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REGIONAL SCALE AGENT-BASED MODELLING OF LAND CHANGE: EVOLVING INSTITUTIONAL ARRANGEMENTS IN FRONTIER AREAS

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São José dos Campos, 30 de Novembro de 2012

“A única sabedoria que uma pessoa pode esperar adquirir é a sabedoria da humildade”.

Eliot Thomas

A meu querido filho, Lucas Henrique e

amada esposa Evaldinolia.

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ABSTRACT

This thesis discusses the use of agent-based models for capturing land change in large frontier areas. Applying agent models in such areas is not straightforward, given the lack of data. To date, most agent based models of land frontiers study local areas using in-situ information. At regional scales, agent-based modellers need additional ways to describe collective decision-making. The work presents two ideas to deal with the complexities of agent-based models at such scales: institutional arrangements and states. Institutional arrangements help to model multi-agent interaction by explaining why, although there are rules and norms for land use, these rules are not always followed. This formalism captures states and transitions of agents in a simulation and helps to build expressive models, where the agent strategies evolve depending of local and external factors. We validate our ideas by building a deforestation model in an area of 60,000 km2 in Amazonia. Results show that we need to set different arrangements to capture changes in agents' behaviour, as they react to external conditions. Thus, combining the ideas of institutional arrangements and states improves the explanatory power of agent models for regional scales.

MODELOS BASEADOS EM AGENTES PARA SIMULAÇÃO DE MUDANÇAS DE USO DA TERRA EM ESCALA REGIONAL: EVOLUÇÃO DE ARRANJOS INSTITUCIONAIS EM REGIÕES DE FRONTEIRA

RESUMO

Esta tese discute o uso de modelos baseados em agentes para capturar a mudança de uso da terra em grandes áreas de fronteira. Os modelos baseados em agentes atuais são empregados em pequenas áreas, onde informações individuais são mais acessíveis. Em escalas regionais, os modeladores precisam descrever as tomadas de decisão coletiva. O trabalho apresenta duas ideias para lidar com as complexidades de modelos baseados em agentes em tais escalas: arranjos institucionais e autômatos híbridos. Arranjos institucionais ajudam a modelar a interação multi-agente, explicando por que, apesar de existirem regras e normas de uso da terra, essas regras nem sempre são seguidas. Um autômato híbrido combina uma máquina de estado discreto com ações contínuas em um dado estado. Este formalismo captura estados e transições de agentes em uma simulação e ajuda a construir modelos expressivos, onde as estratégias dos agentes evoluem dependendo de fatores locais e externos. Nós validamos nossas ideias através da construção de um modelo de desmatamento em uma área de 60.000 km2 na Amazônia. Os resultados mostram que precisamos definir arranjos diferentes para capturar as mudanças no comportamento dos agentes e como eles reagem as condições externas. Assim, combinando as ideias de arranjos institucionais e autômatos híbridos melhoramos o poder explicativo dos modelos de agentes para escalas regionais.

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1 INTRODUCTION

Changes in land use and land cover have increased worldwide substantially in the second half of the 20^{th} Century, mostly as part of the economic growth of emerging nations such as China, India, Brazil and Indonesia. In this work, we follow the literature in distinguishing between land use and land cover. Land cover is the biophysical state of the earth's surface; land use is the purpose for which the land is used (TURNER II et al., 1995). Forest and cropland are examples of land cover and agricultural and pasture are examples of land use. We use the term "land change" to refer to land use and land cover change. Land changes include feedbacks between people and ecosystems, which may be induced by actual or perceived land system changes, or through demographic and economic factors.

In this work, we want to build a model of land change in a large frontier area in the Brazilian Amazonia. This is a hard scientific problem since land changes result from complex economical, social and biophysical causes. As stated by Rindfuss et al. (2004):

> *"Land Change Science has been hampered by a range of data, methodological, and analytical difficulties emerging from the complexity of integrating diverse phenomena, space–time patterns, and social- biophysical processes, and the different disciplinary means of addressing them. These difficulties are amplified by the need to address not only why and how land-use and -cover changes, but where and when it changes. Location and time*

> *specificity generates special problems for land-change analysis, especially that involving dynamic human aspects of land use examined at the microscale (i.e., individual, household, community, catena, patch, parcel, or pixel).”*

Despite the methodological and conceptual challenges, land change models have many potential contributions. At their best, these models show the impact of public policy, point out emerging patterns resulting from collective actions, and can expose wrong assumptions. From a policy-making perspective, retrospective and projective scenarios derived by land change models show how government decisions have affected and may affect people’s behaviour. The Brazilian Amazonia is particularly relevant from a policy-making perspective. Government actions had a considerable impact on land change in Amazonia since the 1970. However, official policies are not always followed. Land change models need to capture the interplay between policies at a national scale and actions at a local scale. Models that find the right balance between the external forces and internal actions are valuable contributions to the debate on land policy in Brazil and also to land change science.

Agent-based modelling (ABM) has recently been receiving attention in the land-use modelling community (PARKER et al., 2002) (VERBURG, 2006). (BROWN et al., 2005; MATTHEWS et al., 2007). ABMs offer a way of representing land change using a complex systems approach, where land change patterns emerge from interactions of social actors. Going beyond the “rational decision making” logic of mainstream economics, these models try to capture the social contexts of human decision-making (JANSSEN; OSTROM, 2006). In land change studies, agent-based models put farmers in a landscape. Their aim is to express their decisions on land use, their impacts in the environment, and the feedback of these impacts in further decisions (PARKER et al., 2002).

Using agent-based models for studying land change is particularly relevant in frontier areas. Following the literature, we define a 'frontier' as an area of changing resource use. The boundaries of a frontier are continually evolving as people convert pre-existing land cover into land use for economic or social purposes (PARKER et al., 2008) (RINDFUSS et al., 2004). Currently, most land change frontiers occur in developing countries. There, economic growth combined with increasing incomes and bigger demand for agricultural production has led to massive land change. As a result, we have large frontiers of land change in South America, Central and Eastern Africa, India and South-East Asia, and East Asia. Since frontier areas are dynamic places with a lot of anthropic actions, many researchers consider that agent-based models can provide new insights on what goes on a land change frontier (PARKER et al., 2008).

Our motivation for designing ABMs for large frontier areas stems from our work on Brazilian Amazonia, an area of 4,100,000 km^2 where 720,000 km^2 have been deforested since the 1970s. Most land change models for Amazonia have used pattern-based statistical analysis to link census data to deforestation rates. Laurance et al. (2001) used a nested grid of resolutions of 50 km × 50 km and 20 km × 20 km and found that population density, distance to roads, and dry season extension are the most likely causes of deforestation. Soares-Filho et al. (2010) showed that indigenous lands and protected areas restrained deforestation between 1997 and 2008. Using data from the 1996 Agricultural

Census, Aguiar; Câmara and Escada (2007) split deforestation patterns into pasture, temporary and permanent agriculture. Using a grid of 25 km x 25 km, they found out that good connections to national markets are more relevant than distance to roads, and that large and medium farms have a higher impact than small ones. Such correlation-based are useful for explaining the present, but it is hard to use them to predict social reactions to public policies. Agent-based models (ABM) offer a valid alternative as they can express complex behaviour and model social interactions.

Applying ABMs in large frontier areas is not straightforward. Most ABMs for land use rely on fieldwork in small areas where researchers can have access to individualised information (BOUSQUET; LE PAGE, 2004) (BROWN et al., 2005; ROBINSON et al., 2007). For example, Deadman et al. (2004) built a model to study family farms on 100-ha lots along the Transamazonica highway, west of Altamira, Brazil. The model describes behaviour of colonists with similar origins, but different household compositions and capital endowments.

In large frontiers, in-situ data does not exist or is hard to get. In these and similar cases, agent-based modellers need good methods to describe decision making in large areas. They have to rely on indirect information, such as census or remote sensing images. Using this data for building agent-based models has potential drawbacks (ROBINSON et al., 2007). There is a mismatch between the scale of observation and that of the individual agent. What is seen on a remote sensing image is the *result* of agents' decision-making. There are many ways by which the patterns shown in land change maps could have emerged as outcomes of agent interactions. Building an agent-based model that reproduces these patterns does not imply that the model has captured the underlying agent behaviour.

While recognizing these challenges, we consider it is possible to advance scientific knowledge about land change in large frontier areas. Specifically, we are dealing with a data-rich situation. Although the Brazilian Amazonia is a frontier region, there has been a lot of field research there (MORAN, 1981) (WALKER; HOMMA, 1996; BRONDIZIO et al., 2002; PERZ; WALKER, 2002; ESCADA et al., 2005). There have been decadal population and agrarian census since the 1970s. Previous researchers on Amazonia have also showed how to combine remote sensing images, census data and field information to understand land change in the region (MORAN et al., 1994; MCCRACKEN et al., 1999; WALKER, 2003).

Thus, the scientific question of this thesis is: *How can we develop agent-based models in large frontier areas that provide useful insights for land policy?* To answer this question, our hypothesis is: *To build an informative ABM for large frontier areas, we need to combine all information available, preferably from remote sensing, census and expert field knowledge. The ABM needs to balance endogenous behavior (agents autonomous interactions) with exogenous driving forces (changes in government land policy).* Thus, when developing an ABM for large frontier areas, we need to find the right mix between agent autonomy and external forces. We also need to use all data available in a consistent way. This approach addresses many of the known drawbacks of using ABMs in large areas.

One of the key concepts in the model is the idea of *institutional arrangements* that capture the rules and norms followed by agents. The idea of institutional arrangements allows us to distinguish between the official government land policy and the actual rules agents abide by. The concept of institutional arrangements allows us to better capture how the exogenous forces influence agents' decisions.

We tested the model on a case study of the São Felix do Xingu region, the place in Amazonia with the highest deforestation rate in the 1990s and 2000s. The model captures large-scale land change during the 2000s and is used to build scenarios until 2020.

This thesis is structured as follows. Chapter 2 presents a brief review on the region occupation history and current situation. Chapter 3 describes the model entities, following the ODD protocol (GRIMM; RAILSBACK, 2012). Chapter 4 presents the simulations, scenarios and results. Chapter 5 compares this work to other agent-based models of frontier areas. Chapter 6 presents the conclusion of this thesis and suggestions for future work.

2 LAND USE CHANGE IN SAO FELIX DO XINGU

The purpose of our work is to explore the use of agent-based models (ABM) to represent land change in large frontier regions. To do this, we chose the São Felix do Xingu (São Felix) region, an area of 100.000 km^2 in the South-East of the Pará state in Brazil, presented in Figure 2-1.

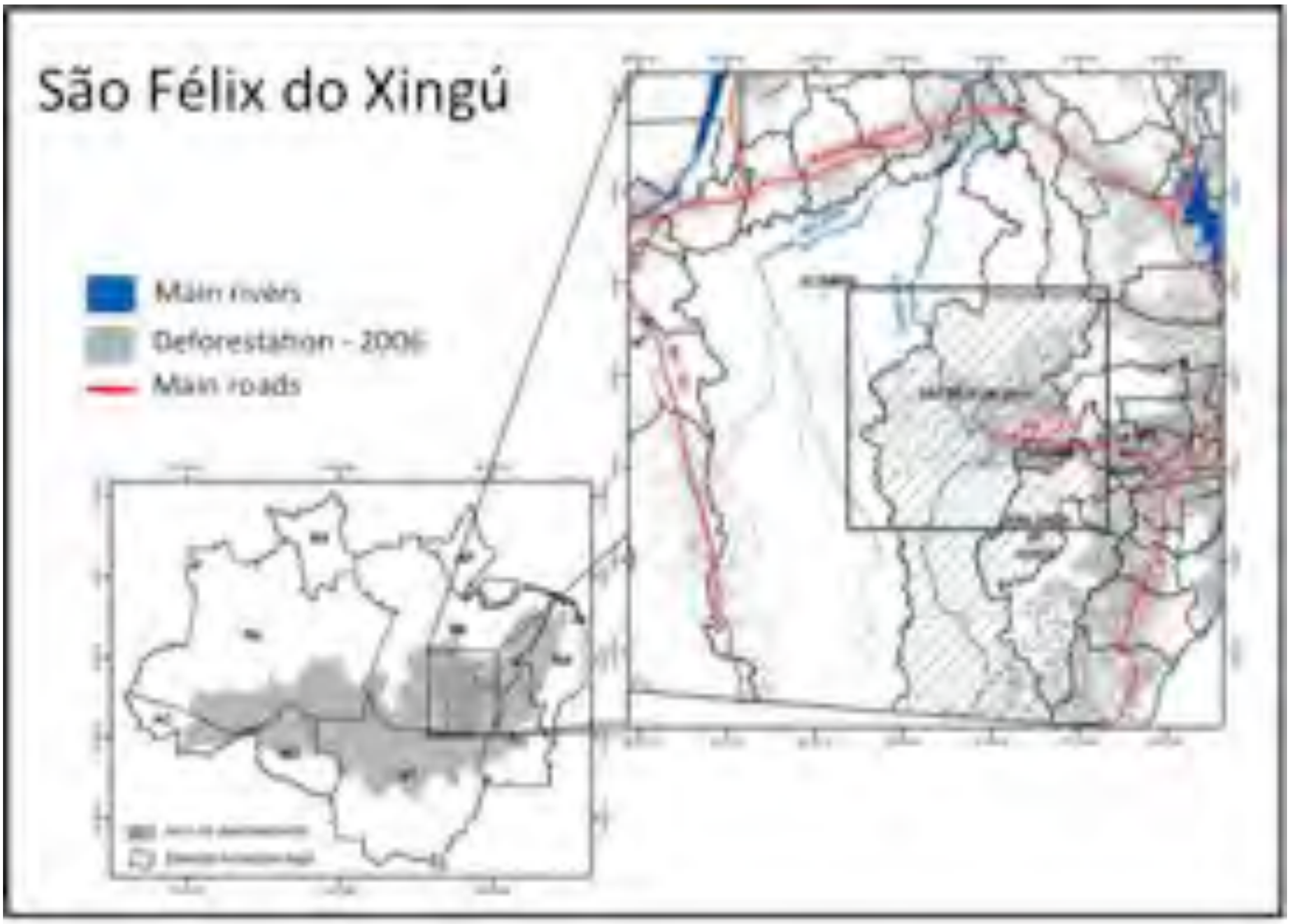

Figure 2-1. Study area: São Félix do Xingú, Tucumã and Ourilandia do Norte.

We consider the SFX region has many features that are relevant for understanding deforestation in Amazonia. Until the 1980s, the region had a small population with little deforestation. Large numbers of migrants came to the region in the 1980s and 1990s and also rich investors set up large farms. During most of the 1990s, São Felix do Xingú was the municipality with the largest deforestation rate in Amazonia. It was only after 2004 that, due to increased actions by the Brazilian government, the pace of deforestation slowed in the region (CASTRO; MONTEIRO; CASTRO, 2004; ESCADA et al., 2005).

São Felix makes for a good case study for agent-based modelling of frontier areas. There are large protected areas and native reservations that helped protect part of the region's forest and biodiversity. Due to climatic, economic and social reasons, cattle production dominates the local economic activity since the 1980s. The farmers established in São Felix were heterogeneous. Some of them had little capital and settled in small properties. A few investors had a lot of capital and bought much land. The land and cattle market led to a concentration of land ownership and an increase in forest clearings. Then, in the late 2000s, government action changed the deforestation trends. We have both detailed data on deforestation from satellite images and also data on demographics and land ownership from population and agrarian census. Thus, São Felix from 1970 to 2010 provides a suitable mix of features that makes it a good case study for agent-based modelling of land change.

Much land change occurred in São Felix from 1970 to 2010. Nevertheless, the economic and social drivers are not so overly complex and can be modelled. The resulting ABM has a good explanatory and predictive power without excessive complexity of design. Before discussing the ABM in Chapter 3, we first present a detailed review of the region's evolution since the 1970s.

According to the 1970 population census, the São Felix region had only 2,300 inhabitants. These settlers focused on extractive activities (Brazil nuts, rubber), hunting, fishing and gold prospection. Some practised subsistence agriculture and raised small animals (CASTRO; MONTEIRO; CASTRO, 2004). There were some initiatives of installation of cattle ranches supported by the state agency SUDAM (*Superintendência do Desenvolvimento da Amazônia*). (ALENCAR; FARIAS, 2008) argue that these projects did not cause much the land change because there was little integration with the road network.

Brazil was a military dictatorship from 1964 until 1985. During the 1970s, the Brazilian government set up a many prospective studies to assess Amazonia's potential for natural resources. In the military's strategic vision, Amazonia had untapped natural riches and exploring them would help Brazil. In 1974 the military regime created the POLOAMAZONIA program (*Programa de Pólos Agropecuários e Agrominerais da Amazônia* – Program for Agricultural and Mineral Outposts in Amazonia). The government wanted to set up various "development outposts in Amazonia", especially mineral production (BECKER, 2005; MONTEIRO, 2005; SANTOS JUNIOR; LENNÁ, 2011). The actions of POLOAMAZONIA led to the "Grande Carajás" project in 1980 for exploring iron ore in the Carajás mining region, the largest in the world, located close to São Felix.

In 1980, São Felix do Xingu was the only municipality in the area and included the current cities of Ourilândia do Norte and Tucumã. Its population was still small (5,000 people). To the East of São Felix, bordering the Belém-Brasilia road, the towns of Conceição do Araguaia and São Geraldo do Araguaia were expanding. These two cities benefited from cattle expansion projects funded by SUDAM during the 1980s. During the 1970s and early 1980s, cattle ranching in Amazonia relied on subsidised government credits. As stated earlier, the military regime had the vision of Amazonia as a frontier to be conquered. They feared international claims that could take away Brazil's sovereignty over the region (BECKER, 2005). The lack of public funds made Brazil's Federal Government support private colonisation programs. One of these programs was *Projeto Tucumã*, developed by the private company Andrade Gutierrez. In 1980, the government gave Andrade Gutierrez the ownership of 400,000 hectares in the São Felix. *Projeto Tucumã* aimed to settle small and medium sized farmers to produce agricultural goods to supply the Carajás iron ore mine (SCHMINK; WOOD, 1992; ALENCAR; FARIAS, 2008).

Attracted by government publicity, many migrants came to the Tucumã area. However, the owner (the private company *Andrade Gutierrez*) granted land only to settlers who could buy it. The company controlled the access to the project's land and to other areas of São Felix. Unable to buy land in Tucumã, many of the migrants created the settlement of Ourilândia do Norte nearby. This spontaneous agglomeration was composed of wood and straw tents. These landless migrants worked in constructions sites, gold-digging, and timber extraction (ALENCAR; FARIAS, 2008).

The influx of poor migrants increased the conflicts and social problems of the region. The government tried to solve the problems by promoting public settlements based on agricultural production. Between 1983 and 1984, poor families were given public parcels of up to 48 ha. However, this only made the problem worse. Instead of containing the conflict and the invasions of *Projeto Tucumã*, they promoted an even stronger migration to the South of Pará. Many poor families from the Brazilian North-east migrated to the region hoping to gain land for free (ALENCAR; FARIAS, 2008). The flow of migrants was so intense to the point of overcoming in population the municipal headquarters of São Felix. Without support for agricultural production and with limited work available In gold-digging, logging grew rapidly. Large timber factories encouraged and sponsored the invasion of private area of *Projeto Tucumã*. Their aim was to explore the valuable timber available in the area.

Brazil restored its democracy in 1985, when the military handed over political power to civilians. Bowing to pressure from local politicians, the newly elected federal government allowed the settlers to invade *Projeto Tucumã* by withdrawing the Federal Police agents that guarded the site. By June 1986, the area of *Projeto Tucumã* project had been fully occupied by migrants. In 1988, the cities of Tucumã and Ourilândia do Norte were emancipated. The government had to pay *Andrade Guttierez* a large settlement fee for regaining public ownership of Tucumã (ALENCAR; FARIAS, 2008).

In Tucumã and Ourilândia, after exhausting prime wood, farmers tried to develop agricultural activities. However, the migrants' lack of capital and technology and the distance to markets led to failure. Agriculture gave way to cattle production. From the point of view of the migrants, cattle raising has advantages (MUCHAGATA; BROWN, 2003; SIEGMUND-SCHULTZE et al., 2007). Cattle can be disposed of quickly and easily at any time, to acquire cash or the equivalent in kind. The liquidity gained from keeping living stock is preferable to the risks associated to agricultural production. For the smallholder, cattle provides a sense of security despite the problems of productivity in Amazonia (discussed later in this work).

Cattle production is also of value for large landholders. In areas where land prices are low and transport costs are high for agricultural activity, large-scale cattle raising can be profitable. If the cattle market is sufficiently developed, the economies of scale of large cattle farms motivate the expansion in frontier areas such as São Felix. In Amazonia, large-scale cattle production can be a stable source of income and thus play a significant part on economy of the region (WALKER et al., 2009a).

From 1985 to 1996, the new civilian government cut subsidies for cattle ranching in Amazonia. At that time, Brazil was in an economic crisis due to impact of oil prices in its external debt (PERZ, 2000). As a result of the reduction of funding in the late 1980s, both rich investors and poor farmers moved to Sao Felix do Xingu, where land prices were lower. The area around Sao Felix thus became a focus for migrants from the Northeast and Midwest of the country. Small, medium and big cattle ranches grew rapidly in the late 1990's, despite the decreasing amount of official credit available to cattle expansion at the time. The São Felix region went from 5,000 people in 1980 to 85,000 in 1991, a 1,600% increase in eleven years.

The cattle expansion was also motivated by the interest in occupying public lands. Amazonia's land is mostly state-owned and occupying it needs concessions. In the 1960s, 87% of the land in Amazonia was public area (LOUREIRO; PINTO, 2005). Historically, part of this public land was inhabited by indigenous people and by *caboclos* (mestizos). In the 1970s and 1980s, the government sold public land in large lots for new investors. Public officials also tolerated re-selling of public land by private actors. Land grabbers ("grileiros") also got land tenure rights by illegal means. As the military regime wanted to occupy Amazonia at any cost, it tolerated and accepted land grabbing as a matter-of-fact. In 1976, a Presidential Decree allowed illegally acquired properties up to 60,000 hectares to get legal tenure rights. The government justified the measure by saying: "*These projects, even if established illegally, will redeem themselves by their results, since they will promote the development of the region*". Land grabbing was legitimated and further strengthened by granting loans and public subsidies (LOUREIRO; PINTO, 2005).

Unlike agriculture, which is fixed to a piece of land, cattle production is fit to be associated to land grabbing. The fastest way to occupy public land in Amazonia was to burn down the forest and put cattle there. Cattle production quickly dominated São Felix's economy in the 1980s. Cattle's mobility also creates an active land market. It becomes possible to grab land, put cattle there, get tenure rights, sell the land, and move the cattle elsewhere. Combining the land and cattle markets allowed rapid movement of capital and income generation in São Félix (CASTRO; MONTEIRO; CASTRO, 2004). Boosted by the cattle market and land grabbing and speculation, São Félix turned in a few years into a mosaic of cattle farms of different sizes (Figure 2-2).

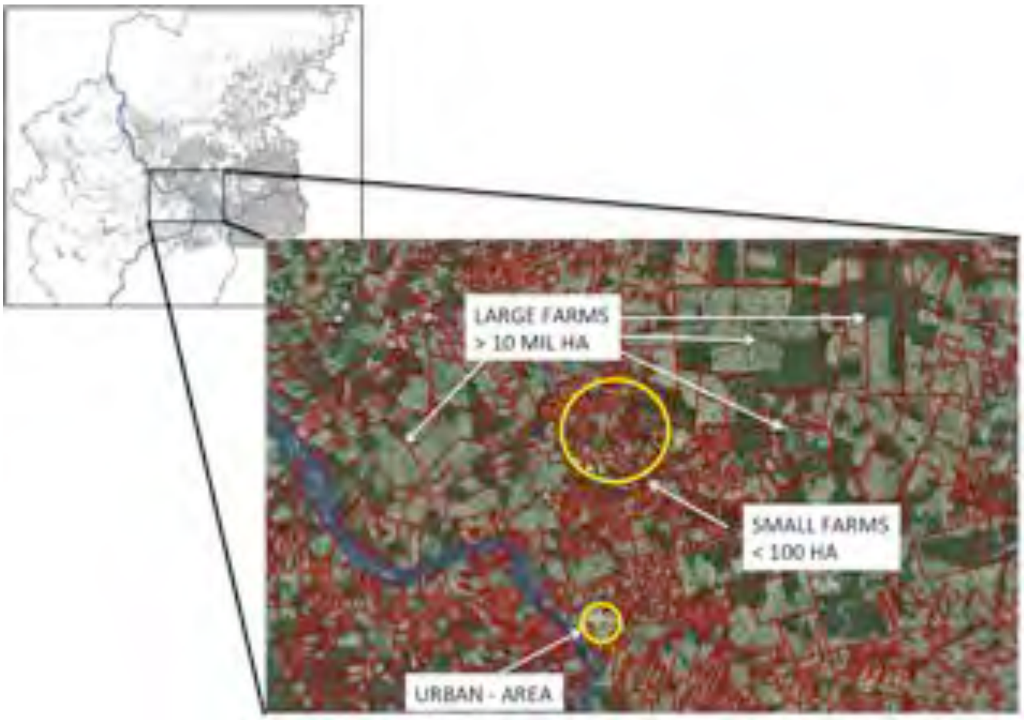

Figure 2-2 Agrarian structure in São Felix. Data source: (SEMA-PR, 2012).

Brazil's economy recovery since 1994 lead to increased deforestation. From 1996 onwards, the government started to provide credits for cattle raising and milk production (WALKER et al., 2009a; PACHECO; POCCARD-CHAPUIS, 2012). Livestock grew rapidly in the region. By 1998, Sao Felix do Xingu had already the biggest herd size in the state of Pará. The ecological impact was huge. The combined effect of continued migration, land grabbing, and the cattle market in deforestation is shown in Table 2-1. As population increased from 2,300 people in 1970 to 150,000 in 2010, and cattle heads soared from 190 to 2,500,000, accumulated deforestation in the region reached 20,500 km^2 in 2010. The spatial extent of deforestation is shown in Figure 2-3. For reference, the deforested area in São Felix up to 2010 is greater than the country of Israel.

Table 2-1 Evolution of population, agrarian structure and deforestation in the study area. sources: (IBGE, 2007; INPE, 2012).

	Population	Number of farms	Area of farms (km^2)	Heads of cattle	Deforestation (total km^2)
1970	2,332	127	129	190	
1980	4,954	181	4,462	22,534	
1985	14,016	282	2,393	32,000	638
1991	84,984			110,854	
1996	95,742	6,730	12,499	443,039	
2000	79,401			1,182,621	9,674
2007	106,166	7,827	20,745	1,932,519	18,909
2010	152,389			2,472,053	20,511

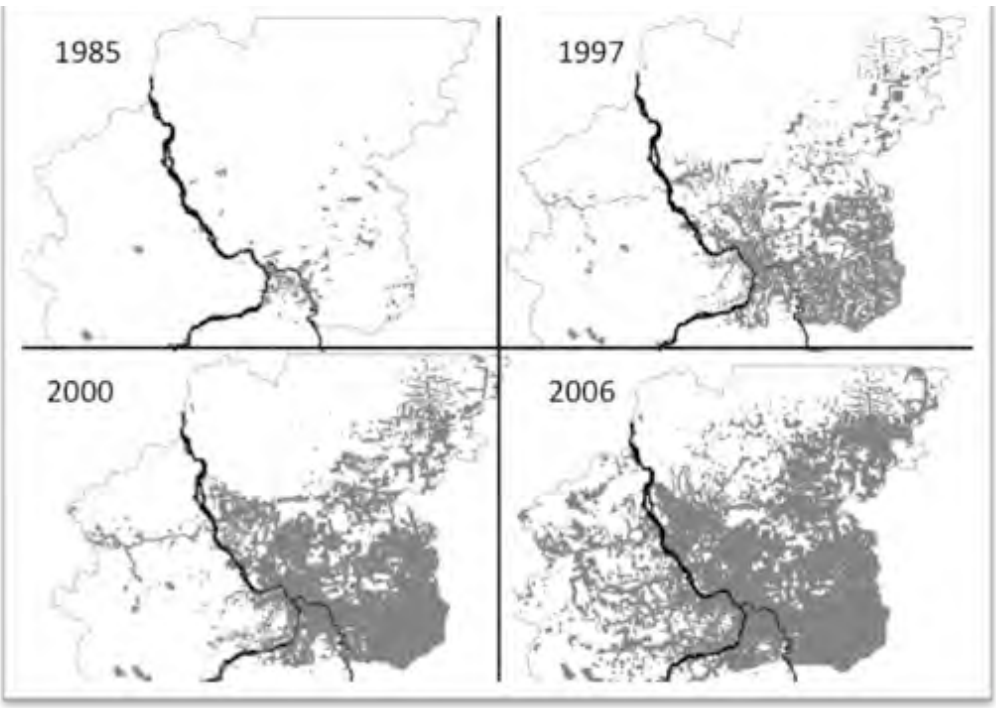

Figure 2-3 Deforestation patterns in 1985, 1997, 2000 and 2006 (INPE, 2012).

Until 2000, the deforested areas were mostly located in the East side of the Xingu river (show in the centre of the pictures). As large farmers with capital came into region, many small farmers sold their land in the East side of the Xingu river and moved to new frontiers on the West side of the river. This was due to increase of land prices in Tucumã and Ourilândia, cities on the East side of the Xingu river (CASTRO; MONTEIRO; CASTRO, 2004). The concentration of land ownership in Tucumã is shown in Figure 2-4. In 1996, large farms (greater than 1000 ha) made up 8% of the total farm area. In 2006, they comprised more than 60% of the total (see Figure 2-4). In the same period, the number of farms decreased from 2,518 to 1,039, which points out that part of the small farmrs was sold to the large land holders.

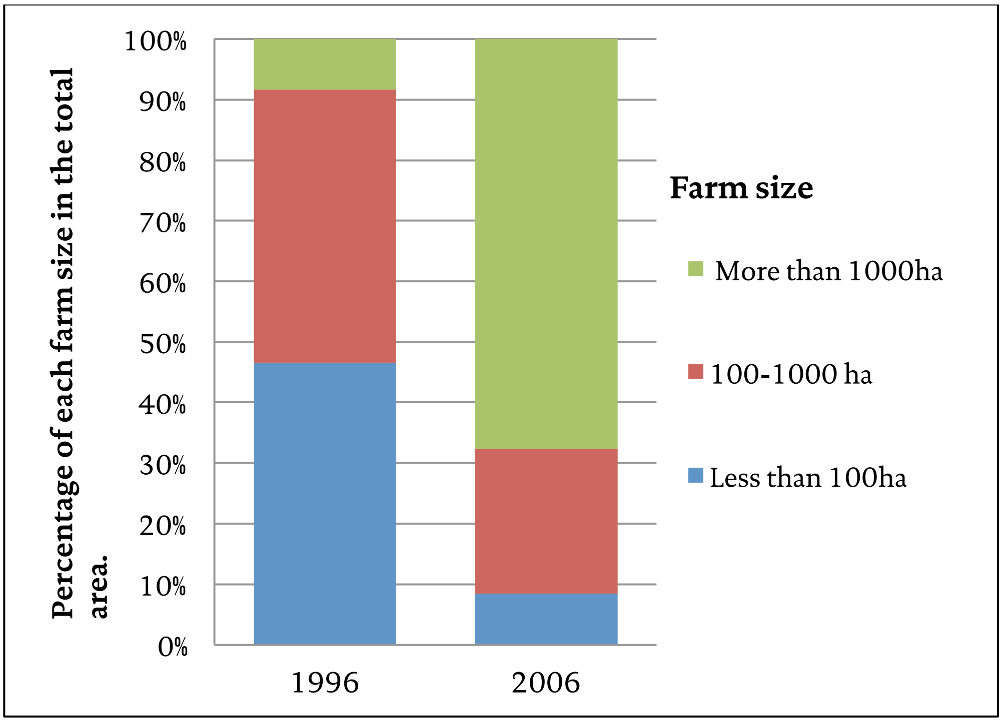

Figure 2-4 Concentration of land ownership in Tucumã (source: IBGE agrarian census (IBGE, 1996; IBGE, 2007)).

In 2004, under strong external and internal pressure because of the large rates of deforestation in Amazonia, the Brazilian Federal Government changed its policies. The government launched the Action Plan for Prevention and Control of Deforestation in the Legal Amazon (PPCDAM). Brazil set up a combined effort of improved satellite monitoring, increased law enforcement, and creation of protected area. In 2008, reacting to a surge in deforestation, the government limited bank credits in municipalities with high deforestation rates.

The policing actions were based on better enforcement of Brazil's Forest Code. After a farmer gets a concession, Brazilian law mandates landowners to set aside part of their farms for forest preservation. The Forest Code, passed in 1965, stated that farmers in Amazonia have to keep 50% of the area of native forests in their properties. However, given the military regime's interest and incentives for occupying Amazonia, the Forest Code was not enforced in the region. In 1986, the government increased protection to 80% of the forest in farmers in Amazonia. In practice, owners ignored the law, cutting much more than allowed, with the government's informal consent. This resulted in large deforestation rates during the 1990s and early 2000s. The Forest Code started to be enforced in Amazonia only after 2004.

The second part of the government's strategy was an increase on environmental accountability, using maps extracted from satellite images. INPE (Brazil's National Institute for Space Research) had been publishing measurements of annual rates of deforestation by clear-cuts since 1998. However, INPE only started to make maps of deforested areas available publicly after 2003. The spatially explicit content of maps enabled the government to have a much better control of deforestation patterns and to focus on the "hot-spots" (AMARAL; D'ALGE, 2009).

The third axis of public action was a substantial increase in protected areas. By 2000, 10% of Brazil's Legal Amazonia had been placed under conservation. Since 2000, conservation areas (both federal and state lands) have increased five-fold to more than 1,25 million km2, which is nearly 25% of Amazonia (WALKER et al., 2009b).

São Felix do Xingu, the city with biggest deforestation rate, received a series of measures, including a new mosaic of protected areas, better land tenure control, law enforcement actions and credit suspension. In São Felix region, the federal and state government created three large protection areas since 2005 that comprise 6,500,000 hectares (or 65,000 km^2). All of these actions brought about a significant drop in deforestation rates in Amazonia, from 27,000 km2 in 2004 to 6,500 km2 in 2011 (INPE, 2012).

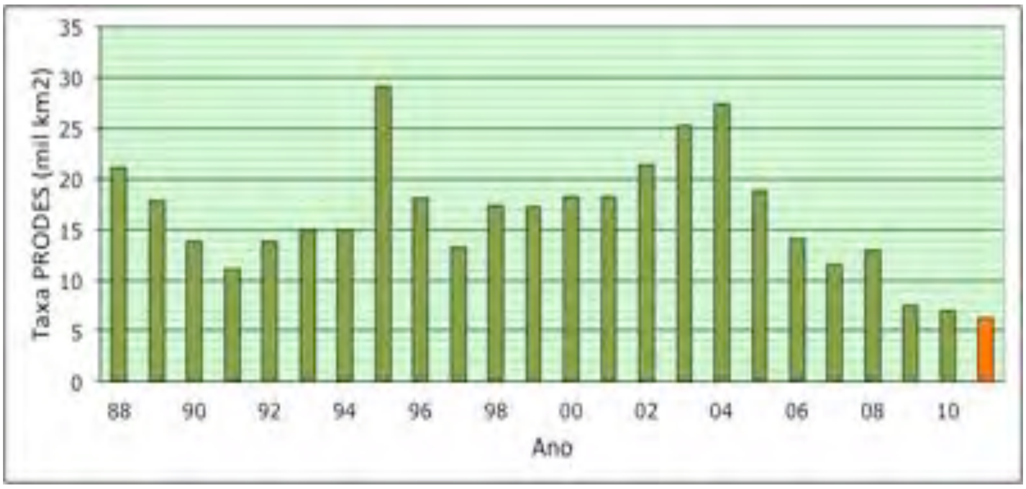

Figure 2-5 Yearly deforestation (clear-cuts) in Brazilian Amazon monitored by INPE (1988-2011)

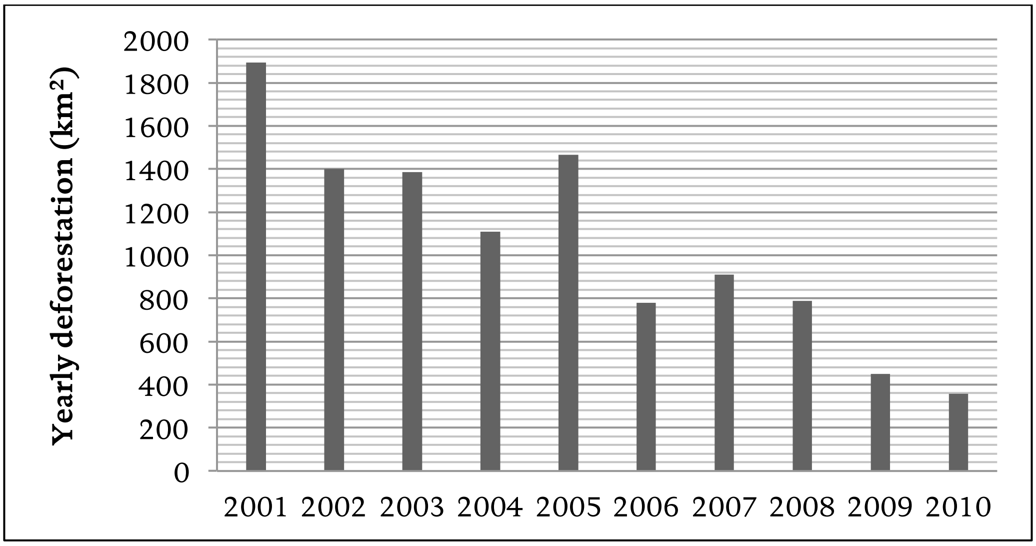

Figure 2-6. Yearly deforestation (clear-cuts) in São Félix Region monitored by INPE (2001-2010)

Recent statistical and econometric analysis of the reduction of deforestation reinforces the argument that government policies were the major driving force. Analysing the evolution of cattle and soya prices, (ASSUNÇÃO; GANDOUR; ROCHA, 2012) concluded that "*changes to conservation policies implemented beginning in 2004 and 2008 significantly contributed to the curbing of deforestation rates, even after controlling for different sorts of price effects*".

Despite the recent successes in reducing deforestation, there is much room for improvement in land policy in Brazil. The experience of the 1980s and 1990s point out that future institutional arrangements that promote deforestation and involved public and private interests cannot be ruled out. In Brazil's Congress, the rural areas have a disproportionate share of seats, a relic of the country's military dictatorship period (1964-1985). Given the skewed proportional representation in Brazil, environmentalists have much less power in Congress than they have in public opinion. In 2010-2012, this power imbalance led to a legislative proposal to reform Brazil's Forest Code to reduce the rigour of the current legislation. As a result, Brazil has a new Forest Code since the end of 2012. The new Forest Code reduces the protection of the Amazon forest, by softening the rule that 80% of the forest area in private properties has to be kept intact. The actual impacts of the new Forest Code are still unclear, which provides a further motivation for this work.

In short, the São Felix do Xingu region has witnessed much change since the 1970s. As we argued above, the extent of change, the changes in policy, and the demographic, social and economic features of the region make it a good case study for land change modelling in frontier areas.

3 AGENT-BASED MODEL AT REGIONAL SCALE

3.1 Introduction

In the preceding section, we reviewed the history of the São Felix region and outlined the importance of the cattle raising activities in being the most important driver of land change. We also showed how increased action by the Brazilian government since 2005 brought about a major reduction in deforestation in the region. In this chapter, we investigate the use of agent-based modelling for representing the land change in the region.

Before describing our model, we discuss some theoretical issues. The first issue is the purpose of the modelling exercise. In a review of applications of ABM for land change, Matthews et al. (2007) point out five broad areas for such studies:

- *policy analysis and planning;*
- *participatory modelling;*
- *explaining spatial patterns of land use or settlement;*
- *testing social science concepts;*
- *explaining land use function.*

In this work, we are concerned mostly with *policy analysis and planning*. Our main concern is to understand the land change in São Felix in the context of the broader policy decisions that led to substantial transformations in the region. As we discussed earlier, we believe that the São Felix case has lessons for the whole of Brazilian land policy. We want to understand what happened in São

Felix, considering the different policy changes that influenced land use in the area since the 1970s.

The second theoretical issue relates to the way the model is built. A recent paper by Robinson et al. (2007) discusses different ways of how to set up an ABM. Although most ABMs are built empirically, their construction differs a lot. For small-area studies, *sample surveys* and *participant observations* are commonly used. The authors argue that, for large areas and regional scale modelling, *GIS and remote sensing techniques* are prevalent. They also point out major drawbacks when using GIS and remote sensing tools to build ABMs:

> *"Because the method relies on inference from existing data, it is limited to questions that involve existing data, and requires a pre-specified set of hypotheses—there is no mechanism to discover new decision-making frameworks or structures. In particular, actions, characteristics, and motivations of human actors are rarely directly revealed through data on spatial outcomes. A host of other issues also exist, such as those associated with matching the scale of spatial data to the scale of agent decision-making, disaggregating data to inform agents, unobserved variables driving the underlying processes, non-stationarity in time and space, the fact that observed land use outcomes may be the result of competition between multiple agent groups, and incongruity between the observations used to fit the statistical model and the agents in the ABM."* (ROBINSON et al., 2007).

We are aware of these challenges, but we consider these problems can be dealt with. We designed the model to minimize these limitations as much as possible. In doing so, we had to decide on what is an "agent" in our model, considering the internal interactions between agents and the external forces.

The complex systems view (largely coming from the AI community) is that an agent-based model (ABM) consists of a number of 'agents' that interact both with each other and with their environment, and can make decisions and change their actions as a result of this interaction (MATTHEWS et al., 2007). Thus, the standard AI approach focuses on the internal interactions between agents. When applying ABMs to land change, this view leads to an emphasis of micro-scale modelling of agent behaviour (DEADMAN et al., 2004; HUIGEN; OVERMARS; DE GROOT, 2006). However, when trying to capture the effects of policy-making over large areas, the focus on internal interactions has to be balanced with the effects of external drivers. As shown earlier, public policies were the primary cause and motivation for the occupation of São Felix. Thus, they have to be included in land change models for the region.

We have tried not to unduly restrict the agents' autonomy of decision-making. To do so, we consider that agents interact through the land market. We modelled the land market at the individual level. In our model, farms are sold and bought one by one. We have also modelled the action of land grabbing and occupation as personal decisions. When an agent sells his farm, in most cases he moves to other parts of the frontier to occupy new land. In our view, these two agent decision-making procedures (*land market* and *frontier occupation*) are sufficient to represent the farmers' behaviour in the region for *policy-making purposes*. We are not trying to represent exact agent decision-making, but rather to capture those actions most relevant for land policy assessment.

Robinson et al. (2007) point out that ABMs built with GIS and remote sensing data "are *limited to questions that involve existing data".* We tried to overcome this limitation, by considering the changing external environment that drives agents decision-making. This led us to adopt the concept of "institutional arrangements" as a way to describe past, current and future contexts of individual decision-making. In what follows, we first describe the concept of "institutional arrangements", which is central to our model. Then we describe the model in detail.

3.2 Institutional arrangements

When building agent-based models for land use, one of the key decisions is how to represent individual decision-making. A usual approach is 'economic optimization', where the farmer maximizes a production function (SCHREINEMACHERS; BERGER, 2006). However, economic decision models alone fail to describe human behaviour. These models do not capture actual risk assessment by farmers, especially for those with limited capital and low access to technology. It is hard for economic optimization models to represent the switching costs from one option to other. Arguably, a realistic ABM for land change has to find a balance between economic-based decisions, risk-based heuristic assessments and cultural and social constraints (PARKER et al., 2008).

In the case of São Felix, the cattle and land market is able to both capture the economic-based decisions and the risk-assessment. As argued by (WALKER et al., 2009a), cattle in Amazonia fulfils both the role of providing some financial security to the poor and being a source of cash for the rich. However, modelling the cattle and land market alone is not enough to capture the important changes in São Felix. We need to include the cultural and societal norms and rules that constrain agent interactions.

We hold that agent interactions are shaped by laws and conventions. In land management, there are rules and norms that limit the possible uses and tenure rights, These rules and norms are not followed at all times by all agents. We refer to *institutional arrangements* as deals set up between interest groups, social movements and state agencies to respond to rules and norms that are relevant to them (DIETZ; OSTROM; STERN, 2003). These pacts define how agents manage natural resources (SCOTT; MEYER, 1994). A farmer may switch between different arrangements as he reacts to external conditions. Agents' decisions depend not only on existing rules and norms, but also on the institutional arrangements.

Some examples will clarify matters. Brazil's Forest Code, passed into law in 1965, stated that private farms in Amazonia had to keep 50% of their forest area intact. In 1996, the Forest Code was amended to protect 80% the forest area of private farms in Amazonia. However, many farmers breached this rule without due punishment from the 1970s to the 2000s. An institutional arrangement bound farmers, public officials, and politicians to form a coalition that prevented legal action. This situation changed only from 2005 onwards, when the Brazilian State increased its control actions. Farmers were forced to switch to a new arrangement that no longer protected lawbreakers. The rules did not change, but the institutional arrangements did (HECHT, 2012; INOUE, 2012).

Another example in Amazonia is the soy moratorium. This is a pact by soya exporters, farmers, Government and NGOs. To export his soybean production, a farmer has to abide by an informal norm: no more deforestation after 2006. Some farmers taking part on the moratorium may have cut more than 20% of their forest area before 2006. Although they may have broken official law in the past, exporters buy their soy production if they are no longer cutting the forest. In this arrangement, an informal norm is more relevant than the formal rule (RUDORFF et al., 2011; MACEDO et al., 2012).

Our model is divided in two parts. We run a retrospective scenario running from 1970 to 2010, where we show how the public policies influenced the land change in São Felix. We also run prospective scenarios exploring pathways of change from 2010 to 2020. Considering the historical evolution of the São Felix region, we defined four institutional arrangements for the period 1970 to 2010:

- *Government-induced occupation* (1970-1985): prevalent during the military regime, when the government encouraged people to occupy Amazonia. Poverty in other areas of Brazil led to high rates of migration to the region. Large projects had access to easy credit (CASTRO; MONTEIRO; CASTRO, 2004; BECKER, 2005).
- *Private capitalist occupation* (1985-1997): In 1985, democracy was restored in Brazil. The new government decentralized decision-making to local administrations and reduced its actions for promoting large scale occupation. Local politicians gained power. Brazil was in a economic crisis until 1995, which reduced the amount of public credit for agrarian activities. Subsidized credit for pasture implementation was removed. Occupation in Amazonia was led by arrangements involving local groups

of farmers, capitalists and politicians, with limited intervention from the Federal Government. (CASTRO; MONTEIRO; CASTRO, 2004; BECKER, 2005; ESCADA et al., 2005; WALKER et al., 2009a; PACHECO; POCCARD-CHAPUIS, 2012).

- *Beef marketing chain organization* (1997-2005): In 1994, Brazil had a huge economic change with the Plano Real, which stabilized inflation and enabled long-term economic growth. Starting in 1996, there was a renewal of public credits for cattle production that reinforced the effects on land change. Improvements in infrastructure enable cattle production in Amazonia to be much more profitable than in parts of the SouthEast of Brazil (WALKER et al., 2009a; PACHECO; POCCARD-CHAPUIS, 2012).
- *Deforestation control* (2005-2010)*:* From 2005 onwards, the Federal Government set up a combined effort of improved satellite monitoring, increased law enforcement, and creation of protected areas. In 2008, reacting to a surge in deforestation, the government imposed restrictions on bank credits. Official credit was no longer available for illegal activities. There was a significant increase on environmental accountability at both federal and local levels (AMARAL; D'ALGE, 2009; ASSUNÇÃO; GANDOUR; ROCHA, 2012; HECHT, 2012; INOUE, 2012).

For the period 2010-2020, we consider two possible arrangements to convet possible scenarios, depending on governmental and society organization:

- *Sustainable Development*: a possible future arrangement to bring about equilibrium between social, environmental and economic goals. This choice combines strong law enforcement with green market practices.

- *Economic development*: a possible future arrangement based on a return to 1970s model, where economic growth prevails over environmental or social concerns.

3.2.1 How the institutional arrangements influence the agent's decision-making

The agent's decision-making model depends on his current state and on the external constraints imposed on this state by the institutional arrangements. In this section, we describe the linkages between the institutional arrangements and FSM states. These linkages are provided by the following context variables:

- *Law enforcement strength:* how strong is the control over forest code and over grabbing of public lands?
- *Cattle market strength:* how strong is the beef market chain?
- *Credit for intensification:* there is credit for intensification ?
- *Credit for reforestation:* there is credit for reforestation?

For the period 1970 to 2010, the values of the context variables associated to each institutional arrangement were derived from the historical perspective of the region. For the period 2010 to 2020, we build two contrasting scenarios. For the *sustainable development* scenario, we considered that strong law enforcement is increased, and that there is credit for reforestation associated to programs such as REDD+. The economic development scenario foresees a reduction of law enforcement actions, and no specific credit lines for intensification nor for reforestation. The agent uses these context variables for decision-making. Given a context and the values of his own attributes, the agent will decide either to continue in his current state or to jump to another state, as defined by the transition table below. These variables affect other decisions. For example, an agent will grab public lands if Law enforcement is weaker than agent's risk preference.

Table 3-1 Institutional arrangements and context variables for the SFX Model.

Institutional arrangements	Law Enforcement	Cattle market	Credit for Intensification	Credit for Reforestation
Government-induced occupation (1970-1985)	Weak	Weak	Non-available	Non-available
Private capitalist occupation (1985-1997)	Weak	Weak	Non-available	Non-available
Beef market chain organization (1997-2005)	Weak	Strong	Non-available	Non-available
Deforestation control (2005-2010)	Medium	Strong	Non-available	Non-available
Sustainable development (2010-2020)	Strong	Strong	Available	Available
Economic development (2010-2020)	Weak	Strong	Non-available	Non-available

3.3 The agent model for São Felix

In the previous section, we discussed some theoretical issues about the purpose of the modelling exercise and the way the model is built. In this section, we present our agent model for land change in the São Felix region. In this presentation, we will follow the guidelines of the ODD protocol for presenting agent-based models (GRIMM; RAILSBACK, 2012).

3.3.1 Purpose of the model

The purpose of our ABM model is to represent the past land change and project future land change in the São Felix region from a *policy analysis and planning viewpoint*. We are interested in *capturing the impact of the different institutional arrangements* that drive land change in the period 1970 to 2010. Based on our results, we propose two possible scenarios for the period 2010 to 2020.

The main economic use of the land in São Felix is cattle production, as shown by our literature review. As discussed in our historical, cattle production emerged since the 1980s as the dominant economic activity in the region. Thus, decisions by cattle farmers are the main causes of land change. We consider two types of agents: farmers with little capital and farmers with much capital. For both types of agents, cattle production brings advantages (WALKER et al., 2009a). For the purpose of land policy analysis at regional level, we consider that this binary division is sufficient to represent the main trends in the region.

3.3.2 Entities and attributes

The entities of our model are: (a) the agents; (b) the farms and (c) the geographical space. An agent is a farmer who owns one or more properties in the region. The farms are explicitly represented in geographical space. Farms are built using a farm creation submodel, described below. The use of farms for cattle production is modelled by a support capacity submodel. Agents interact through the land market. When an agent sells his land, he may decide to leave the area or to search for new areas in public land. Thus, we also provide a model for land grabbing of new forest areas. We now describe the entities in detail.

3.3.2.1 Geographical space

We use a cellular space to represent the geographical space in a regular scale. Each cell stores the following attributes:

- *Biophysical attributes:* area, land cover (Forest, Pasture, Secondary Forest, River, Other) and slope.
- *Accessibility attributes:* minimum Euclidean distance to roads, rivers and urban centres.
- *Territorial attributes:* type of land attribution (Indigenous land, Conservation unit, Rural settlement, Other public land, Private land).
- *Pasture attributes:* age of a given pasture.
- *Cattle production:* number of animals per cell.
- *Support capacity:* defined as a function of the technology level of the cell's owner and of the pasture age.
- *Frontier occupation class:* cells are classified according to their relation to the occupation frontier. Following Poccard-Chapuis (2004) and Pacheco (2012), we defined the following classes: *consolidated, pre-frontier, frontier and post-frontier*.
- *Land price:* land prices are calculated relative to the occupation frontier. We use the minimum Euclidean distance from the cell to the post-frontier area to set the relative price of the land.

The biophysical, accessibility and territorial attributes were generated from image classification and census data. The attributes for pasture, cattle production, support capacity, land price and frontier occupation are initialized at the start and recalculated for each model step. The submodels for calculating the support capacity and frontier occupation are discussed below.

3.3.2.2 Farms

A farm is an object that is associated to one or more regular cells. Each belongs to one agent, and an agent can own one or more farms. Farm creation depends of the attribute of the agent and of the geographical space. The farm attributes are:

- Farm area.
- Farm relative price.
- Pasture area and area of degraded pasture.
- Area of remaining forest.

3.3.3 Agents

Considering that São Felix is a large area, we used GIS and remote sensing techniques to set up the attributes of the agents in our model. In such a large region with strong migration patterns, it would be unfeasible to use *sample surveys* and *participant observations*. Given the data available, the time span and the purpose of the model, we restricted the agent's attributes to those more relevant to the understanding of land policy analysis. Thus, we consider five attributes for the agents:

1. *Farm list*: list of farms the agent owns.
2. *Risk preference*: an agent's tendency to follow or transgress the law, as expressed by the rules of Brazil's Forest Code. The risk preference attribute singles out those agents that are willing to risk breaking the law to increase their profit. The possible values are: low, medium and high.

3. *Technological level*: a measure of technological capacity for cattle production. Pastures have different productivity according to the technology employed (MUCHAGATA; BROWN, 2003; VEIGA, 2009). We consider that the agent has two options: extensive cattle production with associated pasture degradation, and intensive cattle raising with periodic pasture recovery.
4. *Available capital*: total cash a farmer has available to buy farms and cattle.
5. *Farm size preference*: expressed as the average size of the farm he wants to buy. As an agent moves towards the frontier, he sells his farm in occupied areas and tries to buy a bigger one elsewhere. As discussed in (CASTRO; MONTEIRO; CASTRO, 2004; ESCADA et al., 2005), when land price increases, farmers sell them to acquire larger farms in regions where land is cheaper. This is the mechanism that poor farmers use to expand.

Since our model is policy-oriented, we did not model the cattle market directly. We considered that the combination of available capital, farm size preference and technological level is a proxy for financial return on investment. Bigger farms that are closer to market and have better technological level will get economies of scale that will provide greater financial return(MUCHAGATA; BROWN, 2003).

3.3.4 Process overview and scheduling

3.3.4.1 Agent decision-making

Since the data available for our model is derived from census and remote sensing data, we did not have access to detailed data on agent decision-making. In such cases, similar works have defined a typology of classes of agents (HUIGEN; OVERMARS; DE GROOT, 2006; VALBUENA et al., 2010). These authors assume that each agent can be classified in classes that will define a common behaviour.

However, in frontier regions the behaviour of agent changes over time, according to the evolution of the frontier and the institutional arrangements (COSTA, 2009; SANTOS JUNIOR et al., 2010). To capture this evolution in agent decision-making, we represent agent classes as states in a finite state machine (FSM).

A finite state machine (FSM) is an abstract model of computation that consists of a finite number of states. In agent-based modelling, an FSM defines a set of different states for the agent and the transitions between them. Each agent is in only one state at a time. The agent changes from one state to another based on pre-defined conditions. Each state of the FSM has a set of decision rules used by agent. In terms of land use decisions, each state defines constraints on how much and when to deforest, plant pasture or use a given pasture management technique. However, *the actual decision* a farmer makes depends on his own attributes, his past trajectory and the context provided by the institutional arrangements. Our model has five states, defined according to the literature review (MERTENS et al., 2002; MUCHAGATA; BROWN, 2003; CASTRO; MONTEIRO; CASTRO, 2004; POCCARD-CHAPUIS, 2004; BECKER, 2005; ESCADA et al., 2005; AMARAL et al., 2006; WALKER et al., 2009a; BOWMAN et al., 2012; HECHT, 2012; PACHECO, 2012; PACHECO; POCCARD-CHAPUIS, 2012):

- *Migration*: Initial state for new arrivals. Newcomers will buy an existing farm or take public land, subject to their capital and risk aversion. They choose land based on price, accessibility and biophysical factors. Some newcomers are classed as speculators and jump to the Speculate state.

- *Small-scale extensive farming*: This is the main state of non-capitalized agents with low to medium technological level. They deforest to open pasture areas. As pasture degrades, they count on getting more land to maintain or increase their cattle herd. When 40% of the pasture area is degraded, they try to sell the farm and buy or get new land. If they succeed, they move to a larger but less expensive area, making the frontier evolve.
- *Large-scale extensive farming*: This is the main state for farmers with capital and low to medium technological level. These farmers buy large areas and try to expand as much as possible, buying more land as their pasture.
- *Speculation:* this agent grabs available land, divides the area, and sells it to other farmers.
- *Intensive Farming*: State adopted by farmers with high technology and good access to credit and markets. They want maximum return from their farms. Relies on credit and markets to keep his practices.
- *Abandoning Rural Activity:* the agent sells all his farms and is removed from the simulation.

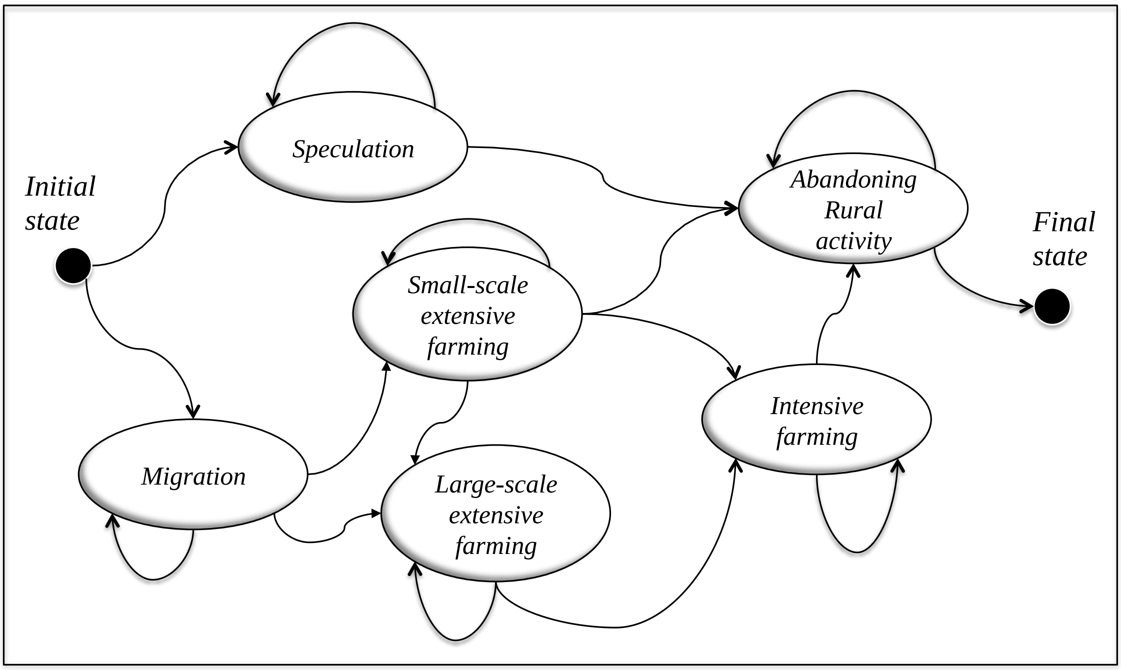

Figure 3-1. Agent states

As an example, a farmer may change from *Small-scale extensive farming* to *Intensive farming* if there is no more land available in the area for expansion (due to land tenure regulation, for instance), and if there is technological support and credit. We will describe the transition conditions among these states below.

3.3.4.2 Process scheduling

For each year (one discrete time step) the model performs the following action:

A. Data preparation: before running the agent's decision-making part, the model updates the cellular space and the farms and agents' attributes:

1. Update the institutional arrangement valid for the current year.
2. Run the *support capacity submodel*, which updates the cell space.
3. Run the *frontier occupation submodel*, which updates the cell space.

4. Aggregate cell attributes for each farm. Farm attributes such pasture area, forest area and farm price are updated.

5. Compute the number of migrants coming to the area. Migrants are added to the agent pool. Migrants are randomly assigned to one of two states: *Migration* (99,5% of agents) and *Speculation* (0,5% of agents).

B. Agent decision-making: after data preparation, the model runs the decision-making part for each agent

1. For all the agents in the *Migration* state, do:
   a. Try to buy a farm in the land market using the *land market submodel.*
   b. If the agent is not able to buy a farm and law enforcement is weaker than agent's risk preference, try to grab an area in the frontier using the *land grabbing submodel.*
   c. If the agent gets a farm that is more than 200 ha, he changes to the *large-scale extensive farming* state.
   d. If the agent gets a farm that is less than 200 ha, he changes to the *small-scale extensive farming* state.
   e. If the agent cannot get new land after trying for three years, he changes to the *abandoning Rural Activity* state.
2. For all the agents in the *Small-scale extensive farming* state that currently own a farm, do:
   a. Make his *available capital* equal to the *farm price.*
   b. Calculate his *farm size preference*, by multiplying his current farm area by a factor that depends on how strong the *cattle market* is. We

use factors 1.2 and 1.6 for weak and strong cattle markets, respectively.

c. Calculate the available area for pasture in the farm, which depends of agent's *risk preference* and the how strong *law enforcement* is.
    i. If *law enforcement* is weaker than agent's *risk preference*, then the available area for pasture is the total of remaining forest.
    ii. Otherwise, calculate the available area for pasture subtracting 50% or 80% of total farm area, depending of Forest Code valid for that year.
d. If there is still available area for pasture:
    i. Calculate the additional area needed for pasture in that year, depending on how strong the cattle market is. Use the proportions of a 5%, 8% and 14% of the farm are for weak, medium or strong cattle markets, respectively. The total area needed for pasture is limited to the area of the farm.
    ii. Run the *pasture creation submodel*, considering the area needed for pasture.
e. If the farm's *support capacity* for pasture is less than 40% of the ideal condition, the agent puts the farm for sale.
f. If the farm's *support capacity* for pasture is less than 25% of the ideal condition, then:
    i. If there is credit for intensification, the agent changes to the *intensive farming* state.

    ii. Otherwise, he changes to the *abandoning rural activity* state.

3. For all the agents in the *Small-scale extensive farming* state that currently do not own a farm, do:
    a. Try to buy a farm using the *land market submodel*.
    b. If the agent is not able to buy a farm and the law enforcement is weaker than agent's risk preference, try to grab an area in the frontier using the *land grabbing submodel.*
    c. If the agent gets a farm that is less than 200 ha, he continues in *Small-scale extensive farming* state.
    d. If the agent gets a farm that is more than 200 ha, he changes to the *Large-scale extensive farming* state.
    e. If the agent cannot get new land after trying for three years, he changes to *Abandoning Rural Activity state.*
4. If the agent is in the *Large-scale extensive farming* state, for each of his farms do:
    a. Add the *farm price* to his *available capital*. The available capital will be the sum of all farm prices.
    b. Calculate his *farm size preference*, by multiplying his current farm area by a factor that depends on how strong the *cattle market* is. We use factors 1.2 and 1.6 for weak and strong cattle markets, respectively.
    c. Calculate the available area for deforestation in the farm, which depends of agent's risk preference and the law enforcement.

i. If *law enforcement* is weaker than agent's *risk preference*, then the available area for pasture is the total of remaining forest.

ii. Otherwise, calculate the available area for pasture subtracting 50% or 80% of total farm area, depending of Forest Code valid for that year.

d. If there is still available area for pasture, then:

i. Calculate the additional area needed for pasture in that year. We use the proportions of a 8%, 10% and 18% of the farm area for weak, medium or strong cattle markets, respectively. If area for pasture calculated is more than available area, then the area for pasture is the available area.

ii. Execute the pasture creation submodel; using the area for pasture calculated previously, the extensive farming management type, and the proximity to farm house.

e. If the support capacity of the farm decreases to less that 40% of the ideal condition, the agent tries to buy a farm using the *land market submodel*. If the agent is not able to buy a farm, he tries to grab a new area in the frontier using the *land grabbing submodel.*

f. If support capacity of his farm is less than 25% of the ideal condition:

i. If there is credit for intensification, he changes to the *Intensive farming* state.

    ii. Otherwise, he abandons his farm. If this is his only farm, he changes to the *Abandon rural activity* state.

5. If the agent is in the *Intensive farming* state, for each of his farms do:
    a. Calculate the available area for deforestation in the farm, keeping 50% or 80% of farm area, depending of the Forest Code valid for the year.
    b. If there is available area for pasture, do:
        i. Calculate the area for pasture in that year. Use the values of 5%, 8% and 10% of the farm for weak, medium and strong cattle markets. The area for pasture is limited to the available area.
        ii. Execute the pasture creation submodel.
    c. If there is credit for reforestation, then execute the *reforest submodel.*
    d. If there is no credit for intensification and the cattle market is low for more than 5 years, the agent abandons his farm. When all of his farms have been abandoned, he changes to the *Abandoning rural activity* state.
6. If the agent is in the Speculation state.
    a. If the Law enforcement is stronger than agent's risk preference, he changes to the *Abandoning rural activity* state.
    b. Otherwise, he grabs an area (4000-6000 ha) in the frontier using the *farm creation submodel*. He divides this area into several farms of 100 ha and puts these farms for sale.

7. If the agent is in the *Abandoning rural activity* state,
    a. He puts his farms for sale.
    b. After selling the farms, the agent leaves the area.
    c. If the agent cannot sell the farms after trying for three years, he abandons the farms and leaves the area.

3.3.5 Design concepts

We review the main design concepts used in the ABM model for São Felix, following the guidelines of the ODD protocol (GRIMM; RAILSBACK, 2012) .

- ***Emergence.*** *What key outputs of the model are modelled as emerging from the adaptive behaviour of its agents?*

  The key outputs of the model are the patterns of land change in the region portrayed as maps and their accumulated values. Both the spatial values and the deforestation totals emerge as a result of the agent's decisions. The values of deforestation by clear-cuts for São Felix are used only during the calibration phase of the model (1985-1997). From 1997 to 2010, the amount and the maps of deforestation are not used in the model.

- ***Adaptation.*** *What rules do agents have for changing behaviour in response to changes in themselves or their environment?*

  The behaviour of the agents is expressed as states in a finite state machine. Each state has internal rules that the agent follows according to his attributes. State transitions depend on context variables defined by institutional arrangements.

- ***Objectives.*** *If adaptive behaviour is represented as explicitly seeking some objective, what is the objective and how is it measured?*

  The objective of each agent is to maximize the use of land for cattle production. He is constrained by his capital, the support capacity of the land and the land market.

- ***Learning.*** *Do individuals change their adaptive behaviour over time as a consequence of their experience? How?*

  The agents do not learn, but they adapt to the external conditions. The choice of adaptation over learning is dictated by the purpose of the model (land use policy assessment).

- ***Prediction.*** *What internal models are used by the agents to estimate future conditions or consequences of their decisions?*

  As the model is focused on policy assessment, its use for prediction is linked to the scenarios of possible institutional arrangements. In our model, we assess how changes in institutional arrangements could influence trajectories of land change in São Felix.

- ***Sensing.*** *What information can agents sense and consider in their adaptive decisions? Are the mechanisms by which agents obtain information modelled explicitly?*

  We model updates the support capacity of the region changes in response to agents' decision. Agents then sense how geographical space has changed and use this information in their decision-making.

- ***Interaction.*** *What kinds of interactions among agents are in the model? How do agents interact with their environment?*

  Agents interact directly via the land market. They also interact indirectly by the different ways in which they build new farms.

- ***Stochasticity.*** *What processes are modelled by assuming that they are random or partly random?*

  The agents' attributes are chosen statistically, to fit an expected distribution of agents, which tries to model the census data on São Felix.

- ***Collectives***. *Are there aggregations of agents that affect, and are affected by, the agents?*

  When we define an agent as a farmer, we are simplifying a collective pattern of occupation. Poor farmers in our model tend to be whole families of migrants, whereas rich farmers may or may not migrate to the region with their families.

- ***Observation.*** *What data and patterns must be observed from the ABM for testing, understanding, and analysing it, and how are they collected?*

  The main data to be observed from the model are the deforestation patterns and values, and the farm's attributes. From these values, we can observe how land policy have affected and might affect the São Felix region.

3.3.6 Initialization and Input Data

As discussed previously, we use data derived from census and remote sensing. Our starting points were a land cover map of São Félix in 1985 and demographic and land tenure data from 1985 to 2010. To get the land cover map for 1985, we classified a set of LANDSAT TM images for this year into forest, deforestation, non-forest, clouds and river.

Figure 3-2 Deforestation map of São Felix in 1985.

To estimate the number of farmers and farms of the region, we took the Agrarian Census from IBGE for 1985, 1996 and 2006 as our basis (IBGE, 2010). We obtained the number of farmers and farms for each year in the period 1985-1997 during the model's calibration phase. Then, we used those calibrated values to estimate the population for each year in the 1997-2010 period, considering the different influx of migrants for each period, as discussed bellow.

The most difficult input data to estimate is the land tenure map. Obtaining land tenure data is hard in Amazonia, as no publicly available records exist for the period 1985-2010. The state of Pará began publishing such information only after 2010 (SEMA-PR, 2012). Thus, we had to make the best possible estimate of a land tenure map based on the following information:

1. Number of farmers and farms in the study area.
2. Size of each farm.
3. Location of the farms.

To get the number and size of farms, we used data from Brazil's 1986, 1996 and 2006 Agrarian Census that provides the number of farms and total farm area aggregated by farm size (Table 3-2). We created a distribution of farm size that approximates the actual data (see Figure 3-3) assuming that each farmer has only one farm at start of the simulation.

Table 3-2 Estimated and the observed data grouped by farm size in 1985

Farm size	**Number of farms**		**Total area by farm size**	
	Estimated	**Observed**	**Estimated**	**Observed**
less than 50 ha	662	685	24170	27625
50-100 ha	590	574	43003	44980
100-200 ha	68	62	9390	8877
200-500 ha	31	30	11142	9618
500-1000 ha	8	9	5340	6467
more than 1000ha	15	14	157874	141863
Total	**1374**	**1374**	**250919**	**239430**

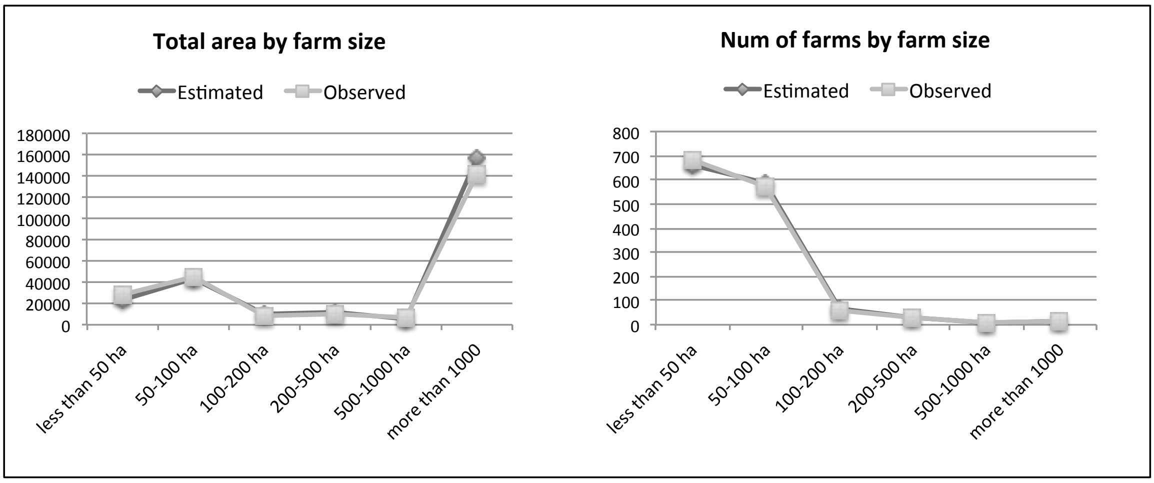

Figure 3-3. Comparing the estimated and observed distribution of farms size in the study area.

To estimate farm location, we used land change patterns on deforestation maps. Different agents (small-scale farmers, large plantations, cattle ranchers) can be distinguished by their different spatial patterns of land use (LAMBIN; GEIST; LEPERS, 2003; SILVA et al., 2008). We used the different types of deforestation patterns (fishbone, corridor, diffuse and geometric) to associate them to small and large farms.

We also used historical reports to estimate the location of farms during the 1980s. In the satellite images of 1985, Tucumã was almost a virgin forest. However, there were already many farms in this region. In addition to deforestation patterns, we included the historical context in our estimate of farms location. Figure 3-4 shows the estimated location of farms (by farm size) for São Felix in 1985. Figure 3-5 shows the final estimated land-tenure distribution (location and farm boundaries) for São Felix in 1985, obtained by agricultural census data, deforestation patterns and literature review. We estimated the location of farms in areas where deforestation had not yet happened.

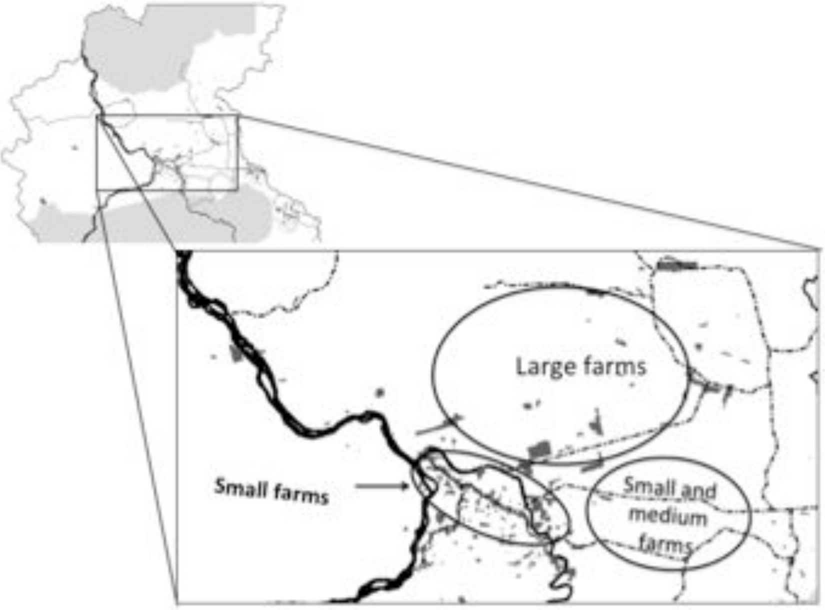

Figure 3-4 Distribution of farms by size in the research area.

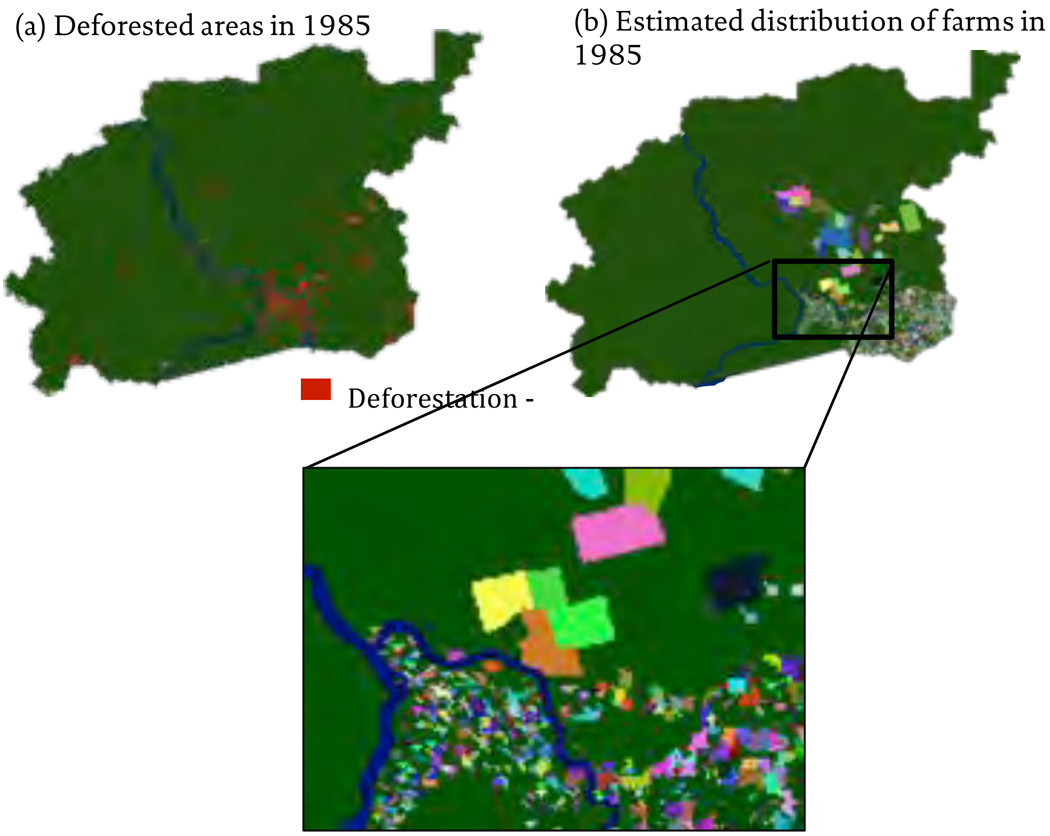

Figure 3-5 Hypothetical land tenure in 1985.

3.3.7 Submodels

3.3.7.1 Support capacity submodel

For cattle famers, the support capacity of a farm is characterised by the number of animals supported per ha. We assume that support capacity is a discrete function of the *pasture management* and the pasture age:

$$support\ capacity\ =\ f\ (pasture\ management\ ,pasture\ age)$$

For each year the support capacity of the pasture decrease dependent on the type of pasture management system. We consider two values for the type of pasture management:

- *Extensive management* rely on expanding the pastureland, often with a low stocking ratio, i.e head of cattle per unit of land (PACHECO; POCCARD-CHAPPUIS, 2012).
- *Intensive management* enhance pasture and herd management to increase production without expanding the area of pasture. This system use improved technologies, which could include more fences, recovery of degraded pastures, and the purchase of more productive animals (PACHECO; POCCARD-CHAPPUIS, 2012).

We describe these different management types through of the discrete function shown in the Figure 3-6. We assume that in *Intensive management* the pasture is recovered when the support capacity reaches 75% of ideal condition. We also assume that a pasture is degraded when have no more capacity to maintain animals, in another words, when reaches it 0 of its support capacity.

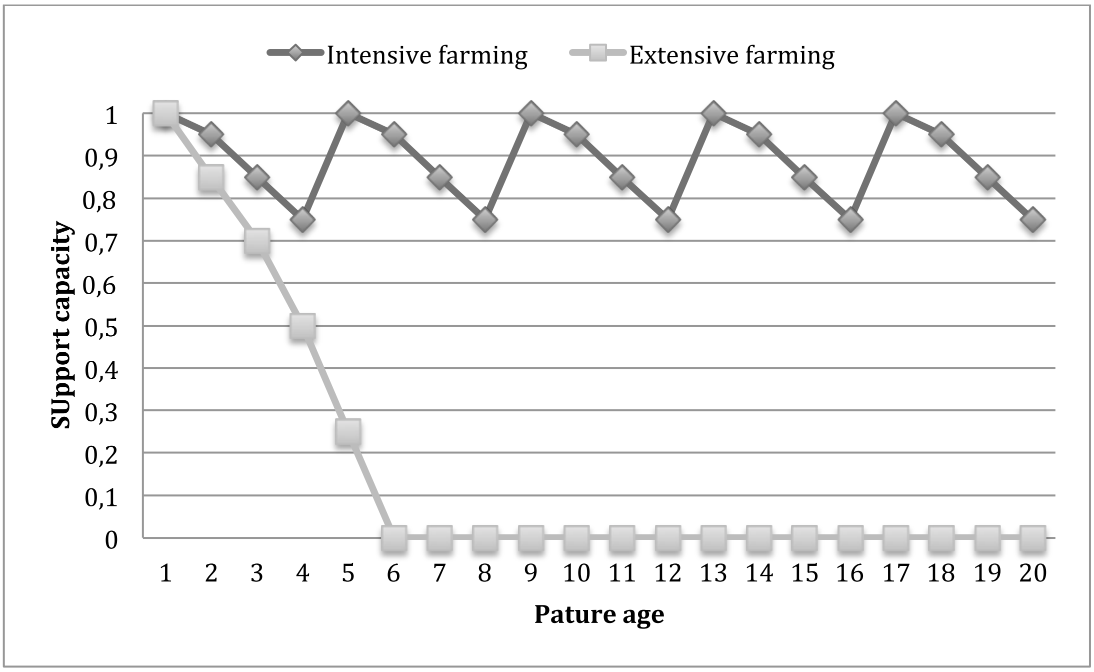

Figure 3-6 Support capacity discrete function for different pasture management.

The support capacity submodel execute the follow actions:

1. For each cell on the geographical space do,
2. If cell cover is Pasture
    a. The pasture age is incremented by 1.
    b. The support capacity is $f\ (pasture\ management\ , pasture\ age)$. Where the function f is described in the Figure 3-6.

3.3.7.2 Frontier occupation submodel

Pacheco (2012) argue that the behaviour of actors is shaped by frontier configuration, where the authors consider four categories: anti-pioneer, pre-frontier, frontier and post-frontier. These regions are areas of varied degrees of occupation that emerge as result of the spatial and temporal arrangement of the frontier itself. An actor's decisions may vary depending on the frontier stage. For instance, as land becomes more expensive and rare, there may be more incentives to intensify the land use. Density of services, market chain nodes and infrastructure also increase over time and change the profitability of each activity. Moreover, respect for environmental laws increases in older areas because of the higher density of governmental organisations. In our model, we use a multi scale cellular space to calculate the occupation.

1. Compute the number of agents within a cell of 225 ha.
2. Normalize the number of agents, previously calculated.
3. Classified in to four categories (anti-pioneer, pre-frontier, frontier and post-frontier), using different thresholds.
4. Calculate the minimal Euclidian distance to post-frontier region. This distance is used as proxy of relative land price, given that in the post-frontier the density of services, market chain nodes and infrastructure are increased.

3.3.7.3 Pasture creation submodel

This submodel describes the process of pasture creation, given a pasture management type. As discussed in the Section 3.3.7.1, we consider two management type: *extensive management* and *intensive management*. The pasture creation process and pasture degradation process yield to different trajectories (Extensive and Intensive), as illustrated in Figure 3-7.

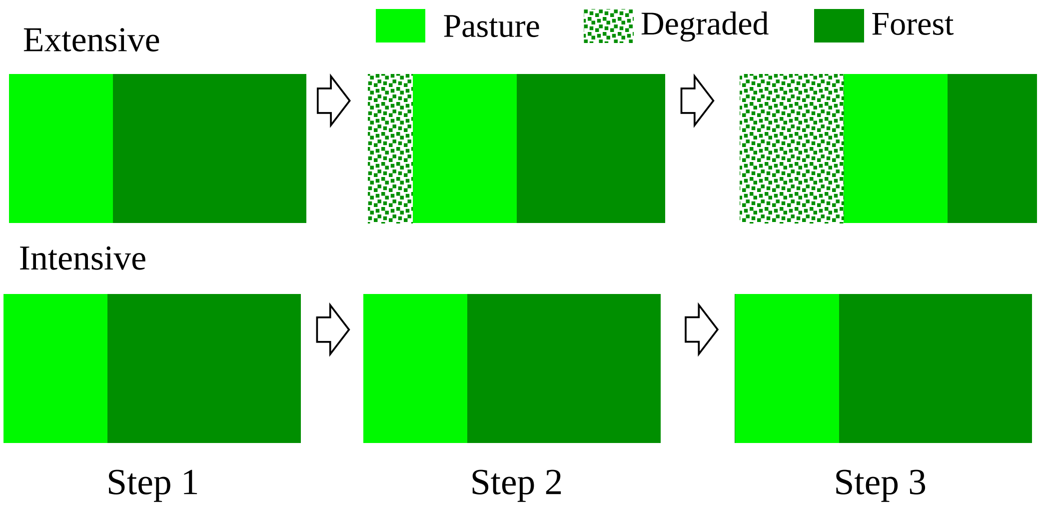

Figure 3-7. Examples of different land change trajectories using different pasture management.

This submodel receives an area for pasture, a set of factors and executes the follow actions.

a. Compute the amount of cells to change, dividing the area for pasture by cell size.

b. For each forest cells compute their potential using the set of factors depending of agent state. In this model we use distance to agent house.

c. Order the cells by potential.

d. Until the amount of cells, change the highest cell from forest cover to pasture cover and apply the management pasture type.

3.3.7.4 Reforestation submodel

Currently, a farmer have to keep 80% of the area of native forests in their farms. If the percentage of native forest is less than 80%, then the farmer must reforest until the percentage of native forests and secondary forest is equal to 80. This submodel receives a farm and the amount of cells to reforest.

1. Until the amount of cells.
    a. Change the cell from pasture cover to secondary forest cover.

As discussed in the Section 3.3.4.2, we assume that this submodel may be executed by agent in the Intensive farming state when there is credit to do.

3.3.7.5 Land market submodel

The land market submodel simulates buying and selling of farms. When a farmer offers his farm for sale, the submodel puts it on a list of offers. The list will then be used by farmers who want to buy new land. The land market works by assuming the buyer wants to extend his existing land by buying land in his neighbourhood. The model works as follows:

1. For all land owners that want to buy new area, do:
    a. For each owner, list the farms for sale in his neighbourhood, which its area is greater than the size of the farm wanted (investment type) and the prices is lower than agent investment capital.
    b. Calculate the potential for each of these farms using the distance from the farm for sale to the buyer's home.
    c. Rank and order the farms for sale.
    d. Buy and merge the farm(s) until the owner gets his desired area.
    e. If the buyer cannot get his desired area close by, go to step 2.
2. For all potential buyers that have no farm and those that cannot find their desired new area close to their farms, do:
    a. List all farms for sale;

b. Calculate the potential for each farm using proximity to roads and proximity to urban

c. Rank and order the farms for sale by potential

d. Buy the farm(s) with greatest potential until the desired area is reached.

3.3.7.6 Land grabbing submodel

Depending on the agent's state and on the context variables, the agent may try to grab a portion of public land, creating a new farm. As shown in Table 3-4, the number of farms in São Félix increased from 1,374 in 1986 to 6,109 in 2006 (IBGE, 1986) (IBGE, 2007). In the same period, the total area of farms increased from 239,000 ha to 1,450,000 ha. Such a large growth was only possible by grabbing of public lands. An action simulated in this submodel that receives a farm area, a set of factors and weighs and execute the following actions.

1. Select a random sample of 500 cells of the geographical space.
2. Calculate the potential for each cell using the set of factors.
3. Order the cells by potential.
4. Select the cell with the greatest potential. Create a farm joining this cell to other free neighbour cells to. The shape of the farm will depends on the farm's location, adjusted according to spatial limits, such as existing farms and large rivers.

5. Mark the initial cell as the location of the agent's house. For each cell, calculate the distance for the house. When changing a set of cells from forest to pasture, the farmer minimises the distance to his house.
6. After the farm creation, the initial cell is marked as the location of the agent's house. Then, for each cell calculates the Euclidian Distance of the cell from the house. This distance is used by pasture submodel, given that the farmer minimises the distance to the house.
7. At least, is calculated the neighbourhood relation to created farm and its neighbours using the *Farm neighbourhood submodel.*

3.3.7.7 Farm neighbourhood submodel

A farmer prefers to buy neighbouring farms rather than distant farms. Thus, we need support the neighbourhood relations amongst farms. The modelling software usually supports relation among cells. However, a farm is a set of cells and not a single cell. This submodel receives a farm and identifies the neighbourhood relations amongst farms using the follow steps:

1. Identifies which are cells are on the boundary of the input farm. The cell is on the boundary of the input farm, if it is next to a cell outside the farm.
    a. We use an attribute to identify these cells; 1 indicates that is on boundary, as illustrated in Figure 3-4.
2. For each boundary cells of the input farm, identify if it is next to a cell of another farm. If true, create the neighbouring relations between this farm and the input farm. A land-market decision may

consider the spatial relations amongst farms because a farmer may prefer to buy neighbouring farms rather than distant farms.

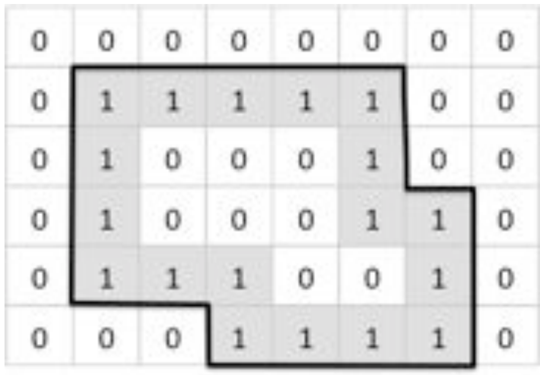

Figure 3-4 The farm boundary representation.

4 SIMULATIONS AND RESULTS

The model simulates the process of occupation of the São Felix do Xingu, a rural region that covers 60,000 Km^2 in the south-east of Pará, Brazil. This region includes the municipalities of Tucumã and São Felix do Xingu, as shown in Figure 4-1. We excluded a region of 20,000 km^2 in the south of the municipality of Sao Felix do Xingu, where 15,000 km^2 are in protected areas and other 5,000 km^2 are part of region on the border between Pará and Mato Grosso. This border region has a different occupation history.

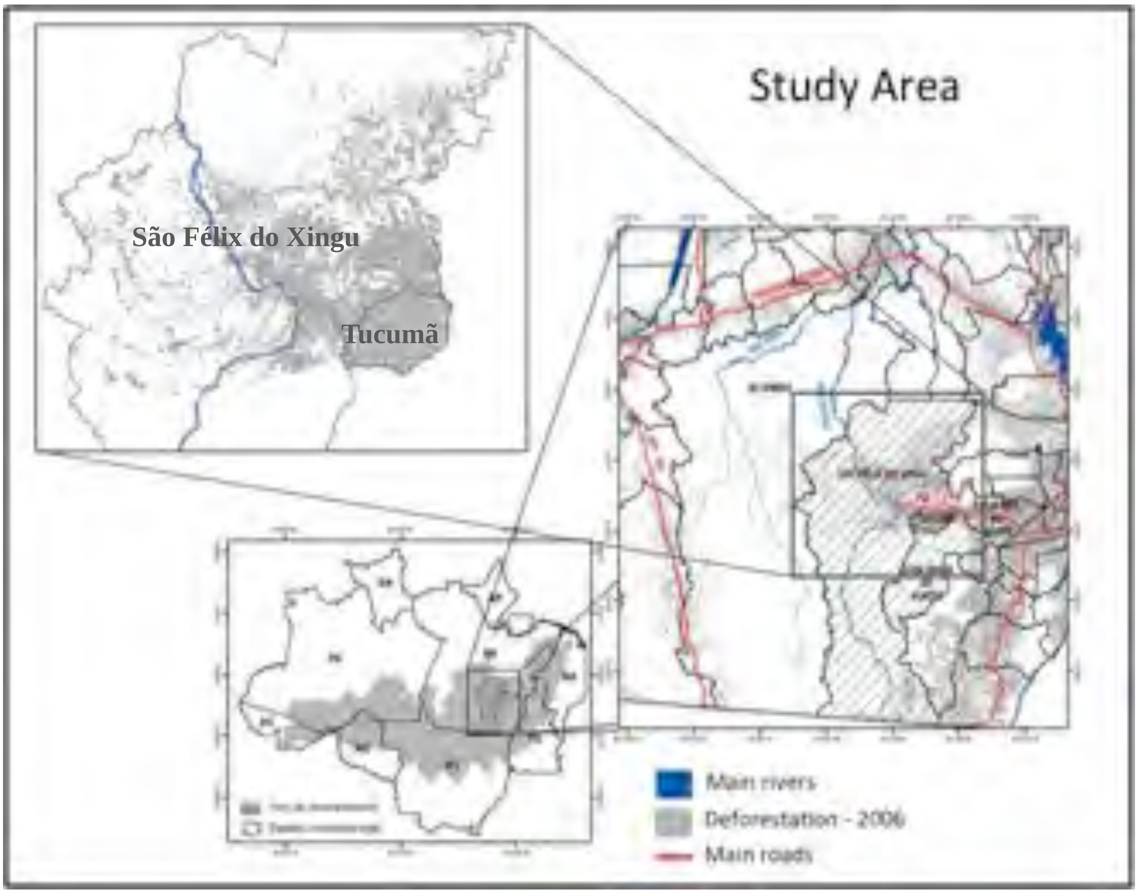

Figure 4-1 Study area: 60,000 km^2 in the Pará state, Brazil.

We use a detailed cellular space with cells of 25 ha x 25 ha to represent the geographical space. The model runs in yearly time steps for 35 years, from 1985 to 2020. The purpose of the simulation was to capture the effects of the different in institutional arrangements on land change. Our hypothesis is that the processes of land change can be represented by a combination of endogenous and exogenous drivers. The *land market submodel* expresses the interactions between the agents. The *support capacity submodel* conveys the environmental conditions. Individual actions make use of the *frontier occupation*, *land grabbing*, *pasture creation* and *reforestation* submodels. The exogenous drivers are represented by the different institutional arrangements and by the yearly number of migrants to the area. Thus, we assume that deforestation in the study area is directly related to migration process, the individual land use decisions and the agents' interactions through the land market. The results of the simulations are yearly estimates of deforestation rates and land change maps

4.1 Calibration

To calibrate the model, we adjust its variables so as to reproduce the process of deforestation from 1985 to 1997. In this period, we consider a single institutional arrangement (*Private capitalist occupation*). Thus, the simulations from 1997 to 2020 under different institutional arrangements are then run based on the calibration step. Beyond 1997, there was no further adjustment of the variables.

We chose 1985 as our starting point because we had data from the Agrarian Census of 1985, as discussed in the Section 3.3.6. Then, we used census data to estimate yearly number of migrants. Since we assumed that the creation of new farms is linked to the arrival of migrants, we estimate the number of new farms created each year as a proportion of the number of new migrants. The Agrarian Census data for land tenure structure is shown in Table 4-1, expressed as differences between the 1985-1995 and 1995-2005.

Table 4-1 Evolution of land-tenure structure in São Félix between 1985-1995 and 1995-2005. Source (IBGE, 1985, 1995, 2005).

	1985-1995		1995-2005	
Farm size	Farms	Area (ha)	Farms	Area (ha)
< 50 ha	1464	59.207	2271	10.186
50-500 ha	1998	237.305	-916	-109.604
500-2000 ha	410	179.819	304	144.473
> 2000 ha	61	244.471	197	786.455
Total	**3933**	**720.803**	**1856**	**831.519**

From the migration data and the land tenure data, we had to estimate the annual increase in new farms and new farmers. We suppose that the increase on farms is partly due to migration and partly due to frontier expansion. During the simulation, the agents interact according to the *land market submodel* and make decisions following the *land use submodel*. Depending on the agent's state and on the context variables, the local agents may to grab public lands increasing the number of farms. Thus, the increasing of the number of farms is the result of the actions of local agents and migration process. Furthermore, some farmers will not succeed and will leave the rural activity.

We estimated the number of farmers in São Felix from 1985 to 2010 assuming a different amount of migrants for each period that reflects the different institutional arrangements valid for this period. We assume there was a huge influx of migrants at the start of the *private capitalist occupation arrangement* (1985-1989). This occupation involved groups of farmers, capitalists and politicians. At the beginning of the *beef marketing chain organization arrangement* (1997-2000) there were also lots of migrants. After 2003, the number of migrants decreased, and ended at the start of the *deforestation control arrangement*. Given these assumptions, we modelled each agent by arrival year, risk preference and farm size preference. The estimated number of migrants for each year is shown in Figure 4-2.

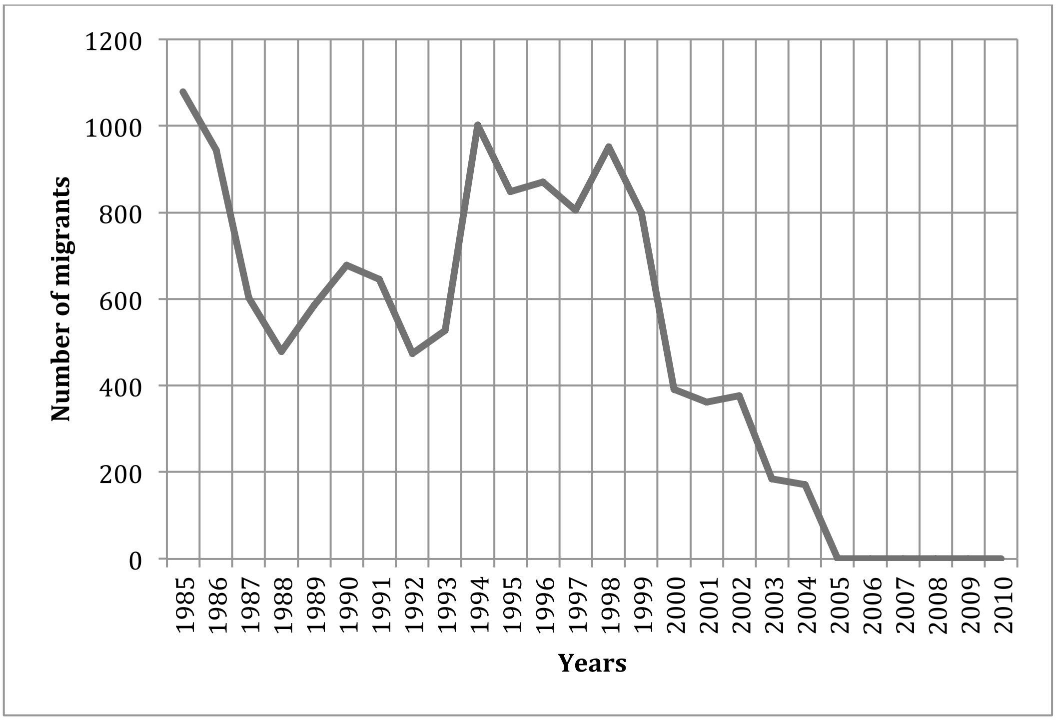

Figure 4-2. Estimated numbers of migrants in São Felix from 1985 to 2010

Given data on land tenure (Table 3-2 and Table 4-1) and migration (Figure 4-2), we need to estimate two parameters of the agent's decisions: (a) the yearly *increase in pasture area*; and (b) his *farm size preference*. These parameters were set by running the model from 1985 and 1997 using a single arrangement (*Private capitalist occupation*). Tables 4-2 and 4-3 show the calibrated values.

Table 4-2. Yearly increase in pasture area (calibrated data)

Strength of the cattle market	Weak	Medium	Strong
Small-scale extensive farming	5% of the farm size	8% of the farm size	18% of the farm size
Large-scale extensive farming	8% of the farm size	10% of the farm size	18% of the farm size
Intensive farming	5% of the farm size	5% of the farm size	10% of the farm size

Table 4-3 Farm size preference depending on cattle market

Strength of the cattle market	Weak	Medium	Strong
Small-scale extensive farming	120%	140%	160%
Large-scale extensive farming	120%	130%	140%

Since we do not have the evolution of farms and deforestation for the entire region between 1985 and 1997, we compared the simulated values with existing data, as shown in Table 4-4. Comparing simulated and observed in the 1996 and 1997.

Table 4-4. Comparing simulated and observed in the 1996 and 1997.

	Deforestation in km^2 (1997)	Number of farms (1996)	Area of farms in km^2 (1996)
Observed	5782	5307	9602
Simulated	5331	5996	9892
Diference (%)	**8 %**	**12 %**	**3 %**

4.2 Simulations for the period 1997-2010

After calibrating the model, we ran three simulations from 1985 to 2010. The simulations explore the different institutional arrangements listed in Table 3-1. From 1985 to 1997, there was only one arrangement (*Private capitalist occupation*). Then, for the period 1997-2010, we consider three different scenarios. In simulation S1, we look at the case if *private capitalist occupation* had been the only arrangement for the whole period. In simulation S2, we suppose that *Private capitalist occupation* is replaced by the *Beef market chain organization* from 1997 until 2010. In simulation S3, we use the *Beef market chain organization* from 1997 to 2004 and use the *Deforestation control* arrangement from 2004 until 2010.

Table 4-5 Arrangements used in each simulation run.

Simulation	Period	Institutional Arrangement
S1	1985-2010	*Private capitalist occupation*
S2	1985-1996	*Private capitalist occupation*
	1997-2010	*Beef market chain organization*
S3	1985-1996	*Private capitalist occupation*
	1997-2004	*Beef market chain organization*
	2005-2010	*Deforestation control*

The total deforested areas resulting from simulations S1, S2, S3 are shown in Figure 4-3. These simulations point out how the institutional arrangements influence model results. In simulation S2, including the *Beef market chain* arrangement after 1998 increases deforestation compared with S1, given the better market conditions. However, simulation S2 rates overestimate deforestation after 2005, the year the government started stronger control measures. In simulation S3, we include the *Deforestation control* arrangement from 2005-2010. The resulting rates for S3 are closer to the actual ones, as shown in the Figure 4-3 and Figure 4.4. The best estimates occurred in the period from 2001 to 2010.

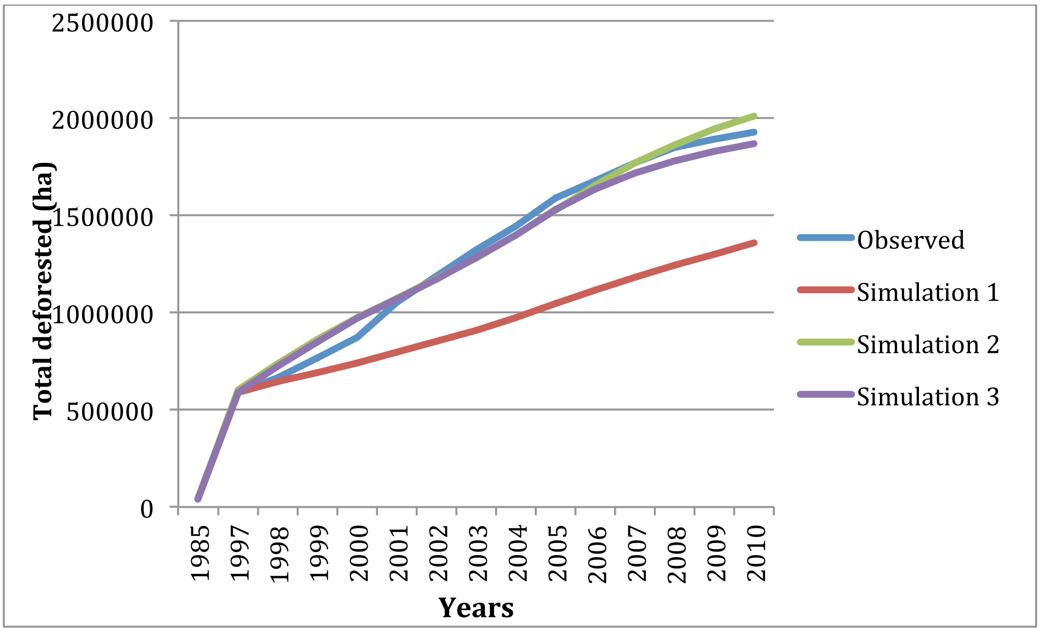

Figure 4-3 Total deforested area for simulations S1, S2, S3 compared to observed rates.

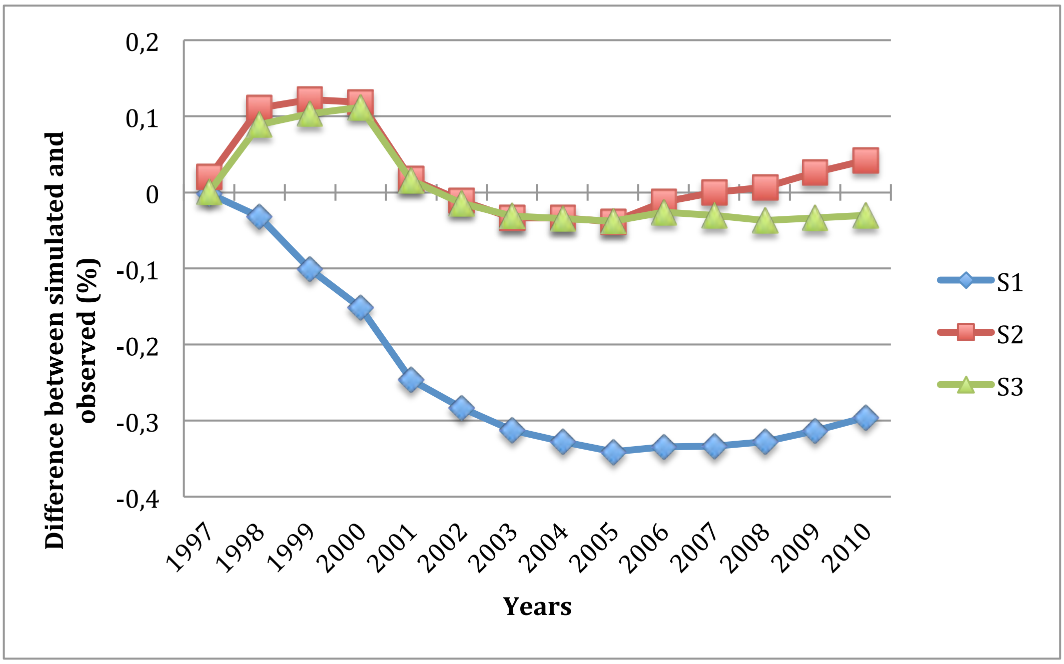

Figure 4-4 Difference (%) between simulated and observed in the total deforested.

We also compared the yearly deforestation rates estimated by simulations with the observed rates measured by INPE, as Figure 4-5 shows. The best estimates occurred in the period from 2001 to 2010. We also compared the spatial patterns resulting from simulation S3 with the actual deforestation patterns measured by INPE. Figure 4-6 presents the spatial patterns.

In Figure 4-7, we show the evolution of the frontier areas. From chapter 3, we divided the frontier areas in the classes: *consolidated, pre-frontier, frontier and post-frontier*.

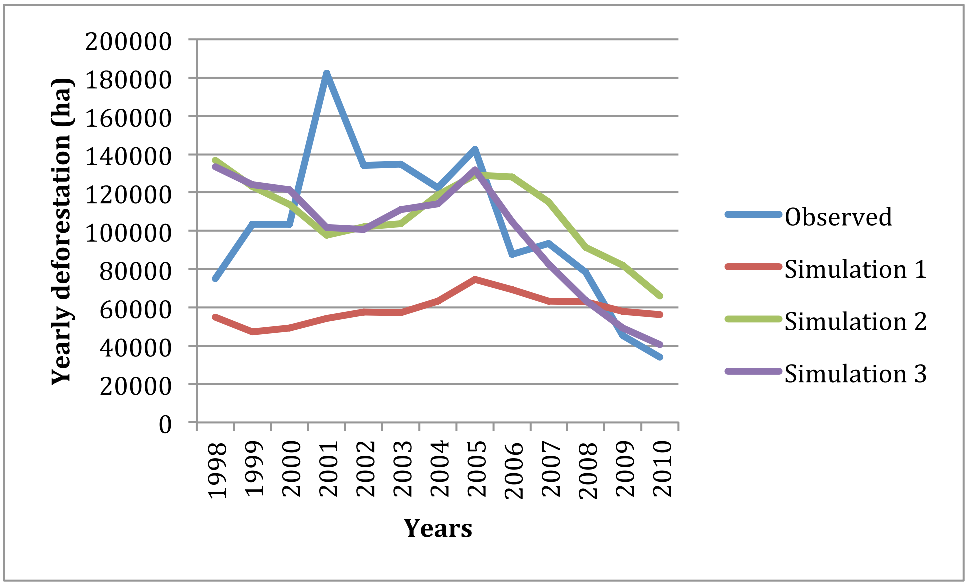

Figure 4-5. Yearly deforestation from model simulations S1, S2, S3 and observed

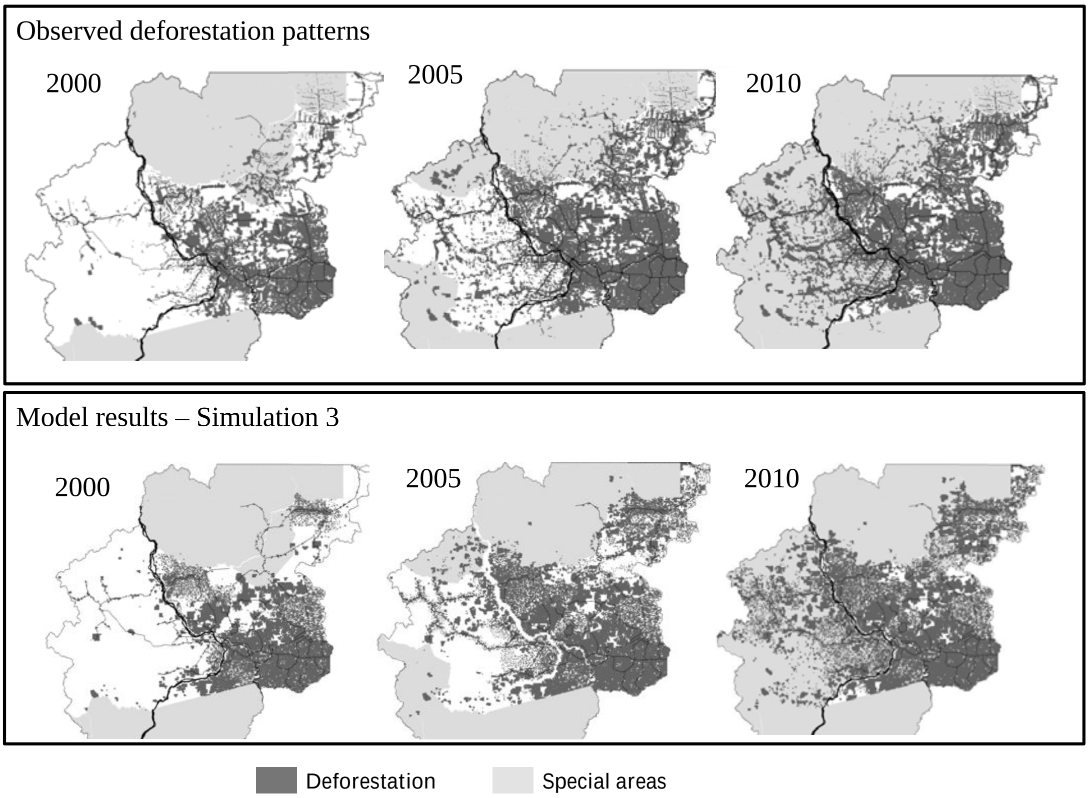

Figure 4-6 Comparison of observed deforestation patters (top) with results from model simulation S3 for 2000, 2005 and 2010 (bottom).

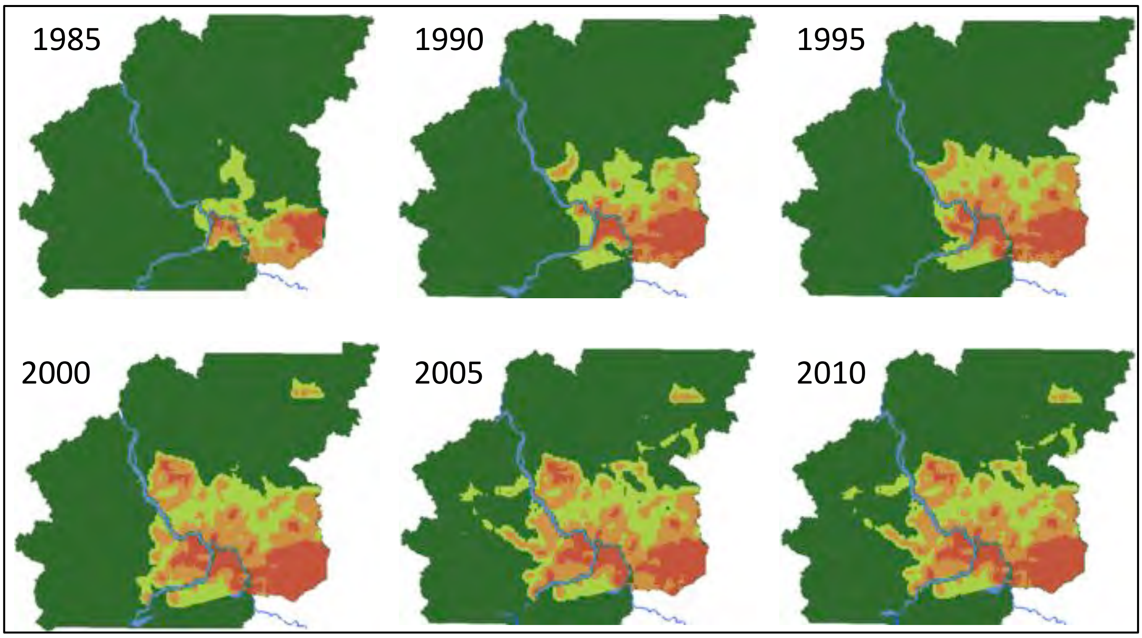

Figure 4-7. Frontier evolution on *Simulation 3 for 2010-2020* with four areas: *consolidated (dark red), pre-frontier (light red), frontier (light green) and post-frontier (dark green).*

When estimating the number of farms and total area of the farms, there was a large difference between simulated values and those reported by the census, as shown in Table 4-6. We think this large difference may be due to errors in the Agrarian Census. São Félix is a large municipality, with regions with difficult access. There are many conflicts and invasions. Many farmers do not know the actual size of their property. For example, the sum of the area of farms in Tucumã reported by the Census is more than the total municipality area. The municipality has 2512 km^2 and Census data indicates that the total area of farms is 3341 km^2 in 2006. In São Félix, the total area of the farms might be more than informed by Census data. The IBGE Agrarian Census states that the total area of farms was 14576 km^2 in 2006. However, INPE's deforestation data shows that the total deforested area was 14541 km^2 in 2006. If both data were correct, it would imply that all farms are 100% deforested. This result shows the problems of data reliability in frontier areas.

Table 4-6 Number and area of farms: simulated versus reported.

	Number of farms (2006)	Area of farms (2006)
Reported by census	7163	17.917 km^2
Simulation 3	9728	21.377 km^2

Finally, Figure 4-8 shows the annual variation of the estimated number of farmers for simulation S3. We see that the number of farmers increases rapidly in the 1990s and then falls after 2000. This simulation results is consistent with our model that has some of the small-scale farmers abandoning the land after the support capacity has been exhausted since they neither have capital nor credit to invest in intensive cattle raising. This conclusion is supported by Figure 4-9, which shows the variation on farmer states for simulation S3. We see an increase on the numbers of small-scale farmers that after trying for some years, are forced to abandon their farms.

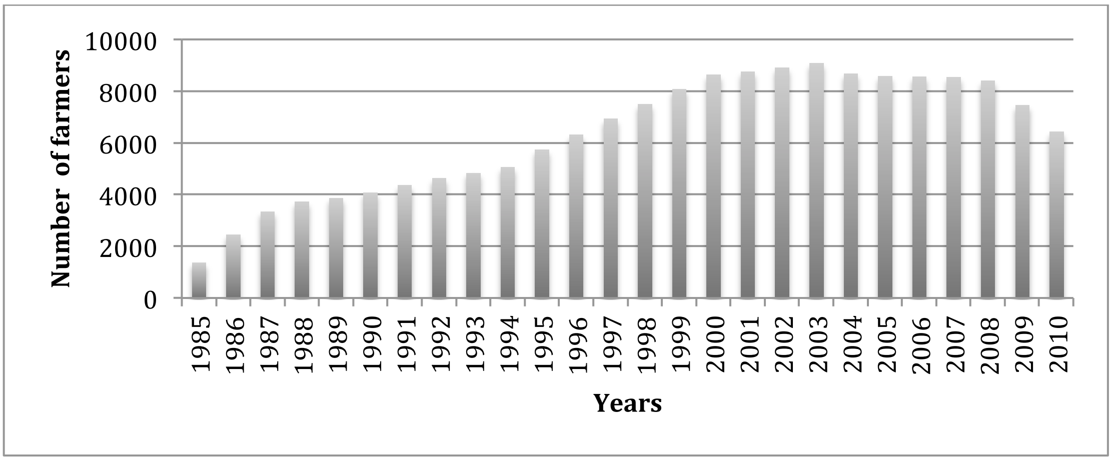

Figure 4-8 Number of farmers estimated by *Simulation 3 (1985-2010)*

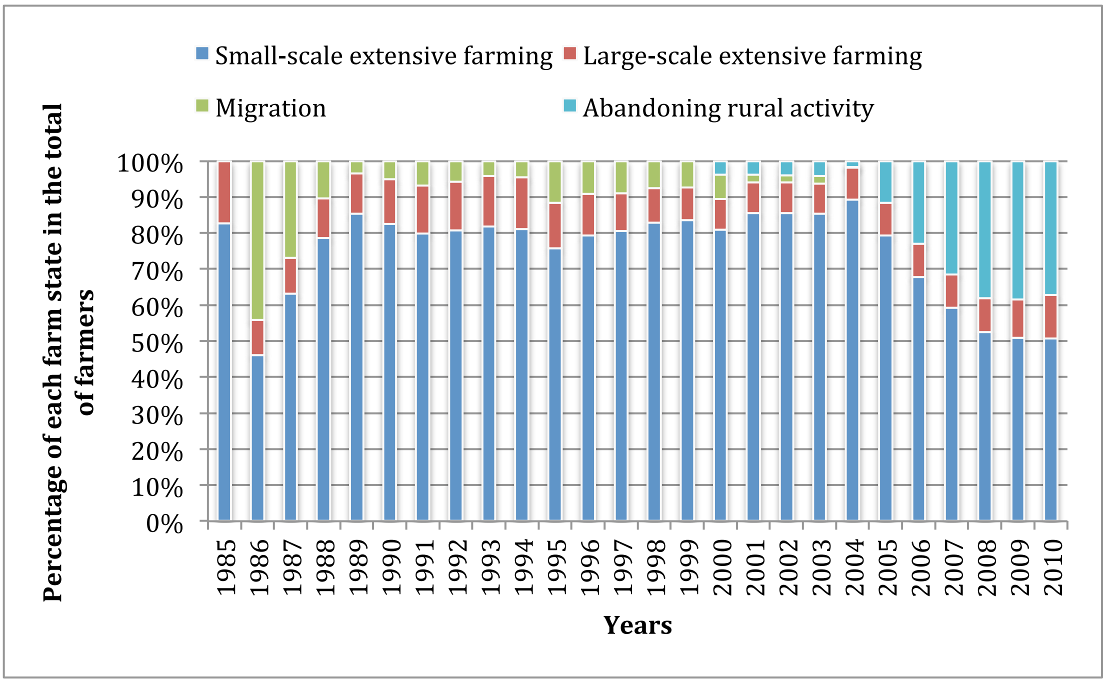

Figure 4-9 Variation of farmer strategies on *Simulation 3 for 1985-2010*

4.3 Scenarios for the period 2011-2020

Based on the results of simulation S3 up to 2010, we ran two scenarios for the period 2011-2020 considering different arrangements. Simulation S4 replaces the *deforestation control* arrangement after 2010 by the *sustainable development* arrangement, which arguably balances social, economical and environmental needs. Simulation S5 replaces the *deforestation control* arrangement after 2010 by the *economic development* arrangement, that puts economic gains before sustainability.

Table 4-7 Arrangements used in simulations for 2011-2020

Scenarios	Period	Institutional Arrangement
S4	1970-1996	*Government-induced occupation*
	1997-2004	*Beef market chain organization*
(sustainable dev.)	2005-2010	*Deforestation control*
	2011-2020	*Sustainable development*
S5	1970-1996	*Government-induced occupation*
(economic dev.)	1997-2004	*Beef market chain organization*
	2005-2010	*Deforestation control*
	2011-2020	*Economic development*

Figure 4-10 shows the evolution of the pasture area as simulated by scenarios S4 and S5. As expected, there is a significant reduction on the pasture area on scenario S4 that is consistent with the emphasis on pasture intensification and reforestation. In scenario S5, pasture area increases as a consequence of the reduction on deforestation control.

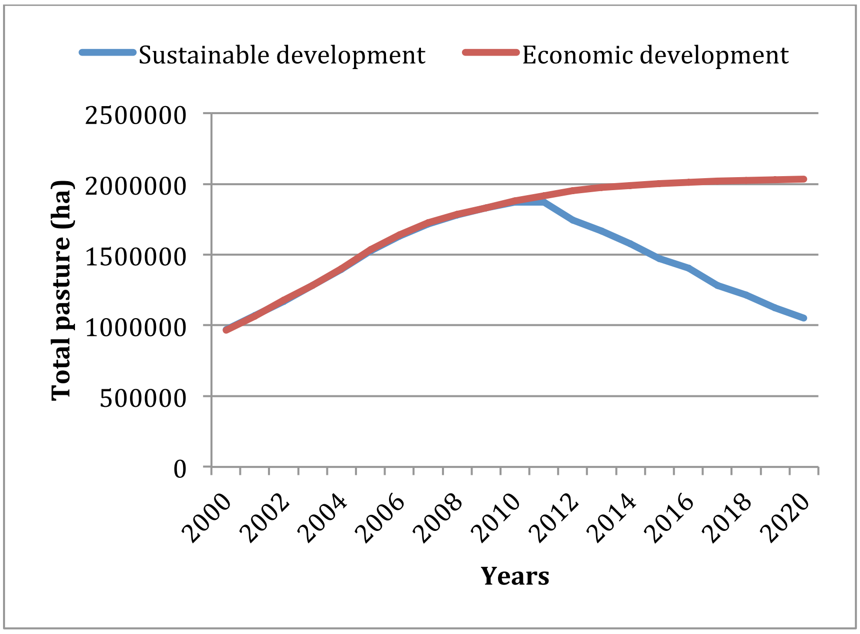

Figure 4-10 Comparison of total pasture area (ha) on scenarios S4 (*sustainable development* and S5 *(economic development)* for 2010-2020.

Figure 4-11 shows the evolution in the number of farms in scenarios S4 and S5. Since scenario S4 includes credit for small farmers, the trend of land concentration that was captured by scenario S3 (until 2010) is halted. In scenario S5, land concentration continues to increase.

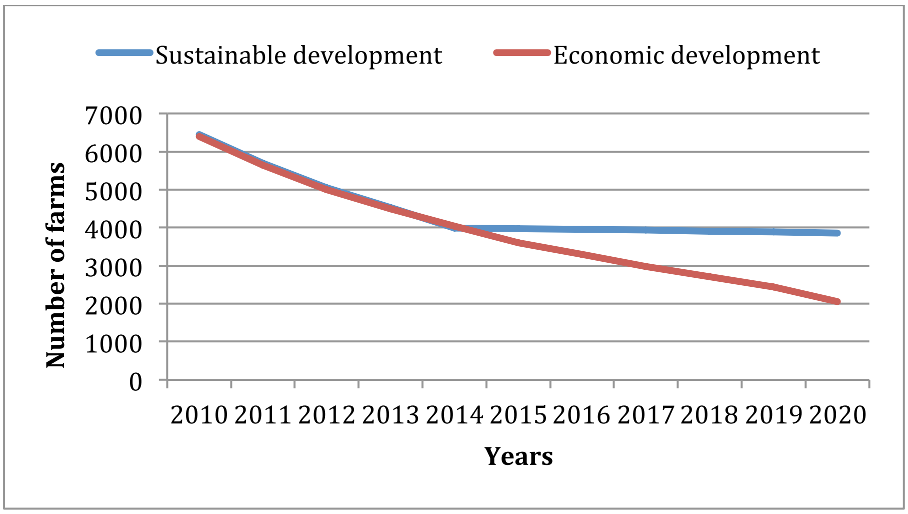

Figure 4-11. Number of farms estimated on scenarios *Sustainable development* and *Economic development* for *2010-2020*

Finally, figures 4-11 and 4-12 show the evolution of the farmers states in scenarios S4 and S5. In scenario S4, there is a significant increase on intensive farming and a large reduction on large-scale extensive farming. Small-scace farming is partially transformed from extensive to intensive. In scenario S5, large scale extensive farming dominates, and most small-scale farmers are led to abandon rural activity. This is consistent with the hypothesis behind the economic development arrangement that privileges credit for large farms without environmental restrictions.

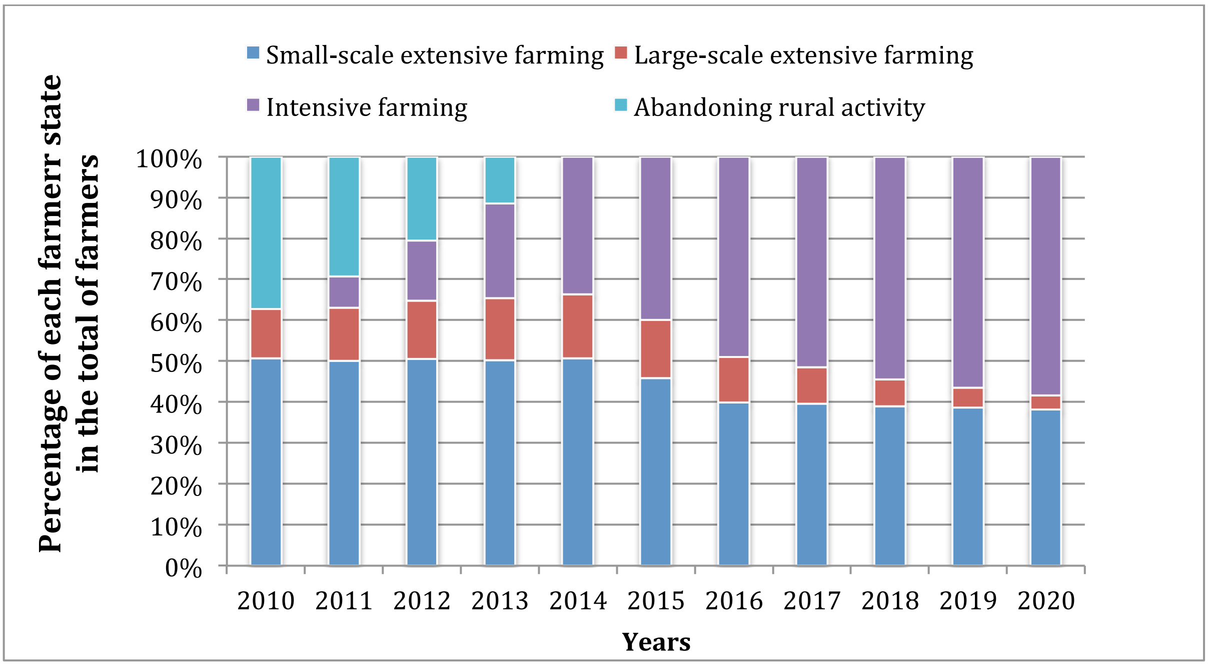

Figure 4-12 Variation of farmer strategies on *Sustainable development scenario for 2010-2020.*

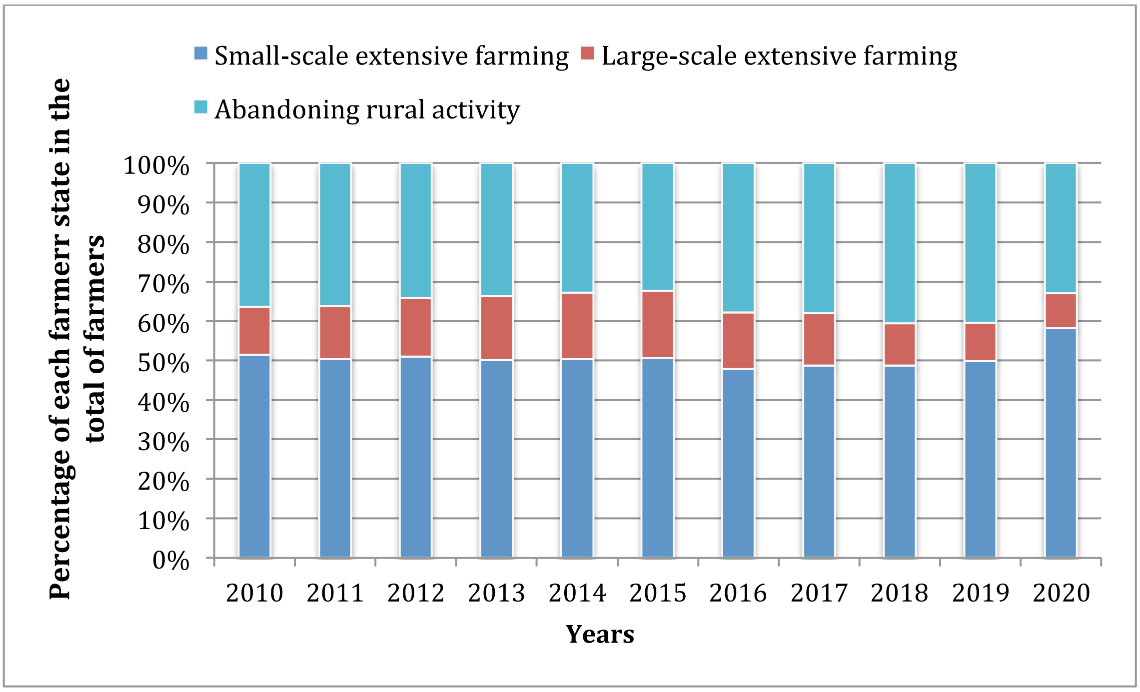

Figure 4-13 Variation of farmer strategies on *Economic development scenario* for 2010-2020

4.4 DISCUSSION

The results presented in this section show the capacities of the model and also its drawbacks. These results are also a good example of the challenges of developing land change models in frontier areas, especially in large ones. As a starting point, one needs to solve the data challenge. Data for frontier areas is hard to get and organize. Even in Brazil, a country that has regular agrarian and population census, data from census may contain significant inaccuracies (as discussed in section 4.2). Land change data derived from remote sensing imagery shows only part of the underlying change. In the case of São Felix, the lack of historical land tenure and land parcel information is a major problem. We don't know exactly how many farms exist in São Felix in each year; let alone their location and size. Thus, we had to make many conjectures in our model.

It could be argued that all agent-based models are based in conjectures about agent behaviour and interaction. The challenge is to make as few conjectures as necessary and also to avoid unnecessary complexity. As Mike Batty states:

> *"The complexity of human systems has meant that right from the first applications, there was continued pressure to develop greater and greater detail – to disaggregate the model's variables to the point where sufficient heterogeneity of the system might be represented in a manner useful to those who sought to use the model to make predictions. (…) Moreover, the key challenge in social systems is to know how much detail to represent. (…) Heterogeneity and hence greater detail is what seems to be required so that ever more plausible models can be constructed.*
>
> *Indeed even in science itself there is substantial questioning of the traditional canons of scientific inquiry as the quest for parsimony, simplicity, and homogeneity is increasingly being confronted by the need for plausibility, richness, and heterogeneity. The question turns on whether or not a simple, parsimonious model that can completely explain a limited set of system characteristics is as useful as one which contains many characteristics which are plausible in terms of the functioning* of t*he system but cannot be proven as being of definitive explanatory value."* (BATTY, 2012)

In the case of land change agents in frontier areas whose productive activity is cattle production, we had to decide what to include and what to leave out. It was natural to include sub-models for pasture expansion and pasture degradation. However, the hard decision is how complex these sub-models had to be. There are many analyses of the effects of extensive cattle production on pasture degradation in Amazonia (MUCHAGATA; BROWN, 2003; VEIGA, 2009; PACHECO; POCCARD-CHAPUIS, 2012). We could have translated these studies into a detailed pasture degradation model. However, the lack of actual data to feed such as model was a major challenge we could not overcome. Moreover, we consider that the simple approach taken in this work was capable of approximating the effects of pasture degradation in a farmer's decision.

A similar problem arose when modelling the interaction between agents. Ideally, the model should contain both a land market and a cattle market where agents interact. However, modelling the cattle market is not easy, requiring data not easily available, since part of the cattle production is sold without official control. Furthermore, the cattle market in Sao Felix is mostly controlled by exogenous drivers, namely the demand for cattle in Pará and in the rest of Brazil. Thus, modelling the cattle market might restrict the expected emergence properties of the agent model, since it would required additional external constraints. Thus, we limited our model to interaction via the land market.

We used the land market as a way to capture the interactions between the large-scale and small-scale farmers. In doing so, we were motivated by census data that shows a large increase in land concentration in São Felix (see Figure 2-4). Our implicit premise is that the economic evolution of the São Felix frontier area follows a similar path as in many other areas in Amazonia. Impoverished migrants are attracted to a frontier area. They carry out hard tasks such as clearing areas for new farms. Once they occupy an area and obtain a land tenure rights, richer investors can buy that land from. Thus, the focus of our model was to be able to capture the "moving frontier" of Sao Felix (see Figure 4-7) and to capture the land change patterns (see Figure 4-6). We believe to have succeeded in our main goal.

A second point concerns the choices between parsimony and complexity. *Is the model more complex than necessary? Would we be able to achieve similar results with fewer constraints? Were the institutional arrangements necessary? Was the finite state machine required?* There is no hard and fast response to these questions. We consider that the *frontier occupation* and the *land grabbing* submodels are needed in all cases. Arguably, we could have written the land market submodel to include proxies for the *support capacity* and the *pasture creation* submodels. This would reduce the number of sub-models at a cost in modularity and clarity. As for the institutional arrangements, we consider they are needed to represent the external conditions that constrain the agents. Recall that occupation in Amazonia results from a balance between external and internal forces. Finally, we could have written the model without the finite state machine, but the cost on modularity and clarity would be significant.

A third point concerns the challenges laid out by Robinson et al. (2007) which we consider below:

- *Is the model limited to questions that involve existing data?*

  In building the model, we made conjectures about missing or incorrect data. For example, we estimated the yearly number and size of farms. Our ability to capture the patterns and extent of deforestation led us to claim that the Agrarian Census misses in-field information (see Table 4-6). This is thus a case of the model going beyond existing data.

Other key point was the model's capacity for representing the frontier evolution and the land concentration. Thus, our results improve our understanding of what happened in São Felix over what he had before and are not limited to questions that involve existing data.

- *What actions, characteristics, and motivations of human actors are directly revealed through data on spatial outcomes?*

No model can claim to reproduce what actually has happened. Our claim is that our model provides a reasonable account of the process of occupation in São Felix from 1998 to 2010. To be able to build such plausible explanation, we include the concept of institutional arrangements to represent the external constraints on agents' decisions. We set up the institutional arrangements based on our account of the history of São Felix (see Chapter 2). Our model shows how the arrangements have influenced the agents in the last decades. The model also proposes plausible explanations about how the land market operates and how land grabbing happens in a moving frontier.

- *How to matching the scale of spatial data to the scale of agent decision-making?*

In our model, this was achieved by design. Agents are farmer and the model operates in farm scale. So, there was no scale mismatch.

- *Are observed land use outcomes the result of competition between multiple agent groups?*

  That is the case in São Felix. This is the reason why our model has two types of agents (large-scale and small-scale farmers). Although this is a simple binary division, it was sufficient to get a plausible explanation of the land change in São Felix.

- *How does the model cope with non-stationarity in time and space?*

  The model uses the concepts of "institutional arrangements" to cope with non-stationarity in time and of "moving frontier" to cope with non-stationarity in space. We believe our model deals with non-stationarity issues.

- *Is there an incongruity between the observations used to fit the statistical model and the agents in the ABM? If so, how does the model deal with it?"*

  Our results show that such incongruity exists. Indeed, it is expected that observations in frontier areas are incomplete and sometimes misleading. Since our aim is to replicate and try to explain the land change patterns, our model is spatially explicit and has in-built coherence. In the initialization and calibration phase, we were able to set robust parameters; as a result, the simulations show more coherence than the census data (see Table 4-6 and associated discussion).

To close this discussion, we believe that our model was able to provide a reasonable account of the occupation process in São Felix. In designing it, we tried to achieve the right level of complexity. We consider to have reached the original goal of showing how the land market, the moving frontier and the institutional arrangements operate in shaping the evolution of deforestation in São Felix. We also show how the model design addresses the Batty (2012) and Robinson et al. (2007).

5 COMPARISON WITH PREVIOUS WORK

In this section, we compare the model we developed for São Felix do Xingu with similar works for modelling land change in frontier areas. This comparison has been guided by the works of Robinson et al. (2007) and Parker et al. (2008). Given the common groups of the models discussed in the second paper and the work of this thesis, we will compare our work to two of those cited in these papers. The first is a model for exploring the life cycle of settlements in Altamira, using the LUCITA (Land use change in the TransAmazonica) framework (LIM et al., 2002; DEADMAN et al., 2004). The second is a model for migration-induced settlements in San Marino, Phillipines, using the MameLuke framework (HUIGEN, 2004; HUIGEN; OVERMARS; DE GROOT, 2006). In what follows, we refer to the first model as the "Altamira model" and to the second as the "San Marino model".

5.1 Model objectives and case study areas

The Altamira model is an ABM for explaining spatial patterns in the Amazon (DEADMAN et al., 2004; CABRERA et al., 2012). Developed in RePast, the model provides an experimental laboratory to explore the effects of different parameters (for example, household composition and soil quality) on patterns of land-use change. The model uses a spatial resolution of 1 ha and the research area is 381,000 ha located in western Altamira, Pará, Brazil. One time step in the model represents 1 year, and the model runs for 30 years (1970–2000).

The San Marino model uses the action-in-context method to build a settlement model for the watershed in the Philippines. The study area is 146,900 ha, and the model has a resolution of 1 ha. One time step in the model represents

1 year, and the model runs for 100 years (1900–2000). Using RePast, the model aims to understand the interaction between migration and deforestation (HUIGEN, 2004; HUIGEN; OVERMARS; DE GROOT, 2006). It models the relation between demography and ethnic identity in a spatially and temporally explicit model. The San Marino model enables one to incorporate life histories from the field into a simulation model.

The first difference between the São Felix model and these three models is the size of the area. Our model covers an area of 10 million ha (100,000 km^2) in a frontier areas, which is about 26 times bigger than that of the LUCITA model, and 68 times that of the San Marino model. The size of the area imposes constraints in the São Felix model. Rather than dealing with individual statements captured by fieldwork, we relied on indirect information (historical accounts, census data and remote sensing images). The Altamira and San Marino study areas covered a bigger time span in terms of settlement, in San Marino going back to the beginning of the 20th Century. Admittedly, we could have performed a detailed fieldwork in the São Felix area. However, it would not have been an easy task to cover a representative sample of the area's history. While the Altamira and San Marino models relied a lot on fieldwork and interviews, we tried to make do with indirect information.

The second important comparison is the objectives of the models. Both the Altamira and the San Marino models aim to describe the settlers' behaviour; the land use patterns emerge as a result. These simulated patterns are then checked using satellite data and fieldwork. They do not building future pathways for the area. The external influences were minimized. Agent's decisions mostly depend on internal considerations, such as local labour pool and land exchange market (for Altamira) and ethnicity (for San Marino). By contrast, the São Felix model considers that land change in Amazonia is driven by a combination of endogenous and exogenous driving forces, following Becker (2005). The historical balance between exogenous and endogenous driving forces in São Felix is captured by the idea of institutional arrangements.

Overall, we consider the Altamira and San Marino models use a canonical perspective of agent-based modelling, that of explaining agents' behaviour and interactions in a closed world. The São Felix model is less concerned with conforming strictly with the conventions of agent-based modelling, but tries to combine ABM techniques with deterministic factors such as government policies.

5.2 Entities, attributes and input data.

The entities used in Altamira model are households, properties and cells. A household is an agent that performs land-use decisions. A household's attributes are its age, gender, capital, and contributing labour. The contributing labour is the labour, in hours per year, which the agent is willing to contribute to farming. Various attributes, such as household size and initial capital, are randomly generated. A household occupies a property of about 100 ha in size. Data for each farm includes its cells, its direction relative to the road and the year it was settled. For each cell, the model keeps track of land use and land cover. The model also keeps track of each cell's location, desired labour, initial fixed cost, maintenance cost, age of the land cover, cessation age, seed requirements, planting density, expected yield, time until production and land cover. Land-cover classes include forest, annual crops, perennial crops, pasture and fallow.

The entities in the San Marino model are agents of different types: location agents, the world agents, and collective agents. A location agent is a grid cell that represents a fixed agent that responds to actions and that may have rules to update its state. The world agent is a set of locations. The world can neither initiate nor respond to actions, but it can contain behaviours that cause its members to be updated. An actor agent is an entity that acts, individually or collectively. Finally, a collective actor agent is an actor that consists of individual actors for which the agent's actions influence all its members. For example, if a collective actor household decides to move, its members (e.g., a father, a mother, and a son) will move too. In the simulation, the collective actor households are members of an ethnic category: *Agta, Ilocano, Ybanag, Ifugao, Kalingha,* or *Tagalog*. The individual actors are members of a household and are classified according to their position in the household, i.e., father, mother, son, or daughter.

There are some similarities and some differences between the São Felix model and the Altamira and San Marino ones. In a similar way as the Altamira model, the São Felix model distinguishes between farms and cells. Each farm has one or more cells. In our model, each cell contains only geographical properties such as land cover and land productivity. Although the Altamira model has more attributes for each cell and each agent, some of these attributes are generated randomly. For the Altamira model, the overall behaviour and the emergence properties are more important than the land cover patterns. The São Felix model has only two types of farmers (low income and high income) and their distribution was inferred based on the Agricultural Census. Since our model's aim was to capture the land cover change patterns, we used as much real data as available.

While the San Marino model is primarily concerned with ethnicity, the São Felix model's primary concern is land tenure and land distribution. Our concern is capturing the inequality of conditions under which Amazonian farmers operate. High-income farmers have had privileged access to credit during most of the last 30 years, whereas support for low-income farmers has increased only in recent years.

5.3 Initialization and land market

The Altamira model initialises the landscape as virgin forest with no settled households and 3,916 available properties. The properties have an average size of about 100 ha. They are arranged along the Transamazonica highway and a series of side roads. These side roads, each about 5 km in size, are at a right angle to the main highway. Each year, households arrive in the region and each occupy an available property. If several properties are available, a household selects the property that is closest to the main road that leads to Altamira. The household randomly chooses how many crops to plant and then randomly selects the crops. The model does not simulate the creation, division or union of farms. The land market is not directly modelled. When a farm fails to produce enough goods to support the household, the family abandons the farm and the land becomes available for another family.

In San Marino, the initial conditions consist of about 1000 actors (roughly 200 households with an average of five members each). The actor and household attributes are randomly assigned. The household spatial distribution is based on where the ethnic groups are. In each model step, a given number of households of a certain ethnicity arrive and find a place to settle. To select a location, they consider factors such as the proximity of co-members of their ethnic group, the slope of the land and the proximity of roads or rivers. When a household actor arrives, he/she searches for a location with a given slope that is within a Moore neighbourhood of the river or a road. The Moore neighbourhood size depends on ethnicity. If an agent does not find a satisfactory farm, it moves in a random direction and repeats the process. Prior to the logging boom, households search for location along the river; afterward, they search for locations along a road. In contrast to Altamira, farms in San Marino can be created and divided during the simulation. When the head of a household dies, the farm is divided amongst the children. If a household is childless, the farm becomes available for occupation by other households. However, similar to Altamira, in San Marino the land market is not modelled directly.

We now compare the differences in land market and land allocation models between São Felix and the Altamira and San Marino models. In the Altamira model, settlers were given 100-ha properties, universally rectangular and generally with 500 m of road frontage and 2000 m deep. These parcels remained relatively stable during the model. The San Mariano model creates settlements along rivers and roads, thus showing how a frontier expands in time. In San Mariano, ethnicity was the dominant factor for attraction and repulsion of new settlers, along the lines of the classic work by Schelling (1971). By contrast, we developed a more detailed model of land allocation for São Felix that tries to represent the moving frontier of a large region. Our land market model is framed after an actual capitalist market, where buying and selling occur. The internal migration patterns are not random. They are created by the market dynamics. Low-income farms settle in frontier areas. High-income farmers come to the area and buy the land from low-income agents who move elsewhere, thus expanding the frontier.

5.4 Decision-making

The Altamira model uses a heuristic for household decisions based on *if-then* decision rules. Upon migration, the family chooses the settlement location and how many and which crops to plant. Households convert or preserve land for cultivation, pasture and fallow according to their needs and resources. Based on the land uses, households can harvest yield and reap revenues. Clean up may be performed after the harvest. Since there many possible alternatives for land use, household choices on the quantity of and preference for crops use random selection (CABRERA et al., 2012). A household's behaviour does not change during the simulation and is homogeneous. To get diversity , the model includes households with different attributes.

The San Marino model uses the action-in-context (AiC) method to represent agent behaviour. This method divides agents in categories, where each category can perform a set of actions. These actions are classified as either Potential Option Paths (POPs) or Potential Option Nodes (PONs). A POP defines a sequence of PONs; each POP consists of at least one PON. The model ranks the PONs. The authors argue that POPs allow temporally explicit modelling because the POPs have an activation year and an end-activation year. For example, only an agent that is a member of the category ‘men’ during the period 1900–1950 is allowed to perform the POP ‘GetMarried1900–1950’ (HUIGEN, 2004). The model includes changes in behaviour that depend on the category of the agents and the time period.

The São Felix model has some decision-making aspects similar to the Altamira, some to the San Marino one, and some unique features. Like the Altamira model, the farmer’s revenue comes from his use of the land. The Altamira model has much detail concerning how the farmer earns money from the land. The model represents how a farmer acts over a long period and allows for different strategies of land use, including perennials, annuals or pasture. Decision-making in the São Felix model is much simpler. There is only one type of land use (cattle production) associated to land degradation and to a land market. As it is often the case on ABM, complexity by itself does not improve the explanatory power of a model. Complexity should be only pursued when necessary. We consider the details of the Altamira model were required because of the models’ objective. For São Felix, even with a simple decision-making procedure, the model had enough explanatory power to meet its goals.

The decision-making models of the San Marino and the São Felix model both use externally defined temporal conditions. In both cases, the history of the regions was used to define period when the external conditions were deemed constant and periods of change. This external forcing reduces the power of these models to produce emergent behaviour since changes in external conditions constrain the model.

6 CONCLUSION

This thesis presents an agent-based model of land change in frontier area in the Brazilian Amazon. The main purpose of our work was to develop a model that represents the land change trajectories in São Felix do Xingu region from 1970 to 2010. Since our model was able to approximate the actual land use patterns, we consider that it has satisfactory explanatory power. Thus, we used the model to develop possible scenarios of land change for this region from 2010 to 2020.

Agent-based models, when properly conceived, have good explanatory power. However, building ABMs for complex problems is hard. As (Couclelis 2002) puts: *"Agent-based modelling meets an intuitive desire to explicitly represent human decision making. (...) The question is whether the benefits of that approach to spatial modelling exceed the considerable costs of the added dimensions of complexity introduced into the modelling effort."* The experience of building the São Felix model is a good example of the challenges of agent-based modelling of land change.

The theory of agent-based modelling is still on a state of flux. The basic idea is enticing: complex behaviour emerges from agent interaction with themselves and the environment. However, there are multiple ways of building agent-based models. In the existing literature on agent models (HEPPENSTALL et al., 2012) and in specific reviews of ABMs for land change one can sense different ways of model building (PARKER et al., 2003; ROBINSON et al., 2007; PARKER et al., 2008). The current proposals for standard description of ABMs such as the ODD framework (GRIMM; RAILSBACK, 2012) focus on common ways explaining such models. The ODD framework allows for considerable variation in model design, as long as certain features are present. The expected properties of ABMs include emergence, adaptation, sensing, and interaction. Thus, agent-based modelling is better framed as a way of model building rather than a concrete theoretical framework.

Arguably, the crucial decision of designers of ABMs is whether to use a "closed world" or an "open world" assumption. The textbook examples of ABMs such as Schelling's segregation model use a "closed world". All of the conditions needed to run the model exist in the model. Given the model's initial condition, the rest follows without external intervention. In closed worlds, it is easier and more straightforward to derive emergent properties from agent interactions. The Altamira model (DEADMAN et al., 2004) is a good example of the use of closed world models for land use change. Once the conditions for settlements are set, the model runs without outside control.

Once the modeller's aims go beyond deriving emergent properties and include reproducing real-world situations, the closed world assumption is no longer tenable. The San Marino model (HUIGEN; OVERMARS; DE GROOT, 2006) is a case in point. The model uses external information to change agent behaviour and interaction, since it tries to capture actions that occurred within a known historic context. When one uses an open world context, it is no longer possible to apply the same criteria to analyse and judge ABMs. Agent interactions no longer generate emergent patterns by themselves, but are better conceived as reactions to external conditions. The open world assumption breaks the standard ABM paradigm.

The São Felix model is a good example of an open world ABM. It uses some of the basic ABM tenets. There is agent interaction through the land market and the agents retain some decision-making power leading to frontier expansion. The environment reacts to agent's decision through the land's support capacity. Nevertheless, when we impose external constraints through the idea of institutional arrangements, the model is no longer a "canonical ABM". The other constraint is the use of population and agrarian structure data to derive parameters and to calibrate the model. Without such external data, the model could not have reproduced the actual land change patterns. Thus, the São Felix model shows that compromise is required when applying ABMs to represent real-world land change patterns.

The experience of designing the São Felix model is relevant to future work on land change in frontier regions. First, it shows that closed world models are not realistic for modelling land change in big areas. Second, it shows that markets for land ownership and for land produce are an essential part of these models (a conclusion supported also by the Altamira model). Third, public policies of environmental control and credit availability need to be represented explicitly. Finally, capturing the environment's support capacity increases the model's explanatory power.

Looking ahead, one should consider in what ways the São Felix model could be improved and extended to other areas. As a starting point, all of the its submodels need improvements, especially the land market and the support capacity one. The farm production model would need to be much enhanced., to include different types of land produce, and changes in the farmers' strategy for land use. The market for the land products needs to be explicitly modelled. The idea of institutional arrangements needs to be extended to consider spatial variations. Arrangements that hold for a region in a period may not be valid for a different region in the same period. All of these improvements show that building ABMs for land change is a difficult matter, since it requires careful consideration of decision-making. The researcher also needs to collect data to support and parameterize his model.

We believe that the ideas of institutional arrangements and states can help reduce somewhat the complexity of agent-based modelling of land change. However, researchers on this area need to be aware of the considerable challenges involved. To sum up, the São Felix model is a good example of the challenges of building an ABM for land change in frontier. We hope that the lessons learned in this work can support future work.

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