and this represents a significant cost compared with the resources needed to initiate a new upland agriculture plot. The ability to convert land to rubber is thus also a function of the availability of household capital (non-land), an attribute updated through the model run as households earn money from their land. Given the heuristic that forces agents to allocate one cell to paddy rice, the expected utility calculation is then reduced to the land use choice of rubber versus upland crops in the context of available capital. The relative preference parameter values α for each land use are thus an indication of a household's risk tolerance as representation of the willingness to allocate land and labor to rubber production.

Households with available labor select the most suitable cell(s) for conversion based on an expected utility maximization calculation. The land use options implemented in the model are paddy, upland crops (i.e., swidden cultivation) and monocrop rubber. The expected utility of each cell is a function of (1) potential revenue for each crop as calculated from the United Nations Conference on Trade and Development (UNCTAD) data, (2) accessibility (distance to village location, distance to road and paths), and (3) topography. Once a cell is allocated to a specific land use, revenue is calculated from a time series of commodity market prices (per hectare) that are endogenous to the model (UNCTAD 2006). We acknowledge that farm-gate prices in Lomue likely differ from the UNCTAD commodity market prices. However, relative prices for each land use product are more important than actual prices in terms of fitting the model to reproduce the observed land-cover composition in the village.

Once an agent chooses a land use decision, a series of cell suitability parameters are used to identify the optimal location. These suitability parameters include distance to village, land use clustering weight (distance to other patches of similar land use), slope and distance to a main east–west path that roughly bisects the village area. Cell suitability is updated at each time step to recalculate the land use clustering weight as new cells are converted through the model run. The nuclear settlement moved in 1995 from a location in the eastern part of the village to a location in the western portion of the village area, changing the relative accessibility of cells. The cell suitability weights control how land use decisions are distributed across the landscape and are responsible for the spatial pattern in the village area.

3.2. Design concepts

Household interviews indicated that farmers did not convert land to rubber production before 1994. We hardcoded this into the model to indicate the date that social networks resulted in the transfer of rubber cultivation knowledge and techniques to the village. In the absence of detailed data regarding the role of social networks and knowledge transfer within the village we assumed that every household had the possibility of converting land to rubber from 1994 onward although the skill to do so likely diffused through the village over time.

Lomue can be characterized by a nuclear settlement pattern (clustered households, distributed land holdings) that in the absence of cadastral data poses particular challenges in creating a one-to-one link between a household and a particular parcel of land or portfolio of spatially distributed land holdings (Rindfuss *et al.*, 2004; Berger and Schreinemachers 2006). This contrasts with agent-based models of other systems where individual households reside on a clearly defined and identifiable landscape partition (Deadman, Robinson, Moran, and Brondizio 2004; Evans and Kelley 2004). In Lomue, a village committee allocates land parcels to individual households as households request additional land for production, which usually is associated with a lack of food security or availability of excess labor. From the household survey data we know the total area of the different types of land holdings each household manages (number of hectares of plantation rubber, upland agriculture, paddy), but not the precise spatial location of a particular household's landholdings.

The dynamics of shifting cultivation systems pose particular challenges in modeling the spatial pattern of land-cover change. In a model of shifting cultivation in the province of Luang Prabang (~200 km southeast of Lomue), Wada, Rajan, and Shibasaki (2007) addressed the challenge of validating shifting land-cover systems by scaling up the model results to produce reasonable representations of the pattern of land-cover change. Our model contrasts this approach in that it operates at a finer scale and smaller extent focused on an individual village. Instead of a model of villages as agents in a large region (Wada *et al.* 2007), the model presented here simulates decisions of individual households acting within the boundaries of a single village.

Rice is a staple food source in Laos and the lowland area suitable for rice cultivation is primarily limited to a northeast section of the village. Farmers prefer to utilize suitable land for rice cultivation if available even though the potential revenue for a hectare of rice is below that of rubber and other annual crops. The benefits of crop diversification also increase the relative benefit of rice cultivation. We consequently built a heuristic into the model to capture the high preference households have for rice. Households first seek to convert at least 1 ha to paddy before they add upland crops and rubber to their portfolios.

3.2.1. Emergence

Households make land use decisions that modify land cover in the Lomue village area. The aggregation of these individual actions produces the village-level land-cover composition and represents the transition from swidden cultivation to longer-term agroforestry production (i.e., rubber).

3.2.2. Adapation

Households adapt to system conditions primarily through the relative price values (potential revenue) for rubber versus upland agriculture through the simulation period.

3.2.3. Fitness/objectives

The model uses a utility maximization algorithm for agent decision-making whereby households select the land use portfolio that returns the highest revenue. If a household's observed actual land use portfolio differs from the utility-maximizing portfolio then the household parameter weights are iteratively modified in the calibration process to fit the household's simulated land use portfolio to the observed.

3.2.4. Prediction

The household decision-making algorithm assumes no deviation from optimal yields for the specified harvest duration for each land use. In other words, households do not take into account the possibility of frost, pests, or other disturbances that affect yields in the real world.

3.2.5. Interaction

Households interact through the spatial clustering of land use, especially rubber, which has a larger mean patch size than upland agriculture.

3.2.6. Sensing

Households in the simulation have perfect knowledge of the land suitability factors that affect the optimal selection of cells for agricultural production. The primary variables used in land suitability calculation are topography and accessibility. Households also have perfect knowledge of the UNCTAD price time series. Households expend all available labor within the household at each time point.

3.2.7. Model calibration

The model was calibrated by fitting the distribution of household-level land use preference and risk-tolerance parameters to (1) the actual land-cover pattern and composition in Lomue in 2005 and (2) household-level land holdings in rubber versus upland derived from the household survey data. Each household starts with a random value for the rubber and upland preference parameters. The model is then run iteratively, modifying each preference weight until the household land use allocation in 2006 matches that reported from the household survey data. These parameters are an expression of a household's willingness to innovate (e.g., transition land to rubber production). A low rubber land use preference parameter suppresses the willingness to transition land to rubber and a high rubber preference parameter increases the probability of transitioning land to rubber. Households that adopt rubber early in the model run have a high risk tolerance parameter value and households that do not adopt rubber during the time period (30 households total) have a low value. We adjusted the distribution of risk parameter values until the land-cover composition produced by the model approximated that from our observed data in 2005, and the household-level land allocation over time matched that identified from the household survey.

Because the amount of land in the village area suitable for paddy was limited, the fitting process effectively is reduced to finding the household-level land use preferences that reproduce the relative allocation of land to upland agriculture versus rubber. The land use clustering weight is then iteratively adjusted to reproduce the spatial pattern of land cover in the village area, specifically the patchiness of each land use (rubber, rice, and upland). The spatial distribution of shifting cultivation is highly heterogeneous and widely distributed among the upland areas in the village outside the protection zone. The mean patch size and mean nearest neighbor distances (McGarigal and Marks 1995; McGarigal, Cushman, Neel, and Ene 2002) are used to fit the spatial pattern produced from the model simulations to the spatial pattern of the observed landscape (Parker and Meretsky 2004).

3.3. Details

3.3.1. Initialization

The model starts in 1984 with an entirely forested landscape in the village boundary. Interview data indicate that 1984 is the year of the initial migration wave to the Lomue area and that before 1984 there was no significant land clearing. Households enter the model at time points derived from the household interview data.

3.3.2. Input

The primary model inputs are the price data for each land use and number of households in the village at different time points. Based on field interviews, we used a 3-year rotation cycle for swidden/upland cells after which they reverted to forest fallow. For plantation rubber, a key driver of the rate of conversion is the lag time between planting and harvest. Cells in rubber do not generate revenue until 6 years have elapsed to reflect the time it takes before trees can be tapped. Literature on rubber production suggests that rubber trees can be productively tapped for approximately 30 years after which they are cut down. This 30-year threshold has not occurred in Lomue during the simulation period (1984–2006).

Land-cover data from aerial photography and satellite imagery, supplemented by GPS-located field data, were used to identify locations of rubber plantations, paddy, upland crops, successional/disturbed forest, and dense/undisturbed forest. Young rubber plantations are comparatively easy to detect relative to other classes, but there is considerable spectral similarity between later stages of rubber growth and some stages of forest succession. Because of this class confusion we used 2003 and 2006 GPS ground truth data to verify locations of rubber plantation in the village. The boundaries of verified rubber planting areas were digitized from high-resolution imagery and then merged with the existing 2005 land-cover classification dataset. Digital elevation data were derived from digitized, 20 m contours on maps acquired from the Forest Inventory Planning Division of the Lao PDR Department of Forestry and used to produce measures of land suitability in the village area.

A time series of commodity price data was developed from historical data acquired from UNCTAD (2006) and used to calculate relative income per hectare for rubber, rice, and upland crops based on data obtained from a report on agricultural products in northern Laos (Helberg 2005). Figure 4 shows the consistently high revenue for rubber per hectare relative to rice and upland crops, supported by previous research on the high economic returns for rubber in the region (Manivong and Cramb 2007).

Household survey data were collected using a random sampling method stratified by household wealth and amenities. We selected 33 of the 85 total households in the village for in-depth interviews in 2003 and 2006. A survey instrument consisting of structured and unstructured questions was used to collect data regarding household demographics, land holdings, labor allocation, and land use practices. The survey included specific questions about rubber production including the number of hectares each household had in rubber production over time and the year the household first planted rubber on their land holdings (Figure 5). The distribution of variables for the 33 sampled households was extrapolated to the full village population size to produce a set of agents and associated characteristics

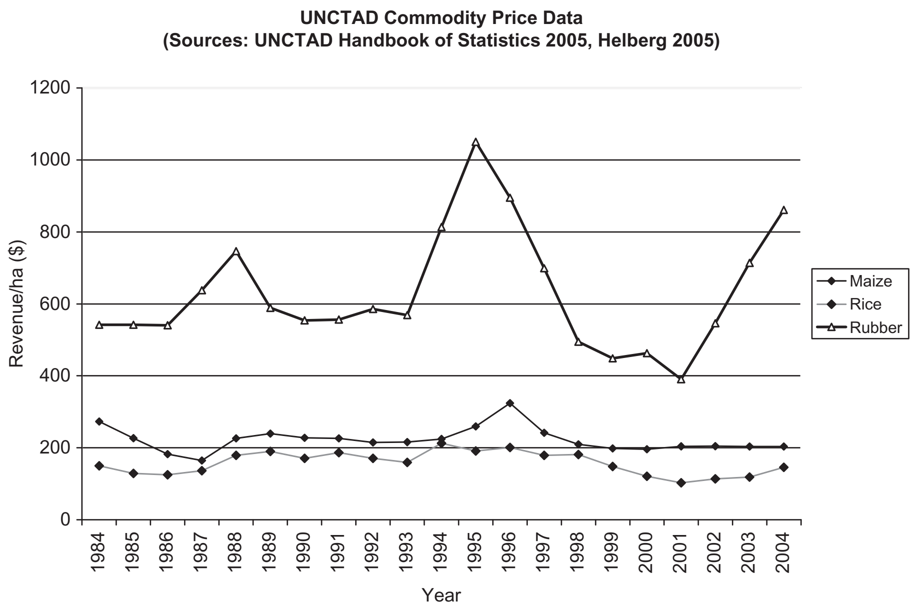

Figure 4. Rubber, rice, and upland crop prices.

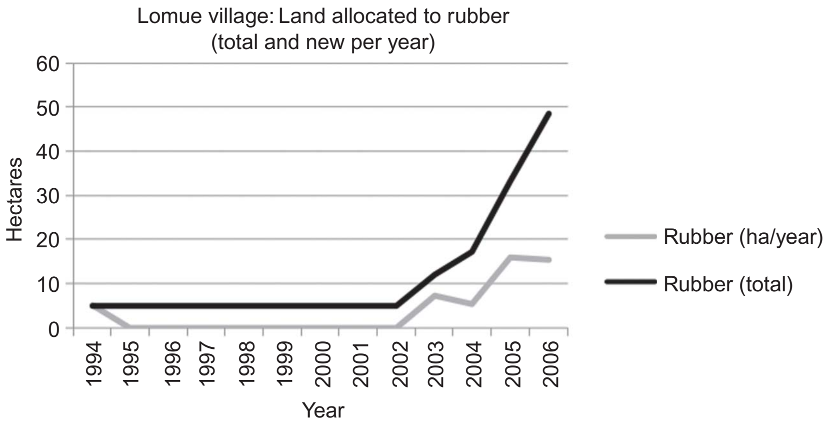

Figure 5. Rubber adoption timeline.

(date joined village, date of first rubber planting, hectares in each land use class) for the model simulations. As of 2006, 55 of the 85 households grew rubber.

4. Results

The results presented in Table 2 provide a comparison of spatial pattern and composition of the calibrated simulation to observed data. By two measures of spatial pattern (mean patch size, mean nearest neighbor distance) the model effectively reproduces the distribution of land cover within the village area. Figures 6 and 7 show the observed land-cover data and simulated land-cover data. Although the specific location of rubber is different between Figures 6 and 7c (for 2006), the general spatial pattern is represented well by the simulation visually and based on a comparison of spatial metrics. The model also reproduces the remnants of previous crop production in the eastern part of the village that converted to successional forest by 2006 after the village households moved to the western location. In addition, the rate of adoption evident from household survey data is represented by the number of households adopting rubber through the model run and the total number of hectares dedicated to rubber.

The model calculates a dramatic change in inequality through the 1984–2006 simulation period (Figure 8). From 1984 to 1994 the Gini coefficient was relatively low because during most of this period landholders were generally planting the same crops (a combination of paddy and upland crops), and there was a high degree of parity regarding total land holdings. Rubber was first planted in the village in 1994, but from 1994 to 2000 the Gini coefficient was still low because the six-year lag from planting to tapping had not elapsed. From 2001 there was a dramatic rise in the Gini coefficient as villagers who were early adopters reaped the benefits from the risk they took in the mid-1990s. Because the revenue per hectare for rubber was so much higher than any other agricultural option, early adopters quickly saw their incomes increasing relative to those who did not adopt rubber. Even though a majority of households had some land in rubber by the end of the model run, the Gini coefficient was still relatively high. And importantly, approximately one-third of all households still have no land in rubber.

The representation of the land use preference parameter is somewhat misleading as we do not know whether a household did not adopt rubber because of risk aversion or a lack

Table 2. Spatial characteristics of observed (O) land cover (2006) and simulated (S) land cover (1994, 2001, 2006).

	Area (ha)	Euclidean nearest neighbor distance (m)
1994 (S)		
Rice	58	351
Upland	86	322
Forest	3265	277
2001 (S)		
Rice	112	274
Upland	106	295
Forest	3145	267
Rubber	46	574
2006 (S)		
Rice	126	274
Upland	98	294
Forest	3086	273
Rubber	99	389
2006 (O)		
Rice	130	409
Upland	91	317
Forest	3087	253
Rubber	97	299

Figure 6. Observed land-cover data, 2006. (Available in colour online.)

of capital to purchase seedlings. However, the model reproduces a finding from the survey data that labor is not the constraining factor as some households continue to allocate a majority of their labor to upland crop production through the model simulation.

The model also demonstrates several pulses of rubber adoption that are supported by the household interview data. Despite the existence of rubber across the Chinese border and the high revenue potential of rubber, farmers in Lomue did not adopt rubber before 1994. In 1994 only a small set of pioneers converted upland areas to rubber with most villagers continuing the traditional agricultural modes of paddy and shifting cultivation. In Lomue village, households were able to observe the success of the early adopters by 2001 when the early adopters were harvesting latex. This process of observation can motivate late adopters to begin to convert land to rubber production, creating a more diversified

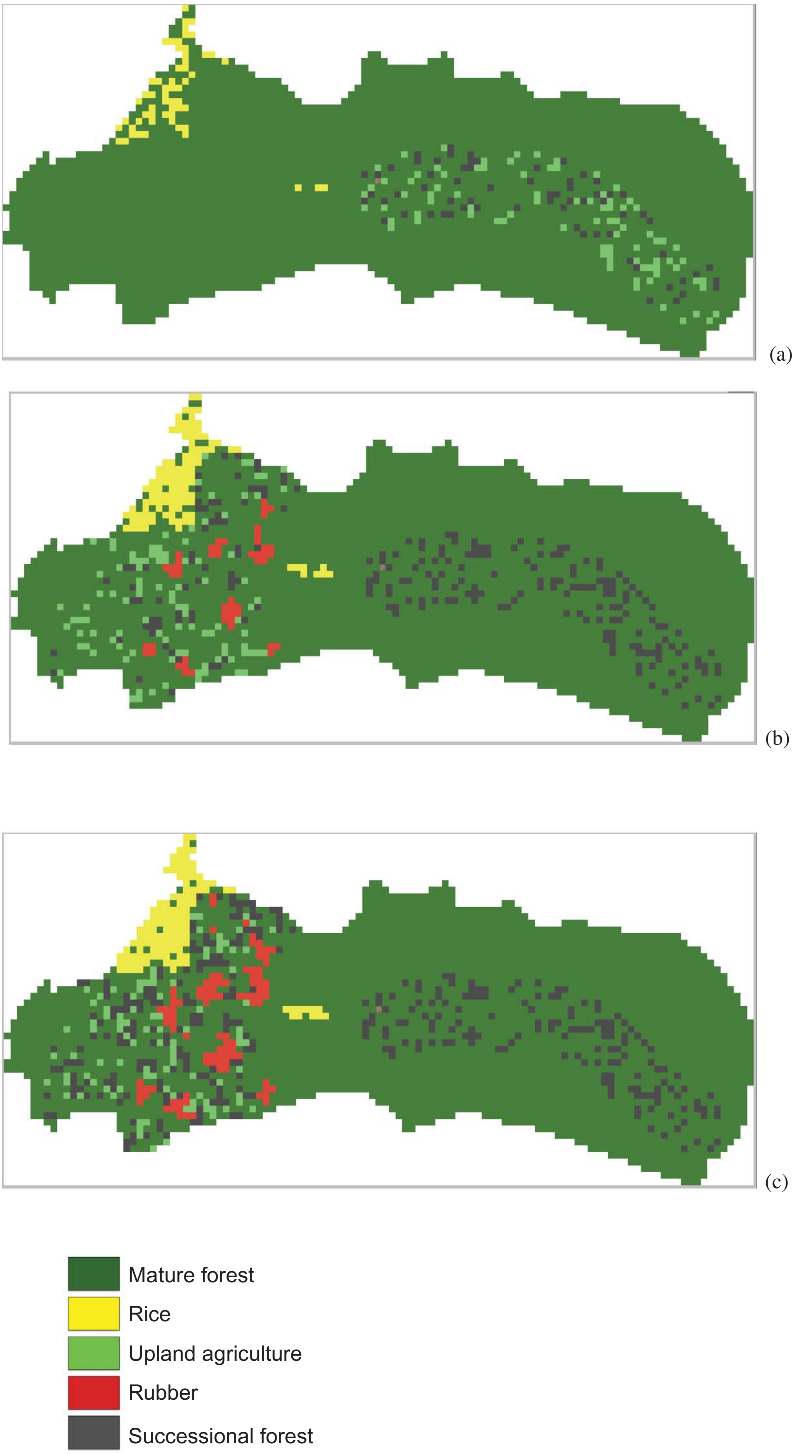

Figure 7. Simulated land cover, 1994 (a), 2001 (b), and 2006 (c). (Available in colour online.)

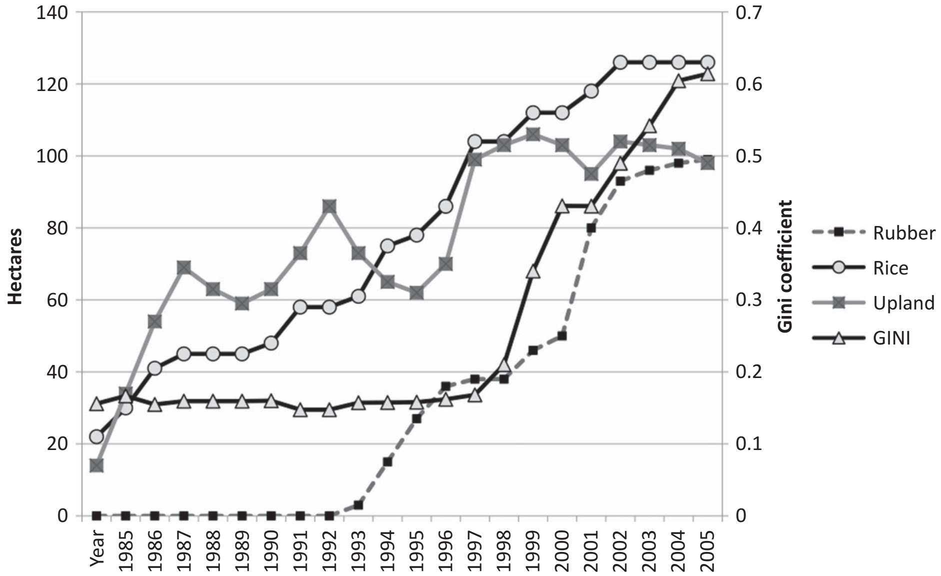

Figure 8. Simulation Gini coefficient, land cover (ha), 1984–2006.

portfolio of landholdings. This is represented in the model not through an explicit process of agent observation, but rather in fitting the preference parameters for each individual agent. This assumes that each household has equal opportunity to observe the actions and outcomes of other agents that we think is reasonable given the small village size. Both the survey data and the model demonstrate the cumulative adoption curve hypothesized by Rogers (1995). The relative distribution of preference parameters for rubber and upland land uses are shown in Figure 9. The distribution shows a concentration of low-preference parameters for rubber, with the exception of a cluster of households with a high-preference

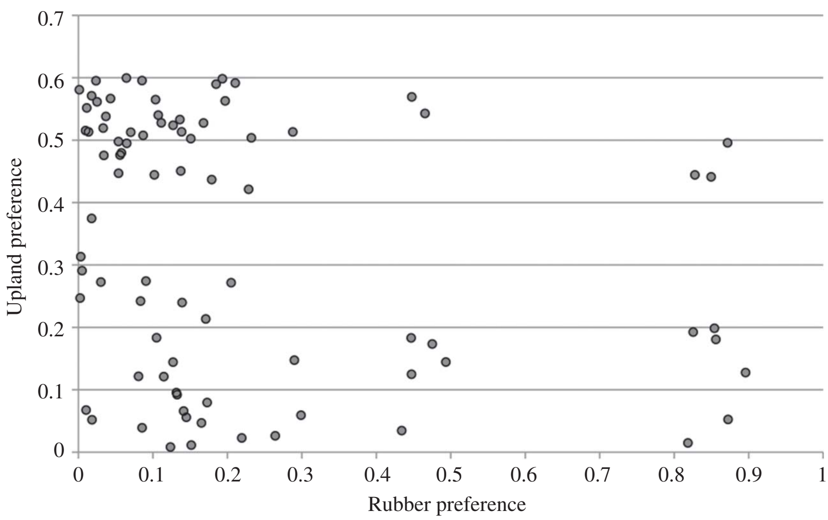

Figure 9. Distribution of fitted rubber and upland preference parameters.

parameter for rubber and high preference for upland, and a second cluster with a high preference for rubber and a relatively low preference for upland. These last two clusters are the ‘early adopters’ who planted rubber starting in 1994 in the model simulation.

The model shows that even with the existence of protected forest areas (albeit with modest land conversion) there is still available land for additional rubber production. Thus, land constraints do not appear to have been a limiting factor to more rapid adoption of rubber. However, by 2006 much of the agricultural zone was under active cultivation or some stage of fallow. With the movement of the settlement from the east to the west side of the village there was a commensurate shift in land conversion through the study period. The eastern portion of the village area saw less-dense conversion than the west, as would be expected given the change in accessibility and initiation of the land use plan.

5. Discussion

This article examined the role of smallholders in Lomue village as they transitioned from upland farming to rubber, and explored the triggers that led to the patterns of conversion observed in the empirical data. In developing agent-based models of land-cover change, modelers face the challenge of representing dynamic decision makers. This is particularly a challenge when examining land-cover change over long periods of time. Did actors change their risk preference or did the momentum of land conversion in the village give them greater confidence that adopting rubber was not a risky action? It is difficult to answer this question definitively but we believe that when farmers in Lomue observed that early rubber adopters reaped economic benefits from their action, they also then adopted this innovation. This hypothesis provides a plausible explanation for the model results and suggests that the phases of adoption observed will have specific impacts on income inequality in the village.

We modeled the adoption of rubber as a function of labor availability, capital (initial and annual costs), land use preferences, and expected utility (expected revenue). Any of these elements can keep an agent from converting upland crops to rubber. An actor who does not have knowledge of the revenue possible from rubber will not have the motivation to adopt. Likewise, an actor who lacks adequate financial capital to purchase rubber seedlings will not have the ability to pursue this land use option, even if they perceive it as having higher potential revenue compared with other options and they are not averse to risk. Lastly, some actors may have the capital to buy seedlings but choose not to because they are risk averse (e.g., an older couple who may not believe they will see an adequate return on their investment in their lifetimes).

Why did the first pioneers not adopt rubber earlier than the mid-1990s given the potential revenue of rubber was greater than for upland crops in this period? The timing appears to be directly related to events in China. It was not until China dissolved the communes and allocated agricultural and forest lands to farmers in the mid-1980s that farmers in Southern Yunnan started to plant rubber. These trees began to produce latex in the early 1990s, and within a few years of this production, farmers in Lomue began to plant rubber. Some villagers in Laos provided labor in these areas of China where rubber was adopted, and it was these villagers who were later responsible for bringing that technology and knowledge to Lomue. But no market or infrastructure for rubber existed in Lomue until the mid-1990s. This highlights the risk of using only global market prices to drive the model dynamics. Without a technology-transfer-based trigger in the model, households would have started to adopt rubber earlier in the model as a function of the relative commodity prices. But this technology diffusion also provides some insight into potential land-cover trajectories in Lomue. The area of southern China that borders Laos has experienced dramatic deforestation due to the expansion of rubber over the last decade (Fox and Vogler 2005), and the rate of land conversion in Laos may follow a similar trajectory.

Why do we see households in Lomue who still have not allocated any land to rubber by 2006? Rogers' (1995) conceptual model of innovation describes a 'laggards' category – that is, those who are last to adopt an innovation, or who may never adopt an innovation. With respect to the Lomue case study, there are several possible explanations for the existence of laggards. First, they may be extremely risk averse and simply lack the desire to be an adopter even though they see their peers adopt and reap the benefits of that decision (for the few households that adopted early). Given the need to shift labor from subsistence crops to a cash crop, those who are at the edge of subsistence have less capacity to absorb potential shocks associated with rubber cultivation such as exposure to commodity price markets and meteorological events. Alternatively, they may have the desire and motivation to be an adopter but lack the means to do so. The household survey data found the non-adopters are those with the fewest assets in terms of land and finances. Thus they may have lacked sufficient capital to purchase seedlings, hire labor to help with land clearing, or gain credit for those actions. In other words, they may desire to innovate but lack the means to do so. Yet another explanation is that these holdouts are not laggards but rather late adopters who are on the cusp of adoption.

Data from household interviews in 2006 indicate a dramatic increase in the number of households with rubber holdings in 2003. This phenomenon has not only happened in Lomue but also in most villages in the province. However, smallholders still do not have extensive knowledge regarding which varieties of rubber are the most suitable for this montane region. The technology transfer in the village is primarily villager-to-villager rather than through an agricultural extension agent, although Chinese entrepreneurs have been an emerging source of technical information. Farmers in Laos also question whether their rubber trees will yield the same amount of latex as in China. Rubber tapping requires substantial skill, and poor technique can result in lower yields and also affect future productivity. Most rubber tappers in Lomue are women with relatively little formal training and fewer connections to social networks outside the village.

It is worth noting that the first rubber trees planted in 1994/1995 were only harvested in 2001/2002. But 1999 was a particularly cold winter and frost killed up to 50% of the trees in some rubber plots. The price spike in rubber in 2000 reflected in the UNCTAD data is a product of the supply problems associated with this loss. This observed sensitivity of rubber trees to climate variations may have been a strong deterrent for those villagers who were not early adopters, in effect modifying the relative expected utility calculation due to the strength of the memory of recent events. However, by 2001/2002 villagers had learned of the high income per hectare early adopters were receiving from the initial tapping, which even with the loss of trees in 1999 exceeded the potential revenue of upland crops. A reinforcement learning approach has been applied to agent-based models (Bone and Dragićević 2009) and modification of our model to incorporate learning dynamics is a step for future work.

Lomue does not have formal land titling, but an informal land market exists. Interviews with Lomue villagers indicate that a few early adopters have capitalized on the vulnerable economic status of late adopters by buying their land. Thus, those who missed the first two waves of rubber innovation (1994 and 2001–2003) and then sold land are relegated to receiving only secondary benefits (wage labor opportunities) from the income advantages of this land use transition. However, the emergence of rubber in the region is a relatively nascent phenomena spanning only 13 years at the time of survey data collection and some late adopters may catch up to early adopters depending on the availability of land in the village. Here a key factor is the enforcement of the village-level land use plan, which is currently not strictly observed. The village committee that makes decisions about land use in the village area is under significant pressure to help poorer households find additional land for agricultural production. With the limited availability of land in the agricultural zoned territory there have been discussions about changing the existing land use zones that may make some areas formally eligible for conversion. In 2007 the Laos military and a company entity both planted rubber areas in excess of 200 ha within the village boundary. Villagers are questioning how they will benefit from these major conversions in the village area that may allow them to justify changes in the land use plan that will enable smallholders to clear new areas for rubber.

The transition from swidden cultivation to rubber has numerous potential ecosystem impacts (Ziegler, Fox, and Xu 2009). First and foremost are the impacts on biodiversity (Li, Aide, Ma, Liu, and Cao 2007; Qiu 2009) as a successional forest system is replaced by a monocrop (Bunker *et al.* 2005), particularly in the early stages of rubber growth. Rubber plantations may also be associated with a reduction in carbon sequestration, which has important implications for carbon accounting and the efficacy of REDD programs in Southeast Asia. Rubber plantations are considered forests by some definitions yet some modes of plantation rubber production have considerably less biomass than natural forests. Because rubber expansion is occurring at the expense of both upland agriculture and the natural forests in Laos, there is considerable risk that this transition will result in a net loss of carbon over time. Lastly, the hydrological implications of rubber expansion are also a concern (Guardiola-Claramonte *et al.* 2010; Ziegler *et al.* 2009) with initial studies showing greater water losses associated with rubber-dominated landscapes compared with traditional forests (Guardiola-Claramonte *et al.* 2010). Surface runoff has particularly been shown to increase with rubber monocrop systems (Wu, Liu, and Liu 2001). The rubber transition in Lomue is still relatively young, and the full potential of these ecosystem impacts will depend on the ability of the village committee to preserve areas of natural forest within the village boundary and manage the practices of smallholder production.

Ultimately the transition from a forest–agriculture rotation to a monocrop forest plantation appears to be a process that initially emerged slowly and now is expanding rapidly with critical implications for inequality in Lomue. There appears to be a consistently strong demand for rubber with no major decline in price over time despite the increasing amount of land moving into rubber production in the MMSEA region. The demand for rubber has been increasing and has apparently not outpaced increases in supply. Thus far households in Lomue have benefited from this strong demand for rubber through the relatively high revenue they are able to receive. Early adopters have particularly benefited, which has resulted in increased inequality among household income in the village. However, the pace of conversion poses some reason for caution. As villagers place more of their landholdings in rubber at the expense of other crops, they increase their vulnerability to exogenous commodity price fluctuations. The demand for rubber has consistently been strong over the last 30 years, but changes from this regime would have dramatic impacts on livelihoods given the pace of conversion to rubber in Lomue.

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