Land use and land cover dynamics in the Brazilian Amazon: understanding human-environmental interactions

Luciana de Souza Soler

Land use and land cover dynamics in the Brazilian Amazon: understanding human-environmental interactions L.S. Soler 2014

Land use and land cover dynamics in the Brazilian Amazon: understanding human-environmental interactions

Luciana de Souza Soler

Thesis committee

Promotors

Prof. Dr A. Veldkamp
Dean of the Faculty of Geo-Information Science and Earth Observation (ITC),
University of Twente, Enschede, The Netherlands

Prof. Dr P.H. Verburg
Professor of Environmental Spatial Analysis
VU University Amsterdam, The Netherlands

Co-promotor
Dr K. Kok
Assistant professor, Soil Geography and Landscape Group
Wageningen University

Other members
Prof. Dr A.K. Bregt, Wageningen University
Dr M.A. Slingerland, Wageningen University
Prof. Dr W.T. de Groot, Leiden University, The Netherlands
Dr M. Batistella, EMBRAPA Satellite Monitoring, Campinas, Brazil

This research was conducted under the auspices of the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC).

Land use and land cover dynamics in the Brazilian Amazon: understanding human-environmental interactions

Luciana de Souza Soler

Thesis
submitted in fulfillment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus
Prof. Dr M.J. Kropff,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Tuesday 30 September 2014
at 1:30 p.m. in the Aula.

Luciana de Souza Soler
Land use and land cover dynamics in the Brazilian Amazon: understanding human-environmental interactions,
186 pages.

PhD thesis, Wageningen University, Wageningen, NL (2014)
With references, with summaries in English and Dutch

ISBN: 978-94-6257-088-7

TABLE OF CONTENTS

Chapter 1 - General introduction

1.1 Relevance

The Amazon forest is undoubtedly the world's most important hot spot of deforestation that has been argued to compromise crucial environmental services for both the regional and global population (Fearnside, 2008a; Gullison et al., 2007). Three main points of view can characterize the scientific efforts in studying the environmental and human aspects of the Brazilian Amazon. First, the importance of the Amazon forest in regulating biogeochemical, water and climatic cycles and how human activities affect this balance, which have been the primary motivation of most scientists (Aragao et al., 2007; Cardoso et al., 2009; Cox et al., 2000; Malhi et al., 2009; Marengo et al., 2008; Nobre et al., 1991). Then, sociological and anthropological studies have emphasized the importance of the Amazon biome in understanding how forest conservation is related to cultural and ethnical diversity, and how forest conversion can be explained by socioeconomic issues and human occupation hierarchies (Brondizio, 2004; Browder et al., 2008; Costa, 2007; Evans et al., 2001; Hecht, 2007; Ludewigs et al., 2009; Moran et al., 2003; Perz, 2005; Pfaff et al., 2007b; Walker et al., 2002). Finally, there is the investigation of viable and rather sustainable land use practices engaged to keep Amazonian ecosystems resilient (Becker, 2010; Carvalho et al., 2001; Cunha and Almeida, 2001; Hecht and Cockburn, 1989; Pinho et al., 2012; Santos Jr. and Lena, 2010; Schneider et al., 2000), which is the context of this thesis.

Different from other inhabited areas in the globe, the relevance of studying the role of feedback mechanisms in the Amazonian deforestation frontier lies on the fact that the standing forests still pose a number of constraints to economic development, but at the same time provides the ideal configuration to sustainable practices of land occupation, depending mostly on past and present policy history (Becker, 1995; Costa, 2010; Hecht, 2007; Ludewigs et al., 2009; Muchagata and Brown, 2003; Padoch et al., 2008; Turner II et al., 2004). In this context, land use and land cover modeling is a powerful learning tool, also in relation to policy making regarding land occupation issues (Aguiar, 2006; Overmars and Verburg, 2006; Rindfuss et al., 2004; Soares Filho et al., 2006; Veldkamp and Verburg, 2004;

Verburg et al., 2006), but its limitation in modeling feedbacks interactively is still present (Parker et al., 2008; Verburg, 2006). This is not only because of computational problems, but also because of the conceptual difficulty in equalizing the distinct approaches adopted by modelers and social scientists to explain land use and land cover change far beyond (Ostrom et al., 2007).

Human's response to land use/cover changes is partly subjective and, therefore, new frameworks are required to tackle this subjectivity, such that research conducted by spatial modelers remains robust and reproducible. We propose to use a combination of empirical statistical models (representing state-of-the-art in spatial modeling) and fuzzy cognitive methods (developed from social studies). This proposed combination can help us to better understand feedback loops between local population and land cover changes considering current and historical socioeconomic aspects, land distribution issues and biophysical conditions of the land. Thus, the main objective of this thesis is to analyze Amazonian land use and land cover pattern dynamics in order to identify the underlying system dynamics. By combining static and dynamic methodologies, system feedbacks within this non-linear human-environmental system can be explored for more sustainable development pathways.

1.2 The Amazonian frontier

"All I will describe here, is a sight testimony of a man to whom God's will was to give the privilege of a never before seen discovery, like the one I am about to tell (…) in here we heard about the *Amazonas* and its natural treasures that can be found deep into the region (...) the available land is good, so fertile and natural just like ours in Spain; as we entered through São João the native people had started burning their fields. It is temperate land, from where we can harvest a lot of wheat and crop many fruit trees. Also, the land is suitable for any type of cattle as it grows many herbs."

The citation above, extracted from Ribeiro & Moreira Neto (1992), is a written register of the first relevant expedition down the Amazon river by the Spanish conqueror Francisco de Orellana in the XVI century. It reflects the misread view of never ending resources in vast unpopulated spaces, also referred as 'free lands' by Turner to legitimate land appropriation in the American West (Turner, 1893). It is known that both regions – the American West and the Amazon forest – had been home for native people long before colonization. Thus, the text above reflects that Portuguese and Spanish colonizers had a similar view to Turner's work regarding the idea that the 'free lands' could only become a suitable place to live through economic activities such as non-wood forest products exploitation, cattle raising and cropping. Not surprisingly, the embedded idea of *wilderness* and *uncivilized* space full of enrichment opportunities have still been used to justify deforestation in the Amazon forest and the establishment of the capitalist production systems in detriment of traditional survival strategies (Santos Jr. and Lena, 2010).

The agricultural economic system established in Brazil in the XVI and XVII centuries was characterized by large scale sugarcane plantations based on *latifundia* and slavery. In the late XVII century labor force through slavery was gradually substituted by wage labor of European migrants, but land concentration was maintained by entrenched oligarchies who controlled the land prices to hinder wage laborers to acquire large amounts of land (Monbeig, 1984). Since then, not much had changed in the Brazilian land distribution structure, especially in the recent frontiers of occupation, which consequences have determined the geographic distribution of the agricultural/grazing activities in the XIX century in the center-north of Brazil, and later in the Amazon region. There, land occupation has been legitimated by development policies justified as a response to social conflict, but years later strongly criticized by the society and the funding institutions whose financial support was firstly thought to meet an international agenda nowadays seen as paradox to environmental issues (Becker, 2004; Fearnside, 2003; Lemos and Roberts, 2008).

1.3 Overview of the study area

The lack of convergent agendas between development and environmental policies is usually charged for the official estimates of 18% on total forest loss in the Brazilian Amazon (Becker, 2005; INPE, 2008). Beyond the official numbers, some authors have also indicated that much larger areas are under intense human pressure, at risk of deforestation or already with degraded forest hard to be monitored by satellite images (Asner et al., 2006; Barreto et al., 2005; Laurance et al., 2004). Rondônia State is a good example of forest depletion and degradation that have been motivated by divergent policies.

Rondônia was part of Mato Grosso and Amazonas States until 1943, having rubber extraction and extrativism of native fruits (e.g. Brazilian nuts) as the main economic activities during 40’s and 50’s (Pedlowski et al., 1999b). On the other hand, the colonization in Mato Grosso was strongly linked to gold mining, but since the 50’s, when Rondônia and Mato Grosso were connected to Brasília by the federal highway BR-364, the region has been occupied by loggers, large ranchers and more recently by grain producers. Around this period Rondônia reached the status of an independent State to where the federal government stimulated migration in order to dampen land conflicts and labor surplus in the south-center of Brazil, where long term established agriculture was intensified. Fiscal incentives were granted to agricultural companies as well as distinct land ownership rights and subsidies were given to large and small farmers coming from the South and Central parts of Brazil.

Until the mid-80's deforestation was not considered an environmental issue by governmental institutions. As a consequence, farmers have deforested most of their land as a way to guarantee land tenure and subsidies (Becker, 2005; Machado, 1998). The growing concern with land use change impacts on climate, soil and water availability, and more recently with social/socioeconomic impacts, compelled Brazilian government to increase law enforcement over titled and unclaimed land (Brasil, 2008; Fearnside, 2003; Jenkins and Joppa, 2009; Lemos and Roberts, 2008; Nepstad et al., 2006b). Nowadays, land speculation and illegal appropriation have still triggered several land conflicts affecting socioeconomic development, social equality and especially environmental conservation. The old-fashioned land occupation strategies have been claimed to cause a vicious boom and bust development cycle that causes land degradation and social impoverishment (Celentano and Verissimo, 2007; Rodrigues et al., 2009).

Population pressure through migration has decreased in the last decade in the Brazilian Amazon, but population growth still plays an important role in land use patterns. Aging of householders, land impoverishment, migration of offspring and farmers capitalization shall promote lots consolidation and (re)concentration, with the predominance of cattle ranching activities (Ludewigs et al., 2009; Pacheco, 2009; Walker et al., 2000). Therefore, medium to large farmers hold influence on land use and land distribution structure. In this context, a new trend raises in which land use intensification appears as a suitable option to preserve land assets as familiar units able to sustain their livelihood have much larger probability to keep their lots and avoid land accumulation. Land use intensification have been indicated among different farm size groups, which includes the increase of labor availability, machinery, accessibility to markets and crop yield, especially in well-established and better accessible areas such as along the BR-364 (Browder et al., 2008;

Costa, 2010; Evans et al., 2001; Faminow, 1997; Moran et al., 2003; Muchagata and Brown, 2003; Perz, 2005; Vosti et al., 2002; Walker et al., 2000).

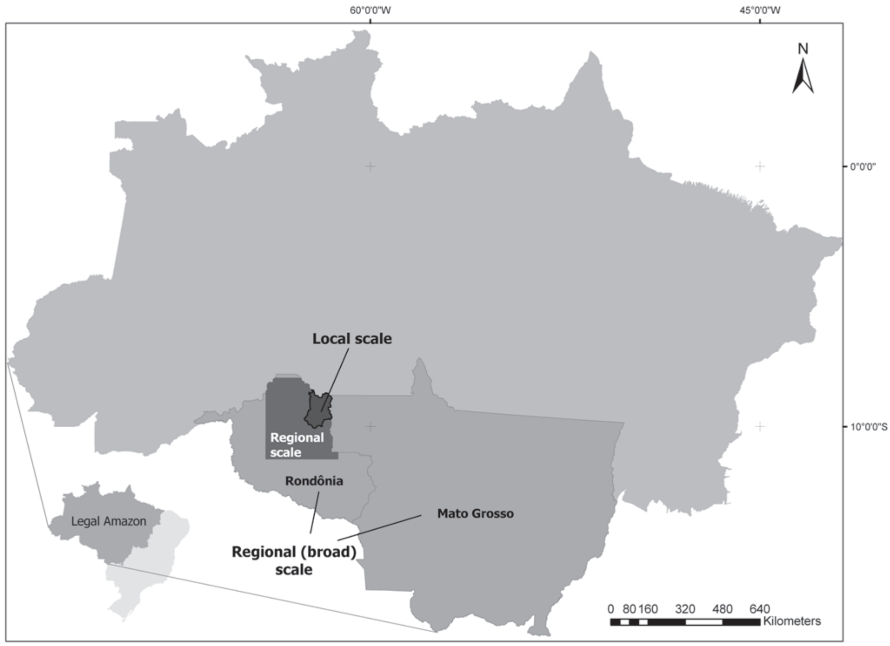


Figure 1.1 – Overview of the study area enclosing Mato Grosso and Rondônia States (at regional broad scale). Geographical areas of case studies in Rondônia at the regional and local scales are indicated by the darker areas.

Eight South American countries share the Amazon forest territory of 7.5 million km^2 that is home for 30 million inhabitants, from which 22 million are in Brazil. It is estimated to hold fifty percent of Earth's total biodiversity and twenty percent of total freshwater of the planet. Eighty five percent of The Amazonian biome is contained within the 8,5 million km^2 of the Brazilian territory (IBGE, 2004). The Brazilian Amazon – considered here as the Amazon biome summed to inner and bordering transitional areas of savannah (*Cerrado*) vegetation – can be also called as the Legal Amazon, which is a political border created during the military government. It encloses nine Federal States from which Rondônia and Mato Grosso are the focus of this thesis, representing the case study at the regional scale. Their original forest coverage represented 99 and 54% of its respective territories of 237 and 903 thousands km^2. They are located in the center-western portion of Brazil bordering Bolivia, according to Figure 1.1.

The region's original vegetation classified as dense tropical rain forest, also presents some spots of savannah in the north of Rondônia and large ones in the center-south of Mato Grosso. Climate and soil fertility are more prone for large scale agriculture in Mato Grosso, while in Rondônia agrarian structure dominated by small farmers tend to create a mosaic of land use/cover types.

The investigation of human-environmental interactions can be especially interesting when dealing with different spatial scales that reveal multi-faced aspects of how farmers' behavior and land occupation history determine the dynamic of land use systems. Therefore, two other spatial scales were adopted: the north of Rondônia at the regional scale and two municipalities at the local scale (Machadinho d'Oeste and Vale do Anari), both supported by interviews at the household level. Their location and spatial extent are illustrated in Figure 1.1. Thus, three levels of analysis consider different territorial units from the municipality level then agrarian project, and finally to the property level, allowing the investigation of human-environmental interactions related to land use and land cover change dynamics over different spatial scales.

1.4 Methodological approaches

Land use and land cover change modeling has been used as an important learning tool to comprehend the role of land use systems and the environmental sciences involved through appropriate governance (Aguiar et al., 2007; Claessens et al., 2009; Overmars and Verburg, 2006; Soares-Filho et al., 2006; Verburg and Veldkamp, 2004). However, complementary and innovative approaches should be considered when generalizing results from localized case studies to distinct spatial extents, or spatial- temporal scales, with similar changes in land cover and human activities (Mertens and Lambin, 1997; Overmars and Verburg, 2005; Scouvart et al., 2007; Walker et al., 2004). Therefore, different methodological approaches are used in this thesis to explain land use and land cover changes and to describe human-environmental interactions, according to the spatial scale considered.

In order to quantify and explain land use/cover changes across different levels of social organization (property, community and municipality levels), different data sources were adopted including household level interviews, remote sensing and census data; allowing for distinct and comparable drives of change that act at different spatial extents. By combining household level data to remote sensing analysis at regional scale, an in-depth understanding of socioeconomic differentiation among small households and ranchers came into sight. It then reaffirmed long term land use change studies at different parts of the Amazon concerning aspects of human ecology dependent on historical and geopolitical issues (Browder, 1994; Browder et al., 2008; Evans et al., 2001; Moran et al., 2003; Perz and Walker, 2002). These results lead us to a comprehensive view of the landscape and community levels, which was revealed by a local exploratory analysis of deforestation and secondary forest determinants adopting different spatial extents. At both scales, local and regional, there were indications that land distribution strongly determined the spatial variability of agricultural land use types, and at smaller extent of pasture land.

Such spatial variability was tackled at the regional scale when adopting census data at the municipality level in two deforestation frontiers: Rondônia and Mato Grosso States. Despite agricultural census data limitations, it has been considered by the scientific community as the most complete and official source of agricultural and population statistics to Brazil. At the regional level land accumulation, spatial policies, accessibility to infrastructure and innovative/traditional land use choices of householders were investigated by using descriptive and exploratory analysis. Distinct spatial concentration of farm size groups under the same drivers´ influence are believed to transform the frontier of expansion differently by evolving to specific land use systems and distinct intensification processes.

Linking the evolution of land cover changes through remote sensing, census data and fieldwork interviews can be at the same time a comprehensive and a contradictory strategy to understand the interactions between human actions and the environment. This is because the combination of remote sensing data to household level analysis, complemented by a broad view with census data can result in a multifaceted view of human-environmental systems that not surprisingly diverge in space and time according to the spatial scale (Overmars and Verburg, 2006). On the other hand, when similar or correlated findings are revealed over different scales, the challenge lies on the adoption of innovative methods that tackle the subjectivity of qualifying, and possibly quantifying, the importance of human-environment interactions and feedback mechanisms.

As a result, the adoption of fuzzy cognitive maps linked to spatial data analysis is proposed in this thesis as an alternate tool that partially fills the gaps of spatial models in dealing with subjective information, especially in scenario analysis. It is evident that this approach does not substitute the importance and utility of spatially explicit modeling. Instead, it can be used as a complementary method to support such models regarding inherent limitations to mention: the lack of spatial data, the understanding of relevant feedback mechanisms (usually of difficult dynamic implementation) and the lack of methods to link spatial data and scenario development to estimate the amount of land use/cover change. Finally, a final discussion is presented about the limitations of the proposed method in filling the existing gaps of spatially explicit models of land use and land cover change regarding the human-environmental interactions.

1.5 Research objectives and thesis organization

This thesis research was carried out as an integrative part of a research project called "Vulnerability and resilience of the Brazilian Amazon forests and human environment to changes in land use and climate' financed by the Foundation for the Advancement of Tropical Research (WOTRO) of the Netherlands Organisation for Scientific Research (NWO). The project started in 2005, with two post-doc researchers and three PhD students, including the one resulting in this thesis. This team had the support of a group of supervisors from both the Netherlands and Brazil aiming to investigate the different aspects of the Amazon system that have kept it a resilient ecosystem, despite of the disturbances on forest coverage, climate and social systems. Thus, the main objective of this thesis is to analyze Amazonian land use and land cover pattern dynamics in order to identify the underlying system dynamics. By combining static and dynamic methodologies, system feedbacks within this non-linear human-environmental system can be explored for more sustainable development pathways.

In chapter 2 deforestation and secondary forest patterns are statistically modeled at the local scale, over different spatial extents that consider the agrarian projects and municipality levels of organization, aiming to explain why and where land cover change occurs and who drives it. The pre-existence of key research results in a socioeconomic and land regime context as well as a spatial database of land use/cover maps were determinant in choosing the municipalities of Machadinho d'Oeste and Vale do Anari as the local scale case study (Alves et al., 1999; Batistella, 2001; Batistella et al., 2003; Escada et al., 2005; Fearnside, 1986; Miranda et al., 2002).

In chapter 3, household level data organized in questionnaires were collected during two fieldwork campaigns in 2006 and 2008. The questionnaires were applied to reconstruct the land use/cover change history at the property level taking into account accessibility measures, soil fertility, property size and distinct years of establishment of agrarian projects. In order to identify similar interactions between land cover dynamics and the spatial policies at the regional level, the results at the household level were compared to remote sensing data stratified according to zoning areas that allow distinct land use practices. In addition, accessibility maps to local and regional infrastructure, roads density and property size influence on deforestation were also tackled at the regional level.

In chapter 4, the central theme is the investigation of the interactions between market chain dynamics and the evolution of land systems. By identifying land use changes in relation to the land distribution structure, we determined different levels of agricultural intensification that could drive favorable scenarios for family farming and/or agro-industrial systems.

Considering the household level interviews together with workshops involving stakeholders for scenario analysis (under the scope of the Post-doc research projects), it was possible to identify a number of land use/cover transitions and likely scenarios. They formed the basis to understand existing interactions that would dampen or accelerate deforestation or degradation. In chapter 5 the implementation of the feedback mechanisms in fuzzy cognitive maps are linked to spatial data and expert knowledge, in order to allow for a semi-quantification of human-environmental interactions in alternative development scenarios.

Finally, in chapter 6 an overview of the findings at distinct extents indicates the relevant feedbacks within spatial scales as well as feedbacks that operate across the different scales. In particular, the feedback loops between deforestation, secondary forest regrowth, accessibility to facilities (health, education, and public services), fires and dry season severity are explored at local scale. Also, feedback loops are explored at regional scale within deforestation, accessibility to markets, land prices, soil fertility, fires, dry season severity, perennial or annual crops, pasture, agro-pasture revenue, labor availability and machinery (tractors). These feedback loops were identified under the perspective of land use intensification (chapters 2, 3 and 4) and explored taking into account the external demand for products and pressure for nature conservation (chapter 5). To contextualize the results found in previous chapters, the relevant feedback loops are listed in chapter 6 and discussed regarding their possible utility to support sustainable land systems. Next, it is discussed the lessons learnt from assembling results of all chapters, especially on how feedbacks loops related to local choices can indicate successful sustainable alternatives, and how they can be reinforced by recently public policies of forest conservation to improve living conditions . At last, in chapter 6 it is discussed the usefulness of putting the data, methods and tools used in this thesis in a broader, conceptual socio-ecological context.

Chapter 2 - Quantifying deforestation and secondary forest determinants for different spatial extents in an Amazonian colonization frontier (Rondônia)[1]

Abstract. Spatial patterns of deforested areas and secondary forest are analyzed in terms of the spatial variation in location factors at different spatial extents. The spatial extents considered are old and new agrarian colonization projects and the administrative units of two different municipalities in Rondônia: Vale do Anari and Machadinho d'Oeste. A grid database was constructed including land cover and potential location factors based on biophysical, accessibility, socioeconomic and policy data. Results of the spatial analyses confirmed the hypothesis that different extents yield different relationships between land use/cover patterns and their location factors, particularly between old and new agrarian colonization projects. It emphasizes that current patterns of forest, secondary forest and pasture/agriculture can only be understood with a combination of policy, accessibility, biophysical and socioeconomic factors while accounting for the historical pathways of change. Because we are dealing with different trajectories of land use/cover change, static analysis of the spatial pattern without acknowledging these trajectories will lead to erroneous interpretations of the current and future land use/cover dynamics.

[1]*Based on:* Soler, L.S.; Escada, M.I.S.; Verburg, P.V. Quantifying deforestation and secondary forest determinants for different spatial extents in an Amazonian colonization frontier (Rondônia), Applied Geography 29 (2009), 182-193. doi:10.1016/j.apgeog.2008.09.005

2.1 Introduction

During the last decades human colonization has caused the loss of 17% of the forest in the Brazilian Amazon. Rondônia State is now the fourth most deforested state in the region with deforestation rates fluctuating from 1110 to 4730 km^2/year between 1988-2007 (INPE, 2007). Known impacts of such land cover changes are losses in biodiversity, increases in carbon release and changes in the water cycle and regional climate, potentially affecting local communities and indigenous people (Millikan, 1992; Miranda and Mattos, 1992; Southworth et al., 1991; Werth and Avissar, 2004). In order to assess these impacts, several analyses of the determinants of deforestation have been done for the Brazilian Amazon at different scales (Dale et al., 1994a; Soares-Filho et al., 2001; Soares-Filho et al., 2006). These studies confirm that the spatial variability of location factors as proximate drivers strongly affect the patterns of deforestation in the Brazilian Amazon (Aguiar et al., 2007; Arima et al., 2005b; Soares-Filho et al., 2006). However, the results of the analysis of land use/cover patterns and their determinants are dependent on the spatial extent and the spatial resolution of analysis (Gibson et al., 2000).

Amazonian spatial variability, as exemplified by different land cover patterns within the same region, appears to be associated with differences in colonization history, actors, economic activities, public policies and sometimes with biophysical aspects (Batistella, 2001; Cochrane and Cochrane, 2006; Escada, 2003; Fearnside, 2005). At the Amazonian scale different deforestation patterns appear to be linked to geopolitical frontiers with locally diverse ecological, socioeconomic, political and accessibility conditions (Aguiar et al., 2007; Becker, 2004). Although significant, these results are not directly applicable to regional and local scale studies due to scale effects related to extent and resolution (Veldkamp et al., 2001b). Furthermore, a more local analysis requires the distinction of more land cover categories, such as secondary forest, allowing more direct links to land use/cover and local actors. A main topic in the Brazilian Amazon is the analysis of secondary forest patches inside colonized areas, because their dynamic can indicate different aspects of land management and actors decisions (Alves et al., 2003). Beyond the relevance of secondary forest to carbon budgets, climate change and biodiversity (Dale et al., 1994b; Hughes et al., 2000), from the human dimension point of view, secondary forest dynamics potentially yield valuable information about household decisions (Perz and Skole, 2003). The link to household decision making is especially important to comprehend land dynamics in areas where small landholders predominate such as Rondônia State (Fearnside, 1993).

Rondônia is predominantly occupied by small landholders as a result of colonization projects created along the major roads in the 70's (Becker, 1997). The constant flux of migrants demanded colonization of new areas far from the major roads, such as Machadinho d'Oeste and Vale do Anari municipalities, created in the 80's. They present similar biophysical characteristics and lots sizes, but with significant differences in their spatial configurations and planning (Batistella, 2001). Within these municipalities there are two different generations of agrarian colonization projects, old projects created between 1980 and 1990 and new ones created between 1990 and 2000. Agrarian colonization projects in Vale do Anari are typically drawing-table plans characterized by the well-known fishbone patterns, while Machadinho's agrarian colonization projects were better planned taking local biophysical conditions into account leading to dendritical deforestation patterns. This offers us the possibility to investigate how spatial variability of proximate land cover change drivers contributed to the different deforested area and secondary forest patterns over different spatial extents.

Many different methods have been used to identify location factors of land cover (Briassoulis, 2000; Koomen et al., 2007) with statistical models being one of the most common techniques to quantify the contribution of land use/cover determinants at various levels of analysis (Aguiar et al., 2007; Verburg and Veldkamp, 2004). Particularly, logistic regression is often used because the resulting probability maps can directly be used in land use/cover change models (Lesschen et al., 2005; Mertens and Lambin, 1997). Statistical analysis using field observations together with remote and census data can reveal the driving factors acting from the household level to higher levels of organization (Perz and Skole, 2003; Rindfuss et al., 2004). As a result, statistical land cover models of deforestation and secondary forest patterns at local scales can provide insights about the underlying processes of land cover change. Such insights might help governmental and non-governmental organizations to target more effective deforestation policies. (Fujisaka et al., 1996; Verburg, 2006). The present chapter aims to identify differences in the location factors of deforested areas and secondary forest patterns in 2000 over different spatial extents in Machadinho d'Oeste and Vale do Anari municipalities using logistic regression analysis.

First, the land use/cover history in the study area is described, followed by a short review of existing land use/cover studies which relate directly to the study area. Subsequently the study area and all collected data are described including the statistical methods employed. The results are presented for different spatial extents. The final section discusses the general outcomes of the chapter 2.

2.2 Land use/cover processes in Rondônia

The colonization of Rondônia began during the 70's with the establishment of agrarian projects along the main road BR 364 (see Figure 2.1a). Colonization was stimulated with easy credit for housing and subsistence agriculture (Becker, 1997). The National Institute of Land Reform (INCRA) built secondary roads to connect the agrarian projects to urban areas as part of the governmental support to the migrants. However, agricultural extension, health, education and transport were usually incipient (Coy, 1987). During the 80's and 90's INCRA established new agrarian projects with smaller lot sizes to allocate a larger number of families. In this context, Machadinho d'Oeste and Vale do Anari settlements were established in 1982 in the northeast of Rondônia State with initial areas of 2129 and 1246 km^2, respectively. Until 2000, INCRA created 14 more agrarian projects in the vicinities of the initial settlements. Continuous migration pushed the government to split the area into two municipalities in 1997, which names were taken from the very first settlements Machadinho d'Oeste and Vale do Anari. Today, the area of these new municipalities encloses the initial and subsequent agrarian projects, including conservation reserves and claimed or unclaimed lands in the neighboring areas (Figure 2.1b).

As can be observed from Figure 2.1a, the old agrarian projects are more deforested than the new ones. Another aspect is that the pattern of deforestation in Vale do Anari municipality has a typical fishbone pattern, while in Machadinho municipality the patterns are dendritic. This difference can be explained by the different ways of planning. The Anari settlement was planned two years earlier and this was done behind a drawing-table without taking the local topography into account. Machadinho, was planned with roads following the watershed topography. Although different, both patterns follow the design of the roads and the proportional amount of deforestation between them has been quite similar along the years of colonization (INPE, 2007). However, the dendritic patterns in Machadinho appear to result in less fragmented forest, what is reinforced by several conservation reserves spread within the agrarian projects of this municipality (Batistella, 2001).

There is still an ongoing debate at the Amazonian scale what the contribution of different land owner categories is to deforestation. Fearnside (1993) showed that deforestation occurs mostly in medium (100-1000 ha) and large farms (>1000 ha) in the Brazilian Amazon. However, in the northeast of Rondônia, originally occupied by small landholders, most of the deforestation between 1991 and 1997 was due to clearings between 50 and 100 ha (Alves, 2002), indicating that cattle ranchers tend to bought up the smaller holdings and combined them to larger farms. Similar indications that small landholders have sold their farms to cattle ranchers are observed in Rondônia (Mello and Alves, 2005; Pereira et al., 2007). On the other hand, in Pará State where cattle raising activities are increasing among small landholders (Walker et al., 2000), an increase in overall deforestation was observed during 2006-2007 (Souza Jr. and Verissimo, 2007).

Secondary forest plays an important role in smallholder farm management and related decisions. Due to law enforcement concerning forest remnants, high cost of deforestation and poor soil fertility most small landholders tend to slash and burn young secondary forest every 2-3 years. Slash and burn is a common practice to increase the soil fertility, to reduce weeds and to renew pasture (Dale et al., 1994a; Pedlowski and Dale, 1992; Pedlowski et al., 1997). In some cases, these landholders either abandon their lands resulting in the growth of old secondary forest, or they sell off their land in a process of land concentration leading to land use intensification. This intensification occurs mainly in older settlements, as a result of family aging, unsteady profit margins of agricultural products, decrease in land productivity, decrease of labor availability and diseases (Escada, 2003; Millikan, 1992). Land concentration processes are also found in other areas in Rondônia (Pedlowski and Dale, 1992; Pedlowski et al., 1997) and in Pará State (Mertens et al., 2002; Perz, 2001).

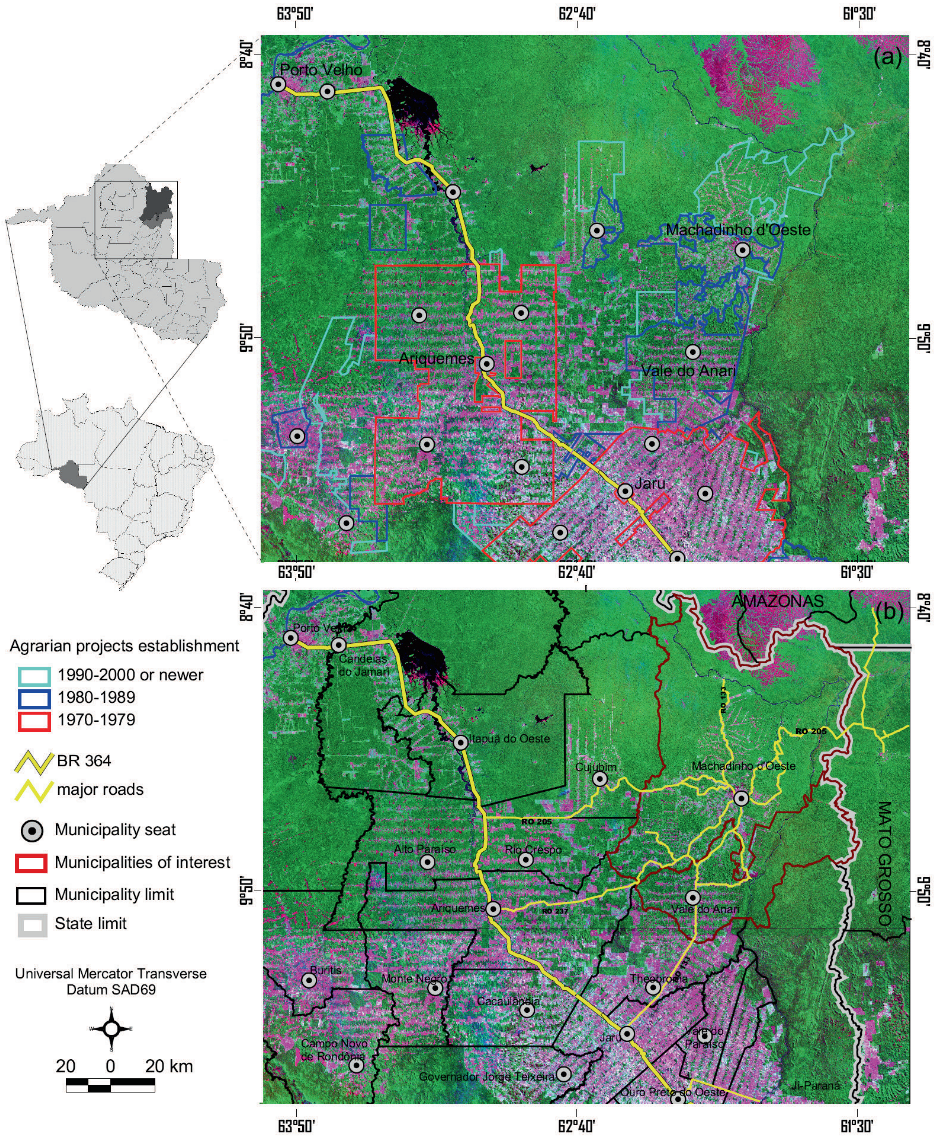


Figure 2.1 – (a) Agrarian projects created in the study area until 2000 (b) Political borders of study area highlighting Machadinho d'Oeste and Vale do Anari municipalities and the main roads. Both backgrounds show a Landsat TM mosaic from 2000 with the channels near-infrared, red and green associated to the colors red, green and blue, respectively. Forested areas are represented by dark green, secondary forest in light green and agriculture, bare soil and urban areas form a mosaic of magenta, light blue and/or white.

2.3 Drivers of land cover change in the study area

An overview of previous land use/cover change studies in Rondônia state including the study area is summarized in Table 2.1. Alves (1999) showed that between 1985 and 1995 deforestation expanded to new areas in Machadinho and Anari municipalities near the major roads RO 133 and RO 205, adjacent to BR 364 (Figure 2.1b). The percentage of deforestation within 12.5 km from these roads, where pioneer settlements were established, increased from 14 to 21% between 1985 and 1995. Cardille & Foley (2003) demonstrated by correlating land cover maps and census data from Rondônia, that planted pastures increased 500% in recently deforested areas between 1980 and 1995.

Table 2.1 – Overview of previous land use/cover change studies in Rondônia state enclosing the study area.

Author	Objective	Method	Land use/cover determinants identified
Alves (1999)	Perform a spatial-temporal analysis of deforestation processes under occupation	Multitemporal analysis of deforestation from 1985 and 1995 by image classification and map-intersection	Distance to major roads, areas of pioneers settlements
Alves et al. (2003)	Estimate spatial-temporal distributions and evaluate the interdependence of deforestation and abandoned land	Multitemporal analysis of deforestation from 1985 and 1995 by image classification, fieldwork and map-intersection of deforestation and land abandonment	Land use intensification, pasture expansion near roads over forested and secondary forest areas, secondary forest concentration at forest fringes in new agrarian projects
Cardille & Foley (2003)	Examine changes in broad-scale patterns of agricultural land-use practices in part of the Brazilian Amazon	Multitemporal image classification from 1980 to 1995 and correlated them to census data	Distance to urban areas, pasture expansion for cattle raising over forested areas
Escada (2003)	Analyze spatial-temporal changes in land use/cover patterns and their associated actors in the centre-north of Rondônia	Multitemporal image classification and interpretation from 1985 to 2000 of deforestation and secondary forest patterns and fieldwork	Road infrastructure along time, pioneer settlements, agrarian structure and land concentration along time, spatial variability of patterns and actors
Batistella (2001)	Analyze distinct land use/cover patterns and institutional support impacts on deforestation and socioeconomic aspects	Multitemporal image classification from 1988 to 1998, landscape metrics, ANOVA and fieldwork	Settlement design, institutional support, Conversion of cropped land to pasture, land abandonment, biophysical properties (soil fertility, water supply, slope)

This increase in pasture occurred especially near the urban areas Ji-Paraná and Ariquemes. Alves et al. (2003) observed that land intensification processes are mostly due to pasture expansion in long term deforested areas at the cost of secondary forest. Highly deforested areas increased between 1985 and 1995 occupying large areas adjacent to BR 364. Conversely, the areas of secondary forest generally increased at the edges of the forest, where new settlements are starting. Escada (2003) developed a method to construct maps of occupation based on farm size. These maps demonstrated a continuous expansion of pasture in the area of Machadinho at the expenses of forest cover during 1991 to 2000. This analysis demonstrated that areas occupied by large, medium and small farms contributed equally to local deforestation processes. Combined with image interpretation and fieldwork, it was demonstrated that land concentration process occurred in Vale do Anari during the period of analysis.

Batistella (2001) developed a land use/cover change analysis for both Machadinho and Anari settlements using remote sensing data and household level interviews between 1988 and 1998. The analysis showed that in Anari settlement forest conversion to pasture and land abandonment of both crops and pasture areas were the most dominant changes. In Machadinho settlement a different result was found with similar occurrence of pasture and agricultural fields. Small landholders used secondary forest for cattle grazing. According to local landholders, crop productivity was better in Machadinho, what was also indicated by land evaluation data from a previous census.

It is expected that the spatial analysis of land cover patterns will result in similar location factors as reported in the review above. It is also expected that by using different spatial extents a more in-depth understanding of the observed patterns is achieved. In order test these hypothesis the whole study area was analyzed, followed by a stratification into the two municipalities (see Figure 2.1b red boundaries) and a stratification by old and new agrarian colonization projects (see Figure 2.1a, blue and cyan boundaries).

2.4 Material and methods

2.4.1 Study area characterization

The study area consists of the municipalities Machadinho d'Oeste and Vale do Anari, both located in the northeast of Rondônia (Figure 2.1b). Their total areas are respectively 8509 and 3135 km^2, which corresponds to 5% of Rondônia State and 0.3% of the Brazilian Amazon. They are situated about 400 km from the capital Porto Velho and are accessible by roads while river transport can be particularly useful during the wet season. Dense tropical rain forest is the predominant natural vegetation, but patches of savannah are found in the north (RADAMBRASIL, 1978). The regional climate is classified as tropical rainy, according to the Köppen classification, with a dry season from June to September and a rainy season from October to May (Rondonia, 2004). The predominant soils are Feralsols, Aerenosols, Planosols and Gleysols, according to the FAO classification (Rondonia, 2000). Slopes are predominantly flat (0-3%), but undulating terrain (8-20%) is observed near river valleys. Conservation reserves are planned throughout the whole area and have various degrees of protection depending on the level of human intervention. The area has no indigenous reserves.

In 2000, the population of Machadinho consisted of 22739 inhabitants, with 51% living in rural areas while Anari had 7737 inhabitants, with 76% in rural areas. The average population growth between 1991 and 2000 was 3.4% in Machadinho and 0.7% in Anari (IBGE, 2000). In 2007, the total population in Machadinho and Anari was estimated to be 29548 and 8751 inhabitants, respectively (IBGE, 2007b). Another heterogeneous aspect between the two areas is that Machadinho has a more structured economy with better commercial and public infrastructure than Anari (IBGE, 2007a, 2000). The main economic activities of small landholders are subsistence agriculture and cattle raising for milk to local and regional markets. Medium and large farmers produce beef for local to international markets (SIF, 2006). Land selling or abandonment by small landholders is related to lack of subsidies, aging and offspring migration. In both municipalities, land management such as manure application, irrigation or crop/pasture rotation is hardly observed (EMATER-RO, 2006). Overgrazing is a common practice leading to pasture degradation and plagues (IDARON, 2006). Wood extraction has decreased in many agrarian projects due to extinction of commercial species and law enforcement, but fieldwork observations indicated a migration of illegal wood extraction to the northeast of Machadinho d'Oeste, into Colniza municipality in Mato Grosso State.

2.4.2 Database of potential location factors

Potential land use/cover proximate drivers and location factors were selected based on the review of previous land use studies, fieldwork information from 2001 and 2006 and data availability. The selected variables include biophysical, accessibility and socioeconomic aspects, as well as public policies. The first exploratory models included 55 variables, but only 38 had significant contributions in the final models (see Table 2.2). Classes of the categorical variables geomorphology, lithology and soil types are counted each as a unique variable. The grid database was built at a spatial resolution of 250 x 250 m, the highest resolution possible with the available data. This resolution is an exact multiplier of the average size of lots in the agrarian projects (2000 x 500 m). The original scale and resolution of the variables selected were quite different; especially biophysical variables have a different spatial variability than socioeconomic data and the accessibility measures. This suggests that some loss of information took place during the data aggregation process. In a preliminary test all data was aggregated to 500 m resolution. Initial analysis demonstrated similar patterns and correlation between deforested areas, secondary forest and location factors indicating limited loss of information. These results are consistent to other studies at multiple scales (Veldkamp and Fresco, 1997; Walsh et al., 1999). Therefore, it was decided not to change the data resolution and use only the 250 m resolution data.

The land use/cover map used in this research was constructed from a series of 1985-2000 Landsat/TM images. The agrarian structure was obtained from as existing 2000 database containing the limits of properties and their classification per size (Escada, 2003). Only two land use/cover types were included in the analysis: pasture and agriculture (mapped as deforested area) and land abandonment or vegetation regrowth (*i.e.* secondary forest land cover).

Table 2.2 – Variables representing the potential determinants of land use/cover selected for the analyses.

VARIABLES	DESCRIPTION		SOURCE
BIOPHYSICAL			
Slope	Slope (%) derived from elevation data SRTM at 90 m		NASA(2000)
GEOMORPHOLOGY			
Flat	Flat areas with fluvial deposits, at risk of floods		CPRM (2004)
Floodplain	Sandy and muddy areas at risk or not of floods		
F_Terrace	Fluvial deposits with flat shapes and smooth inclination		
Differential_1	Crystalline rocks, medium drainage density, flat to smooth slope		
Differential_2	Crystalline or sedimentary rocks with	medium drainage density,	
Differential_3	convex peaks and smooth slope	high drainage density	
Differential _4	Sedimentary rocks tabular smoothly	coarse drainage density	
Differential _5	ramped peaks and smooth slope	medium drainage density	
LITHOLOGY			
Sand_Silt	Alluvium, Sand, Clay, Lignite, Turf, Gravel		CPRM (2004)
Sand	Sand and Gravel		
Conglomerate	Sandstones and Conglomerates		
Gneiss	Amphibolite, Marbles, Gneisses, Migmatites		
Gabbro	Mafic and ultra-mafic crystalline rocks		
Granite	Granites and Granodiorites		
Trachyte	Trachyte and other Possium feldspar rich rocks		
SOIL TYPE			
Quartz_Soil	Soil type: Quartz Psamments		SEDAM ZEE/RO (Rondonia, 2000)
D_Y_Latosols	Soil type: Dystrophic Yellow Latosols (FAO: Ferralsol)		
D_RY_Latosols	Soil type: Dystrophic Red-Yellow Latosols (FAO: Ferralsol)		
E_RY_Latosols	Soil type: Eutrophic Red-yellow Latosols (FAO: Acrisol)		
E_DR_Latosols	Soil type: Eutrophic Dark-red Latosols (FAO: Nitisol)		
Plansoils	Soil type: Dystrophic Plansoils (FAO: Planosol)		
Gleysoils	Soil type: Dystrophic Gleysoils (FAO: Gleysol)		
Precip_W	Average of monthly precipitation in the wet season - October to March,1970 to 2000		INPE/ CPTEC (2005)
Precip_D	Average of monthly precipitation in the dry season - April to September,1970 to 2000		
Fires	Euclidean distance to fire spots in 2000 obtained from AVHRR sensors		
ACCESSIBILITY MEASURES			
TT_Town_R	Travel time to towns using only rivers net		IBGE (2000)
TT_Town_W	Travel time to towns in the wet season		
TT_Town_D	Travel time to towns in the dry season		
ED_Sawmills	Euclidean distance to sawmills		MMA(2005), Fieldwork
TT_SFarms_R	Travel time to small farms using only rivers net		INCRA(2006)
TT_SFarms_W	Travel time to small farms in the wet season		
ED_BFarms	Euclidean distance to large farms		Escada (2003)
TT_BFarms_W	Travel time to large farms in the wet season		
SOCIOECONOMIC			
Pop_Density	Population density at district level		IBGE (2000)
Income_Pcap	Income *per capita* at district level		
Num_People	Number of people per district at district level		
PUBLIC POLICIES			
Cons_Reserve	Conservation reserves at 1:1.000.000		IBAMA (2005)

Monthly precipitation data from 1970 to 2000 with a resolution of 0.25 degrees were aggregated for the period from April to September and October to March, according to the seasonality in the region. Deforested area might have a significant correlation to dry season rainfall because precipitation is generally lower in deforested areas (Sombroek, 2001). As a result of low precipitation, colonists tend to burn their pasture and secondary forest in the dry season, thus a positive correlation of fires with dry season rainfall is expected in secondary forest models. Slope, geomorphology, lithology and soil types describe the biophysical location factors used in this analysis.

Table 2.3 – Average speed of travel according to the type of access and the season.

Type of access	Average speed (km/h)	
	Dry season	Wet Season
Forested areas	3.0	3.0
Secondary rivers	11.5	11.5
Main rivers	23.0	23.0
Vicinal roads	30.0	15.0
Major roads	70.0	35.0
Highway BR 364	110.0	80.0

Accessibility measures, *i.e.* travel time to reference points were calculated using cost distance algorithms (Geurs and Ritsema van Eck, 2001). Differences in average speed of transportation for the road network according to seasonality of rainfall were taken into account. The average speed of transportation by roads, rivers and paths was estimated based on field measurements; interviews with landholders and local inhabitants (see estimates in Table 2.3). In order to evaluate the importance of roads in local deforestation processes, alternative models were tested using Euclidean distance to the destinations and travel time disregarding the road network as opposed to the accessibility measures that include the road network.

Socioeconomic data were selected from census data (IBGE, 2000). The year 2000 was chosen as the baseline for statistical analysis. Finally, conservation reserves were included in the analysis as a public policy aspect. Initially the conservation reserves were stratified according to the level of intervention allowed, but this yielded no significant differences, consequently all the reserves were considered equally.

2.4.3 Statistical methods

Statistical procedures were used to find coherent explanatory models of the deforested and secondary forest areas. Based on the earlier mentioned stratification, logistic regression analysis was performed at three different spatial extents: A) the whole study area; B) Machadinho d'Oeste and Vale do Anari municipalities separately; C) old and new agrarian projects established in the 80's and 90's seperately,. Samples of deforested areas and secondary forest areas were produced using a balanced, random sampling method avoiding adjacent cells to reduce the possible bias of spatial autocorrelation on the regression results (Overmars et al., 2003).

Multicollinearity among variables was investigated using Pearson's correlation. The accessibility measures turned out to be the most inter-correlated variables. From the variables with inter-correlation coefficients ≥ 0.80, only the one most related to the land use/cover was retained in the analysis. The value used as a cut-off for inter-correlation is usually adopted in logistic regression models (Menard, 2001). After the correlation analysis, a more refined variable selection was done comparing the odds and the standardized regression coefficients of the independent variables, which were calculated following Menard (2001). Eventually, variables for which modeled relationships could not be explained by a causal explanation were excluded. Goodness-of-fit values were evaluated between initial and final models using the area under the ROC curve (relative operating characteristic) (Pontius and Schneider, 2001). Values for this statistic vary from 0.5 to 1.0. Logistic land use/cover models with ROC value higher than 0.7 are considered acceptable and values higher than 0.8 indicate a good model fit (Lesschen et al., 2005).

2.5 Results and Discussion

2.5.1 Extent A: Machadinho d'Oeste and Vale do Anari as a whole

Table 2.4 presents the regression coefficients for the whole study area for models with accessibility measures based on the road network and for accessibility measures disregarding the road network. It is clear that regression coefficients for accessibility measures considering the road network are higher than in the models without the roads. As a result, the increase in the ROC values for models including road network indicates the importance of roads in determining land use/cover patterns in the region. Socioeconomic and public policy variables have a similar contribution for both sets of models, demonstrating their independent contribution to the pattern of deforested and secondary forest areas.

Table 2.4 – Results for the models with and without road network for the whole area of Machadinho d'Oeste and Vale do Anari, showing standardized regression coefficients and ROC values.

Machadinho and Anari	*Models without road network*		*Models with road network*	
Land use/cover	*Deforested area*	*Secondary forest area*	*Deforested area*	*Secondary forest area*
ROC	0.8800	0.7990	0.8960	0.8070
Slope	-	-	-	0.0400
Flat	-	-	-	−0.0474
Floodplain	-	−0.3586	-	-
F_Terrace	−0.0490	−0.0196	-	-
Differential_1	0.0117	0.0241	0.0234	-
Differential_2	-	0.0661	-	-
Differential _4	0.0373	0.0468	-	-
Differential _5	-	-	-	−0.1128
Sand_Silt	−0.0587	−0.0796	-	−0.0868
Sand	−0.0822	−0.0738	-	−0.1009
Conglomerate	−0.1071	−0.2418	-	−0.2950
Gabbro	-	−0.0672	-	-
Trachyte	0.0142	-	0.0202	-
Quartz_Soil	0.0419	-	−0.0134	−0.0593
D_Y_Latosols	-	-	−0.0680	-
D_RY_Latosols	0.0783	-	-	-
E_RY_Latosols	0.0347	-	-	-
E_DR_Latosols	0.0490	0.0261	-	0.0353
Plansoils	0.0461	−0.0124	-	−0.0363
Gleysoils	−0.4138	-	−0.3828	-
Precip_W	-	0.1151	0.0915	0.0707
Precip_D	-	-	−0.1127	-
Fires	-	-	0.1419	0.1531
TT_Town_R	−0.0473	−0.0314	NOT INCLUDED	
ED_Sawmills	−0.0620	-		
TT_SFarms_R	−0.1795	−0.1877		
ED_BFarms	−0.0852	-		
TT_Town_W	NOT INCLUDED		−0.3491	-
TT_Town_D				−0.4394
TT_BFarms_W			−0.2038	-
Income_Pcap	0.0539	0.0865	-	0.0775
Num_People	0.0522	-	0.1063	-
Cons_Reserve	−0.1587	−0.1500	−0.1395	−0.1830

In models that include the road network the variables travel time to towns in the wet and in the dry season showed significant contribution in explaining the variability of deforested and secondary forest areas. A similar importance of travel time to main urban areas has been identified by other studies at different scales of analysis (Aguiar et al., 2007; Soares Filho et al., 2001). Accessibility measures during the wet season were more important in explaining the deforested area because some locations are hardly accessible during the wet season. Similarly, travel time to large farms in the wet season contributed significantly to the deforested area model. In the dry season the travel time to towns determines the secondary forest area distribution, which is an indication that secondary forest occurs mostly at the forest fringes, as stated by Alves (2003).

2.5.2 Extent B: Machadinho d'Oeste and Vale do Anari municipalities

Results of the models for deforested and secondary forest areas for each municipality are shown in Figures 2.2 and 2.3. The main contributing variables for deforested areas in both municipalities were precipitation during the dry season, fires, travel time to towns and to large farms during the wet season, and the occurrence of conservation reserves (see Figure 2.2). The significant coefficients of biophysical variables in the deforested area in Machadinho appear to confirm that the planning of roads was done according to biophysical conditions.

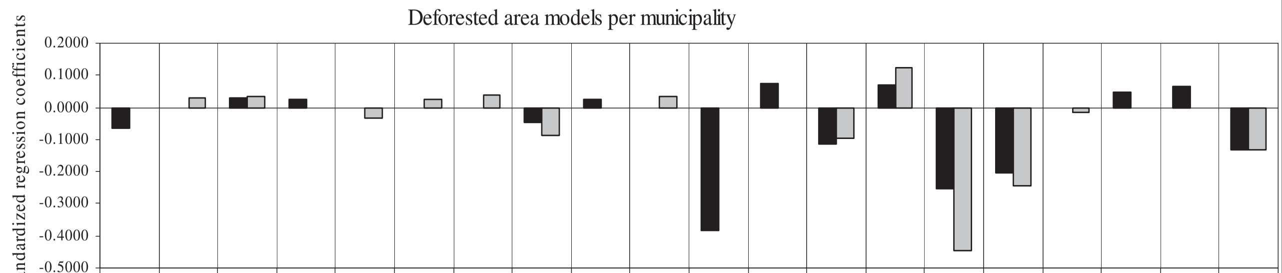
Travel time to towns during the wet season is more important for Anari municipality, most likely because of Anari's proximity to larger towns. Machadinho municipality is relatively independent in terms of commercial, health and public services. This independence was confirmed by interviews with landholders. This difference is also related to a higher spatial correlation between roads and fishbone patterns in Vale do Anari than the dendritic patterns in Machadinho. The spatial variability between the municipalities was also captured by the socioeconomic variables income per capita and number of people that explained the spatial variation in deforested area only in Machadinho. Population density had a negative contribution to deforested area in Anari. These results reflect the higher and more spatially concentrated population in Machadinho compared with the less densely distributed population in Anari during the last decade (IBGE, 1991, 2000). The higher population density in Machadinho combined with better economic conditions has apparently attracted an additional influx of in-migration and stimulated more deforestation.

The main explaining variables for both secondary forest area models were sandy lithology, income per capita and conservation reserves (see Figure 2.3). In general lithology and geomorphology contribute more to secondary forest models in Machadinho, while soils were more important in Vale do Anari models. The variable 'Conglomerate', cemented gravel pointing to flat relative fertile areas, had a negative influence in the secondary forest model for Machadinho likely because these areas are favored for agriculture or because they still present considerable forest remnants. Travel time to small farms in the wet season was only important in the Machadinho secondary forest area model. This relationship can be attributed to the high density of small farms in Machadinho (INCRA, 2006). In Vale do Anari travel time to towns in the dry season was a significant contributor for similar reasons as stated for the models for the whole area.

2.5.3 Extent C: Old and new Agrarian colonization projects

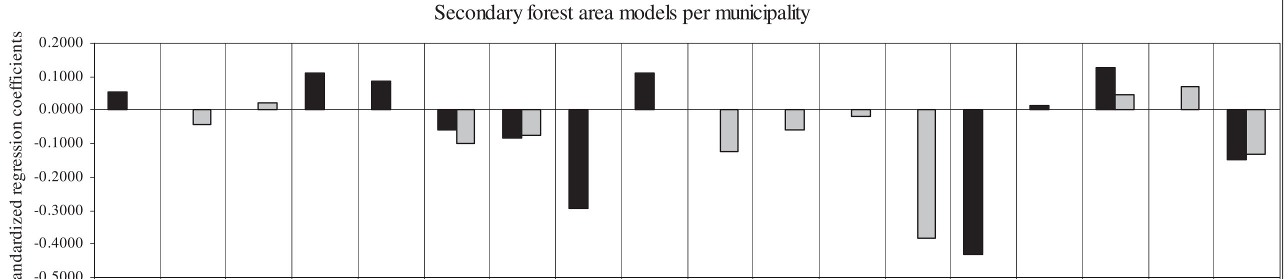
The deforested area and secondary forest area models for the old (1980-1990) and new (1990-2000) agrarian projects are shown in Figures 2.4 and 2.5 respectively. The most important variables for both deforested area models are travel time to towns and to large farms during the wet season, soil types, number of people and conservation reserves. In general, the low spatial variability in biophysical variables within this stratification is reflected by their minor importance in explaining the deforested areas. There appears to be a higher influence of number of people on deforested area in the older frontier (agrarian projects) and of population density in the new frontier. Although these variables look similar, these differences indicate land use intensification in the older frontiers. New frontiers have a low number of people, but a relatively high population density due to smaller lot sizes with dispersed deforested area patterns. These results confirm previous studies that show deforestation in old settlements linked to land use intensification and aggregated lots resulting from land concentration processes (Alves et al., 1999; Escada, 2003; Mertens et al., 2002; Millikan, 1992).

For the secondary forest area models the relevant variables were lithology, precipitation, travel time to towns in the dry season and conservation reserves. The secondary forest variability is captured by lithology, soil types and income per capita. As expected, the models demonstrate that very poor soil types predominate in new agrarian projects, while in old ones small patches of better soils can be found, what affects secondary forest growth. The divergent responses of lithological categories within the two groups of settlements reflect that new projects are closer to the main river and present a higher occurrence of secondary forest patches, which are scarce in the old projects where land use intensification driven by high income per capita is significant, so secondary forest occurs in a few areas in the back of lots near the watershed and at steeper slopes (Alves et al., 2003; Soares-Filho et al., 2001). This can explain why the positive contribution of precipitation in the dry season is higher in new projects areas, because less rainfall is expected in highly deforested areas (Sombroek, 2001).



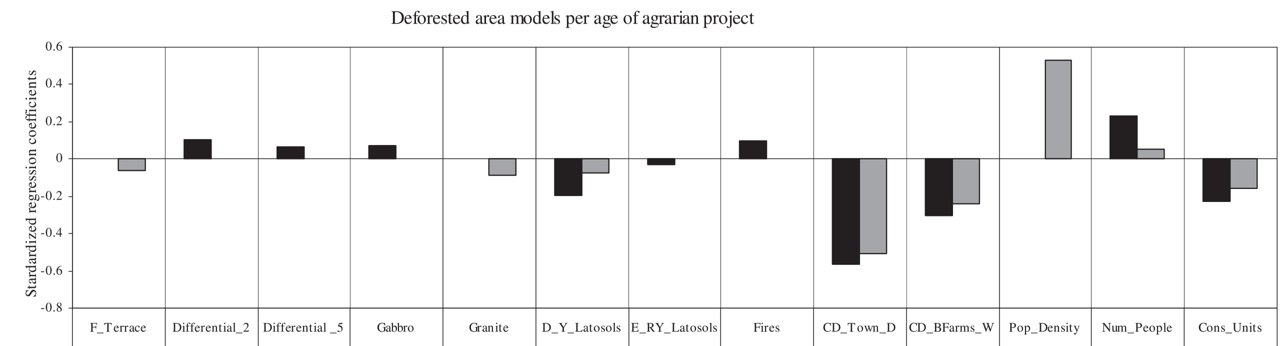
	F_Terrace	Differential_1	Differential_2	Differential_4	Sand	Gneiss	Gabbro	D_Y_Latosols	E_RY_Latosols	E_DR_Latosols	Gleysoils	Precip_W	Precip_D	Fires	CD_Town_W	CD_BFarms_W	Pop_Density	Income_Pcap	Num_People	Cons_Units
■ Machadinho d'Oeste - ROC 0.902	-0.0633		0.0302	0.0238				-0.0476	0.0245		-0.3854	0.0741	-0.1161	0.0698	-0.2522	-0.2055		0.0453	0.0657	-0.1341
□ Vale do Anari - ROC 0.802		0.0286	0.0327		-0.0346	0.0231	0.0377	-0.0876		0.0318			-0.0969	0.1217	-0.4467	-0.2442	-0.0160			-0.1332

Figure 2.2 – Graphic comparison of individual deforested area models for Machadinho d’Oeste and Vale do Anari municipalities.



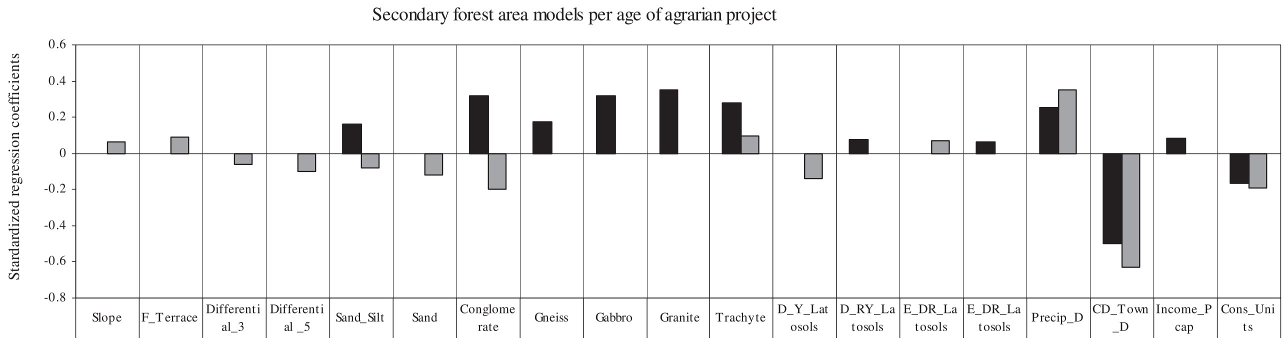
	Slope	F_Terrace	Differential_1	Differential_2	Differential_4	Sand_Silt	Sand	Conglomerate	Granite	D_Y_Latosols	D_RY_Latosols	Plansoils	CD_Town_D	CD_Sfarm_W	Pop_Density	Income_Pcap	Num_People	Cons_Units
■ Machadinho d'Oeste - ROC 0.899	0.0531			0.1092	0.0868	-0.0572	-0.0823	-0.2928	0.1103					-0.4329	0.0157	0.1262		-0.1486
□ Vale do Anari - ROC 0.829		-0.0408	0.0215			-0.0975	-0.0744			-0.1236	-0.0599	-0.0175	-0.3836			0.0480	0.0700	-0.1336

Figure 2.3 – Graphic comparison of individual secondary forest models for Machadinho d’Oeste and Vale do Anari municipalities.



	F_Terrace	Differential_2	Differential _5	Gabbro	Granite	D_Y_Latosols	E_RY_Latosols	Fires	CD_Town_D	CD_BFarms_W	Pop_Density	Num_People	Cons_Units
■ Old agrarian projects - ROC 0.773		0.1041	0.0656	0.0715		-0.1964	-0.0284	0.0948	-0.563	-0.301		0.2288	-0.2281
■ New agrarian projects - ROC 0.831	-0.0602				-0.0852	-0.0755			-0.5088	-0.2390	0.5328	0.0499	-0.1580

Figure 2.4 – Graphic comparison of individual deforested area models for old (1980-1990) and new agrarian projects (1990-2000).



	Slope	F_Terrace	Differenti al_3	Differenti al _5	Sand_Silt	Sand	Conglome rate	Gneiss	Gabbro	Granite	Trachyte	D_Y_Lat osols	D_RY_La tosols	E_DR_La tosols	E_DR_La tosols	Precip_D	CD_Town _D	Income_P cap	Cons_Uni ts
■ Old agrarian projects - ROC 0.804					0.1641		0.3193	0.1764	0.3193	0.3517	0.2796		0.078		0.0613	0.2547	-0.4992	0.0824	-0.1673
■ New agrarian projects - ROC 0.732	0.061	0.0907	-0.0596	-0.0975	-0.0784	-0.121	-0.1986				0.0972	-0.1377		0.0718		0.3541	-0.6287		-0.1912

Figure 2.5 – Graphic comparison of individual secondary forest models for old (1980-1990) and new agrarian projects (1990-2000).

2.6 General outcomes for all spatial stratification

2.6.1 Accessibility measures

It is clear that accessibility measures adopting the road network determine deforested and secondary forest areas for all studied extents. Accessibility is more significant in explaining differences between the old and new agrarian projects, indicating that the agrarian projects as such predominantly determine land use/cover patterns together with road network. The most relevant accessibility measures were travel time to towns and to large farms for deforested area, and travel time to towns and to small farms for secondary forest area. This dependence of land use/cover variability on agrarian structure and urban areas was also observed by recent modeling studies in the Brazilian Amazon at broader regional scales (Aguiar et al., 2007; Soares Filho et al., 2001), but they can not be considered as the sole determinants of deforested area given our results. It is essential to use a combination of accessibility, biophysical, socioeconomic and public policies considering the variability of actors and previous land use planning (Geist and Lambin, 2001; Verburg, 2006).

2.6.2 Biophysical variables

The biophysical variables, soils, geomorphology and lithology had a more significant influence on secondary forest than in deforested area models. Sandy lithology was negatively related to secondary forest area in Machadinho and in the old agrarian projects. It demonstrates that soil quality in these areas influences secondary forest dynamics. Similar interpretations based on household survey were found in other areas of the Brazilian Amazon (Moran et al., (2000). Precipitation during the dry season was more significant in explaining deforested area variability, most likely because the amount of rain is generally limited in deforested areas (Sombroek, 2001).

2.6.3 Socioeconomic variables and conservation reserves

The variables 'number of people' and 'population density' contributed positively to most deforested area models, while income per capita contributed best to secondary forest area models. In addition, income per capita was highly correlated to deforestation in Machadinho and in old agrarian projects, confirming the hypothesis that higher income causes land use intensification in old frontiers. Finally, it was observed that conservation reserves were significant in all the models with negative relationships. This demonstrates the importance of public policies to reduce deforestation in designated areas, which is also noted by other authors (Nepstad et al., 2006a).

2.6.4 General conclusions

In this chapter land use/cover patterns of deforested area and secondary forest in Rondônia State were related to potential location factors by means of logistic regression modeling at 250 m resolution. As potential location factors socioeconomic, political and biophysical variables were analyzed. Different spatial extents were used in order to evaluate the explanatory power of location factors over different spatial units. The results shown in this chapter confirmed earlier findings based on both coarser scale analyses of the whole Brazilian Amazon (Aguiar et al., 2007; Soares Filho et al., 2006), as well as findings based on detailed and elaborate household studies (Alves et al., 2003).

The accessibility measures used in the analysis turned out to be significant land use/cover determinants at all different spatial extents. Accessibility measures were more important at the extent of the agrarian projects from which we conclude that deforestation tends to be closer to roads and pioneer areas as also stated by other authors (Aguiar et al., 2007; Alves, 2002), but also that the diffusive patterns of deforested areas are correlated to the spatial configuration of the agrarian projects as identified in the same area by Batistela (2001). Similar dynamics have occurred in the north of Mato Grosso and south of Pará States, where economic conditions are the main attractors and the easy access by roads influence, but do not determine the process (Soares Filho et al., 2004).

Our multiple stratification approach, *i.e.*, separate analyses by different municipalities and by old and new agrarian colonization projects, yielded many new insights in the land use/cover system dynamics. It was demonstrated how location factors play out differently in explaining deforested and secondary forest area patterns within different extents in Rondônia.

Most new insights for the study area were obtained by comparing old and new agrarian colonization projects. Indications were found that land use intensification (clearing of forest/secondary forest remnants) takes place in the old agrarian projects, characterized by a relatively large population and high income per capita (Alves et al., 2003). Land abandonment in the old agrarian projects happened in the more remote parts and on steeper slopes. In the new agrarian projects secondary forest patches were associated with the forest fringes. These results led us to conclude that we are dealing with land use/cover trajectories in time. Therefore static spatial pattern analysis without acknowledging these trajectories will lead to erroneous interpretations of the current and future land use/cover dynamics.

Chapter 3 - Combining remote sensing and household level data for regional scale analysis of land cover change in the Brazilian Amazon[2]

Abstract. Land cover change in the Brazilian Amazon depends on the spatial variability of political, socioeconomic and biophysical factors, as well as on the land use history and its actors. A regional scale analysis was made in Rondônia State to identify possible differences in land cover change connected to spatial policies of land occupation, size and the year of establishment of properties, accessibility measures and soil fertility. The analysis was made based on respectively remote sensing data and household level data gathered with a questionnaire. Both types of analysis indicate that the highest level of total deforestation is found inside agrarian projects, especially in those established more than 20 years ago. Even though deforestation rates are similar inside and outside official settlements, inside agrarian projects forest depletion can exceed 50% at the property level within 10-14 years after establishment. The data indicate that both small scale and medium to large scale farmers contribute to deforestation processes in Rondônia State encouraged by spatial policies of land occupation, which provide better accessibility to forest fringes where soil fertility and forest resources are important determinants of location choice.

[2]*Based on:* Soler, L.S.; Verburg, P.V. Combining remote sensing and household level data for regional scale analysis of land cover change in the Brazilian Amazon. Regional Environmental Change 10 (2010), 371-386.doi: 10.1007/s10113-009-0107-7

3.1. Introduction

Spatial variability associated with the diversity of geopolitical issues, actors, socioeconomic contrasts, public policies, biophysical aspects and land use history has been addressed in a considerable number of studies to better understand land use/cover change in the Brazilian Amazon (Aguiar et al., 2007; Arima et al., 2005b; Becker, 2004; Fearnside, 2005; Laurance et al., 2004; Laurance et al., 2002; Millikan, 1992; Moran et al., 2000; Soares-Filho et al., 2006). From these studies it can be concluded that land cover changes in the Brazilian Amazon can only be understood by an in-depth comprehension of both land use history and the spatial variability of biophysical and socio-economic factors.

Land change trajectories in Rondônia State are strongly connected to spatial policies of land reform. Since the early 70s, the establishment of official settlements (agrarian projects) has attracted peasants mainly from the Southern region of Brazil. These policies also attracted a diversity of actors such as landless migrants, squatters, loggers, miners, and ranchers (Becker, 1997; Coy, 1987; Fearnside, 2008b; Machado, 1989). As a consequence, today the occupation of Rondônia is characterized by official agrarian projects established at distinct periods, spontaneous colonization by medium and big farmers, conservation reserves, indigenous areas and illegal occupation areas.

Land use in Rondônia State can be characterized by a pasture dominance of cattle raising activities (IBGE, 1996, 2006; Pacheco, 2009). Pasture expansion has occurred mainly over forest remnants and in the most accessible areas, where older settlements are located (Alves, 2002; Cardille and Foley, 2003; Machado, 1998). Highways and population density play important roles in driving deforestation (Alves et al., 1999; Laurance et al., 2002), while secondary forest occurs at the forest fringes usually in the back of the lots (Alves et al., 2003; Soler et al., 2009). The soil (fertility) conditions and spatial heterogeneity of the terrain can influence farmers' decision to deforest their plots (Browder et al., 2004; Browder et al., 2008; Fearnside, 1986). In addition, land occupation history plays an important role in the spatial distribution of household types and plot size (Coy, 1987; Millikan, 1992). Significant differences were found in deforestation between small and big farmers at the Amazonian scale (Fearnside, 1993).

According to estimates based on remote sensing data, official agrarian projects created between 1997 and 2002 were responsible for 15% of the total deforested area in the Brazilian Amazon up to 2004, mainly in Pará, Rondônia and Mato Grosso States (Brandão and Souza, 2006a). These figures indicate a significant contribution of small farmers to the overall deforestation. At the same time the aggregation of existing lots into larger farms is also frequently mentioned as a determining factor of deforestation processes (Coy, 1987; Escada, 2003; Pedlowski et al., 1997). The process of land aggregation is difficult to derive from remote sensing data, and household level surveys are necessary to study such processes. Household level studies can never cover large regions even with an exhaustive sampling. Therefore, the combination of different levels of information like remote sensing, maps and census data together with household level information can provide a detailed and complementary comprehension of land cover change and its determinants (Overmars and Verburg, 2005; Parker et al., 2008). By combining both remote sensing and household level estimates this chapter aims to analyze deforestation as a function of the land use planning history and correlate deforestation to possible determinants at regional scale in Rondônia State.

3.2 Methods

3.2.1 Study area

The study area is located in the south-western part of the Brazilian Amazon (see Figure 3.1), including 30 municipalities in the northeast of Rondônia State. The area encompasses 86382 km^2, which corresponds to 36% of Rondônia State and 2.2% of the Brazilian Amazon. The dominant natural vegetation is classified as dense tropical rain forest, but patches of savannah are found in the northern part (RADAMBRASIL, 1978). The regional climate is classified as Tropical Rainy, according to the Köppen classification, with a dry season from June to September and a rainy season from October to May (Rondonia, 2004). The predominant soils are Ferralsols, Arenosols, Planosols and Gleysols, according to FAO classification (Rondonia, 2000). The terrain is mostly flat (slope 0-4%), but undulating terrain (8-20%) is observed near river valleys and a steeper area (20- 38%) occurs in the southwest.

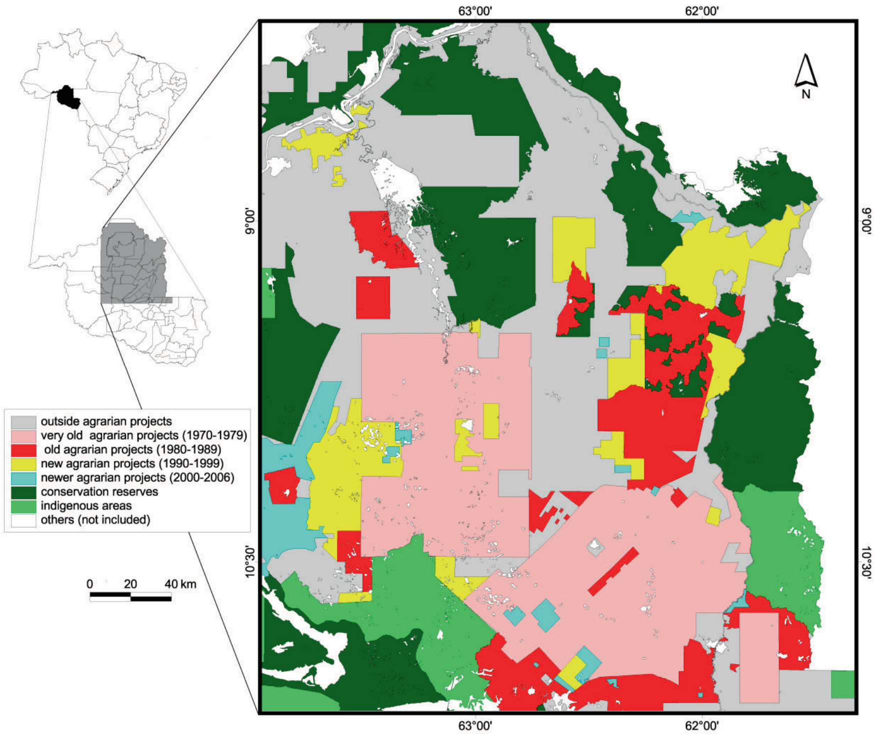


Figure 3.1 – Location of the study area in Brazil and Rondônia indicating the delineation of the agrarian projects according to year of establishment, conservation reserves and indigenous areas.

The area is characterized by old and new frontiers of colonization, which are formed by official agrarian projects and spontaneous settlements occupied by small and medium size landholders. In 2008 agrarian projects occupied 38% of the study area, while spontaneous colonization and unclaimed land represented 31% of the area. Conservation reserves and indigenous areas covered 21% and 8%, respectively (see Figure 3.1). During the last four decades agrarian projects have been created by the National Institute for Colonization and Agrarian Reform (INCRA) in different areas of the Brazilian Amazon. Initially, these land distribution was an attempt to minimize land conflicts in the Centre-south part of Brazil resulting from a labour force surplus caused by agricultural change (from coffee to soybean and wheat) and mechanization (Browder et al., 2008; Millikan, 1992). However, intense migration and population growth were also stimulated by land availability and subsidies until the mid 80's, adding to a more structured economy, social organization and accessibility by roads in the following years (Becker, 2004). In Rondônia State the total population increased from 70 to 500 thousand inhabitants between 1960 and 1980 (IBGE, 1981). In 2006 census estimates indicated more than 800 thousand inhabitants only within the limits of the study area, which represented 60.4% of Rondônia's total population (IBGE, 2007b).

The area is crossed by the highway BR-364, which was built in the early 60s to connect the South-western Amazon to Brasília and is still considered the main connection to the large consumption markets like São Paulo and Rio de Janeiro. Most of the important cities in the study area are located along the BR-364 such as Porto Velho, Ariquemes, Ji-Paraná, Jarú and Ouro Preto d'Oeste. However, some peripheral towns have increased their economic importance in the last decade including Buritis, Campo Novo de Rondônia, Machadinho d'Oeste and Cujubim (IBGE, 2000, 2007b). Fieldwork observations, as part of the study presented in this chapter, indicate that developments are related to land availability, beef and milk markets and logging, as well as soil fertility mainly in Buritis and Campo Novo de Rondônia.

Pasture has become the dominant land use type not only inside big farms, but also in medium and small lots. Between 1996 and 2006 pasture areas increased 24% in Rondônia State mainly on the expense of forested areas (IBGE, 1996, 2006). In general, small farmers apply poor land management in terms of manure management, mechanization or fertilizer application. Although medium/big farmers are better capitalized, only a small number of them apply proper land management. In spite of the lack of investments on land management, Rondônia's importance on milk national markets increased significantly in the last years, being ranked today as the seventh most important State in dairy production in Brazil (IBGE, 2008). Sanitary barriers for beef and milk production have improved the overall quality as a result of law enforcement and market requirements. This land use trajectory is also related to the household life cycle of medium and small landholders, who consider cattle raising as a long term source of income that requires moderate labour.

3.2.2 Database and data preparation

In order to make an analysis of land cover change in Rondônia, three different types of data were required: spatial data, statistical data and household level data. Two types of analysis were applied: a spatial analysis and a household level analysis. Table 3.1 provides an overview of the data types, their sources and units of measurement adopted in the two different analyses. In the following sections data processing is described in more detail.

Spatial data

The spatial data included a multi-temporal database of land cover maps for 2000 and 2008 based on remote sensing images (INPE, 2009). These land cover maps are the official instrument to monitor deforestation in the Brazilian Amazon and for that reason they have been the main data source of deforestation estimates for the scientific community. The land cover maps are based on a spectral linear mixture model followed by a supervised classification procedure of Landsat TM images and final editing by visual interpretation. These land cover maps are used to derive yearly land cover maps at a spatial resolution of 60 meter classified into three classes – forest, non-forest and deforestation. Validation of the final land cover maps are done by expert knowledge through visual interpretation with the support of historical series of fieldwork observations. The overall error is estimated at 4% (INPE/EMBRAPA, 2011).

Further spatial data consisted of geographical limits of conservation reserves and indigenous areas (IBAMA, 2005), geographic limits and year of establishment for all agrarian projects in the study area (INCRA, 2008) and the road and river networks (Rondonia, 2000). The remote sensing images were also used to improve the map of the road network.

In addition to these spatial data, statistical data were used to indicate the size of the properties per municipality in Rondônia in 2005. Property size is reported in three classes: smaller than 60 ha, between 60 and 240 ha, and larger than 240 ha (INCRA, 2007). Although these data are based on a sample of individual properties they are only available aggregated at the level of municipalities.

Household level data

Throughout the study area a total of 86 interviews were conducted with landholders during June 2008 in order to record land-use histories in official agrarian projects with different years of establishment. The survey resulted in 19, 17, 29 and 16 interviews in agrarian projects established in the 70s, 80s, and 90s and after 2000, respectively. In areas of spontaneous colonization, *i.e.* outside the agrarian projects, 2 interviews were conducted with big farmers and 3 in invaded areas.

Table 3.1 – Data description, data sources and spatial units subdivided by the different types of analysis employed.

Variable	Description	Source	Spatial unit
Spatial analysis			
Percentage deforested in 2000 and 2008	Percentage deforested per cell derived from land cover maps based on Landsat/TM images classified for 2000 and 2008	INPE (2009)	Pixels (60x60 m)
Size of forest clearing in 2000 and 2008	Calculated size of continuous forest clearing from land cover maps (classes (ha): < 6.25, 6.25-10, 10-20, 20-40, 40-60, 60-100, 100-200, >200)	INPE (2009)	Pixels (60x60 m)
Zoning areas	Municipalities' boundaries	IBGE (2000)	Scale 1: 250000
	Geographical limits of official agrarian projects per year of establishment (very old 1970-1979, old 1980-1989, new 1990-1999, newer 2000-2008)	INCRA (2008)	Scale 1: 100000
	Conservation reserves and indigenous areas	IBAMA (2005)	Scale 1: 250000
Accessibility (cost distance to roads)	Travel time to the nearest road by different means of access (as described in Table 3.2)	ANTT, ANTAQ, Fieldwork information	Pixels (250x250 m)
Density of roads	Number of cells with roads /total number of cells in different zoning areas	Rondônia (2000), Landsat/TM images	Pixels (250x250 m)
Road patterns	Classification of generalized road patterns (orthogonal, dendritic or irregular)	Rondônia (2000), Landsat/TM images	Pixels (250x250 m)
Property size	Percentage of area allocated to property per size (classes : < 60 ha, 60-240 ha, > 240 ha) per municipality in Rondônia in 2005	Census data from INCRA (2007)	Municipality level
Household level analysis			
Percentage deforested per property in 2000 and 2008	Percentage deforested per property in 2000 and 2008, reported by landholders.	Household level survey conducted with 86 landholders in June 2008 either insider or outside agrarian projects established within 1970-2008 in the study area	Property level
Average size of forest clearing within 2000 and 2008	Estimated size of forest clearing from area deforested inside the lots reported by landholders		
Year of establishment	Year of official establishment in the lot		
Property size	Size of properties in 2000 and 2008		
Accessibility	Distance to the main road (BR-364) and means of access to the property (paved, unpaved road).		
Soil fertility	Fertility level reported by landholders (classes: high, medium, low)		

The questionnaire adopted in the household level survey was based on a template proposed by CIFOR (Sunderlin and Pokam, 2002) and adapted by Lorena (2008). The final questionnaire was condensed to focus on land use history and specific characteristics of land use systems. Thus, besides information to reconstruct the land use/cover history from 2000 to 2008, the questionnaire also included questions related to soil fertility, year of occupation, rate of deforestation and accessibility. In invaded areas this questionnaire was adapted as there is no information about the total plot size; instead the occupied area was recorded. Big farmers could not be interviewed with the preformatted questionnaire, instead they were asked about their production systems, the areas allocated for different land use types and their rates of change.

3.2.3 Analysis of spatial data

Two different analyses were made based on the land cover maps for 2000 and 2008. The first analysis aimed at relating the deforestation processes to the land use planning history. The second analysis focused on other determinants of the deforestation patterns.

For the analysis of the influence of land use planning, deforestation was compared according to the land use planning history and zoning. Deforestation inside and outside agrarian projects of different years of establishment, conservation reserves and indigenous areas were compared. The year of establishment is expected to explain differences in the rate of deforestation between old and new frontiers (Dale et al., 1994a; Fearnside, 1986). For each of these zones the percentage deforested as well as the percentage deforested per size of forest clearing were calculated for 2000 and 2008. Forest clearings were subdivided in 8 categories: smaller or equal to 6.25 ha, 6.25-10 ha, 10-20 ha, 20-40 ha, 40-60 ha, 60-100 ha, 100-200 ha and larger than 200 ha. In all analysis pixels of urban areas, rock outcrops, savannah areas, rivers and other water bodies were excluded.

The location of deforestation was related to a series of potential determinants of deforestation. Potential determinants analyzed besides the zoning, year of establishment and the size of the forest clearings were the size of the properties, road patterns and the overall accessibility. Previous studies concluded that accessibility by roads and rivers network is an important driver of deforestation (Aguiar et al., 2007; Alves et al., 2003; Soler et al., 2009). However, it is hypothesized that its influence on deforestation should decrease after some years of colonization (Fujisaka et al., 1996). In addition, the size of deforested areas and property size are indicators of differences in deforestation processes and types of farming (Alves, 2002; Escada, 2003; Fearnside, 1993).

The road pattern typology was defined using simple concepts of geometry as orthogonality, connectedness and sinuosity. Three main patterns were considered in the analysis: regular (or orthogonal), dendritic and irregular. The regular pattern consists of secondary roads perpendicular (or oblique) to the main roads and parallel to each other at a regular distance. The dendritic pattern consists of main roads with several ramifications, where main and secondary roads follow landscape characteristics of slope and drainage network. At last, the irregular road pattern does not follow a preferred direction and is characterized by a tortuous road network.

The role of accessibility and road density as a determinant of deforestation patterns in Rondônia was assessed by relating deforestation to measures of accessibility and road density respectively. Density of roads was obtained by dividing the cells with roads by the total number of cells in each zone analyzed. Overall accessibility (travel time to roads) was calculated using cost distance algorithms considering highways, main and secondary roads (paved or not), river network, bays, dams, lakes and lagoons (Verburg et al., 2004). The average travel speed (Table 3.2) was estimated using fieldwork information and logistic information from Brazilian National Agencies of Terrestrial and Aquatic Transports (ANTT and ANTAQ).

Table 3.2 – Estimated average travel speed by infrastructure type in Rondônia

Access type	Average speed (km/h)
Paved highway	110.0
Paved main roads	90.0
Unpaved main roads	70.0
Secondary roads	40.0
Paths	15.0
Main rivers	23.0
Secondary rivers	11.5
Tertiary rivers, bays, lagoons, lakes, dams	5.0
Intermittent rivers, lagoons and flooded areas	3.0
Deforested areas	2.0
Secondary forest/forested areas	0.5

3.2.4 Analysis of household level data

Similar to the spatial data, the household level data were analyzed by comparing the data for different zones, *i.e.* comparing the agrarian projects per year of establishment. This parallel analysis allows the comparison of outcomes based on respectively the spatial and the household level data. The analysis focused on information concerning the amount of deforestation at the plots between 2000 and 2008 reported by householders, as well as possible determinants of deforestation. Similarly to the spatial analysis, the percentage deforested and the size of forest clearing were determined for the different land use planning zones. The size of forest clearings was estimated using the average area cleared reported by householders within the years considered.

In the second step of the analysis of household level data four possible determinants of deforestation were evaluated: year of establishment, property size, soil fertility and accessibility. Soil fertility was considered at this level of the analysis and not in the spatial analysis due to lack of data at the appropriate scale for the whole region. Soil fertility is expected to be one of the factors in the decision making explaining the choice to deforest (Roberts et al., 2002). In addition, we also compared the differences on deforestation rates between aggregated and non-aggregated lots, an analysis only possible with the household level data. Then, ANOVA was used to evaluate accessibility influence on the reported deforestation rates per property between 2000 and 2008. At last, regression analyses of percentage deforested per property against year of occupation, soil fertility, property size and accessibility were made.

3.3. Results

3.3.1 Analysis of spatial data

3.3.1.1 Deforestation processes and land use planning

The analysis according to the zoning of the study area shows that deforestation is highly concentrated inside the agrarian projects. Figure 3.2a illustrates the percentage of forest coverage in the study area for 2008, while Figure 3.2b illustrates the percentage deforested in the study area between 2000 and 2008. It can be observed that most of the deforestation within the period of study occurred in new and newer agrarian projects (created in the 90's and after 2000 respectively), but also a significant percentage is observed in some old agrarian projects as well as outside the projects.

The percentage deforested inside the agrarian projects increased from 62% of the area 2000 to 78% in 2008 (see Figure 3.3a). Even though outside the agrarian projects a much lower percentage of land is deforested, 27% in 2000, an increase of 13% was observed between 2000 and 2008. A small percentage of deforested area was observed in 2000 inside the conservation reserves with an increase of 5% between 2000 and 2008. In the same period, a minor increase of deforested areas (1%) was observed inside indigenous areas. These results clearly show that most deforestation is found inside the agrarian projects. However, at the same time it is clear that deforestation outside the agrarian projects is very large as well and certainly cannot be ignored.

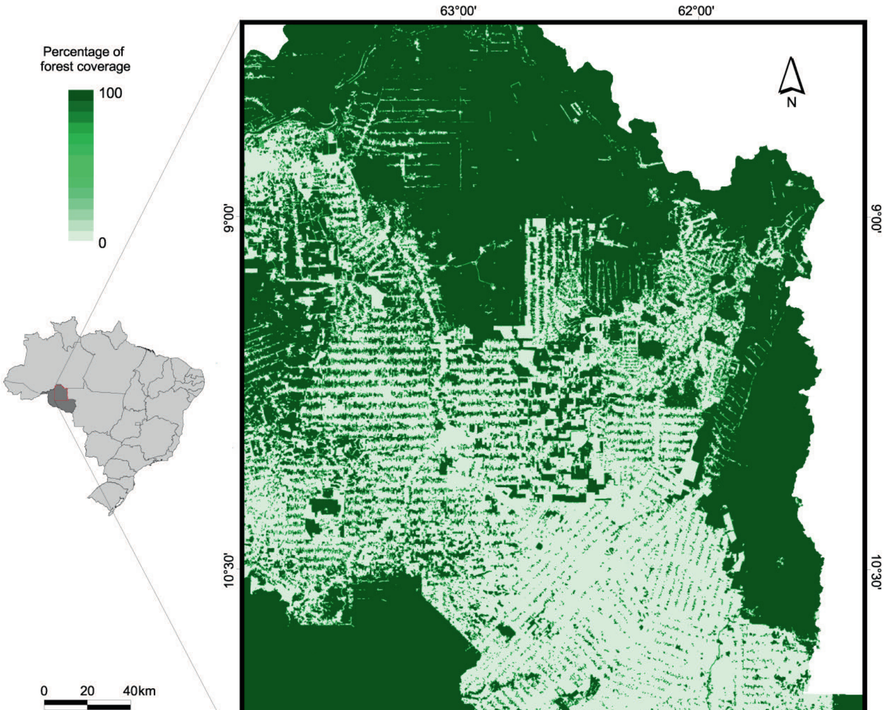


Figure 3.2a – Percentage of forest coverage in 2008.

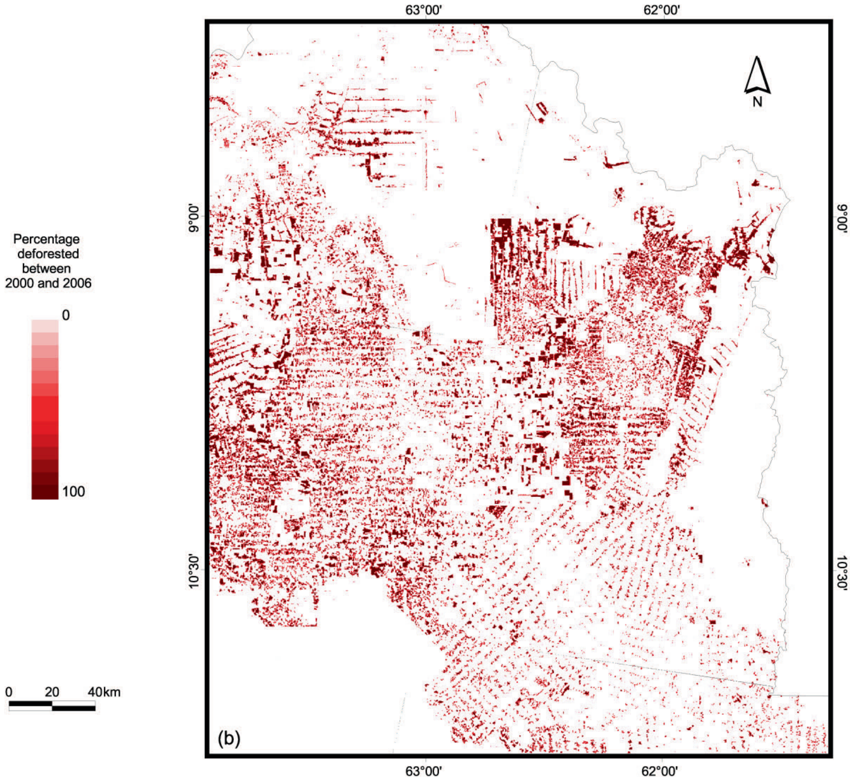


Figure 3.2b – Percentage of area deforested between 2000 and 2008 in the study area.

When accounting for the year of establishment of agrarian projects the analysis showed that deforested areas are highly concentrated inside very old and old agrarian projects, *i.e.* created in the 70's and 80's respectively (Figure 3.3b). These results indicate that the year of colonization is a key determinant in explaining deforestation levels. Although very old and old projects show large deforested areas in 2000, their rates of change between 2000 and 2008 were not as high as in the new and newer projects.

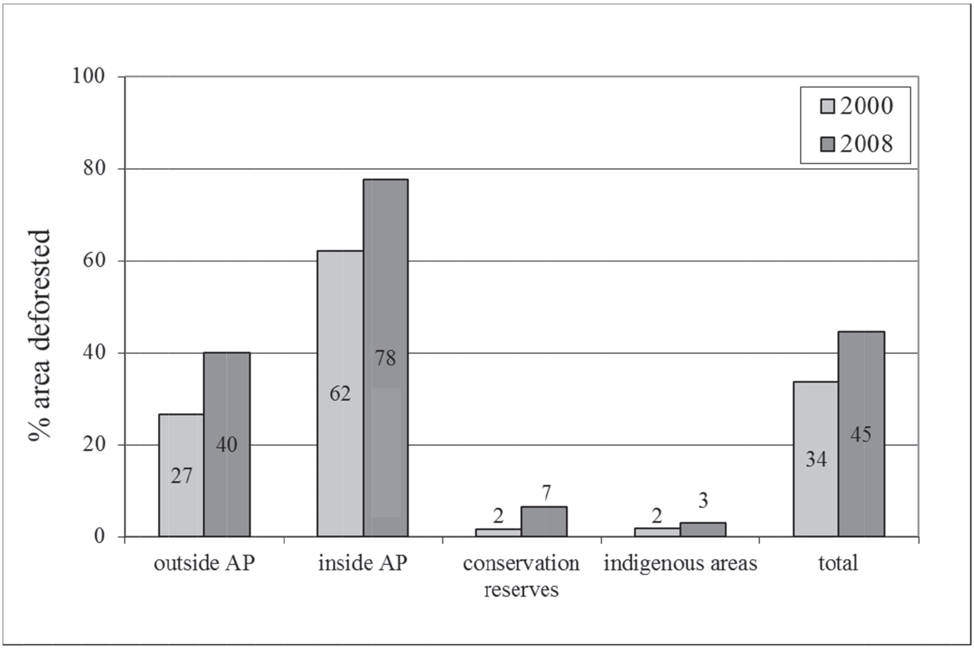


Figure 3.3a – Percentage deforested in 2000 and 2008 inside/outside the agrarian projects, conservation reserves and indigenous areas.

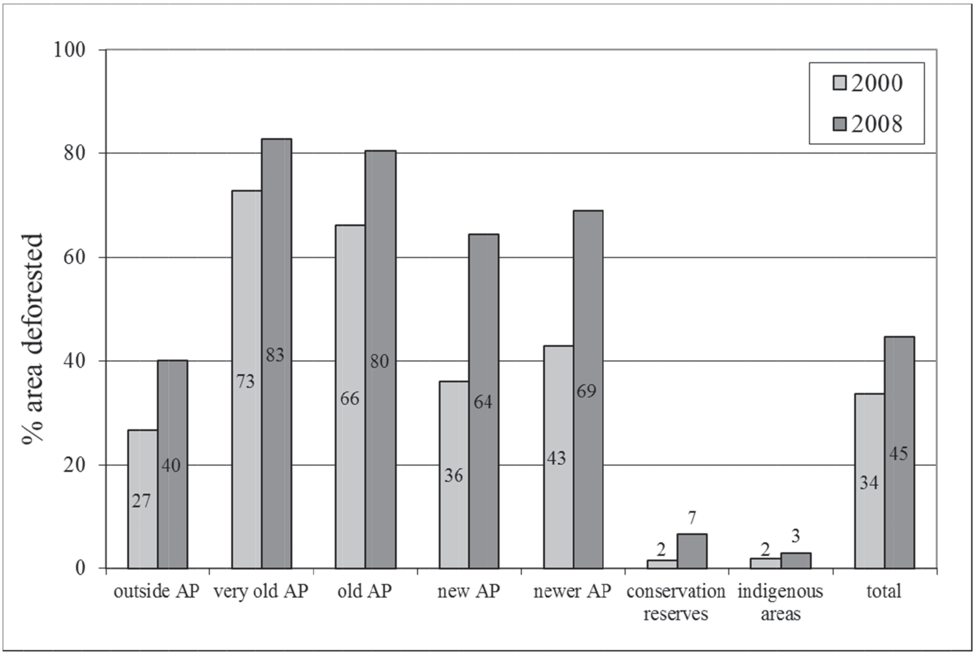


Figure 3.3b – Percentage deforested in 2000 and 2008 inside/outside the agrarian project per year of establishment (very old 1970-1979, old 1980-1989, new 1990-1999, newer 2000-2008), in conservation reserves and indigenous areas.

Even though presenting a smaller total area deforested, new and newer agrarian projects faced deforestation between 2000 and 2008 of 28% and 26% of their total area, respectively. This indicates intense land cover conversions inside recently colonized areas, where the increase of pasture occurs on the expense of forest, secondary forest and small scale agriculture (Alves et al., 2003; Batistella, 2001; Cardille and Foley, 2003). Such land cover changes are mostly driven by better profits at milk and beef markets encouraging large to small landholders to increase cattle raising production (Faminow, 1997; Fearnside, 1997; Walker et al., 2000). In 2008 the average difference in total deforestation between projects established in different years is much smaller: both recent and older projects have high fractions deforested.

The larger part of the deforestation between 2000 and 2008 is due to clearings between 10 and 40 ha. But, also clearings larger than 100 ha represent a considerable share of the total deforestation in the period (see Figure 3.4a). Although the overall area deforested outside the agrarian projects is smaller, forest clearings larger than 40 ha represented 56% of the deforested area outside agrarian projects in the same period. Even though the amount of deforestation inside conservation reserves and indigenous areas is small between 2000 and 2008, forest clearings larger than 60 ha represented respectively 40 and 31% of the deforested areas. The results of this analysis indicate that forest clearings are generally smaller within the agrarian projects areas than outside.

When considering the size of forest clearings in agrarian projects per year of establishment very similar tendencies for the three oldest groups can be observed (Figure 3.4b). For these groups deforested areas are mostly between 10 and 40 ha. For the older group of agrarian projects a higher frequency of deforested patches smaller than 10 ha as compared to newer projects is observed, which indicates a higher forest depletion and/or fragmentation. In contrast, in newer agrarian projects deforested patches between 60 and 200 ha and larger than 200 ha represented respectively 31% and 17% of the total deforested areas. An important aspect is that forest clearings smaller than 10 ha are less frequent inside newer projects than in the older ones. Outside the agrarian projects deforested patches larger than 60 ha represent more than 44% of the deforestation for the mentioned period.

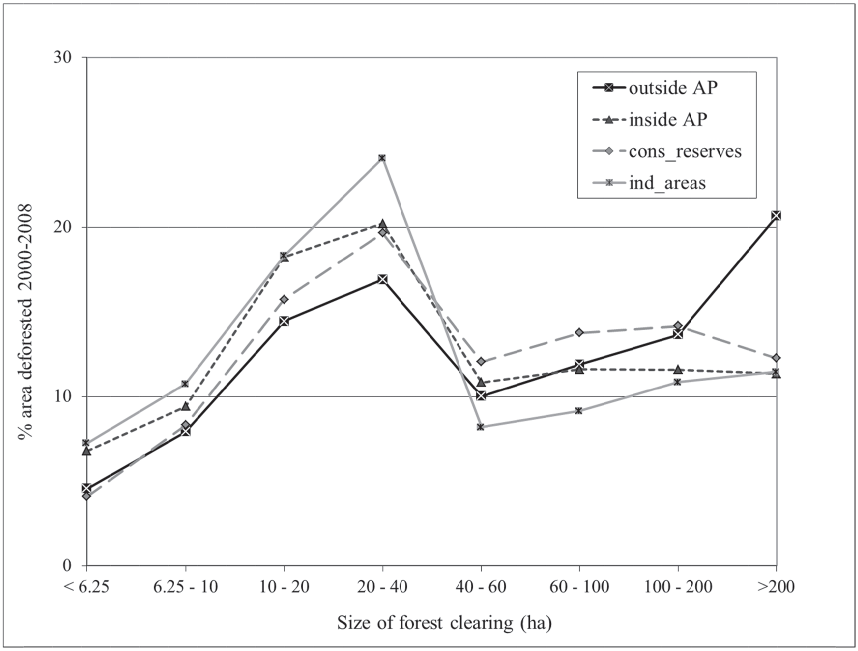


Figure 3. 4a – Percentage deforested between 2000 and 2008 per size of forest clearing inside and outside the agrarian projects, inside conservation reserves and indigenous areas.

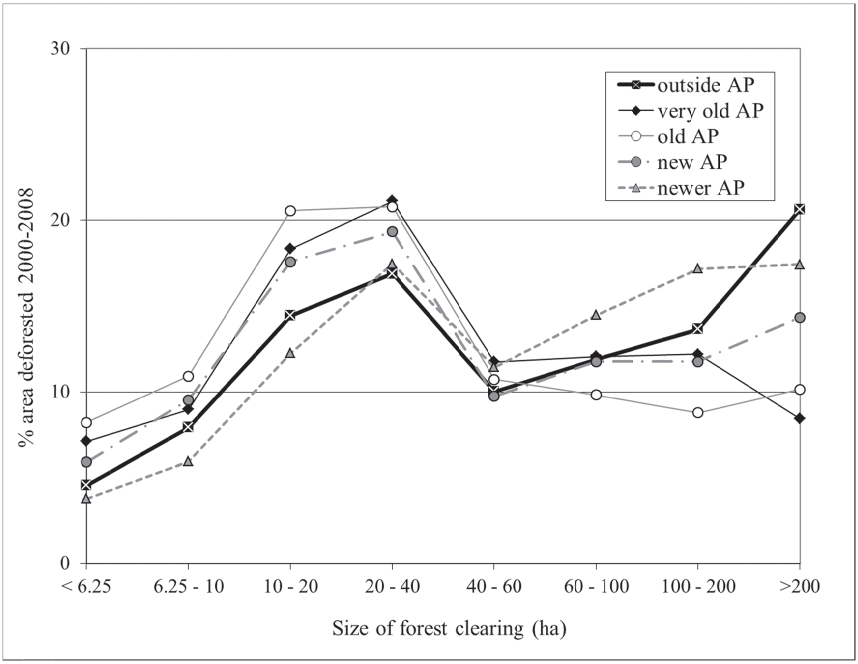


Figure 3.4b – Percentage deforested between 2000 and 2008 per size of forest clearing outside and inside the agrarian projects per year of establishment (very old 1970-1979, old 1980-1989, new 1990-1999, and newer 2000-2008).

3.3.1.2 Determinants of deforestation patterns

Property size

In the last years, the process of land concentration has been investigated in the Brazilian Amazon with indications that the size of forest clearing is linked to the property size (Alves, 2002; Fearnside, 1993; Mello and Alves, 2005). No data of property size are available at the property level. However, census data provide information aggregated at the municipality level, which can reveal the correlation between property size and the deforested area in 2008. Simple correlations between the area deforested in 2008 and the percentages of properties (in three classes according to size) showed a strong negative correlation -0.54 ($p<0.01$) between the area deforested and the percentage of area allocated to properties larger than 240 ha. Positive correlations were found for properties smaller than 60 ha as well as between 60 and 240 ha, corresponding to 0.41 ($p<0.05$) and 0.48 ($p<0.01$) respectively.

These results mainly indicate that deforestation is higher in municipalities with agrarian projects as they enclose predominantly small properties. The correlation between percentage deforested between 2000 and 2008 and the property size distribution is, however, not significant. These results indicate that although small landholders are connected to a large portion of deforestation, larger properties were, for the period of analysis, important contributors to deforestation in the area.

It should be noted that these results are based on aggregated data at municipality level while large variations at the property level may occur. Analysis at the aggregated level may be biased due to scaling problems ('ecological fallacy'). Therefore, these results should be compared to the analysis at household level.

The influence of roads on deforestation

It is well known that deforestation patterns are connected to road access, especially in areas of agrarian projects (Alves, 2002; Alves et al., 1999; Brandão et al., 2007; Soares-Filho et al., 2001). In order to evaluate the influence of roads on deforestation the density of roads and the travel time to the nearest road were compared to patterns of deforestation outside and inside the agrarian projects (Table 3.3).

This analysis showed that the accessibility to forest increased more than 76% in spontaneous colonization, conservation reserves and indigenous areas between 2000 and

2008. Likewise, the travel time to roads in deforested areas of recent and spontaneous colonization was reduced by 64% in the period of analysis, equalizing to values inside older projects. Forested areas inside agrarian projects showed significantly smaller distances to roads as compared to spontaneous occupation areas.

Table 3.3 – Mean cost distance to roads and density of roads in 2000 and 2008 in areas inside and outside agrarian projects (AP), conservation reserves and indigenous areas.

Variables	% deforested		Mean cost distance to roads (travel time in minutes to nearest road)						Density of roads (fraction of pixels with road segments).10^{-1}					
			deforested cells		forested cells		all cells		deforested cells		forested cells		all cells	
Zone	2000	2008	2000	2008	2000	2008	2000	2008	2000	2008	2000	2008	2000	2008
outside AP	27	40	74	26	573	121	384	83	1.4	1.3	0.2	0.2	0.5	0.6
very old AP	73	83	29	22	81	47	38	26	1.3	1.2	0.3	0.3	1.0	1.0
old AP	66	80	23	18	63	38	31	22	1.9	1.7	0.4	0.4	1.4	1.4
new AP	36	64	53	20	126	43	82	29	2.1	1.7	0.5	0.4	1.1	1.2
newer AP	43	69	63	23	146	51	86	31	1.4	1.2	0.3	0.3	0.8	0.9
conservation reserves	2	7	248	39	1063	187	1009	177	1.5	1.4	0.1	0.1	0.1	0.2
indigenous areas	2	3	163	47	1023	228	992	222	0.8	0.6	0.0	0.0	0.0	0.0
all zones	34	45	93	28	439	102	375	84	1.5	1.4	0.2	0.2	0.6	0.7

The density of roads inside deforested areas is much higher than in forested areas. Upon further deforestation, this density decreases as a result of further forest depletion within the existing plots. The density of roads in forested areas did not show a significant change between 2000 and 2008 inside agrarian projects.

Besides the influence of roads on deforestation an analysis of road patterns may provide an indication of the actors of land use changes. Whereas the regular road pattern is closely related to the well-known fishbone pattern of deforestation, the dendritic road pattern is a result of a new assessment of INCRA’s projects to guarantee at the same time individual access to water while keeping forest reserves in the surroundings. The irregular pattern is normally related to spontaneous colonization. The regular and irregular road patterns can also be related to selective or indiscriminate logging, respectively (Brandão and Souza, 2005).

An analysis of road patterns showed that outside the agrarian projects orthogonal and irregular road patterns represent respectively 60% and 36% of the occupation (Table 3.4). Although dominated by orthogonal road patterns, in the new and newer agrarian projects respectively 17% and 26% of all roads were showing an irregular pattern. In very old projects orthogonal road patterns are largely dominant (99%), while in old projects this percentage is 61% and the dendritic patterns represent 30%. However, the deforested area did not clearly differ between orthogonal road patterns (88% of the area deforested) and dendritic road patterns (86% deforested). Taking into account the new settlements, 87% and 86% of the road cells presenting respectively orthogonal and dendritic patterns were deforested in 2008, while considering only old settlements these percentages increased to 96% and 92%, respectively.

Table 3.4 – Percentage of area classified with a typical road pattern outside and inside the agrarian projects, conservation reserves and indigenous areas

road pattern	outside AP	very old AP	old AP	new AP	newer AP	conservation reserves	indigenous areas
orthogonal	60.76	99.11	61.98	62.41	73.37	83.31	95.10
irregular	36.68	0.89	7.82	17.88	26.63	12.41	4.90
dendritic	2.56	0.00	30.20	19.71	0.00	4.28	0.00

3.3.2 Analysis of household level data

According to the household level data individual plots are most deforested inside the very old and old agrarian projects (Figure 3.5). However, deforestation between 2000 and 2008 was 4 and 36% of the area in very old and old projects, respectively. The estimates for old projects can be biased because of the absence of a representative number of samples containing the aggregation of lots. Although many big farms with large pasture areas were observed in both very old and old projects, no interviews could be done. This is because big landholders usually live in cities nearby hiring farm hands which are not able to provide detailed information (Walker et al., 2000). Nevertheless, the household level data show that properties sampled in very old and old agrarian projects have respectively 18 and 14% forest remaining while in new and newer projects respectively 34 and 46% are remaining. The estimates of the percentage deforested for new and newer agrarian projects show a smaller fraction deforested for both years 2000 and 2008 as compared to older projects. However, deforestation during the aforementioned period was on average 25 and 30% of the plot area respectively, indicating a much higher deforestation rate than in the very old agrarian projects.

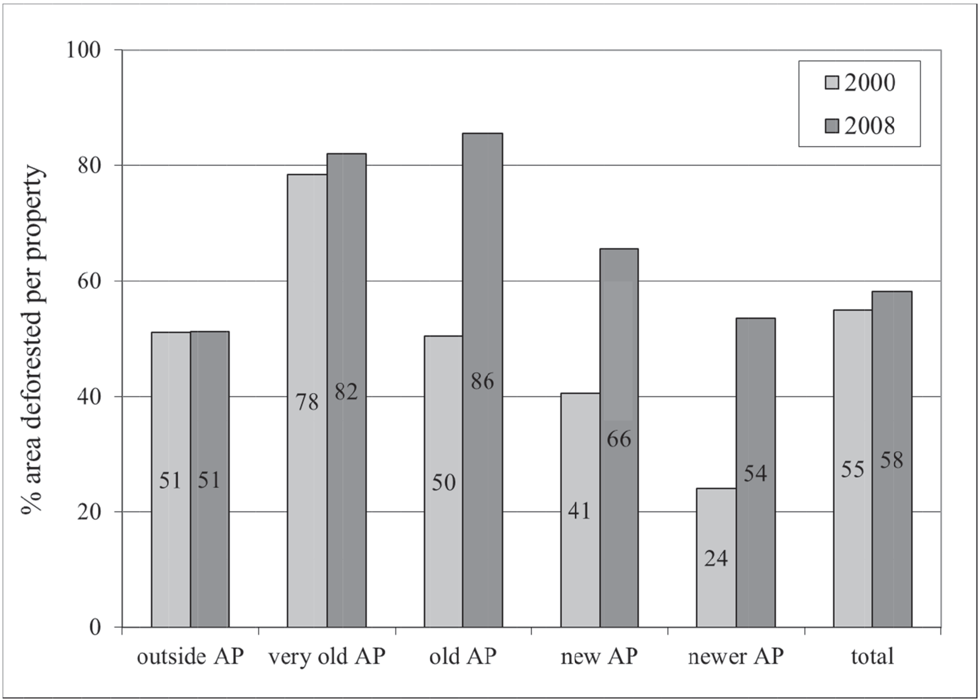


Figure 3.5 – Percentage deforested per property in 2000 and 2008 inside/outside the agrarian projects per year of establishment (very old 1970-1979, old 1980-1989, new 1990-1999, newer 2000-2008) based on household level data.

The analysis of the influence of the size of forest clearings indicates that within very old agrarian projects the average size of forest clearing was around 0-2 ha/year, while in old agrarian projects the average size of forest clearing ranged within 1-4 ha/year over the period considered. In new agrarian projects most properties had an average size of forest clearing of 1-3 ha/year and only a few properties presented values higher than 4 ha/year. Finally, in newer projects about half of the properties presented an average size of forest clearing around 0-3 ha/year, while size of forest clearing for the other half was 4-5 ha/year.

3.3.3 Determinants of deforestation patterns

In order to investigate the impact of land concentration processes on deforestation at the household level, deforestation rates between aggregated and non-aggregated lots were compared. The results show that properties with aggregation of lots in new and old agrarian projects faced much higher deforestation rates than non-aggregated lots. However, in areas of newer and very old projects deforestation rates are similar for aggregated and non-aggregated lots. Figure 3.6 shows a negative association between the year of occupation and the percentage deforested. This association is less clear in 2008 as compared to the situation in 2000 as a result of intense forest depletion in older properties. At the same time, the relation is biased by some properties in new and newer projects that were established in previously occupied land. Such properties already show forest depletion in the first years of occupation due to land clearing before official establishment of the agrarian project.

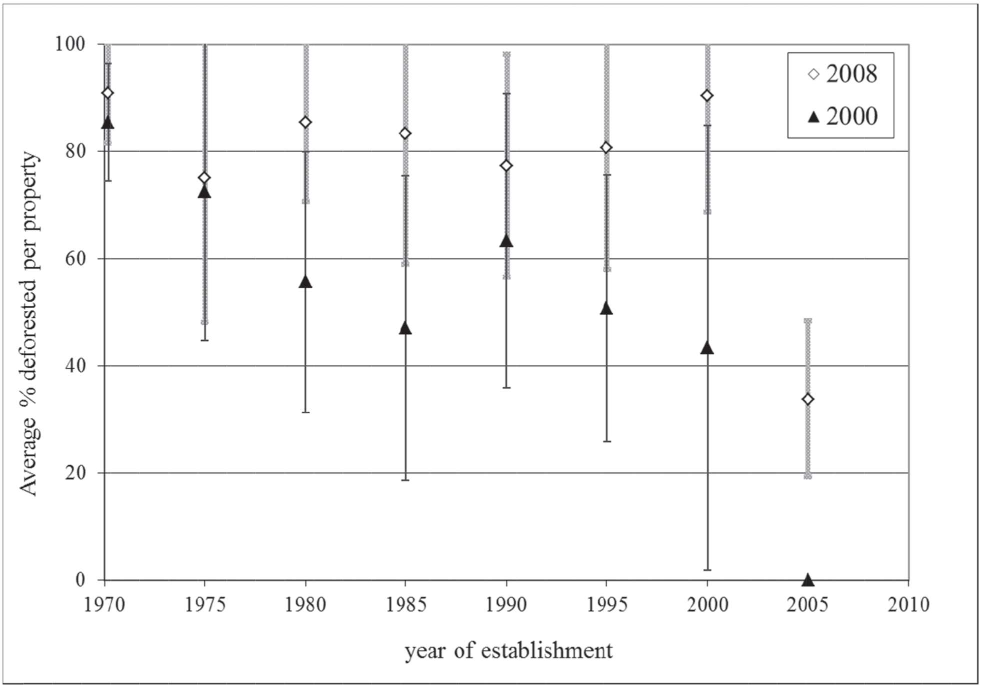


Figure 3.6 – Relation between year of occupation and percentage deforested per property based on household level data for 2000 and 2008.

For the evaluation of possible relations between fertility and deforestation three main classes of soil fertility were distinguished in the household level data: low, regular and high. The reported soil fertility was correlated to the percentage deforested per property and the results indicate high fertile areas to be strongly correlated to the percentage deforested for both years. In order to better comprehend such relationships an ANOVA analysis was performed and the results are illustrated in Figure 3.7.

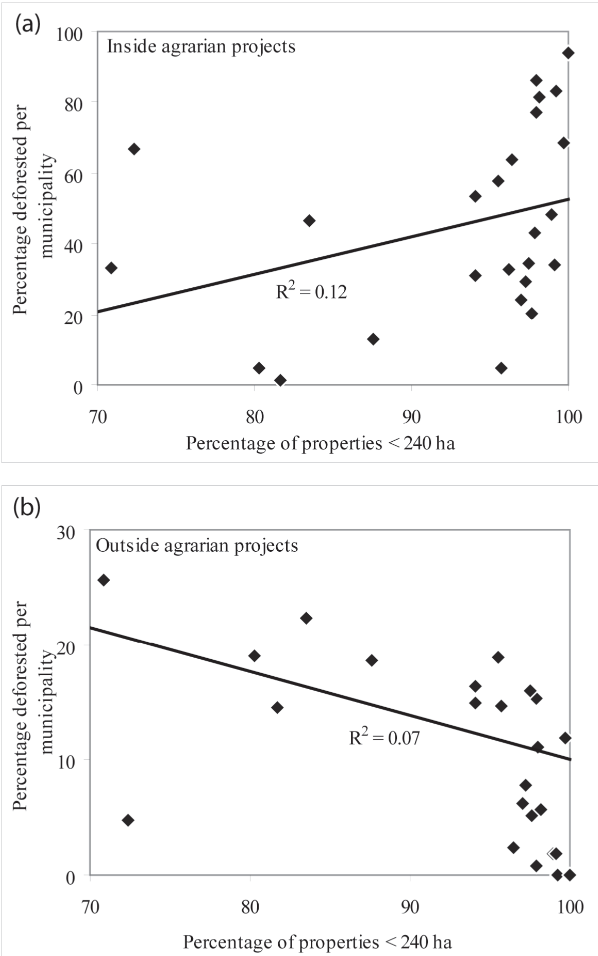


Figure 3.7– Percentage deforested per property for different soil fertility classes estimated based on household level data for 2000 and 2008.

The ANOVA results indicate that the mean percentage deforested is different between the classes of low and high soil fertility in 2008, as well as between regular and high for 2000. For both years the percentage deforested in low and regular fertile areas were not significantly different, but both means differ from high fertility areas ($p<0.05$). The ANOVA analysis between the year of establishment and the percentage deforested indicated that the deforested area of very old projects in 2000 still differed significantly from old, new and newer projects ($p<0.07$). As a result of the high deforestation in old and new projects between 2000 and 2008 the mean percentage deforested among very old, old and new projects was statistically similar, only differing significantly from newer projects ($p<0.05$).

The Pearson correlation results among percentage deforested in 2000 and 2008, distance to BR-364 and means of access (*i.e.* the nearest road type defined by the average travel speed following Table 3.2) showed that the year of establishment of agrarian projects is highly correlated to the distance to BR-364 and the means of access ($p<0.01$). Older projects are usually closer to BR-364 and have consequently the best access type. In addition, distance to BR-364 and means of access were also significantly correlated ($p<0.01$) to the percentage deforested per property in 2000. However, in 2008 these correlations drop and only distance to BR-364 remains significant ($p<0.05$).

The regression models explaining deforested area based on the household level data are presented in Table 3.5. Although the importance of all variables is comparable for both years, it is observed that the year of occupation has a larger role in explaining deforestation and is more important in the 2000 model while the variables describing the access situation are more important in 2008. The models including all variables explain 40% of the variation between households ($p<0.01$). Given the high variation in household level behaviour and conditions this can be considered a reasonable fit indicating that we have captured a number of key determinants of deforestation patterns.

Table 3.5 – Standardized coefficients of independent variables of linear regression explaining the percentage deforested per property in 2000 and 2008.

Reference year	2000	2008
high fertility	0.1270	0.1473
low fertility	-0.1109	-0.1910
property size	-0.2251	-0.3090
year of establishment	-0. 6611	-0.4661
means of access	-0.1112	-0.2477
distance to BR-364	0.0338	-0.1681
R^2	*0.395*	*0.334*

3.4. Discussion

Both types of analysis presented in this chapter add insight in the determinants of deforestation processes in the region. The two types of analysis can not be integrated in a simple manner due to measurement differences. While the household level analysis measures the processes at the level of the properties of individual households, the spatial analysis measures the change for the entire territory of the region, including land not allocated to households. Therefore, the fractions deforested as calculated by the different methods are not similar and have a different meaning. At the same time, a comparison of the findings of the different methods of analysis helps to provide insight into the processes of land change in the region.

3.4.1 The role of land use planning

The spatial analysis clearly shows higher deforestation inside agrarian projects. Deforestation rates inside the projects in the study area were estimated at 2.3% per year between 2000 and 2008, which is two times the deforestation rate of Rondônia as a whole during the same period (INPE/EMBRAPA, 2011). Even though less deforested, areas outside the agrarian projects presented comparable deforestation rates to agrarian projects between 2000 and 2008. These results add empirical input to the discussion on the role of land use planning and colonization policies in deforestation in Rondônia (Geist et al., 2006; Matricardi et al., 2007). As a result of the past and current spatial zoning of the study area, the contribution of small farmers is significant on the total deforested area. However, medium and big farms, more common in areas outside the agrarian projects, have contributed similarly to the average deforestation rates in the region.

With respect to the year of establishment of the agrarian projects, spatial data and household level data presented differences in the deforested area. Explanations for this difference include the limitation of the TM sensor derived data of 6.25 ha as the minimum identified deforested area. This limitation can result in overestimated deforestation in highly fragmented areas (as result of ignoring small remnants of secondary forest) or underestimate deforestation in areas with low forest fragmentation. However, the high deforestation rates given by household level data in old projects are not well explained by such limitations. Instead, the sampling method is most likely another reason for the high deforestation rates observed. The old projects sampled are located in municipalities among the most deforested in Rondônia during the last 8 years (INPE/EMBRAPA, 2011). Old agrarian projects located in the southern part of the study area were not included in the sample due to logistic problems during fieldwork. Finally, the main explanation for these dissimilarities lies in the differences in measurement. Whereas the household level data report on deforestation within the properties, the spatial data estimates also include the areas not allocated to individual properties, thus leading to a different measurement.

Remote sensing data indicate that the fractions deforested in 2000 and 2008 are larger in agrarian projects established after 2000 (newer) than in the projects established in the 1990s (new). Expert analysis and field observations have shown that most of the newer projects in Rondônia are being created in unofficial colonization areas previously occupied by big or medium landholders. This is confirmed by deforestation patterns observed in Landsat/TM satellite images previous to 2000 inside areas currently defined as newer projects, *i.e.* beforehand official land demarcation. In addition, the lots in newer projects tend to be smaller leading to faster forest depletion.

Because of the small number of samples *in situ* outside the agrarian projects, the estimates obtained from remote sensing for such areas, are certainly more reliable. Due to the intrinsic limitation of obtaining a representative sample outside the agrarian projects and the poor accessibility to some newer projects, the deforestation estimates based on the household level data may be biased leading to less reliable results as compared to the spatial analysis.

3.4.2 Patterns of forest clearing size

Different categories of landholders are related to the size of forest clearing as identified by spatial data. While inside agrarian projects the forest clearings were smaller, characteristic of small landholders, outside the projects larger forest clearings are likely connected to big landholders. The results in very old and old agrarian projects indicate that these projects have similar deforestation dynamics. These two groups of projects can be considered consolidated settlements. In these areas the amount of forest remnants was estimated around 18%, which can be connected to a high frequency of forest clearings smaller than 10 ha. Both at the scale of individual plots and the agrarian projects as a whole the deforestation exceeds 50% of the total area. Deforestation up to 50% of the total property size is not allowed by the Brazilian Forestry Code. The exceeding of 50% deforestation even in recently created projects (new and newer) indicates that the objectives of the Forestry Code are no longer realistic for most of the area considered. This is not only an indication that forest is highly fragmented in areas of old frontiers, but also that forest depletion can be significant at the property level already after 10-14 years of occupation in the study area.

Even though intense forest depletion happens in old frontiers, spatial analysis showed that forest clearings between 10 and 60 ha are found in all agrarian projects. These larger forest clearings are often related to aggregation of lots. Previous studies have indicated similar processes of land concentration in old settlements in the same region at the cost of forest remnants and secondary forest (Alves et al., 1999; Escada, 2003; Millikan, 1992). Spatial analysis also showed that forest clearings between 60 and 200 ha and larger than 200 ha were important in newer agrarian projects. Based on fieldwork information and literature review, two main reasons were identified. Both the larger forest clearings taking place during the initial phase of occupation, and the forest conversion into large scale agriculture/pasture activities (as a consequence of land concentration processes) can explain the importance of large forest clearings. The first hypothesis does not apply for all newer projects once a considerable number of them had a high fraction deforested already in 2000, reflecting previous occupation processes before INCRA’s land demarcation. Thus, aggregation of lots may be an important reason for the high deforestation rates. Lot aggregation processes in some newer projects were observed in the field and also reported by INCRA in the study area.

The results found in this chapter confirm the findings of studies in the Ecuadorian Amazon (Messina et al., 2006; Pan et al., 2004) that spatial patterns of deforestation are often closely related to the land use history, colonization process and spatial policies including land tenure situations. At the same time, due to the different policies and context, the landscape patterns develop differently in these different regions.

3.4.3 The influence of property size

The analysis of the deforested area in relation to property size distribution at municipality level indicated that municipalities with a high percentage of properties smaller than 240 ha are more deforested. This reveals the significant contribution of small farmers settled by INCRA on deforestation processes in the region, also shown in the literature (Alves, 2002; Brandão and Souza, 2006a). A similar result was found based on the analysis of household level data. Therefore, both data sources indicate that small properties play an important role in total deforestation and large properties contributed more significantly to deforested patches within 2000 and 2008. Even though in the spatial analysis at the municipality level the risk of ecological fallacy due to scaling issues of aggregated data must be considered, the similar results of property size influence on deforestation in both data sources indicate the complementarities of the analysis.

When connected to the size of forest clearing it was observed that 61% of the total deforestation within 2000-2008 was due to patches smaller than 60 ha, which are related to small farmers. Conversely, forest clearings larger than 60 ha represented 39% of the total deforestation in the same period and are mostly correlated to the larger properties. Similar results were found in previous studies in Rondônia (Alves, 2002; Fearnside, 1993).

3.4.4 Year of occupation and soil fertility

Both spatial and household level analyses draw the attention to the year of occupation, revealing that deforestation is more intense in old frontiers. Household level data indicated a temporal dependence between the year of occupation and the percentage deforested at the property level, as deforestation is higher during the first years of occupation and declines when forest remnants decrease. Besides, in a few interviews in very old and old projects very low deforestation rates were connected to poor soil fertility and steep terrain of the remaining forest land.

The ANOVA results showed high soil fertility as an important determinant of deforestation in the study area, with similar indications noted by other authors in the same area and for the Amazon as a whole (Aguiar et al., 2007; Numata et al., 2003).

3.4.5 Accessibility

The analyses of accessibility measures across different zones showed that both travel time and road density are highly correlated to previous deforestation inside and outside agrarian projects. The analysis of road patterns revealed that occupation in some areas inside new and newer agrarian projects such as Buritis and Campo Novo de Rondônia have been driven first by logging activities linked to orthogonal and irregular patterns, followed by small farmers claiming land tenure. On the other hand, the increase on accessibility to forest in spontaneous colonization indicates a frontier of expansion, also observed in conservation reserves and indigenous areas. Despite of being related to different planning systems both orthogonal and dendritic road patterns contribute similarly to forest fragmentation, while the year of establishment rather than the settlement design is a key determinant of forest clearing. At the household level the results indicated that the means of access and distance to BR-364 determine significantly the deforested area in the properties. These results confirm the observations through remote sensing data. Furthermore, they indicate that accessibility plays an important role in the beginning of the colonization process determining the deforestation rate. A similar conclusion was made by Mertens et al. (2002) based on observations done in Para State at a similar spatial scale.

Deforestation patterns in Rondônia are sometimes seen as a result of synergism among soil fertility, distance to markets and land availability (Roberts et al., 2002). The regression model derived in this chapter (Table 3.5) confirms this hypothesis by listing year of occupation as the dominant determinant of deforestation patterns while soil fertility and accessibility are important contributors to the explanation in the spatial variation of deforestation.

3.5 Conclusions

Remote sensing and household level data indicate similar patterns of land cover change for the study area. Even though the different data sources present some divergent results, a careful analysis accounting for the limitations of data sources can lead to complementary conclusions. Examples are that both data sources showed that small farmers contribute significantly to total deforestation in the area, as well as that well established areas with better accessibility tend to be more deforested. However, because of its ability to provide a synoptic view of large areas, remote sensing data are more suitable to identify overall patterns and to estimate the total percentage deforested. On the other hand, some determinants of deforestation especially in recently created settlements and the influence of processes like lot aggregation can only be revealed by analysis of household level data.

The complementary use of both household level and remote sensing data has been proven useful in previous studies (Fox et al., 2002; Overmars and Verburg, 2005; Rindfuss et al., 2003; Rindfuss et al., 2008). Rindfuss et al. (2003) and Pan et al. (2004) have used methods that actually integrate remote sensing data and household surveys by delineating the property areas of sampled households within the spatial data. Such a linkage allows a relatively straightforward and consistent integration of the different data types. However, this method needs intensive fieldwork in delineating the property boundaries and is, therefore, only feasible for small regions or in cases with adequate cadastral information. Overmars and Verburg (2005) have, similar to this chapter, compared the results of analysis at household level with an analysis of spatial data and interpreted the results to achieve a complementary understanding of the region.

This chapter has indicated that also in relatively large regions insights in land cover change and regional determinants of deforestation processes can be improved when the analysis is based on both spatial data (based on remote sensing images) and household level data.

The analysis shows a significant contribution of both small scale and medium to large scale landholders to deforestation. It also shows the year of establishment together with accessibility, soil fertility and forest remnants as important determinants of patterns and allocation of deforestation. It should be noted that a large portion (38%) of the occupied area is allocated to agrarian projects. Thus, the conclusions could be only extended to specific areas in the Brazilian Amazon. The analysis also reinforces an ongoing discussion of the urgent need of public policies to tackle the different land use trajectories of small and big landholders in current issues as biodiversity maintenance, forest recovery, carbon credits and biofuel initiatives. Such policies must consider not only biophysical and accessibility constraints, but also the land use history that includes land tenure issues.

Chapter 4 - Evolution of Land Use in the Brazilian Amazon: From Frontier Expansion to Market Chain Dynamics[3]

Abstract. Agricultural census data and fieldwork observations are used to analyze changes in land cover/use intensity across Rondônia and Mato Grosso states along the agricultural frontier in the Brazilian Amazon. Results show that the development of land use is strongly related to land distribution structure. While large farms have increased their share of annual and perennial crops, small and medium size farms have strongly contributed to the development of beef and milk market chains in both Rondônia and Mato Grosso. Land use intensification has occurred in the form of increased use of machinery, labor in agriculture and stocking rates of cattle herds. Regional and national demands have improved infrastructure and productivity. The data presented show that the distinct pathways of land use development are related to accessibility to markets and processing industry as well as to the agricultural colonization history of the region. The data analyzed do not provide any indication of frontier stagnation, *i.e.*, the slowdown of agricultural expansion, in the Brazilian Amazon. Instead of frontier stagnation, the data analyzed indicate that intensification processes in consolidated areas as well as recent agricultural expansion into forest areas are able to explain the cycle of expansion and retraction of the agricultural frontier into the Amazon region. The evolution of land use is useful for scenario analysis of both land cover change and land use intensification and provides insights into the role of market development and policies on land use.

[3]*Based on:* Soler, L.d.S.; Verburg, P.H; Alves,D.S.. Evolution of Land Use in the Brazilian Amazon: From Frontier Expansion to Market Chain Dynamics. Land 3 (3), (2014), 981-1014. doi:10.3390/land3030981

4.1 Introduction

Conversions of forest to cropland and cattle ranching are major causes of deforestation in the Brazilian Amazon, which is a core environmental concern (Barona et al., 2010; Faminow, 1998; Fearnside, 2008a; Margulis, 2004b; Morton et al., 2006). Studies based on remote sensing data estimate that the cleared area in moist closed forest alone has increased from 100 thousand km^2 in the 1970s to more than 730 thousands km^2 in 2008 (Alves, 2007a; INPE, 2011; Tardin et al., 1980). This rapid increase of deforestation was triggered by federal policies established in the 1970s and 1980s, which included the construction of a road network, government-assisted settlements and colonization programs. Spontaneous migration, land speculation, and in general, short-lived land productivity with poor land management practices suggest that productive agriculture would be only marginally viable in the Amazon, where land ownership would be dominated by large, unproductive *latifundia* (Hecht, 1985; Machado, 1998; Sawyer, 1984; Velho, 1976).

In addition, discontinuities in crop production, low productivity rates and the relatively high occurrence of land abandonment observed in the region, may corroborate the idea of the limited viability of agriculture in the Amazon (Miranda et al., 2009). These ideas reinforce the premise of the stagnation, *i.e.*, the significant slowdown of the agricultural frontier. The stagnation of the agricultural frontier in the south of Brazil can be linked to migration of surplus population to northern areas, which has resulted in changes in the location of productive areas into portions of the Amazon with more fertile and better drained soils (Machado, 1998; Sawyer, 1984; Velho, 1976). On the other hand, available literature suggests that a likely stagnation of the agricultural frontier in the Brazilian Amazon would be characterized by a specific combination of market development, accessibility to infrastructure and unequal land distribution that limit further evolution of land use systems (Becker, 2004; Foweraker, 1981; Machado, 1998; Sawyer, 1984; Velho, 1976).

Previous points of view have assumed that further frontier expansion is driven by the need for new land to ensure agricultural production (Machado, 1998). At the same time, a number of studies have argued for the need to recognize geographical differences across the region and consider more complex processes to better understand how land use and human systems evolve after deforestation (Alves, 2007a; Alves et al., 2003; Alves et al., 2009;

Browder et al., 2008; Chomitz and Thomas, 2001; Faminow, 1998; Muchagata and Brown, 2003; Rodrigues et al., 2009). Alves (2007a) reported significant geographic differences including intensification of cattle ranching activities. Analyzing spatial and temporal changes in land abandonment, recent studies observed a decrease in the fraction of abandoned land, especially in highly deforested areas, suggesting that land use intensification is more likely in areas with high deforestation levels (Alves, 2007a; Alves et al., 2003; Mello and Alves, 2011; Soler et al., 2009).

The development of market chains and a number of specialized production systems have been argued to trigger economic processes that re-structure agriculture and cattle production. Faminow (1998) argues that a major cause of the growth of cattle production in the Amazon was the considerable expansion of regional demand for food in the context of urban expansion and private investments in cattle ranching. Previous authors studied the many motivations for cattle ranching and intensification of pasture land, and concluded that this activity became lucrative and no longer dependent on subsidies due to increasing regional demand and the need for agricultural inputs only years after deforestation (Andersen et al., 2002; Margulis, 2004a).

Also important to notice is that crop production has faced a number of changes. The increasing importance of soybean plantations in the Brazilian Amazon has been associated with high levels of mechanization and agricultural inputs. Historically, such productive agriculture is dominated by large farms (Foweraker, 1981; Hecht, 2005; Machado, 1998; Velho, 1976). At the same time, several authors have found viable family farming agriculture and agro-industrial systems coinciding with consolidated market chains, and have shown that total production value generated by such farm unit group can surpass the production value of a large farm (Barona et al., 2010; Brown et al., 2005; Chomitz and Thomas, 2001; Hecht, 2005; Morton et al., 2006). In addition, Costa (2010) has indicated that land use intensification can be a result of the evolution of existing land use systems and depend on the land distribution structure and market conditions.

Most of these studies conclude that it is required to consider the interactions of market accessibility, agro-pasture revenue and land productivity in analyzing the temporal dynamics and spatial distribution of land use types in recently deforested regions (Costa, 2007; Morton et al., 2006; Verburg et al., 2004). Other factors to be considered are land distribution per farm size, land tenure systems, technology and household life cycles (Alves et al., 2003; Costa, 2009; Futema and Brondizio, 2003; Moran et al., 2003; Muchagata and Brown, 2003). Therefore, in order to understand the evolution of land use it is essential to comprehend the complex interactions among land use/cover change, market accessibility and land productivity that follow farm establishment after forest clearing (Alves et al., 2009; Costa, 2009; Soler et al., 2009).

Rondônia and Mato Grosso states have very different characteristics in terms of land distribution structure (*i.e.* the distribution in property size) and land use types (Alves, 2002; Becker, 2004, 2005; INPE, 2013a, b), and a more similar development of market accessibility over the last decade (Becker, 2005; Machado, 1998; Pfaff et al., 2007a). Thus, their comparison can reveal how land use expansion and intensification are evolving in response to market accessibility and demand at local and regional scales.

In this chapter, agricultural census data from Rondônia and Mato Grosso states at the municipal level and fieldwork observations from 2006 and 2008 are used to relate changes in the land distribution structure to spatial differences and temporal change in production systems. The spatial variation and temporal changes of land use/cover and agricultural intensification are analyzed in relation to the dynamics of market accessibility to better understand the evolution of land use in the region.

4.2 Land cover and land use history in the study area

The distinct land use/cover history in the study area requires a detailed understanding of how land cover and land use evolved in the area during the last decades. Rondônia and Mato Grosso political territories occupy 237 and 903 thousand km2, respectively. The original land cover in these states is characterized by dense tropical forest, the Amazon biome, as well as by savannah vegetation types, the *Cerrado* biome. In Rondônia, the Amazon and the *Cerrado* biomes occupy respectively 99% and 1% of the territory. In Mato Grosso, the Amazon and the *Cerrado* biomes occupy 54% and 39%, respectively, of the territory (IBGE, 2004; SEPLAN, 2002). It is important to notice that a substantial share of the *Cerrado* biome in Mato Grosso meets the biophysical definition of forest.

Rondônia was part of Mato Grosso and Amazonas States until 1943, with rubber extraction and extrativism of Brazilian nut being the main economic activities until the 1950s

(Pedlowski et al., 1999a). After the 1960s, Rondônia became an independent State where the federal government stimulated migration to dampen land conflicts in southern-central Brazil. Fiscal incentives were granted to agricultural companies, and distinct land ownership rights and subsidies were given to large and small farmers coming from the South and Central parts of Brazil. Conversely, the colonization in Mato Grosso was strongly linked to gold mining, but since the 50s when the government built the federal highway BR-364 connecting the region to Brasília, Mato Grosso has gradually been occupied by loggers, large farms specialized in cattle raising and more recently by grain producers (Barreto et al., 2005; Becker, 2004; Brasil, 1971; Browder, 1988; Fearnside, 2005; Pinto, 1993; Rondônia, 2000). Climate and soil fertility are more supportive of large scale ranching and agriculture in Mato Grosso, while in Rondônia, agrarian structure clashes among large, medium and small farmers creating a mosaic of land use/cover types.

Nowadays, the states of Mato Grosso and Rondônia are amongst the most deforested states in the Brazilian Amazon. Between 2012 and 2013, deforestation rates increased by 20% in Mato Grosso and 9% in Rondônia, while the total area of forest loss in 2013 was 43% in both states according to annual deforestation assessments done since 1998 using Landsat/TM imagery (INPE, 2013b). An additional governmental tool to assess monthly deforestation using Terra-Aqua/MODIS and CBERS/WFI imagery has ranked deforestation among all Amazonian states to be first and third highest in Mato Grosso and Rondônia, respectively, for both the years 2012 and 2013 (INPE, 2013a). Despite that, deforestation rates in 2013 have significantly decreased by around 62% in Mato Grosso and 36% in Rondônia compared to their average rates between 2000 and 2012 (INPE, 2013b). Important information on deforestation rates was provided by the DETER and PRODES projects on monitoring land cover change (INPE, 2013a,b), which are core parts of the governmental effort PPCDAm, considered by the Federal government to be a landmark to encourage many actions to slow down deforestation (Brasil, 2012).

Deforestation patterns have shown significant spatial variability determined by the proximity to major roads and by development zones defined by governmental policies, which has resulted in specialization of land use systems and landscape fragmentation (Brondizio et al., 2002; Ferraz et al., 2005; Machado, 1998; Mello and Alves, 2011; Walker et al., 2002). Large, geometrically regular clearings are concentrated in medium to large farms and often correlate with areas of high forest conversion rates. Small farms are found in more fragmented landscapes; in areas of small farm colonization projects, they are also associated with high deforestation rates (Alves, 2002; Alves et al., 2003; Batistella, 2001; Browder et al., 2004; Soler et al., 2009; Soler and Verburg, 2010).

In Rondônia, the original vegetation is characterized by dense tropical rain forest on soils with low fertility, similar to the northern part of Mato Grosso. The *Cerrado* biome, with better drained and more fertile soils, is sparse in Rondônia and dominant in the center and south of Mato Grosso (INPE, 2009a). Whereas some parts of the *Cerrado* are indeed grassland, they are considered as natural pasture, also when privately held and used for grazing activities. In this sense, the term "natural pasture" is adopted by Instituto Brasileiro de Geografia e Estatística (IBGE) in census data, which confuses the description of the Mato Grosso natural pasture not as the native *Cerrado* biome, but rather as a planted pasture, which causes some miscalculations of the amount of these two land use categories.

Average annual precipitation of 2000 mm with 3 to 5-months of dry season in the middle of the year are typical for Rondônia (Rondonia, 2004), while Mato Grosso shows an average annual precipitation of 1500 mm/year and a longer dry season (SEPLAN, 2002).
Road accessibility to Mato Grosso and Rondônia has progressively improved from the 1970s as colonization projects, land concessions and development zones were established (Becker, 2004; Machado, 1998). Planted pasture is the predominant land cover, especially in older settlements, but small-scale arable agriculture is also observed (Batistella, 2001; IBGE, 2006). Figure 4.1 illustrates the study area location, major highways, main urban areas (municipality seats) and political borders of state and municipalities.

Although private and governmental colonization projects intended for small-scale agriculture have been established in Mato Grosso in the last years, but most of the occupied land consists of large farms. Case studies show that deforestation in this state has been caused by timber exploitation and cattle ranching at initial stages of occupation, but evolved to include highly mechanized soybean cultivation in significant parts of the area (Fearnside, 2005, 2001; Matricardi et al., 2007; Morton et al., 2006). Natural and planted pasture have historically covered most of the farmland in this state, but since the late 1980s mechanized agriculture, especially soybean cultivation, has significantly increased due to profits and local government incentives to large scale agriculture (Barona et al., 2010; IBGE, 2006; Santana, 2003). Rondônia's occupied land is still dominated by a large number of governmental colonization projects intended for small farms, but some areas are dominated by medium and large farms (Alves, 2002; Browder, 1994; Machado, 1998; Pedlowski et al., 1997). Such distinct development histories between Rondônia and Mato Grosso are linked to a large variety of land use change trajectories, including the evolution of different types of farms, intensification, stagnation and land abandonment (Browder, 1994; Costa, 2010; Fearnside, 2008b; Moran et al., 2003).

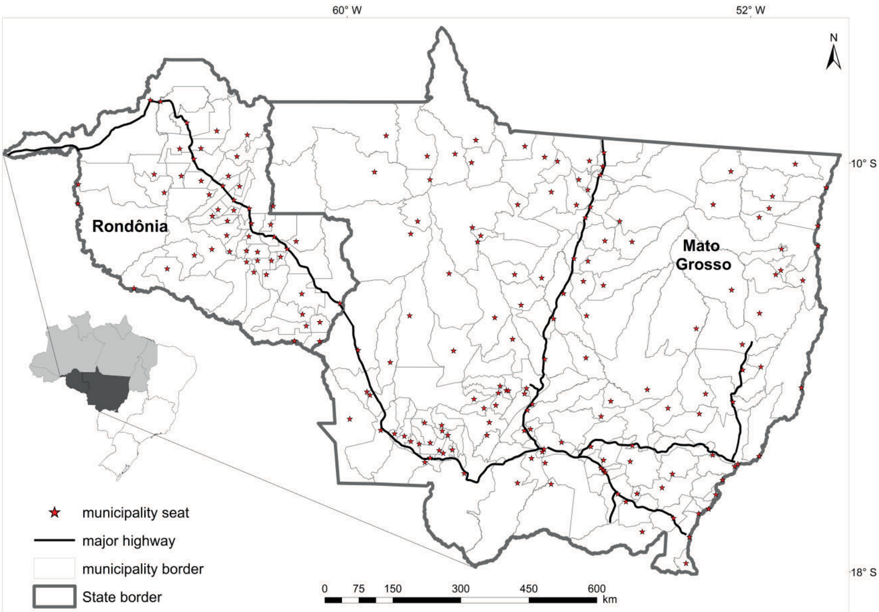


Figure 4.1 – Study area location indicating major highways, main urban areas (municipality seats) and political borders of municipalities, in Rondônia and Mato Grosso states.

4.3 Data and methods

The chapter was based on statistics from several Brazilian Agricultural Censuses and fieldwork observations from 2006 and 2008 in Rondônia and Mato Grosso states. Overall, the analysis comprised 3 major steps: 1) census data preparation to compare several years of surveys; 2) analysis of land use/cover changes and land use intensification indicators based on aggregated census data at the state level from 1970 to 2006 and at the municipality level from 1996 and 2006; 3) integration of file fieldwork observations to compare and interpret the statistical data. The steps are described in the following sub-sections.

4.3.1 Census and data preparation

Statistics from the agricultural census were obtained from the Brazilian Statistics Bureau, both in CD-ROM format (IBGE, 2006) and from the Bureau's Portal (http://www.ibge.gov.br) at the state and municipality levels, including data from the Agricultural Census from 1970, 1975, 1980, 1985, 1995/96, and 2006, comprising the period of accelerated agricultural expansion in the Brazilian Amazon.

Major data acquired for this study consisted of land use and land cover categories ("categorias de utilização das terras" according to IBGE), including the areas of perennial and temporary crops, planted and natural pasture, and forest. Also municipality and state level proxies for land use intensification were acquired. These include number and revenue of cattle head, milk production and revenue, number of tractors, harvested area and revenue of individual crops per total number of properties. Land use/cover categories given in the two last censuses (from 1996 and 2006) were reported for different categories of farm size. In total, five farm size categories were considered in the analysis at the municipality level: smaller than 100 ha, within 100–200 ha, 200–500 ha, 500–1000 ha, and larger than 1000 ha. In the cluster analysis step (see Sections 4.3.2.3 and 4.4.2.2), these categories were merged into three groups (smaller than 200 ha, within 200–1000 ha, larger than 1000 ha) in order to facilitate the analysis of similar spatial trends of land use change and intensification.

Because of the frequent changes in the number of municipalities due to creation of new ones, the use of census data to track land use changes presents some limitations such as the lack of consistency between surveyed years. These inconsistencies make the development of inter-census comparisons difficult in terms of absolute values. Therefore, the analysis of the changes between the different censuses was done in terms of percent changes instead of absolute values (Alves, 2007a; Helfand and Brunstein, 2001). It could be noticed, in particular, that the 2006 census data did not report data on unused productive land, limiting the possibilities of estimating changes in land productivity.

Data on land use/cover categories were calculated as the fraction of total and productive farm size represented by perennial and temporary crops, planted and natural pasture (aggregated in a single category named pasture land) and forest.

4.3.2 Analyses at the state and municipal level

At the state level the fractions occupied by different land use types together with variables that proxy for land use intensification were retrieved for six distinct censuses since 1970 until 2006 (IBGE, 1970, 1975, 1980, 1985, 1996, 2006). Fractions of the area occupied by different land use types were computed for Rondônia and Mato Grosso relative to their total area. At the municipality level, fractions of land use types and variables that proxy for land use intensification were retrieved per farm size category for the censuses from 1996 and 2006 (IBGE, 1996, 2006). This is because most variables adopted as proxies were not available at this level of analysis in the census surveys from previous years. The number of municipalities is 40 in Rondônia and 117 in Mato Grosso when using the municipalities in 1996 as baseline.

The land distribution concentration was analyzed by calculating Gini coefficients of the Lorenz curves of the land use types (Gastwirth, 1972). Lorentz curves were built representing the cumulative percent distribution of different characteristics of farms (*i.e.*, land use types, cattle herd, milk production, number of tractors or labor force). The calculation of Gini coefficients was done using Equation (4.1):

$$G = 1 - \frac{2}{\mathrm{n}-1}\left(n - \frac{\sum_{i=1}^{n} iC_n}{\sum_{i=1}^{n} C_n}\right) \quad \text{(equation 4.1)}$$

where *n* represents number of different categories of farm sizes (5; listed in Section 4.3.1), while *C* is the percentage value of each characteristic of farms calculated per farm size category.

4.3.2.1 Variables as proxies of land use intensification

To obtain variables that proxy for land use intensification at the state level, the total number of cattle was retrieved and compared, in relative terms, to the same figures in the Brazilian Amazon and in Brazil as a whole. Raw milk production, cattle per farm and the number of farms per tractor were also calculated at the state level. The lack of consistency among surveyed years of census data due to changes in the number of municipalities forced us to use fractions instead of absolute areas per land use type. The same limitation could bias the comparison between variables that proxy for land use intensification if they were calculated per total area of cultivated land. Despite these limitations, we also present the number of tractors as well as labor force per total area of cultivated land (perennial and annual crops) at the state level to give an indication of the quantities.

Land use intensification indicators at the municipal level were calculated per category of farm size and include the stocking rates as the total cattle herd per hectare of planted and natural pasture. Also, it includes the number of tractors computed as the number of farms per tractor, and labor force, computed as the number of workers belonging to the household (or temporarily/permanent hired) divided by the total number of farms. Labor force was considered only at the municipality level per category of farm size and not at the state level. Census data regarding the number of tractors per farm size category were available only for 2006, while for 1996 the same data were only available aggregated per municipality, *i.e.*, with no information per farm size category. Therefore, estimates of the number of tractors per category of farm size for 1996 were done for each municipality using data from both years, according to Equation (4.2):

$$\widehat{Tr_i}^{1996} = Tr^{1996} \times Tr_i^{2006} \quad \text{(equation 4.2)}$$

where $\widehat{Tr_i}^{1996}$ is the estimator of the number of tractor for farm size category *i* in 1996, which is then estimated by Tr_i^{2006}, the given number of tractor for farm size category *i* in 2006, and Tr^{1996}, the number of tractors per municipality in 1996. Once such estimates where obtained for each farm size category in each municipality, the final land use intensification indicator given as the number of farms per available tractor could be assessed.

At the municipality level, milk production per area was retrieved as the total milk production in the year of analysis divided by the total area of planted pasture. In addition, milk revenue was given as the total milk revenue per total milk production. Cattle revenue was assessed by dividing the total revenue of cattle herd selling per area of pasture land (planted and natural pasture) in each municipality, where cattle herd selling refers to the sale of cattle for slaughter or to fattening operations.

The use of solely planted pasture or planted plus natural pasture to calculate the total revenue per unit area from milk production or cattle herd selling is sensitive to differences in land occupation history in natural pasture areas. These differences relate to the fact that natural pasture areas are historically occupied by cattle ranching and not milk production farms and – within the study area – natural pasture are highly concentrated in the center-south of Mato Grosso state (Morton et al., 2009; Morton et al., 2006).

Average revenue per type of crop was used as a land use intensification indicator considering the most common perennial and annual crops in both regions in terms of percent area, which represent 95% of crop production. In addition, the average revenue per crop was retrieved, even though only estimates per municipality were used due to data unavailability for different farm size categories. All these land use intensification indicators were retrieved from the censuses of 1996 and 2006 (IBGE, 1996, 2006).

4.3.2.2 Market accessibility at the municipality level

Market accessibility is a relevant driver of land use/cover change in the Brazilian Amazon at different scales (Aguiar et al., 2007; Soler et al., 2009), and possibly also an important drive of land use intensification in the region. Market accessibility was calculated as the travel time to dairy plants (milk storage and processing) or slaughterhouses accounting for road conditions (Geurs and Ritsema van Eck, 2001; Verburg et al., 2004). The travel time is calculated as the cost distance between a point on the map and the reference location (*i.e.*, slaughterhouses and dairy plants). Travel time was calculated using cost distance algorithms using weighted travel time based on fieldwork measurements (Geurs and Ritsema van Eck, 2001; Soler and Verburg, 2010; Verburg et al., 2004).

Roads conditions are given as an average speed obtained during our field trips or reported by locals for highways, main and secondary roads (paved/not paved), river network, bays, dams, lakes and lagoons. Information from the Brazilian National Agencies of Terrestrial and Aquatic Transports (ANTT and ANTAQ) were useful to calibrate information obtained in the field. The algorithms used to calculate the market accessibility maps allow the use of higher weights in cells (*i.e.*, the unit of analysis when calculating the accessibility measures) in which the number of dairy plants/slaughterhouses are two or more. This procedure results in a balanced average travel time to market facilities. Geographic data of road networks and locations of dairy plants and slaughterhouses, essential to calculate the accessibility measures, were retrieved from a state level governments' database (SEPLAN, 2002; Witcover et al., 2006), and complemented by Landsat/TM images interpretation and fieldwork observations in 2006 and 2008. Changes in travel time between 1996 and 2006 were calculated by subtracting the final travel time maps for 2006 from the maps for 1996. As a measure of change, percentage decrease in travel time between 1996 and 2006 was calculated relative to the 1996 travel time.

4.3.2.3 Cluster analysis at the municipality level

To combine changes in land use and/or in land use intensification indicators a cluster analysis was made at municipality level. First, the relationships among land use types and the land use intensification indicators in Rondônia and Mato Grosso were quantified per category of farm size in 1996 and 2006 by using Spearman´s ranking correlation (Equation 4.3).

$$\rho = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2 (y_i - \bar{y})^2}} \quad \text{(equation 4.3)}$$

The Spearman correlation coefficient is defined as the simple Pearson correlation coefficient between the ranked variables (X_i and Y_i). This means that values of x_i and y_i are assigned a rank equal to the average of their positions in the ascending order of the values of variables X_i and Y_i. Thus, for a sample of size *n*, the *n* raw scores X_i ,Y_i are converted to ranks x_i ,y_i to compute ρ.

Spearman´s ranking was obtained for every pair of variables combined among area of land use types and land use intensification indicators per municipality and per farm size category (see variables in Table 4.4). Finally, the variation of coefficient correlation in the 10 year period was calculated according to Equation 4.4, as follows:

$$\Delta\rho_{06\text{-}96} = (\rho_{06} \text{-} \rho_{96})/(\rho_{06} + \rho_{96}) \quad \text{(equation 4.4)}$$

where ρ_{96} and ρ_{06} are the Spearman's ranking correlations for every pair of variables (area of land use types and land use intensification indicators per municipality and per farm size category) respectively in 1996 and 2006. Non-parametric ranking correlation was chosen for its suitability regardless of the statistical distributions of the variables, and also because outliers, common in aggregated census data, have less effect on this type of correlation (Chen and Popovich, 2002). Farm size categories presenting variables with correlation values equal or higher than 0.60, were considered as having similar trends of change and intensification. Similar farm size categories were merged to facilitate the cluster analysis performed at the municipality level.

Once similar farm size categories were merged according to the procedure described above, we performed a k-means clustering method aiming to identify clusters of municipalities based on similarities in their evolution of land use and their land use intensification indicators. The k-means clustering method was applied to the changes (in %) between 1996 and 2006 of the variables listed in section 4.4.1. These variables were all given by farm size category as follows: smaller than 100 ha, between 100 and 200 ha, between 200 and 1000 ha and larger than 1000 ha. Four cluster analyses were run separately for each farm size category using the above-mentioned variables, and all runs also included percent changes of some variables at municipality level only (*i.e.*, not split into farm size categories). These additional variables included deforestation rates, milk and cattle revenue, average revenue of either annual or perennial crops, and travel time to dairy plants or slaughterhouses. Travel time to such facilities, calculated in raster format at 250 m resolution, was aggregated to municipality level by taking the average value of the pixel values inside the boundaries of each municipality. In each clustering, an exploratory analysis was adopted to select the best combination of variables and number of clusters that maximized the differences or similarities between/within clusters of municipalities.

The results of cluster analysis at the municipality level were used to discuss the spatial patterns of evolution of land use systems in the study area (see Section 4.5.3). The discussion was supported by the calculation of changes to each land use type based on the combination of clusters (as described in Section 4.4.2.2) with similar temporal land dynamics.

4.3.3 Fieldwork data

Data from two fieldwork campaigns performed in 2006 and 2008 were used in this paper. During these fieldwork campaigns, 30 municipalities were visited in Rondônia and 10 in Mato Grosso in order to interview key informants of market and small landholders inside official settlements (also named agrarian projects). The key informants consisted of representatives of local civil organization of farmers, rural extension organizations, municipality governments, research organizations (e.g., local headquarters of EMBRAPA, INCRA, IBGE, CPRM among others), non-governmental organizations, cooperatives, community organizations, milk dairies, slaughterhouses, agro-pasture regulation agencies and local commerce of agro-pasture inputs. The interviews consisted of standard questions, which were adapted to fit the role of the informant during the interviews. Questions aimed to capture the functioning of market chains and document stakeholder observations on land intensification for either milk or beef production.

With small landholders, a total of 86 interviews were conducted in 20 municipalities in Rondônia to record land-use histories in official settlements with different years of establishment. The results obtained in these interviews reflect the overall evolution of land use systems among small landholders and were compared to remote sensing assessments of deforestation (Soler and Verburg, 2010). The results were useful to better understand the spatial structure of land use, indicating a dominance of pasture land among small landholders with crops (usually perennial crops) occurring in areas far from roads.

These results of fieldwork campaigns were used to parameterize the calculation of accessibility measures, as described in Section 4.3.2.2 and to hypothesize and interpret the changes in the land distribution structure in relation to spatial differences and temporal changes in production systems. The outcomes from interviews with key informants and small landholders were used to develop a strategy of analysis of census data in order to understand how changes in land use could be related to market chains. Thus, fieldwork observations mainly supported the analysis and interpretation of the statistical data used in this chapter.

4.4 Results

4.4.1 State level land use changes during the 1970-2006 period

Aggregate land-use statistics at the state level during the 1970-2006 are shown in Tables 4.1 and 4.2. They expose the continuous changes in the region’s landscapes following the expansion of the agricultural frontier into Mato Grosso and Rondônia (Machado, 1998), where the forest area declined as farm land occupied a larger portion of each state with increasing crop and pasture areas.

Considering that the states of Mato Grosso and Mato Grosso do Sul were a single federal unit in 1970, statistics for this year is unreliable, as IBGE does not provide separate data for these two states. Mato Grosso has kept 71% of its original territory, but the more accessible areas at the time were left to Mato Grosso do Sul. Thus, regarding Mato Grosso our analysis relies on statistical data only from 1975 onward, but considers both years for Rondônia. Pasture land occupied more farm land than crops in Rondônia in 1970 and 1975, as well as in Mato Grosso in 1975. In Mato Grosso pasture covered the largest part of the total farm area in 1975, while in Rondônia, forests still covered the majority of the total farm area in 1970 and 1975 (Table 4.1). At this time, the difference in the relative importance of pasture land between the two states is due to the large predominance of savannah areas (*Cerrado*) in Mato Grosso, which are mostly used as rangeland for extensive cattle production. Yet, stocking rates and tractor use are low everywhere, as well as milk production despite higher values in Mato Grosso than Rondônia in 1975, (see Table 4.2), indicating low input levels in agriculture that characterize an expanding frontier.

Table 4.1 – Fractions of farm area under different land use types in Mato Grosso and Rondônia states based on Brazilian Agricultural Censuses from 1970, 1975, 1980, 1985, 1996 and 2006.

	% of total farm area per land use type											
Years	**1970**	**1975**	**1980**	**1985**	**1996**	**2006**	**1970***	**1975**	**1980**	**1985**	**1996**	**2006**
Land use types	**Rondônia**						**Mato Grosso**					
forest	86.42	85.92	77.27	71.29	59.51	34.26	21.05	37.63	44.95	43.22	46.25	39.05
perennial crops	0.99	1.54	3.43	3.77	2.97	3.12	0.15	0.22	0.44	0.42	0.35	0.84
annual crops	2.61	4.97	4.10	5.52	2.79	2.95	1.69	2.43	4.78	6.10	7.06	12.68
pasture land**	9.94	7.56	15.19	19.28	34.19	59.47	77.08	59.59	49.66	50.19	46.20	47.32
planted forest	0.04	0.01	0.00	0.14	0.48	0.23	0.04	0.12	0.17	0.08	0.15	0.12

Note: * Exceptionally statistics for 1970 in Mato Grosso are officially reported together with statistics for Mato Grosso do Sul state, thus not considered in our analysis; ** pasture land represents the total planted and natural pasture land use types.

In the census data for 1975, annual and perennial crops occupy a smaller fraction of the total farm land area in Mato Grosso as compared to Rondônia, where small farm settlements with more crop production are predominant. In terms of crop production, a large increase in the relative area of annual crops is seen in Mato Grosso between 1985 and 2006, but not in Rondônia (Table 4.1). The fraction of perennial crops remains smaller than that of annuals, particularly in Mato Grosso where it never represents more than 1% of total farm area. It can be noticed that stocking rates and average milk production increase in both states (Table 4.2). Tractors per farm or per total area of crops also increase in both States. However, between 1996 and 2006 tractors per total area of crops decrease significantly in Rondônia and especially in Mato Grosso.

Statistics of land use in the census data for 1980 and 1985 suggest both the concentration of agricultural production in areas of pioneer occupation as well as expansion into new areas. In Rondônia, where farm land has been concentrated in colonization projects along the BR-364 highway (Alves, 2002; Alves et al., 2003; Machado, 1998), older colonization areas tend to concentrate farm land and forest loss (Alves, 2002; Alves et al., 2003).

Between 1970 and 1996, the fraction of forest in farmland increased in Mato Grosso, likely because of the stronger effect of the frontier expansion into new areas still under original vegetation, and lower importance of forest loss in existing farms. However, the decline of forest inside properties between 1996 and 2006 might not reflect solely a slowdown of the frontier expansion, but also land intensification. In addition, recent law enforcement over deforestation practices also influenced rates of forest conversion inside properties, especially after 2005 (Brasil, 2008; INPE, 2013b). According to Morton and colleagues (Morton et al., 2006), direct conversion of forest to cropland occurred in large areas during 2001–2004 in Mato Grosso, contributing to historical forest losses that reached 23% in 2003. Their observations show that cropland deforestation averaged twice the size of clearings for pasture, with 90% of clearings for cropland being planted soon after deforestation, which counteracts the argument that agricultural intensification does not lead to new deforestation.

In Mato Grosso, the changes in the fractions of forest, annuals and pasture land (Table 4.1) indicate that deforestation was most closely correlated with the expansion of annual crops, and somewhat to pasture conversion. However, remote sensing assessments showed that expansion of annual crops over forest and pasture land has decreased considerably in the following years after 2006 (Macedo et al., 2012). In addition, the authors indicate that soybean production has occurred rather to yield increases and expansion over already cleared land, which reinforces the idea of land use intensification. The decrease of total farm land area, and increases in pasture land per farm, number of cattle per farm and stocking rates (see Tables 4.1 and 4.2) indicate pasture intensification for cattle ranching mostly between 1996 and 2006. Pasture intensification can explain the peak of stocking rates in a region where pasture land and cattle per farm have decreased as well as total farm land area. Therefore, pasture intensification and the usual practices of extensive cattle raising in savannah areas can explain the slower decline in the fraction of forest in Mato Grosso as compared to Rondônia.

The importance of cattle ranching increased throughout the study area according to the statistics from 1996 and 2006. Whereas the increase in pasture land was accompanied by increases in stocking rates and milk production; the relative increase in cattle in the study area was remarkable compared to the total cattle herd in Brazil or in the Legal Amazon (see Table 4.2). In general, stocking rates have remained higher in Rondônia than in Mato Grosso, suggesting that extensive cattle ranching tended to be more important in the latter. These changes have been associated with the development of beef and dairy market chains, at the regional, national and even international levels, which have contributed to the strengthening of the cattle ranching activity (Faminow, 1998; Margulis, 2004b; Veiga et al., 2004). Also, an important characteristic that contributes to explain the gradual increase of the total number of cattle and milk production per farm since the 1980s is the dual-purpose of milk/beef production (see Table 4.2) usually employed by small farms, which can be connected to the economic strategies of individual farms (Browder et al., 2008; Evans et al., 2001; Moran et al., 2003; Perz, 2005). Despite that, aggregated data at the state level per farm must be interpreted with care, as the numbers of small, medium and large farms diverge significantly in Mato Grosso and Rondônia (see Table 4.3).

Statistics of the Brazilian agricultural censuses from 1996 and 2006 indicate changes in crop production that suggest major shifts in land use, which have an important influence on land distribution structure, as shown next. The continuous increase in stocking rates and raw milk production in both Rondônia and Mato Grosso indicate important changes in these sectors' productivity, which is further analyzed considering farm size for 1996 and 2006.

Table 4.2 – Cattle herd, milk and tractor statistics in the states of Mato Grosso and Rondônia based on census data from 1970, 1975, 1980, 1985, 1996, 2006.

Years	**1970**	**1975**	**1980**	**1985**	**1996**	**2006**	**1970**	**1975**	**1980**	**1985**	**1996**	**2006**
	Rondônia						**Mato Grosso**					
Total cattle herd (thousands)	23	55	251	771	3938	8491	9429	3110	5243	6546	14438	19807
Stocking rates(cattle/ha)	0.19	0.25	0.33	0.70	1.35	1.75	0.30	0.28	0.35	0.40	0.67	0.90
% Cattle herd relative to the Legal Amazon	0.21	1.06	2.72	4.97	12.41	16.60	84.68	59.36	56.79	42.20	45.52	38.73
% Cattle herd relative to Brazil	0.03	0.05	0.21	0.60	2.57	4.95	12.00	3.06	4.44	5.11	9.43	11.54
Number of cattle per farm	3	2	5	10	51	98	205	55	83	84	183	175
Raw milk per farm (100 liters/year)	1.16	1.27	3.77	5.86	44.57	71.73	32.60	6.97	14.44	15.77	47.66	45.78
Raw milk per total area of pasture land (100 L/ha)	0.67	1.44	2.42	4.29	11.74	12.86	0.48	0.35	0.62	0.75	1.75	2.34
Pasture land per farm	17	9	16	14	38	56	685	200	233	211	272	196
Farms per tractor	136	375	85	69	25	15	10	21	5	3	2	3
Tractors per total area of perennial and annual crops (tractors/100 ha)	0.04	0.15	0.22	0.62	1.17	0.58	0.53	0.72	0.92	0.95	0.67	0.04

Note: Exceptionally statistics for 1970 in Mato Grosso are officially reported together with statistics for Mato Grosso do Sul state.

Table 4.3 – Total occupied land area and fractions of the total occupied area used by different land use types, stocking rates, labor force, number of farms per tractor and milk production per farm in Rondônia and Mato Grosso states in 1996 and 2006.

	Small farmers				**Medium farmers**		**Large farmers**			
Farm size groups	**< 100 ha**		**100-200 ha**		**200-500 ha**		**500-1000 ha**		**>1000 ha**	
					Rondônia					
% land use types	**1996**	**2006**	**1996**	**2006**	**1996**	**2006**	**1996**	**2006**	**1996**	**2006**
perennial crops	74.34	73.65	17.36	13.67	5.47	4.93	0.99	0.85	1.84	6.90
annual crops	62.33	34.57	19.80	11.83	7.18	13.26	2.24	13.03	8.44	27.31
pasture land	24.94	29.89	17.05	16.59	14.67	16.30	9.36	10.69	33.99	26.53
forest	14.58	20.98	11.16	13.77	8.93	15.07	6.20	11.87	59.13	38.31
planted forest	27.30	37.96	20.52	14.27	10.76	8.67	2.47	0.20	38.95	38.90
stocking rate (#cattle/ha)	1.75	2.09	1.58	1.94	1.42	1.80	1.30	1.62	0.92	1.38
labor force	3.73	0.67	4.47	0.51	4.57	1.05	4.96	1.55	10.06	3.51
# farms per available tractor	62.43	39.39	20.63	10.61	6.21	4.13	2.52	1.95	1.32	0.90
milk production per pasture land (liters/year/ha)	270	297	194	165	84	72	29	24	6	4
% of occupied land	21.29	28.55	13.65	15.44	10.75	15.44	7.00	10.81	47.32	29.76
total occupied land (10^4 ha)	18.19	21.96	16.64	11.88	13.47	11.87	8.71	8.32	50.37	22.90
number of farms	61199	70800	10591	9855	3389	4081	894	1249	881	1092
	Small farmers				**Medium farmers**		**Large farmers**			
Farm size groups	**< 100 ha**		**100-200 ha**		**200-500 ha**		**500-1000 ha**		**>1000 ha**	
					Mato Grosso					
% land use types	**1996**	**2006**	**1996**	**2006**	**1996**	**2006**	**1996**	**2006**	**1996**	**2006**
perennial crops	37.74	22.22	11.68	7.35	9.65	12.25	5.24	10.70	35.69	47.48
annual crops	4.88	1.90	2.42	1.22	7.59	4.08	11.40	8.56	73.70	84.23
pasture land	3.92	7.97	3.48	4.48	7.12	8.55	7.79	8.79	77.70	70.21
forest	2.16	3.69	2.16	2.48	3.62	4.23	4.09	5.70	87.96	83.89
planted forest	0.39	5.71	0.27	1.52	1.09	5.98	1.62	9.10	96.63	77.69
stocking rate (#cattle/ha)	1.51	1.49	1.15	1.32	1.01	1.15	0.84	1.07	0.56	0.76
labor force	3.29	1.36	3.44	0.34	3.90	1.10	4.46	1.45	10.59	6.98
# farms per available tractor	15.71	20.54	6.06	5.45	2.20	1.90	0.93	0.86	0.42	0.36
milk production per pasture land (liters/year/ha)	196	183	85	78	42	32	19	15	3	2
% of occupied land	3.29	5.62	2.82	3.31	5.53	6.32	6.32	7.56	82.05	77.18
total occupied land (10^4 ha)	23.66	43.18	20.54	24.97	40.95	47.67	46.03	53.86	547.63	507.30
number of farms	46877	77116	10733	11067	8690	9312	4438	5051	8010	8519

4.4.2 Land use changes at the municipality level between 1996 and 2006

4.4.2.1 Changes in agrarian structure and land use

Differences in the evolution of perennial and annual crops between Rondônia and Mato Grosso can be linked to the distinct land distribution structure as a response of historical differences in their land tenure systems. Table 4.3 shows the fractions of land use types and the total land area occupied per category of farm size in Rondônia and Mato Grosso states in 1996 and 2006. Also, statistics in Table 4.3 show that only farms smaller than 100 ha increased their total occupied land area between 1996 and 2006, while in Mato Grosso all farm size categories increase their total land area, except farms larger than 1000 ha. In Rondônia, perennial crops are concentrated in small farms, especially those smaller than 100 ha. Whereas small farms decreased their share on perennial crops by 4% in Rondônia and 20% in Mato Grosso, large farms increased this share by 5% and 12%, respectively. In Rondônia, annual crops were concentrated in small farms in 1996. Annual crops in small farms had a decrease in area by 35% in 2006, while in the same period increases of annual crops by 17% in medium farms and 18% in large farms were observed. In Mato Grosso large farms concentrated more than 70% of annual crops and increased their share by 10% in the period of analysis.

In Rondônia, half of the pasture land was concentrated in small farms in 2006, while in Mato Grosso more than 70% was found in large farms. Milk production in Rondônia state increased more than 50% between 1996 and 2006, with the bulk production concentrated in farms ranging from 100 to 500 ha, but with farms smaller than 100 ha presenting the highest milk production per hectare. In Mato Grosso stocking rates were higher in farms up to 500 ha, while milk production was more significant among farms smaller than 200 ha. The higher concentration of milk production in Rondônia reflects the increasing milk production among small farms, which goes along with significant increases of cattle herd for dual-purpose in small farms. Decreases in labor force per farm between 1996 and 2006 were smaller in Mato Grosso than in Rondônia, especially among farms smaller than 100 ha or larger than 1000 ha.

Gini coefficients estimated for land use types adopting the municipality level indicate there is an association between changes in land use and agrarian structure (Table 4.4). In Rondônia, results from Gini coefficients for perennial and annual crops indicate a lesser importance of such land use types among smaller farms. When analyzed together with results from Table 4.3 (discussed above) increase on pasture land in Rondônia is shown as the reason for the increasing importance of the total land area occupied by these farmers. The increase in occupied area by small farms is also related to a decrease in forest area, and Gini coefficients indicate a more equal distribution among different farm sizes, with changes occurring especially in Mato Grosso. These results indicate a change in the relative importance of most land use types especially among small and large farms in the last decade.

Table 4.4 – Gini coefficients of land distribution per land use type, milk production, cattle herd and labor force using five categories of farm size.

Gini coefficients	**Rondônia**		**Mato Grosso**	
	1996	**2006**	**1996**	**2006**
perennial crops	0.81	0.73	0.05	0.27
annual crops	0.63	0.07	0.73	0.86
pasture land	0.05	0.06	0.76	0.64
forest	0.42	0.16	0.87	0.82
planted forest	0.03	0.24	0.97	0.76
milk production	0.68	0.76	0.34	0.62
cattle herd	0.15	0.19	0.58	0.48
tractors	0.13	0.13	0.54	0.54
labor force	0.79	0.72	0.24	0.23

The changes in fractions of milk production, stocking rates together with Gini coefficients for milk production and cattle herd in Rondônia indicate that the increase of milk production among small farms was accompanied by land intensification. This farm size category had played an important role in the strengthening of dairy market chains (as shown next). In Mato Grosso, despite the fact that bulk of milk production decreased between 1996 and 2006 (Tables 4.2 and 4.3), Gini indexes and fractions per farm size category for milk production indicate a concentrated production among small farmers. The changes in Gini coefficients for milk production and cattle herd in Mato Grosso can be attributed to differences in the dual-purpose use of cattle herds, especially among small and medium sized farms.

Despite constant Gini coefficients for available tractors per farm, the use of machinery showed an overall increase among small and medium farms in Rondônia (as seen in Table 4.3). Also, the small changes in the Gini coefficient for labor force in both states indicate that large farms have a slightly higher concentration of available work in the large scale agriculture of annual crops in Mato Grosso than in Rondônia.

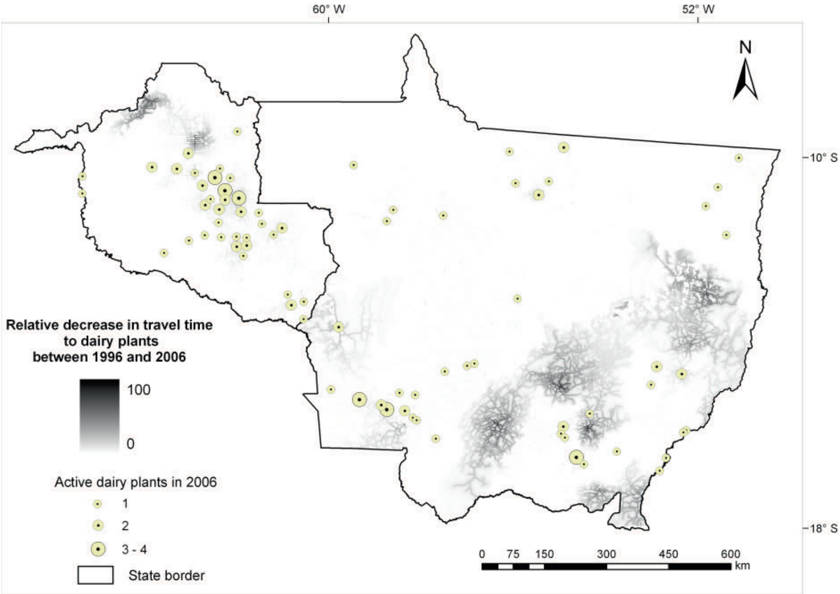
4.4.2.2 Changes in the spatial distribution of major production systems

Changes in road accessibility to dairy plants and slaughterhouses between 1996 and 2006 are shown in Figure 4.2. The census data from 1996 to 2006 shows that most agricultural production in Rondônia and Mato Grosso has been focused on a relatively small number of crops compared to other states with a long-term tradition of agricultural production in Brazil, such as São Paulo, Paraná and Rio Grande do Sul (IBGE, 1970, 1975, 1980, 1985, 1996, 2006).

In Rondônia and Mato Grosso only eight different crops accounted for nearly 95% of all harvested areas for annual and seven for perennial crops (Figure 4.3a,b). While in Mato Grosso the bulk annual agricultural production is a result of soybean and cotton crops in 2006, Rondônia shows a greater degree of crop diversity including beans, corn and rice. It is important to notice that soybean made up more than 90% of the harvested area of annual crops and more than 50% of revenue from the total cropped area in the same year. In Mato Grosso state the perennial crops rubber, coffee and coconut showed large increases, whereas in Rondônia, cocoa showed the most relevant increase in the harvested area between 1996 and 2006. Despite that, coffee still represents around 80% of the perennial cropped area.

Figure 4.3a shows that the soybean area increased significantly in both states between 1996 and 2006. The differences between Rondônia and Mato Grosso regarding soybean expansion are illustrated in Figure 4.3a,c,d. These graphics clearly show that the increase in cropped areas for soybean in Rondônia is linked to the increase of both revenue per total cropped area and average revenue. Also, Figure 4.3a,d indicate a slightly better average revenue of soybeans in Mato Grosso, where a 10% increase in the fraction of harvested area can be observed between 1996 and 2006. It important to note that already in 1996, the soybean harvested area in Mato Grosso represented 4% of the total harvested area in Brazil.

(a)



(b)

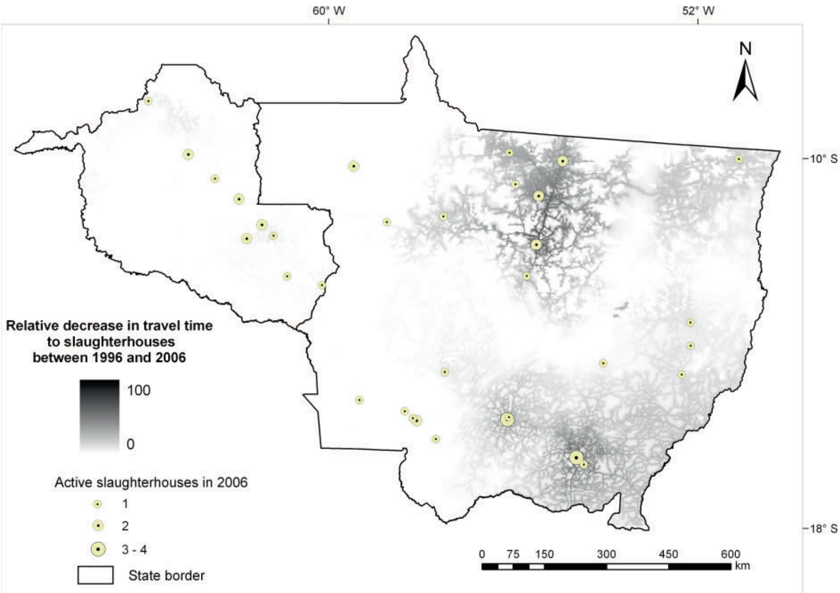


Figure 4.2 – Changes in market accessibility to (a) dairy plants, (b) slaughterhouses, given as the percentage decrease in travel time to market facilities between 1996 and 2006 relative to the 1996 travel time. Changes are calculated separately for Rondônia and Mato Grosso and illustrated at the same scale.

The average revenue of soybean in Mato Grosso represented more than 4% of the total revenue from crops in Brazil. Even with a 29% negative decline of international soybean prices between 1996 and 2006, soybean crops in Mato Grosso still represented more than 11% of the harvested area and more than 6% of the total revenue relative to all annual crops in the country in 2006 (IBGE, 2006). Other crops also showed increases in average revenue, in particular cotton and coconut presented increases in both area and revenue. Even though harvested areas of corn decreased, revenue increased in both states (Figure 4.3a,c,d). This suggests that corn production might have been influenced by changes in international market associated with corn-ethanol production (Gallagher et al., 2006).

The cluster analysis identified clusters of municipalities with similarities in land use changes and intensification indicators between 1996 and 2006. The values of land use/cover types and land use intensification indicators in each cluster are listed in Table 4.5. The spatial distributions of the clusters are presented in Figures 4.4a–d according to the different farm size categories included in the analysis: farms smaller than 100 ha (cluster A), farms between 100 and 200 ha (cluster B), farms between 200 and 1000 ha (cluster C) and farms larger than 1000 ha (cluster D). In the figures the clusters are characterized by the variables that are most typical for the changes in the particular cluster. Also other variables are different between the clusters, as shown in Table 4.5.

The results of cluster analysis (Table 4.5) show that municipalities with farms between 100 and 200 ha were split by k-means method into two clusters (A.1 and A.2), the temporal differences of which are due to spatial concentration of annual and perennial crops, larger fractions of forest inside properties, higher milk production and higher revenue from perennial crops in Cluster A1 as compared to Cluster A.2. Cluster A.2 shows that a significant number of municipalities holds farms between 100 and 200 ha with higher stocking rates, significant lower fractions of forest area, perennial and annual crops and lower revenue from cattle and milk production than Cluster A.1. Similarly, municipalities with farms between 200 and 500 ha were divided into two clusters (B.1 and B2). As compared to Cluster B.2, Cluster B.1 has higher fractions of deforestation, perennial crops, pasture land as well as milk production and cattle revenue.

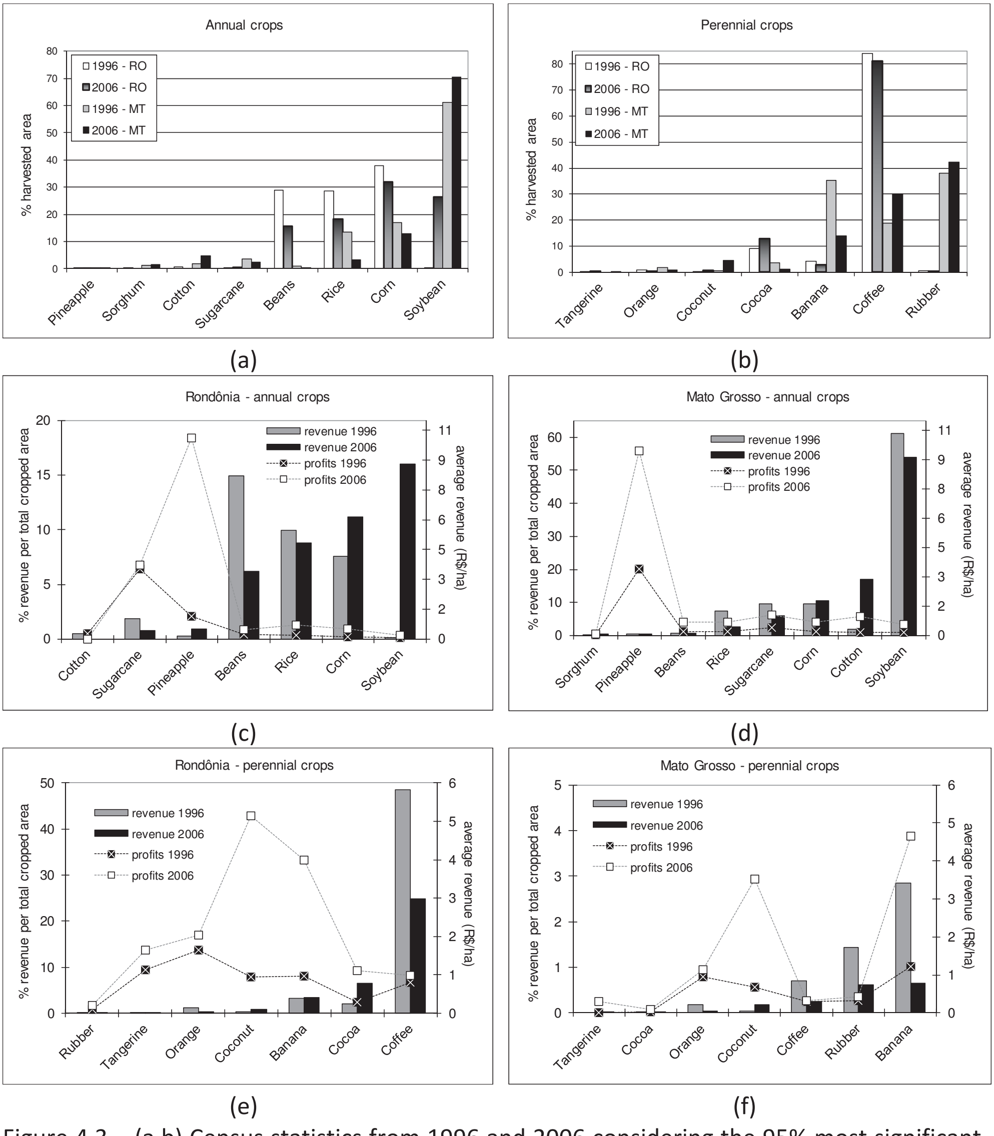
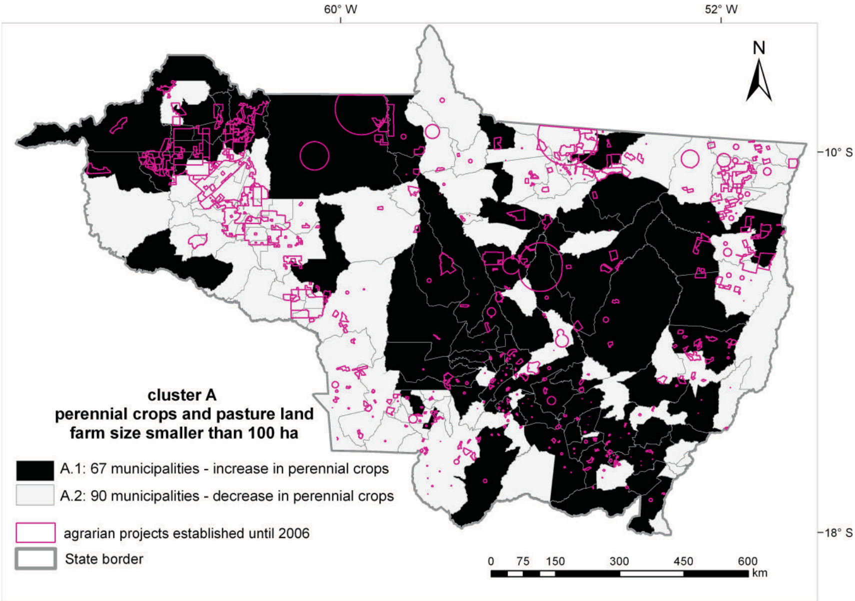


Figure 4.3 – (a,b) Census statistics from 1996 and 2006 considering the 95% most significant crops in terms of total cropped area per type of crop (annual of perennial) in Rondônia and Mato Grosso; (c–f) The fraction of revenue and the average revenue of relevant annual or perennial crops that accounted for 95% of total harvested area in both census surveys.

Note: Average revenue values are not normalized by the observed inflation, which amounted 78% over the studied period from 1996 to 2006 (see INPC-Extended National Consumer Price Index at IBGE, 2006).

(a)



(b)

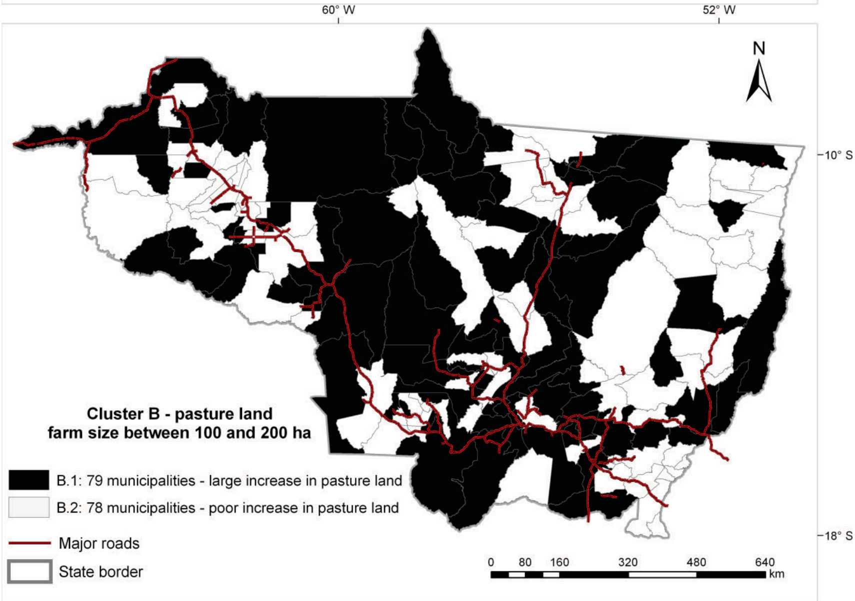
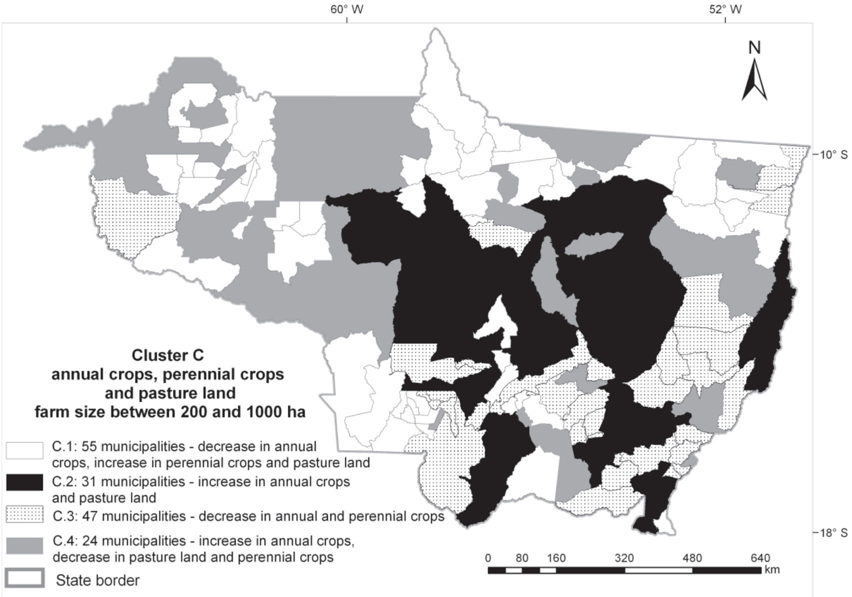


Figure 4.4 – Clusters of municipalities based on changes in land use and land use intensification indicators for different categories of farm size in Rondônia and Mato Grosso between 1996 and 2006. (a) Group A: farms smaller than 100 ha; (b) Group B: farms between 100 and 200 ha; (continue on next page).

(c)



(d)

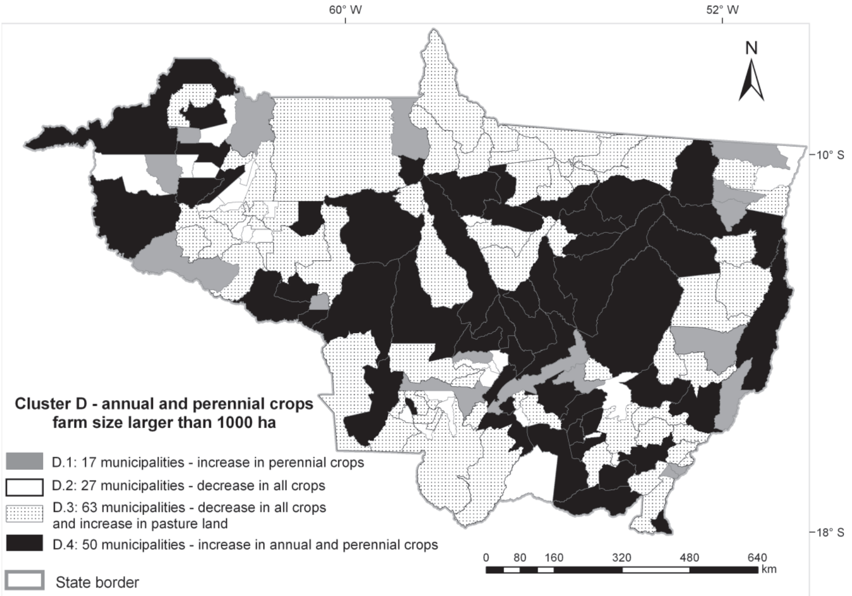


Figure 4.4 – Clusters of municipalities (c) Group C: farms between 200 and 1000 ha; (d) Group D: farms larger than 1000 ha.

Table 4. 5 – Results of k-means clustering based on land use/cover changes and intensification indicators at the municipality level.

Groups of munici-palities		N	Final cluster centers of each group of municipality considering the percent variation of changes between 1996 and 2006											average revenue		travel time to	
			deforestation rate	perennial crops	annual crops	pasture land	forest	stocking rates	labor force	number of tractors	milk production	milk revenue	cattle revenue	perennial crops	annual crops	dairy plants	slaughter houses
A	A.1	67	*n/s*	24	25	*n/s*	49	-5	-68	*n/s*	63	30	75	57	*n/s*	-5	*n/s*
	A.2	90	*n/s*	-35	-53	*n/s*	-14	12	-90	*n/s*	48	29	66	30	*n/s*	-6	*n/s*
B	B.1	79	21	34	*n/s*	23	13	*n/s*	*n/s*	*n/s*	65	*n/s*	69	*n/s*	*n/s*	*n/s*	*n/s*
	B.2	78	13	-64	*n/s*	4	-20	*n/s*	*n/s*	*n/s*	48	*n/s*	52	*n/s*	*n/s*	*n/s*	*n/s*
C	C.1	55	18	47	-31	18	*n/s*	11	-54	17	40	36	72	*n/s*	54	-7	-1
	C.2	31	23	-2	59	22	*n/s*	8	-37	23	25	39	71	*n/s*	47	-7	-3
	C.3	47	12	-65	-64	6	*n/s*	11	-64	11	22	29	67	*n/s*	40	-6	-2
	C.4	24	15	-86	32	-4	*n/s*	2	-55	12	-35	04	44	*n/s*	39	-2	2
	D.1	17	*n/s*	38	-78	13	-2	20	-32	20	*n/s*	*n/s*	76	28	32	*n/s*	*n/s*
D	D.2	27	*n/s*	-74	-80	-34	-72	7	-60	5	*n/s*	*n/s*	-23	38	46	*n/s*	*n/s*
	D.3	63	*n/s*	-95	-21	4	-7	16	-27	18	*n/s*	*n/s*	65	34	45	*n/s*	*n/s*
	D.4	50	*n/s*	48	46	-4	-9	11	-16	20	*n/s*	*n/s*	56	56	53	*n/s*	*n/s*

n/s - non-significant variables discarded in an automatic k-means clustering procedure.

The results of clustering analysis of municipalities regarding larger farms show that the k-means method divided both farm size categories (500–1000 and >1000 ha) into four clusters. Clusters of municipalities based on the characteristics of farms between 500 and 1000 ha are differentiated mostly due to fractions of perennial and annual crops, pasture land and milk production. Conversely, clusters of municipalities for farms larger than 1000 ha are differentiated especially by annual crops and labor force, while milk production had no significant influence on the differentiation of the clusters. It is important to note that the revenue from annual crops and the number of tractors had a significant influence on the differentiation of the clusters considering larger farms only.

4.5 Discussion

4.5.1 Evolution of land use

Analysis of land use dynamics at the regional level indicated that Rondônia and Mato Grosso had a distinct evolution of annual and perennial crops between 1970 and 2006, with pasture land development differing between the two states especially after 1996. Annual crops have increased in importance relative to other land uses in Mato Grosso, where increased mechanization shown by increased tractor use can be explained by the significant growth in commercial agriculture, mostly for soybean cultivation. Experts indicate that amongst the most important reasons for the growth in commercial agriculture for soybean cultivation are international demand and globalization, large profits from recent peaks in soybeans prices allowing for more land purchase, land and profits speculation, regional integration, rapid technological change and improvement of infrastructure supported by from Mato Grosso's government (Hecht, 2005; Mueller, 2003). The results on the spatial dynamics of annual crops and pasture land between 1996 and 2006 agree with de Espindola et al. (2012) who integrated PRODES data (INPE, 2013b) with the same census data adopted in this article. The decrease in tractors per farm and per total crop area (Table 4.1) in both states in 2006 is a result of frontier expansion into new areas, particularly in Mato Grosso, as well as the increasing number of smaller size farms, especially in Rondônia.

Since 1996, pasture land has become the dominant land use in both states. Especially in Rondônia the increase of at least 50% in cattle herd, stocking rates, milk production and tractors per farm/total cropped area can be argued to characterize the evolution of land use systems in this state. During fieldwork interviews, milk production has been reported as representing 30% to 50% of total income for farms smaller than 200 ha, the most common farm size category in Rondônia. Milk production is strongly correlated with high stocking rates and increases in planted pasture, as well as with the maintenance of perennial crops among farms smaller than 100 ha in Rondônia at both levels of analysis.

Rondônia and Mato Grosso were amongst the six Brazilian states with the largest contribution to national milk production in 2006. Even though milk production per farm in Rondônia and Mato Grosso was much higher than the national average in 2006, the spatial scale dependence of milk prices explains that the average milk revenues in these states are

35% and 4%, respectively, lower than the national average. The intensification of milk production in small farms, particularly in Rondônia, has been pushed by an increase in regional and national milk demand (Faminow, 1998; Veiga et al., 2004). Such increases in demand indicate higher milk consumption by local and national markets and suggest a vertical integration of regional milk production, also reported by key informants during fieldwork interviews in 2008, including milk industrialization with UHT (ultra-high-temperature) processing. In addition, the production of some specialized types of cheese has been stimulated by the increasing consumption markets located in Manaus and also at important national markets such as São Paulo and Rio de Janeiro.

If the progress of mechanized agriculture can be seen as an important trait of developments in Mato Grosso, pasture use intensification is the major characteristic of land use development in Rondônia. Results from the TerraClass project based on remote sensing data (INPE/EMBRAPA, 2011, 2013) confirm the trends in mechanized agriculture in Mato Grosso where temporal changes identified by land use classification using Landsat/TM imagery show that annual crops (mostly soybean) increased by 4.9% between 2006 and 2008. TerraClass data also confirm our analysis of intensification in pasture land in Rondônia, where land total pasture land decreased by 1.5% between 2006 and 2008, but at the same time the cattle herd increased by 13% between 2006 and 2008 (IBGE, 2008). Indications of pasture intensification at both levels of analysis, also observed in fieldwork interviews in 2008, show that small and medium farmers have chosen to specialize in milk production activities in response to household socioeconomic differentiation and regional milk market improvement (Costa, 2007; Coy, 1987; Hecht, 2007; Moran et al., 2003; Perz and Skole, 2003; Perz and Walker, 2002; Santana, 2003; Soler et al., 2009; Soler and Verburg, 2010; Veiga et al., 2005).

Mato Grosso reached the largest cattle herd among all Brazilian states, pushing the largest part of the national herd to the Legal Amazon. The census data suggest that pasture intensification in Rondônia is associated with higher stocking rates and milk production. On the other hand, in Mato Grosso, changes in the cattle industry are linked, to some degree, with intensification in cattle ranching, especially in areas of *Cerrado* biome where better-drained and more fertile soils provide a higher suitability for extensive cattle breeding.

Despite the fact that stocking rates augmented, it is important to note that they remained relatively modest ranging from 0.34 to 2.09 heads per hectare throughout the study area. It is also relevant that the low level of land management in cattle ranching activities cannot guarantee long-term intensification or sustainability of this industry (Alves, 2007b; Chomitz and Thomas, 2001).

Of particular interest are changes in the distribution of land use between smaller and larger farm size categories. Changes in Gini coefficients suggest that smaller farms have increased their share in pasture land, while in larger farm sizes perennial and annual crops have become more significant, with the notable relevance of annual crops in Mato Grosso. However, this shift in pasture land to smaller farm sizes should not be seen as evidence of changes in land inequality. Instead, it is indicative of a more effective participation of smaller farms in milk and beef markets. These findings are related to recent observations for the Northern Amazon (Costa, 2007).

4.5.2 Spatial distribution of land use

The changes in travel time to dairy plants (Figure 4.2a) show spatial correlation with the clusters of municipalities with significant changes in perennial crops and milk production among farms smaller than 100 ha (Cluster A.1, Figure 4.4a). This is an indication that improvements of accessibility to dairy plants are related to positive change in perennial crops among farms smaller than 100 ha. Municipalities in Cluster A.1 enclose 37% of official settlements (or agrarian projects) in Rondônia and 57% of those in Mato Grosso, especially the ones established after 1980 where accessibility is usually poorer than in older settlements, and thus are more affected during the rainy season (Soler et al., 2009; Soler and Verburg, 2010).

These results suggest that milk markets expansion has led small farms located in more accessible areas to choose for milk production rather than for crop production. On the other hand, small farms in less accessible areas tend to keep using perennial crops as a survival strategy when milk market profitability is affected (e.g., due to dirty roads in the rainy season and/or impoverished pasture in the dry season). Also, the choice of crops over pasture is more common in recently occupied properties as profits from crops tend to be faster and labor force availability is higher due to the initial stages of household life cycles related to these properties (Brondizio et al., 2002; Moran et al., 2003; Perz, 2001). Deeper understanding of the role of life cycles on the evolution of land use is required through case studies in the area (Brondizio et al., 2002).

These results suggest that accessibility costs to milk markets can determine small farmers' strategies at initial stages of colonization (Santana, 2003). As survival strategy to keep their land, these farmers persist with subsidized, labor intensive crops, such as coffee and cocoa (Browder, 1994). This can also be linked to better profit margins of perennial crops, compared to average revenue from annual crops (see Figure 4.3), while milk production is not well established. As infrastructure is improved and planted pasture is consolidated, milk production increases while at the same time forest remnants are removed. These observations are in agreement with household level studies in Rondônia and Pará that explain land use dynamics among small farms by average revenue and required labor force (Browder et al., 2008; Evans et al., 2001; Moran et al., 2003; Perz, 2005).

Clusters B and C (Figure 4.4b,c) indicate the expansion of pasture into a number of municipalities distant from the main roads, especially in Mato Grosso. The improvement of accessibility to slaughterhouses has been concentrated in the northern portions of both States, between 1996 and 2006 (Figure 4.2b), where the increase in pasture land was determined by farms between 100 and 1000 ha. Revenue from milk production and cattle have played an important role in land use system evolution of farms between 100 and 1000 ha, especially farms located in areas of recent pasture expansion and improved accessibility to slaughterhouses (Clusters B.1 and C.1).

Stocking rates among farms between 200 and 1000 ha followed similar trends of milk production, milk and cattle revenue, as well as improved accessibility to milk market facilities during 1996 to 2006 (see Table 4.5). In areas where stocking rates were higher (Clusters C.1 and C.3) annual crops decreased together with pasture land, while available tractors per farm increased significantly in areas of annual crop intensification (clusters C.2 and C.4). This suggests that some land use systems that supply milk and beef demands might be under high risk of degradation as overgrazing with low technological levels persists over long term planted pasture areas.

Cluster D (Figure 4.4d) indicates that annual crops in Rondônia have increased their spatial distribution among farms larger than 1000 ha to the southern and north-northeastern areas in 2006. In Mato Grosso, large farms not only increased their fraction of annual crops, but also their spatial concentration in the center and central-western portions of the state, *i.e.*, close to the major roads. Average revenue of annual crops was higher in Cluster D.4, which suggests better crop productivity in areas where large-scale agriculture is spatially concentrated and better consolidated. This is strongly linked to a high number of tractors and a more concentrated labor force per farm. However, land use intensification inferences based on forest change and number of tractors cannot only be attributed to annual crops, as pasture land expansion among large farms presented similar cluster centers for these indicators. Further analysis is needed in which deforestation rates are tackled separated by farm size category and not per municipality as given in the source data.

4.5.3 Frontier expansion

A deeper comprehension of the distinct evolution of land use systems linked to farm size categories, as shown in this chapter, can help land use studies to incorporate regionalized, heterogeneous land use pathways taking place in the Brazilian Amazon frontier (Aguiar et al., 2007; Becker, 2004; Costa, 2010). Census estimates of changes in forest at the state level are not consistent with data on increases in deforestation during the period of study (Alves, 2007a; INPE, 2009b). Despite that, our results at the municipality level agree with recent remote sensing based land use mapping in the Brazilian Amazon as well as with spatial land use trends revealed by remote sensing based deforestation data combined with the same census data used here (de Espindola et al., 2012; INPE/EMBRAPA, 2011, 2013). Municipality level data indicate that the frontier of expansion is still active, in particular, among small and mid-size farms. The exploration of such data can help regionalize scenario analysis of frontier development.

Figure 4.5 summarizes changes in forest, planted pasture, natural pasture, annual and perennial crops based on census data at the state level from 1970 to 1996, and at the municipality level between 1996 and 2006. The calculation of changes to each land use type was based on the combination of the municipalities of the following clusters: A.1, B.1, C.1, D.1 and D.4 for perennial crops; C.2, C.4 and D.4 for annual crops; B.1, C.1, C.2 and D.12 for pasture land. Figure 4.5 indicates similarities in the frontier of expansion between Rondônia and Mato Grosso regarding historical land use changes of pasture land increase over forest areas, but with distinct evolution of annual crops, natural pasture and somewhat of perennial crops.

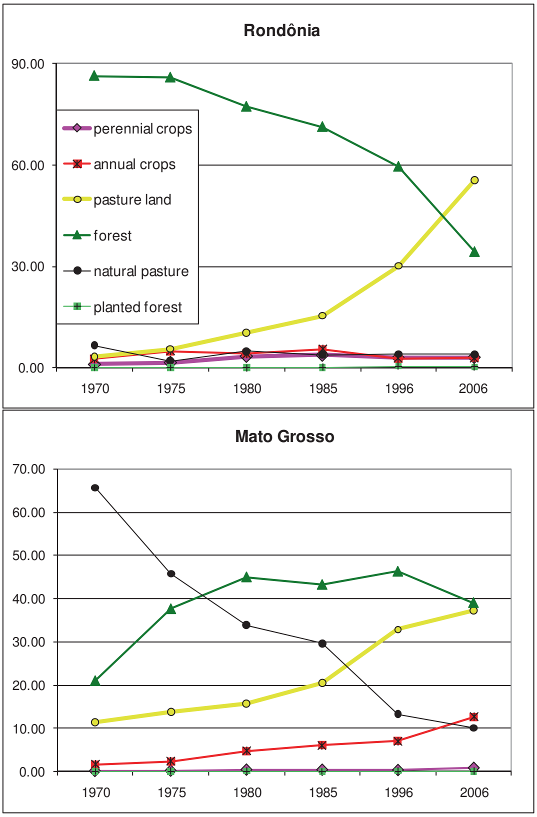


Figure 4.5 – Changes of land use/cover based on regionalized historical census data in Rondônia and Mato Grosso from 1975 to 2006, where the land use changes on perennial crops, annual crops or planted pasture were based on municipalities of groups of clusters, taking into account the increase of the target land use type between 1996 and 2006.

The present analysis disagrees with the premise of frontier stagnation in the Brazilian Amazon that has been suggested in the past by some authors (Miranda et al., 2009), who focus on environmental legislation to explain frontier expansion into new productive areas. The results obtained here indicate that pasture and agricultural expansion are continuing in already deforested areas. At the same time land use intensification can diminish significant frontier expansion further north in the Amazon. Not surprisingly, our analysis has shown that intensification processes in consolidated areas of agricultural production are a result of technological improvement, market accessibility and unequal land distribution, which the same factors are supposed to explain the cycle of expansion and retraction of the Brazilian frontier into the Amazon. As a result, there are no clear insights about possible retraction of the agricultural frontier, so any conclusion regarding the agricultural expansion frontier should not make simplistic assumptions about low productivity and the need to incorporate new areas to guarantee food demands in the future (Miranda et al., 2009). Instead, consistent and plausible scenarios of sustainable development to the Amazon region shall consider the influence of recent and unpredictable factors resulting from the capitalist expansion such as the increase on wage labor near cities, poor land availability, land prices, environmental constraints or law enforcement (Alves, 2007a; Cleary, 1993; Sills and Caviglia-Harris, 2009).

Gini indexes indicate the continuation of a very unequal structure of land distribution with large farms gradually increasing their areas of annual and perennial crops, especially in Mato Grosso. The stagnant land inequality has been reinforced by rural policies benefiting cattle ranching and grain farmers (Brasil, 2002, 2009), who have been identified by a number of studies as important contributors to the deforestation in the Amazonian scale (Brasil, 2008; Fearnside, 1993; Soares Filho et al., 2006). However, changes in Gini indexes show that small farm size categories have significantly increased their contribution especially to milk production at regional and national markets. This could be a result of land redistribution programs and better opportunities to sustain farming among small farmers (Otsuki et al., 2002; Soares Filho et al., 2006). At the same time, one should not forget that these policies have promoted concentrated deforestation in pioneer settlements and fast forest removal in recent settlements (Soler and Verburg, 2010).

The analyses suggest that accessibility to milk markets has facilitated planted pasture consolidation among small farms in Rondônia and Mato Grosso as well as in other states in the Brazilian Amazon as indicated by other authors (Siegmund-Schultze et al., 2010). Milk market chains determined the shift from informal/small scale milk commercialization to industrial organization levels, characterizing the vertical markets integration. This new market structure promotes reduced risks, standardized milk quality and guaranteed income to small milk producers, but might become a threat to rural development by controlling prices and overruling regional markets (Bialoskorski Neto, 2001). Therefore, vertical market integration needs regulation as it may have negative impact on land use choices among small producers. This is because land use intensification and better land productivity do not necessary improve farmers' quality of life.

Further analysis is needed regarding low levels of land management and the threats of pasture degradation, especially among small and mid-sized farms that are the largest contributors to milk production. Sustainable practices of pasture land in the region might strongly depend on appropriate rural extension, accessibility to technology through machinery and promotion of social organization allowing knowledge exchange and resource sharing.

The spatial distribution of land use types shows that medium farms (200–1000 ha) specialized in cattle raising and large soybean producers influence the frontier differently. Cattle farms tend to expand cattle raising in areas close to the forest fringes where small milk producers are also established. Soybean plantations are concentrated in inner areas and their expansion occurs through land consolidation followed by intensification with high levels of technology (Barona et al., 2010; Becker, 2004; Morton et al., 2006). The evolution of land use systems in space and time is determined by land distribution inequality and accessibility to markets, as local changes in basic infrastructure conditions can promote land use intensification by facilitating production and speeding up land consolidation.

Despite data limitations, our analyses indicate regional and intra-regional differences among small, medium and large farms, as well as similarities within these groups regarding the evolution of land use systems and the land use intensification indicators. The general trends of the frontier of expansion indicate that the usual deforestation and degradation cycle has been gradually substituted by land use intensification, especially regarding large scale agriculture of annual crops or perennial crops in long term established settlements. At last, the reader must take into account that the results obtained in this chapter do not imply that further deforestation cycles shall follow similar intensification dynamics. Thus, governmental and non-governmental actions combined to local community efforts must take into account the spatial and temporal variations in development trajectories of land use systems in response to the local and regional socio-economic and biophysical context.

Chapter 5 - Using Fuzzy Cognitive Maps to describe current system dynamics and develop land cover scenarios: a case study in the Brazilian Amazon [4]

Abstract. In this chapter we developed a methodology to identify and quantify relationships among determinants of land cover change using a regional case study in the Brazilian Amazon. The method is based on the application of Fuzzy Cognitive Maps (FCMs), a semi-quantitative tool that provides structured assessment of key feedbacks in scenario analysis. Novel to the application of FCMs is the use of spatial datasets as the main input to build a Cognitive Map. Identification of interactions between land cover determinants and strengths among are based on empirical analysis of spatially explicit data and literature review. Expert knowledge is adopted to identify strengths and weaknesses of the method. Potential pitfalls identified are intrinsic to empirical data analysis such as spatial autocorrelation and scale issues. The outputs of the resulting FCMs are compared to outputs of spatial explicit models under similar scenarios of change. The proposed method is said to be robust and reproducible when compared to participatory approaches, and it can endorse the consistency between demand and allocation in scenario analysis to be used in spatial explicit models.

[4]*Based on:* Soler, L.d.S.; Kok, K.; Câmara, G.; Veldkamp, A., 2012. Using fuzzy cognitive maps to describe current system dynamics and develop land cover scenarios: a case study in the Brazilian Amazon. Journal of Land Use Science 7 (2012), 149-175. doi: 10.1080/1747423x.2010.542495

5.1 Introduction

The comprehension of coupled human-environment systems has been recognized as an important issue by the land science community (Liu et al., 2007; Turner II et al., 2004). This is particularly relevant in the context of the Brazilian Amazon, an enormous and heterogeneous region regarding social, economic and environmental factors (Alves, 2008; Becker, 2004; Fearnside, 2008b; Perz and Walker, 2002). The multi-causality of land use and land cover dynamics has required new approaches combining generic biophysical and socio-economic data as well as human-environment conditions specific to case studies (Lambin et al., 2001). As a result, a number of land change studies have moved from relatively simplistic representations with a few driving forces to a more complex multi-variables understanding (Câmara et al., 2005; Geist et al., 2006).

Tackling the complexity of land cover change requires investigation of interactions among factors at different spatial and temporal scales (Lambin and Geist, 2003; Veldkamp and Fresco, 1996a). These interactions include feedback mechanisms that are key steps to comprehend non-linear landscape processes and their links to human decision making (Claessens et al., 2009). However, inherent limitations of land use/cover change frameworks to incorporate feedback mechanisms between human actions and environmental changes are still a challenge to spatial explicit modellers (Parker et al., 2008; Veldkamp and Verburg, 2004; Verburg, 2006; Verburg et al., 2006).

Implementation of feedback mechanisms has a number of constraints in both spatially explicit and agent-based models. Data availability and computational complexity are some of the limitations to link spatial variation of land use to the social structure of decision-making (Verburg, 2006). Although multi-agent models can combine cellular and agent-based concepts in an integrated approach**,** many challenges remain such as modelling the behaviour of various agents and institutions taking into account the complexity of time and spatial scales in a given land use system (Parker et al., 2003).

Recent studies have indicated the potential of Fuzzy Cognitive Mapping as proxy tools to investigate the role of feedback mechanisms in coupled human-environment systems. Cognitive Maps have been useful in analyzing decision-making and complex social systems (Axelrod, 1976; Carley and Palmquist, 1992; Cossette and Audet, 1992; Montazemi and Conrath, 1986; Roberts, 1973). Kosko (1986) was the first to associate Cognitive Maps to fuzzy logic by incorporating qualitative knowledge as fuzzy causal functions using a matrix representation. Thus, a Fuzzy Cognitive Map (FCM) is a cognitive map where relationships among the elements derive from a given mental map, with their relative importance representing the magnitude of the causality of such elements. In this context, a FCM can play an important role in building semi-quantitative scenarios taking into account different stakeholders' perceptions (Kok, 2009; Vliet et al., 2010).

Applying FCMs to land use science requires the interpretation of subjective information, e.g. stakeholder's perceptions or expert knowledge, into semi-quantitative description of variables and their inter-relations (Kok, 2009; Ozesmi and Ozesmi, 2003; Vliet et al., 2010). Although the semi-quantitative nature of FCMs is considered a weak point when linking them to quantitative models, the dynamic outputs of FCMs in scenario development can facilitate land use/cover models by unveiling hidden feedback mechanisms as shown by Kok (2009). Most land use/cover change models use an external demand based on an economic approach of a trend extrapolation, usually yielding a very static and almost gradual change in demand (Milne et al., 2009). In reality, demand changes rather erratic due to all kinds of feedbacks in land use systems. These feedbacks can be represented in a FCM allowing a semi-quantified evaluation of their role in specific demand scenarios.

In summary, considering the state-of-art of current applications of FCMs in environmental sciences, we identify two aspects that have not received much attention in literature and are essential to explore further:

1. FCMs are often constructed during stakeholders workshops and therefore represent the (subjective) opinion of a small group of individuals. A more objective and therefore reproducible method does not exist.
2. FCMs are not linked to quantitative models, even though its semi-dynamic character provides possibilities to do so.

Taking into account these two aspects, this chapter addresses a new method to develop Fuzzy Cognitive Maps. The main objective is to present and test a reproducible and robust method to develop FCMs based on spatially explicit data in combination with existing literature. The resulting FCM is compared to a FCM constructed directly by a number of experts from leading institutes on spatial research in Brazil. Both products are compared in order to evaluate strong and weak points of the proposed new method of building FCMs. To address the second aspect, we illustrate how FCMs can be converted to land cover change scenarios.

5.2 Fuzzy Cognitive Maps in land use science

A Fuzzy Cognitive Map is a collection of concepts C_i that, in land use science can represent the land use types and their determinants of change. These concepts are linked to each other by causal relationships represented by arrows ($C_i \rightarrow C_{i+1}$) as illustrate by Figure 5.1. Each concept receives an initial value $a \in [-1, 1]$ that is transferred in the first step of the FCM calculation to another concept through the relationship between them. In addition, each relationship is quantified by a weight, varying between 0 and 1, which means the strength of the relationship between two given concepts (Kosko, 1986).

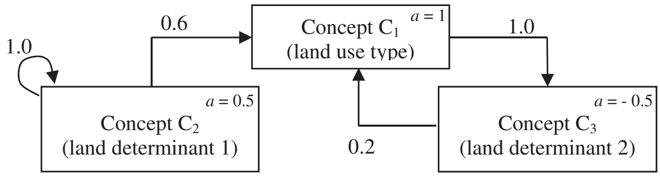


Figure 5.1 – Graphical representation of concepts (with state values *a*), their causal relationships and weights indicated by arrows in a Fuzzy Cognitive Map.

The set of initial values of all concepts form a matrix 1 x n called state vector, where n is the total number of concepts adopted. In addition, the causal relationships can also be represented by a matrix n x n called adjacency matrix, where the position and magnitude of each $C_{i,j}$ element indicate respectively the direction of the causality and the weights between the concepts ($C_i \xrightarrow{weight} C_j$). The iterations in a FCM consist of multiplying the state vector by the adjacency matrix obtaining a new state vector. This step is then repeated until a *quasi* stabilization of the changes in the state vector. The new state vector can assume values outside the interval between -1 and 1. In the example of Figure 5.1 the initial state vector is A = [1 0.5 -0.5] and after the first iteration it becomes A = [0.2 0.5 1]. For further methodological details of FCMs refer to Kok (2009).

When applying FCM to land use science the stakeholders' perceptions and expert knowledge can be considered a strong point of the tool because of its flexibility to include the consensual opinion of any group during a short workshop. However, in order to link FCMs to spatial explicit models of land use/cover change a larger degree of objectivity is desired, which is attempted by the proposed method that links spatial data to described in the next section.

5.3 Linking Fuzzy Cognitive Maps to spatial explicit data

The proposed methodology is illustrated in Figure 5.2 whose steps are described next.

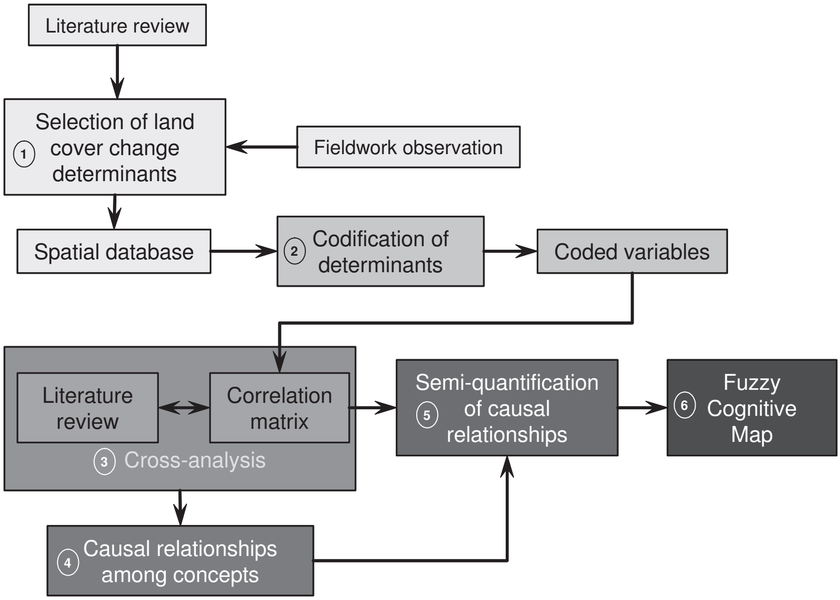


Figure 5.2 – Flowchart of methodological steps proposed to build a Fuzzy Cognitive Map based on spatial explicit data. The six main steps are indicated by numbers.

The methodology comprises six steps 1) Selection of land cover change determinants based on literature review and fieldwork information; 2) Codification of spatial data representing potential land cover change determinants (or their proxies); 3) Cross-analysis between significant correlation coefficients of coded variables and literature review; 4) Establishment of causal relationships based on literature review; 5) Semi-quantification of causal relationships based on the correlation coefficients; 6) Building and calibrating the obtained FCM, which is the central object of the method and is called data-FCM.

5.3.1 Selection of land cover change determinants

Located at the southwest part of the Brazilian Amazon, the study area encloses the northeast of Rondônia State (Figure 5.3). It is characterized by small landholders (< 250 ha) based in official settlements established from the 1970's until recent years (Browder, 1994; INCRA, 2008; Machado, 1998). Most of the old settlements (established before the 1980s) are located along the main road BR-364 on more fertile soils, while the ones established after the 1980s are located in poorer soils along secondary roads (Fearnside, 1986; Machado, 1998). Accessibility is an important driver for small farmers who intensify land use in better accessible areas (Alves et al., 2003). Medium (250 -1000 ha) and big farms (>1000 ha) occupy areas outside the official settlements, but land aggregation is often observed in older settlements (Coy, 1987; Escada, 2003; Millikan, 1992).

Soil fertility is an important determinant mainly when hardly any forest remnants are left (Roberts et al., 2002; Soler and Verburg, 2010). Rainfall determines deforestation at regional scale as a more pronounced dry season increase agro-pasture productivity (Schneider et al., 2000; Sombroek, 2001). Thus, areas with more consecutive dryer months are more prone to deforestation, which is directly linked to fire occurrence (Aragão et al., 2008; Aragao et al., 2007). Furthermore, consecutive years of intense droughts can cause more fire events in the long term (Malhi et al., 2009; Nepstad et al., 2001).

Ranching is the predominant land use among medium and big farmers, but it can also be an important source of income to small landholders (Pedlowski et al., 1997; Walker et al., 2000). The regional and global beef demands are pointed as the main causes driving the increase in cattle herd in the Brazilian Amazon (Arima et al., 2005b; Faminow, 1997). Even though government subsidies have decreased in the last two decades, subsidized loans for pasture activities can still influence household level decisions (Brasil, 2007; Moran, 1993). In old settlements the aging of householders affect labour force availability, which can lead to an increase of pasture area and even force small famers to sell their land in areas progressively dominated by large farms (Browder et al., 2008). This local dynamics can explain the stronger causality between deforestation and the number of inhabitants as well between deforestation and *per capita* income rather than population density in old settlements in the northeast of Rondônia State (Soler et al., 2009).

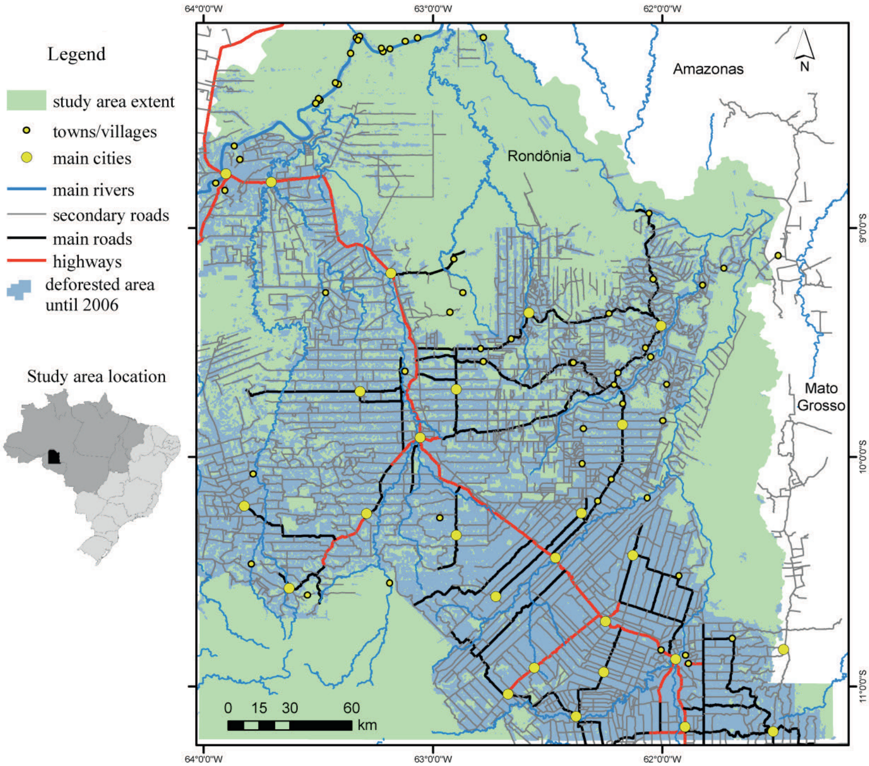


Figure 5.3 – Study area extent indicating roads, rivers, urban areas and deforested areas.

Despite the fact that public policies have strengthened forest conservation in the Brazilian Amazon (Jenkins and Joppa, 2009), forest reserves and indigenous lands are still threatened by the lack of appropriate enforcement (Fearnside, 2003; Pedlowski et al., 2005). In parallel, land speculation, mining and logging markets attract *land grabbers* to either unclaimed or protected areas that might end up occupied by squatters. In some cases, the forest reserves required inside properties (*legal reserves*) are invaded by squatters compelling the local authorities to create new settlements (Fearnside, 2005). Although land tenure data is incomplete, deforestation at the fringes of old settlements on legal or forest reserves indicate informal land markets linked to illegal occupation (Brandão et al., 2007; Fujisaka et al., 1996; Sills and Caviglia-Harris, 2009).

From the location factors described above the following deforestation determinants were selected: location of old and new settlements (*i.e.* established before and after the 1980s); accessibility to infrastructure; size of properties; cattle herd; subsidized credits; forest and indigenous reserves; land prices; number of inhabitants; age of householders and *per capita* income. Further data description can be found in Table 5.1

5.3.2 Coding spatial data of potential land cover determinants

The selected deforestation determinants in Rondônia State were organized in a cellular database at 250 m resolution. These potential land cover determinants were coded into variables (listed in Table 5.1) using as reference the procedure adopted by Scouvart et al. (2007). The coded variables represent the concepts to be adopted in the data-FCM.

Deforested and forested cells were extracted from land use maps from PRODES project (INPE, 2009b) and coded as 1 and 0 respectively. Accessibility was calculated as the cost distance to existing infrastructure in 2000 (urban areas, slaughterhouses, dairy industries, sawmills and mining areas), as described in Verburg et al. (2004). Infrastructure data included roads, urban areas, sawmills, mining areas, slaughterhouses and dairy industries (CPRM, 2004; IBAMA, 2005; IBGE, 2000; MAPA, 2008). Based on Alves et al. (1999), infrastructure was calculated as a buffer area of 12.5 km from existing infrastructure and coded as 1 or as 0 elsewhere.

The occurrence of fires in 2000 was retrieved from remote sensing products (INPE/CPTEC, 2005) and assessed by the Euclidian distance to hot spots with no codification. A soil fertility map retrieved from RADAMBRASIL (1978) was coded as 1 for two classes indicating the highest fertile soils and 0 for all other classes. Following Sombroek (2001), the database cells with rainfall lower than 100 mm during the dry season (April to September) were considered the driest areas. Thus dry season severity was coded as 1 when lower than this cut-off value or as 0 elsewhere.

The variables retrieved from census data as number of inhabitants, *per capita* income and age of householders were not coded to avoid considerable loss of spatial variability due to their aggregation at the district level (IBGE, 2000). Also, no codification was applied to cattle herd, subsidized credits and land prices (Brasil, 2007; IDARON, 2006; INCRA, 2007). Old and new settlements were retrieved from official colonized areas until 1980 and 2000, respectively while spontaneous colonization areas were assessed subtracting areas of official settlements, conservation reserves and indigenous lands (IBAMA, 2005; INCRA, 2008). Each of these spatial partitions was considered a unique variable coded as 1 or as 0 elsewhere.

Table 5.1 – Description of variables adopted to represent the concepts in the data-FCM indicating the data source and the type of codification used.

Variable name	Spatial data description	Source	Codification
Agro-pasture expansion	Deforested area extracted from land cover map at 1:250,000 from 1988 to 2000 (TM/Landsat image classification)	(INPE/EMBRAPA, 2011)	Binary
Dry season severity	Cells where precipitation was below the average in the dry season	(INPE/CPTEC, 2005)	Binary
Land prices	Average of total property value per hectare per municipality in Rondônia in 2000	(INCRA, 2007)	Continuous
High fertility	Areas with the most fertile soils extracted from soil fertility map at scale 1:1,000,000	(RADAMBRASIL, 1978)	Binary
Accessibility	Travel time through paved and unpaved roads to main urban areas, slaughterhouses, dairy industries, sawmills and mining areas.	(CPRM, 2004; IBAMA, 2005; IBGE, 2000; MAPA, 2008)	Continuous
Infrastructure	12 km buffer from main infrastructure (roads, urban areas, slaughterhouses, dairy industries)		Binary
Fire spots	Euclidian distance to fire spots (hot pixels) in 2000	(INPE/CPTEC, 2005)	Continuous
Forest reserves	Areas allocated to conservation reserves and indigenous lands in 2000	(IBAMA, 2005)	Binary
Subsidized credits	Credits granted to landholders and rural association for either pasture or agriculture activities within 1999-2000.	(Brasil, 2007)	Continuous
Old settlements	Areas allocated to official settlements established within 1970-1989 and		Binary
New settlements	within 1990-2000	(INCRA, 2008)	Binary
Spontaneous colonization	Areas allocated outside official settlements, *i.e.*, areas of spontaneous colonization		Binary
Cattle herd	Cattle herd per municipality in 2000	(IDARON, 2006)	Continuous
Per capita income	Total nominal income/inhabitants per census district in 2000		Continuous
Number of inhabitants	Inhabitants per census district for 2000	Census data (IBGE, 2000)	Continuous
Age of householders	Age of householders per census district in 2000.		Continuous

5.3.3 Correlation values vs. literature review

The third step of the proposed methodology consisted of a cross-analysis between the coded variables, presented in a Pearson correlation matrix, and the literature review. The cross-analysis consisted of selecting the significant correlations (at 99% confidence level two-tailed test) that were confirmed by the literature. The selected correlations indicated the relevant causal relationships among any pair of concepts.

The decision rules adopted in the cross-analysis are given in Table 5.2. The chosen relationships to build the data-FCM had to necessarily fulfil both conditions: to present a significant Pearson correlation and to be relevant to one or more case studies retrieved. Relationships without significant correlations and with no evidence from the literature were excluded. The literature review was limited to cases adopting spatial analysis at local or regional scale in Rondônia, or to areas presenting similar land occupation history, such as official settlements in Pará and in Acre States. Relationships occurring at broad temporal scales, such as fires reoccurrence due to intensified dry seasons, could only be confirmed by case studies at the scale of the entire Amazon (for the complete list of case studies per relationship see Appendix A.5). Figure 5.4 illustrates the relationships selected in the cross-analysis and used to build the data-FCM.

Table 5.2– Decision rules adopted in the cross-analysis between the correlation matrix of coded variables and the literature review of case studies in the Brazilian Amazon.

<table>
<tr><th colspan="2" rowspan="2">Decision rules</th><th colspan="2">Significant Pearson correlation ($p>0.005$)</th></tr>
<tr><th>Yes</th><th>No</th></tr>
<tr><td rowspan="2">Relevant to the literature</td><td>Yes</td><td>Included in the data-FCM</td><td>Explored in the sensitivity analysis</td></tr>
<tr><td>No</td><td>Explored in the sensitivity analysis</td><td>Not included in the data-FCM</td></tr>
</table>

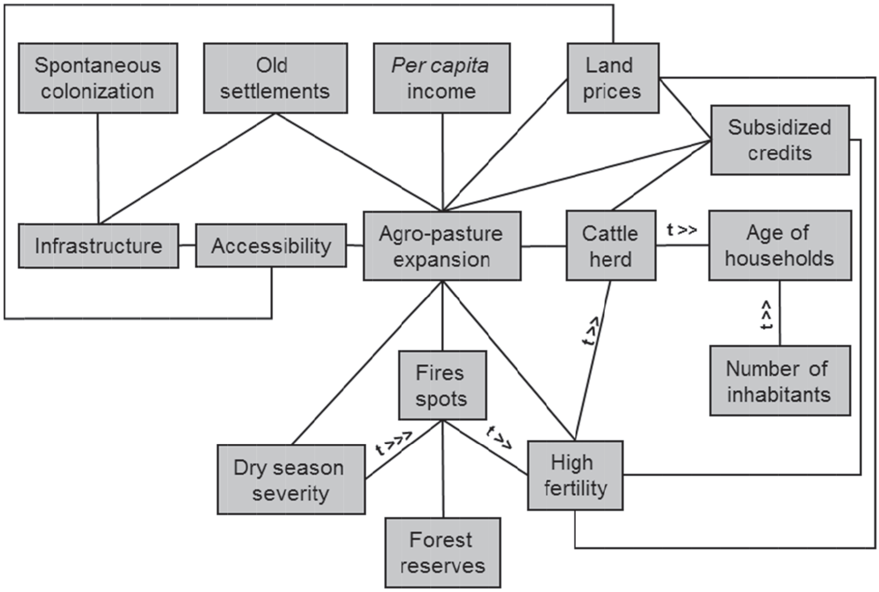


Figure 5.4 – Relationships among concepts resulted from the cross-analysis between the Pearson correlation values and literature review of specific case studies. Relationships occurring at longer time scales are indicated by t >> (demographic and landscape processes) or by t >>> (climatic processes).

5.3.4 Causal relationships

Once the relationships among concepts were established in a Cognitive Map based on spatial data, the next step was to determine their causality. The causality among relationships can take opposite directions depending on the assumptions made. As a result, the directions of the arrows necessarily have to be derived from literature. Table 5.3 indicates the directed edges (direction of the arrows) of the causal relationships identified and their supporting literature.

Regarding disputed causality, road construction and deforestation is a typical example in the Brazilian Amazon. While some authors argue that roads are the main cause of deforestation and forest fragmentation (Arima et al., 2008; Laurance et al., 2004), others claim that roads play a synergic role with other location factors and cause less impact when appropriate enforcement is applied (Câmara et al., 2005; Fearnside and Graca, 2006; Soares-Filho et al., 2004). For the cases where literature was inconclusive, we argue that the most recent publications applied to Rondônia at regional scale represent the most significant insights.

Table 5.3 – Causal relationships among the concepts in Rondônia State with the respective case studies. The positive or negative arrows indicate whether the relationship increases or decreases the corresponding concept in the first column.

Causal relationships assumed among concepts		Supporting literature
Agro-pasture expansion	← + Dry season severity ← + Land prices ← + High fertility ← + Accessibility ← + Old settlements ← + Cattle herd ← + Subsidized credits ← + *Per capita* income	*(Aguiar et al., 2007; Alves et al., 2003; Alves et al., 1999; Andersen and Reis, 1997; Aragão et al., 2008; Arima et al., 2005b; Browder, 1988; Browder et al., 2008; Chomitz and Thomas, 2003; Escada, 2003; Fujisaka et al., 1996; Margulis, 2004a; Roberts et al., 2002; Sills and Caviglia-Harris, 2009; Soler et al., 2009; Sombroek, 2001)*
Dry season severity	← + Fire spots ← + Agro-pasture expansion	(Aragão et al., 2008; Laurance and Williamson, 2001; Sombroek, 2001)
Land prices	← − Agro-pasture expansion ← + High fertility ← + Accessibility ← + Subsidized credits	*(Arima et al., 2005b ; Margulis, 2004a; Sills and Caviglia-Harris, 2009)*
High fertility	← − Fire spots ← + Subsidized credits *← + Dry season severity*	*(Cochrane and Cochrane, 2006; Fearnside, 1986; Hughes et al., 2002)*
Accessibility	← + Agro-pasture expansion ← + Infrastructure *← − Forest reserves*	*(Alves et al., 1999; Pedlowski et al., 2005; Soler et al., 2009; Soler and Verburg, 2010)*
Infrastructure	← + Old settlements ← + Spontaneous colonization *← + New settlements*	*(Alves, 2002; Alves et al., 1999; Brandão and Souza, 2006b; Brandão et al., 2007; Pedlowski et al., 2005; Soler et al., 2009; Soler and Verburg, 2010)*
Fire spots	← + Agro-pasture expansion ← − Forest reserves ← + Dry season severity	*(Aragão et al., 2008; Aragao et al., 2007; Nepstad et al., 2001; Nepstad et al., 2006b)*
Cattle herd	← + High fertility ← + Subsidized credits ← + Age of householders *← + Number of inhabitants*	*(Andersen and Reis, 1997; Arima et al., 2005a; Brondizio and Moran, 2008; Browder et al., 2008; Faminow, 1997; Perz, 2001)*
Per capita income	←+ Agro-pasture expansion	*(Browder et al., 2008; Soler et al., 2009)*
Age of householders	←− Number of inhabitants	*(Brondizio and Moran, 2008; Moran et al., 2003; Perz, 2001)*

Note:Relationships in italics with a grey colour were not significant in the correlation matrix, but mentioned by the experts).

5.3.5 Semi-quantifying relationships

In this step the correlation matrix was used to estimate the strength of any relationship, which followed the same logic of adopting a reproducible and objective method. Similarly to the method described by Kok (2009), ranking the correlation values into an interval variable X ∈ [0, 1] representing the weights, we obtained the precise numeric distance between the correlations. Two initial assumptions were made. First, no relationship received a value 1.0

indicating that a change in none of the concepts can lead to an equally strong change of another concept. It also implies that deforestation can only be explained by a synergy of several aspects (Aguiar et al., 2007; Soares Filho et al., 2006; Soler et al., 2009). Second, no significant relationships in the correlation matrix received a value 0.1, assuming that relationships identified in the literature had a strength of at least 0.2.

The highest and the lowest correlation values of selected relationships received values 0.9 and 0.2, respectively. The correlation values in between were then classified into a number of categories matching the exact numeric distance between 0.9 and 0.2 (see Table 5.4). To be concise, the semi-quantification of relationships was assessed by ranking the strengths of relationships where the final weights represent the relative strengths of causality.

5.3.6 Building and calibrating Fuzzy Cognitive Maps

The final step consisted of bringing together the structure of the relationships (Figure 5.4), their causality (Table 5.3) and weights (Table 5.4) into a FCM in a matrix form arranging the adjacency matrix and the state vector.

The FCM is assumed to be calibrated when it reaches the *quasi* stabilization, *i.e.* when the state values of all concepts become steady. Therefore, the calibration was done by varying the state values of specific concepts (from 0 to 1), until their stabilization after a number of iterations. In general, the concepts chosen for the state vector calibration are those that stabilize the system as a whole. Stabilization is also obtained by varying the *eigenvalues* in the adjacency matrix (from –1 to + 1), which represent the self-reinforcing relationships ($C_i \rightarrow C_i$). In general, concepts with no input from other concepts need a self-reinforcing relationship to sustain their influence in the FCM. The resulting FCM (data-FCM) can also be represented in a graphic form, as illustrated in Figure 5.5.

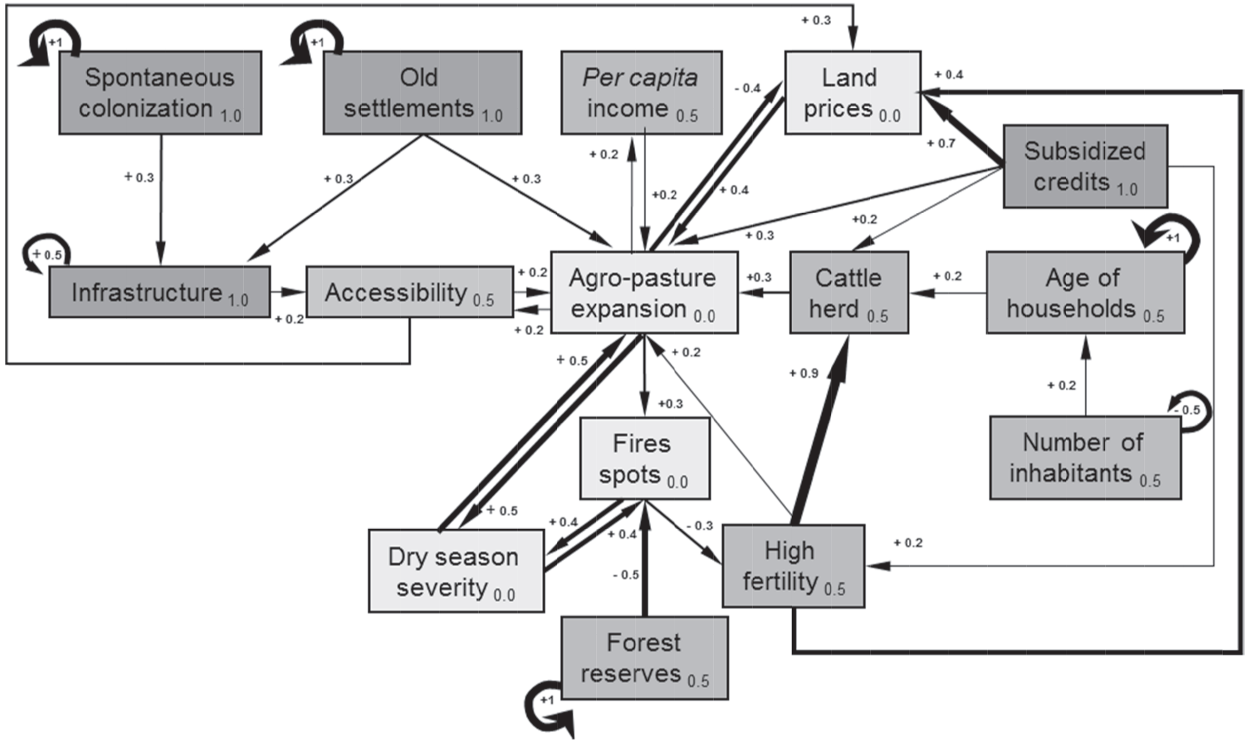


Figure 5.5 – Graphical form of the Fuzzy Cognitive Map (data-FCM) resulted from combining correlation matrix and literature review of expert knowledge. The weights of each relationship are indicated next to their corresponding arrows and initial state values of concepts are given inside their boxes.

5.4 Interpreting Fuzzy Cognitive Map outputs

The interpretation of a FCM is done keeping in mind the semi-quantitative nature of numbers representing the concepts and weights. The interpretation of FCM outputs is done by comparing the final state values of concepts after the system stabilization. The data-FCM stabilized after 10 iterations (Figure 5.6) and reflects the current system dynamics in Rondônia State, *i.e.* with high final state values for agro-pasture expansion (1.42) driven by dry season severity (0.93) and a relative high value of fire spots (0.55) and accessibility (0.52). The final state values of subsidized credits (1.00), infrastructure (1.20), old settlements (1.00), spontaneous colonization (1.00) and conservation units (0.50) were also indicated in FCM as important determinants of the system. However, their dynamic outputs were constant and therefore not included in the graphical FCM. The final state values of land prices (0.30), *per capita* income (0.28) and cattle herd (0.23) indicated they play a less important role in the regional agro-pasture expansion. The low state value of high fertility (0.03) indicate this determinant plays a lesser important role in the land systems in Rondônia when compared to the other determinants. This can be due to low frequency of high fertile soils in the region (Cochrane and Cochrane, 2006; Fearnside, 1986).

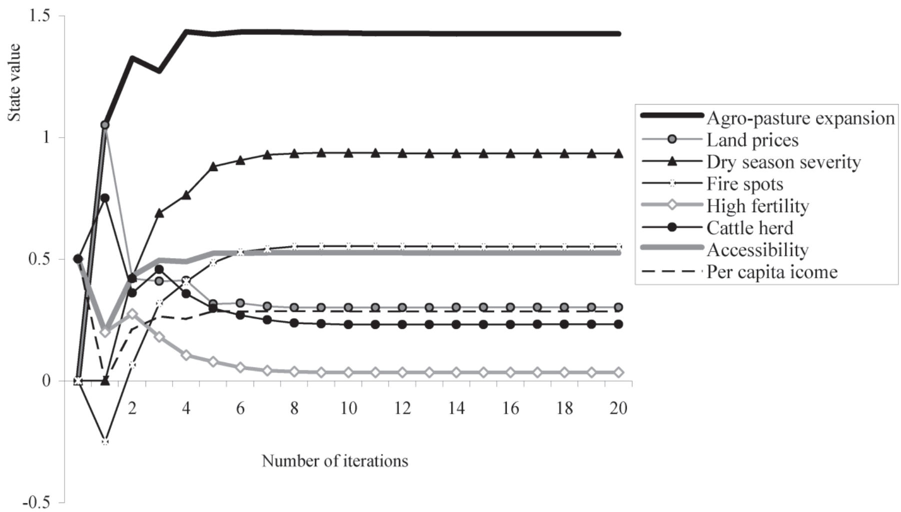


Figure 5.6 – Graphical outputs of 20 step iterations using the Fuzzy Cognitive Map resulted from the method proposed (data-FCM). The system stabilization is reached after 10 iterations.

5.4.1 Analysis of interactions and feedback mechanisms

The analysis of the initial iterations shows that agro-pasture stabilization occurs due to the combined effect of a number of concepts, particularly land prices, subsidized credits, dry season severity and old settlements. Land prices are weakly influenced by the negative feedback mechanism with agro-pasture expansion, but it stabilizes due to the interaction to subsidized credits. Accessibility contributed significantly to stabilize land prices, which indicates the gradual stabilization of land markets in old frontiers that are more accessible to local markets. Infrastructure contributed to stabilize accessibility similarly to its feedback with agro-pasture expansion, which indicates that deforestation can occur before infrastructure expansion as e.g. in logging activities in the region (Matricardi et al., 2007). Fire spots stabilized in a positive trend due to the contribution of agro-pasture expansion and dry season severity, even though the latter is less important.

Agro-pasture expansion determined the increase in fire spots rather than the feedback mechanism with dry season severity. However, by removing this feedback dry season severity is decreased by 26 % and fire spots by 70 %. Agro-pasture expansion also determined dry season severity and *per capita* income. By removing the contribution of agro-pasture in such feedbacks, dry season severity and *per capita* income decreased by 96 %, while agro-pasture expansion decreased by 26 %. The data-FCM indicates that the feedbacks among agro-pasture expansion, land prices and dry season severity drive the system in a more significant way than the feedbacks between agro-pasture and accessibility or *per capita* income.

The proposed method has indicated coherent outputs regarding the relative differences of importance of determinants of deforestation and their interactions in the case study adopted. However, a sensitivity analysis of the main outputs of the data-FCM is done in next section in order to identify potential limitations of the method. Also in the subsequent sections we develop a scenario analysis based on the data-FCM and compare the reliability of the outputs to published results using spatial explicit models of land use/cover change. Only then it is possible to address conclusions about the advantage of building FCM based on spatial data rather than on participatory approaches, and endorse the consistency between demand and allocation in scenario analysis.

5.5 Incorporating expert knowledge

Although the direct link between weights and Pearson correlations is an objective procedure, an inherent uncertainty is present. Scale issues and inaccuracy of spatial data, as well as spatial autocorrelation among variables can affect correlation values (Overmars et al., 2003; Veldkamp et al., 2001a; Veldkamp and Verburg, 2004). To evaluate such uncertainties, we performed semi-structured interviews with experts to capture their interpretation of significant concepts and relationships. In total 10 experts were interviewed among land use modellers, ecologists, agronomists, biologists and social scientists from INPE (National Institute for Space Research), MPEG (Museu Paraense Emílio Goeldi) and UFRJ (Federal University of Rio de Janeiro). They were selected by their relevant scientific background in Amazonian deforestation studies and their influence on the policy decisions.

Using the concepts and the causal relationships adopted in the data-FCM, the interviewed experts were asked to rank the relative importance of each relationship (strong, medium and weak). The outcome of each interview was depicted as a FCM. Consequently, a consensual opinion from experts was obtained for each relationship and ranked into numerical weights according to Table 5.4. The experts mentioned three relationships not significant in the correlation matrix, and one relationship with supporting literature. These relationships were not included in the data-FCM and only considered in the sensitivity analysis. Using the weights from expert consensus and the data-FCM structure, we obtained a new adapted FCM, called expert-FCM and illustrated by Figure 5.7.

The expert-FCM stabilized after 20 iterations and the final state values of dry season severity (4.65) and fire spots (4.46) indicate these concepts are strong determinants of agro-pasture expansion. *Per capita* income (2.32) and accessibility (1.81) are also important drivers of agro-pasture expansion. However, cattle herd (0.13) and land prices (–1.28) have little influence on the system, which diverges from the literature (Andersen and Reis, 1997; Margulis, 2004a; Sills and Caviglia-Harris, 2009). Similarly to the data-FCM, high fertility (–1.34) had little influence on agro-pasture expansion, even though this relationship had only been observed at the household level (Soler and Verburg, 2010; Witcover et al., 2006).

Table 5.4 – Ranking of correlation intervals adopted in the data-FCM and associated weights resulting from the expert consensus.

Pearson correlation value	Correlation values ranked into weights	Expert consensus on relationship's importance	Associated weight to expert consensus
>0.450	0.9		
0.400-0.450	0.8	Strong	0.8
0.350-0.400	0.7		
0.300-0.350	0.6		
0.250-0.300	0.5	Medium	0.5
0.200-0.250	0.4		
0.150-0.200	0.3	Weak	0.25
0.100-0.150	0.2		
<0.100	0.1	not significant	0.1

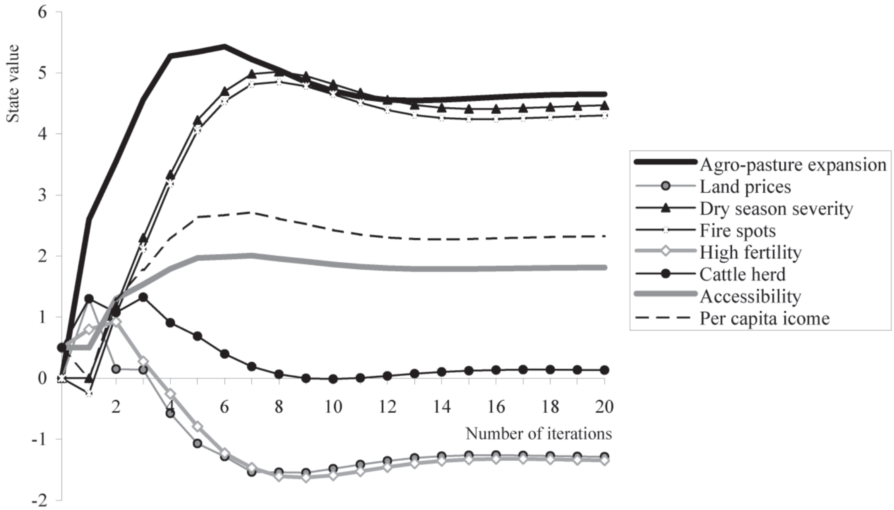


Figure 5.7 – Graphical outputs of 20 step iterations using the Fuzzy Cognitive Map resulted from correlation matrix (data-FCM structure) and strengths among relationships given by expert consensus (expert-FCM). The system stabilization is reached after 20 iterations.

5.5.1 Spatial data vs. expert knowledge

The semi-quantification of weights of relationships can be taken as the main weakness when comparing two FCMs build with the same relationships, but with distinct weights as the expert-FCM and the data-FCM. Despite that, the normalization of concepts and the final state values can provide a partial link to qualitative outputs and facilitate the comparison between these two FCMs. However, the concepts representing variables acting at distinct temporal scales can not be well represented as the number of iterations in a FCM can not be direct translated into temporal units. Spatial and temporal issues have no simple solution especially in a FCM representation, and they must be taken into account when interpreting and comparing two FCMs.

The comparison between normalized state values of the data-FCM and the expert-FCM indicated that agro-pasture expansion, high fertility, cattle herd and forest reserves were quite similar in both FCMs. Striking were the higher outcomes in the expert-FCM compared to the data-FCM for the final state values of fire spots (166%), *per capita* income (120%) and dry season severity (92%). In contrast, significant higher state values were observed in the data-FCM compared to the expert-FCM for infrastructure (131%), subsidized credits (103%), land prices (72%), spontaneous colonization (103%) and old settlements (103%). Such differences are mostly on the concepts acting at longer time scales (e.g. fire spots and dry season severity) in the expert-FCM, while in the data-FCM concepts acting at similar spatial scales showed higher state values.

These results indicate the inherent limitations of the method, *i.e.* the expert opinion give higher importance to long term variables that have a high impact on deforestation (Aragão et al., 2008; Nepstad et al., 1999), but cannot be appropriately represented in a FCM specially when built from correlation values of one single year. On the other hand, the data-FCM seems to show higher importance for concepts acting at similar temporal and spatial scales. Although the importance of most feedback mechanisms was similar to the stabilization of both FCMs, the more evident hectic behavior of concepts during the initial iterations in the data-FCM indicate a higher influence of feedback mechanisms than in the expert-FCM.

5.5.2 Sensitivity analysis of relationships

The divergence of strengths of causal relationships between the data-FCM and the expert-FCM were evaluated. Two levels of disagreement between the two FCMs were considered: a *disagreement* (a mismatch within 0.2–0.4) and a *strong disagreement* (a mismatch ≥ 0.5), as illustrated in Table 5.5. By adding an external concept, representing land demand or public policies and by exploring the weights between this concept and the existing ones, it is possible to draw conclusions about the sensitivity of the relationships. Sensitive relationships are assumed to cause a change of ≥ 0.5 in the state value of agro-pasture expansion in the data-FCM and are indicated in the last column of Table 5.5.

Table 5.5 – Degrees of disagreement between the weights given by the correlation matrix and experts' consensus on the importance of relationships. The sensitive relationships are identified in the last column.

Relationship	Correlation value (module)	Weight	Expert consensus	Ranked weight to expert consensus	Degree of disagreement	Sensitive relationships in the data-FCM
Agrop ↔ DrySv	0.251	0.4	medium	0.5	no disagreement	no
Agrop ↔ Lpri	0.242	0.4	medium	0.5		no
Agrop → Acces	0.106	0.2	weak	0.25		no
DrySv ↔ Fire	0.205	0.4	medium	0.5		no
FoRes → Fire	0.296	0.6	medium	0.5		yes
Cred → Lpri	0.356	0.7	strong	0.8		yes
Hfert → Lpri	0.239	0.4	medium	0.5		yes
Infra → Acess	0.128	0.3	medium	0.5	disagreement	no
Agrop ↔Incap	0.109	0.2	medium	0.5		no
Hfert → Agrop	0.128	0.2	medium	0.5		no
Acces → Agrop	0.106	0.2	medium	0.5		no
CHerd → Agrop	0.153	0.2	medium	0.5		no
Agrop → Fire	0.172	0.3	medium	0.5		no
AgeH → CHerd	0.118	0.2	medium	0.5		no
Hfert → CHerd	0.458	0.9	medium	0.5		yes
Fire → Hfert	0.155	0.3	medium	0.5		yes
OldSet → Infra	0.167	0.3	medium	0.5		yes
Acces →Lpri	0.189	0.2	medium	0.5		yes
Inhab → AgeH	0.109	0.2	medium	0.5		no
NewSet → Infra	*0.023*	*0.1*	*medium*	*0.5*		*no*
Inhab → CHerd	*0.085*	*0.1*	*medium*	*0.5*		*no*
DrySv ↔ Hfert	*0.487*	*0.9*	*medium*	*0.5*		*yes*
Cred → Agrop	0.158	0.3	strong	0.8	strong disagreement	yes
OldSet → Agrop	0.164	0.3	strong	0.8		yes
Cred → CHerd	0.14	0.2	strong	0.8		yes
Cred → Hfert	0.116	0.2	strong	0.8		yes
SptCol → Infra	0.163	0.3	strong	0.8		yes
FoRes → Acces	*0.078*	*0.1*	*strong*	*0.8*		*yes*

Note: Agrop (Agro-pasture expansion), DrySv (Dry season severity), Lpri (Land prices), Cred (Subsidized Credits), Hfert (High fertility), Acces (Accessibility), Infra (Infrastructure), Fire (Fire spots), CHerd (Cattle herd), FoRes (Forest reserves), OldSet (Old settlements), NewSet (New settlements), SptCol (Spontaneous colonization), Incap (*Per capita* income), Inhab (Number of inhabitants), AgeH (Age of householders). Relationships in *italic* had not been included in the data-FCM, but were mentioned by experts as relevant ones.

Taking into account the 24 relationships included in the data-FCM, a total of 12 were identified as sensitive. Additionally, two relationships not included in the data-FCM, but mentioned by the experts were also identified as sensitive. Out of 12 sensitive relationships in the data-FCM, 4 presented a *disagreement* and 5 presented a *strong disagreement*.

Only 20% of the relationships in the data-FCM presented a strong disagreement to the expert-FCM, which indicates a reasonable coherence of the proposed method. All the relationships with a strong disagreement were sensitive, and they indicated the weights were underestimated in the data-FCM because of data limitations concerning scale issues. While deforested cells are given in a detailed resolution of 30 m, subsidized credits and cattle herd are aggregated at the municipality level and high fertility is given at a much coarser scale (1:1,000,000).

The sensitive relationships with a disagreement were affected by poor data quality and spatial autocorrelation. The relationship between fire spots and high fertility was undervalued while the relationship between cattle herd and high fertility was overvalued when using the correlation matrix. Spatial autocorrelation between accessibility and land prices or accessibility and forest reserves resulted in undervalued weights in the data-FCM. This occurs mainly in old settlements where highly deforested areas mask the influence of main roads.

5.6 Land cover change scenarios

In this section, the sensitive relationships were explored in a scenario analysis, as an example of application of the data-FCM. Two external concepts were added representing demand and public policies, and received the initial state values 1.0 and 0.5, respectively. The scenarios were based on two main issues tackled with new policies by the Brazilian government in the Amazon: land reform in confrontation to forest conservation and climate change mitigation (Brasil, 2008, 2009).

1) Land reform & conservation: The increase of both official settlements and spontaneous colonization is considered to cause significant deforestation (Alves et al., 2003; Brandão and Souza, 2006a; Fearnside, 1993; Ludewigs et al., 2009). However, deforestation is controlled by law enforcement over forest reserves and indigenous lands (Nepstad et al., 2006b; Soares-Filho et al., 2006). In this scenario the influence of demand on spontaneous colonization received a weight 1.0, while the influence of public policies on old settlements or on conservation reserves received 1.0 and 0.5, respectively.

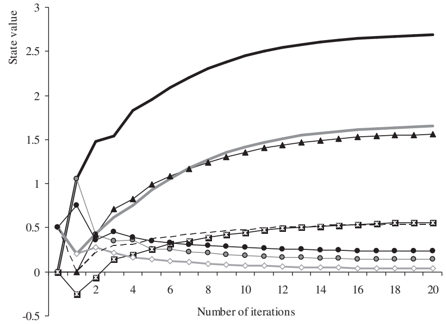
2) Climate change mitigation: We consider public policies that cut subsidies and stimulate forest conservation through environmental services rewards (Borner and Wunder, 2008; Fearnside, 2008a). However, we depict a scenario with intensification of dry season severity as a response to climate change (Malhi et al., 2009). In this scenario the influence of demand on dry season severity receives a weight 1.0 while the influence of public policies on subsidized credits or conservation reserves receive -0.5 and 1.0, respectively.

The scenarios evaluation was done comparing the variation of the final state values within the same system (data-FCM or expert-FCM) to their respective scenarios illustrated in Figure 5.8. Normalized state values were assessed as an attempt to compare the data-FCM and the expert-FCM.

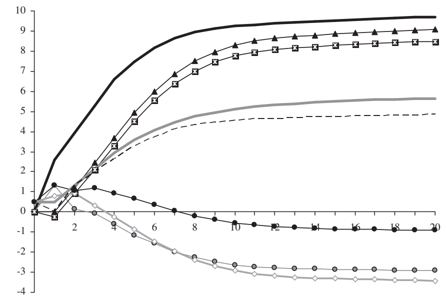
Similar to the current situation, the expert-FCM presented higher amplitude of the final state values than the data-FCM for both scenarios. The land reform & conservation policies scenario indicated a relevant increase on deforestation (*i.e.* agro-pasture expansion) for both the expert-FCM (9.70) and the data-FCM (2.68), although the latter to smaller extent. This difference is due to a higher (indirect) contribution of spontaneous colonization to the final state value of accessibility (5.65) in the expert-FCM, in comparison to the data-FCM (1.65). Note that neither FCMs indicated a decrease on deforestation rates with law enforcement over forest reserves, but in the data-FCM forest reserves equalized fire spots (0.55), soil fertility (0.03) and cattle herd (0.23) to the current situation. This indicates a more optimistic trend of land impoverishment.

In the climate change mitigation scenario both FCMs showed a decrease in deforestation particularly because of reduced subsidies. Agro-pasture expansion in the data-FCM and the expert-FCM was 0.86 and 1.93, respectively. Thus, the stabilization of a concept in a FCM does not mean its stagnation. In both systems dry season severity and fire spots decreased significantly under the influence of public policies over forest reserves, which reflects the role of protected areas in regulating rainfall patterns (Walker et al., 2009). In addition, the data-FCM indicated a more positive scenario of high soil fertility (0.18) and cattle herd (0.11), with decreased fire spots (–0.77). This scenario suggests that despite intensified dry seasons might not stop agro-pasture expansion; it can disturb the land system resilience and notably affect agro-pasture activities (Aragao et al., 2007; Laurance and Williamson, 2001; Malhi et al., 2009). A return to current degree of resilience is suggested by both systems with high subsidies.

Scenario: *Land reform & conservation*

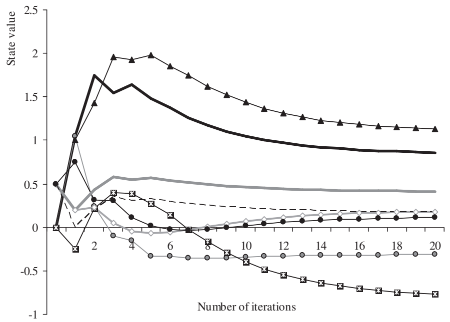


data-FCM

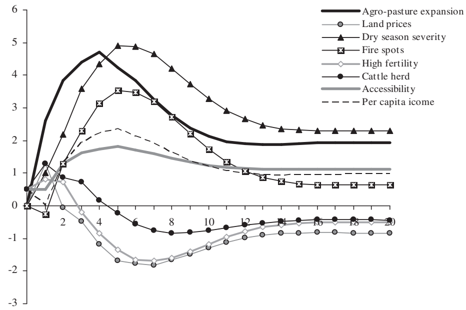


expert-FCM

Scenario: *Climate change mitigation*



data-FCM



expert-FCM

Figure 5.8 – Graphical outputs of data-FCM and expert-FCM under the two different scenarios proposed. Final state values of concepts are not normalized in the graphics.

5.6.1 Qualitative outputs of scenario analysis

In order to evaluate the applicability of scenario analysis using FCMs, the normalized scenario outputs are compared to the output of similar scenarios assessed by spatial models of deforestation in the Brazilian Amazon (see Table 5.6). The different outputs were normalized based on the data-FCM in the current situation.

Aguiar (2006) presented projection of deforestation, over 23 years, by using spatial data at macro and mesoscale. The results are presented for some hot spots of deforestation from which we took the Transamazon highway case to be compared to the FCMs outputs. Soares Filho et al. (2004) simulated two scenarios of deforestation at local scale over 30 years, with detailed spatial data for the Transamazon highway among other three areas. Dale et al. (1994a) simulated deforestation models at the property scale in Rondônia State using spatial data at fine scale. The authors simulated a best-case scenario with innovative land practices and a typical case scenario where the whole property, including its legal reserve, is deforested after 20 years.

Table 5.6 – Comparison among relative deforestation rates simulated by spatial models and outputs of Fuzzy Cognitive Maps based on spatial data and expert consensus.

Normalized deforestation rates obtained from spatial models			Fuzzy Cognitive Maps normalized outputs		
Case study	Scenarios		Scenarios FCM	data-FCM	expert-FCM
Aguiar (2006) meso-scale: Transamazon highway (Rurópolis/Trairão)	*Accessibility*	1.86	Current situation	1.77	1.75
	Control of deforestation	1.92	Climate change mitigation	0.40	1.16
Soares Filho et al. (2004) local scale: Transamazon highway	*Business as usual*	0.76	Current situation	1.77	1.75
	Governance	0.31	Land reform & conservation	0.63	1.64
Dale et al. (1994a) property level: Ouro Preto d'Oeste	*Typical case*	2.95	Current situation	1.77	1.75
	Best case	1.24	Land reform & conservation	0.63	1.64

Deforestation rates obtained in the scenarios of spatial models are reasonably comparable to the rates obtained in the FCMs. Similar deforestation rates between the FCMs outputs under the current situation and the accessibility scenario presented by Aguiar (2006) can be due to a higher similarity in the scenarios assumptions. Moreover, this case study adopted spatial data and scale of analysis comparable to our case study in Rondônia State.

In the scenarios presented by Soares et al. (2004), lower deforestation rates were obtained in comparison to both FCMs outputs, although in the data-FCM under the *land* *reform & conservation* scenario the difference was smaller. Plausible reasons are the use of detailed fieldwork information and different assumptions in conservation policies between the *land reform & conservation* and the *governance* scenario. At the property level the simulated changes by Dale et al. (1994) under the *typical case* scenario were almost two fold higher than both FCMs under the current situation. Differences between the *best case* and the *land reform & conservation* scenarios were relevant in the data-FCM. This incongruence at the fine spatial scale is likely due to drivers and processes acting at smaller scales than our regional case study accounts for, which might limit the exemplified application.

5.7 Strong and weak points of the proposed method

The reproducibility and robustness can be considered the strongest points of the proposed method, in comparison to participatory methods of building FCMs. The main similarities between the data-FCM and the expert-FCM were the equalized final state values of agro-pasture expansion and the importance of most feedback mechanisms. Furthermore, feedback mechanisms between agro-pasture expansion and land prices and between agro-pasture expansion and dry season severity have shown coherent responses to the literature (Aragao et al., 2007; Nepstad et al., 2001; Sills and Caviglia-Harris, 2009), which reinforces the structure based on the correlation matrix.

The weakest points of the method are arguably data and literature availability limiting the identification of causal relationships. The semi-quantification of relationships was most limited by pitfalls intrinsic to empirical and multi-level data analysis such as scale issues, poor data quality and spatial autocorrelation. Processes occurring at different time scales were poorly captured in the correlation matrix (as the increase of fire spots with drier periods). Feedbacks between fire spots and high fertility and between accessibility and land prices were undervalued in the data-FCM, as a result of poor data quality and spatial autocorrelation. Different data aggregation of subsidized credits and *per capita* income as well as incomplete land tenure data resulted in undervalued relationships in the data-FCM.

In the scenario analysis regional processes are better simulated in the data-FCM (e.g. soil impoverishment due to the increase on fire spots). On the other hand, the expert-FCM translated better processes occurring at broader scales, for instance the role of forest reserves in rainfall patterns. Despite that, both systems indicated the high sensitivity of conservation policies being negatively affected by the current paradigm of agrarian settlements and existing subsidized credits (Pacheco, 2009; Pedlowski et al., 2005) and positively affected when subsidies are removed. The qualitative comparison of scenarios outputs between spatial models and FCMs indicated the latter provide coherent demands of change. Limitations lie on data availability and scale dependence of processes within the case study adopted.

5.8 Conclusions

By using the data-FCM in scenario analysis it is possible to evaluate the sensitivity of governance and to assess rates of land cover change comparable to spatial explicit models outputs. Thus, the data-FCM can be used as new method of scenario analysis. We argue that by incorporating the proposed method to spatial explicit models we endorse the consistency between demand and allocation. In addition, we prevent the potential incongruence of considering divergent realities from stakeholders or too different backgrounds given by expert's consensus.

The resulting FCM based on spatial explicit data has been proved as a coherent tool to assess land cover change scenarios. Even though there are no strong arguments to claim the data-FCM is more suitable than the expert-FCM for scenario analysis, the data-FCM represents a more robust and reproducible method. The main limitations of the method lie on data and literature availability as well as spatial and temporal scaling issues when dealing multi-level data.

Because of data-FCM limitations, the expert-FCM can be claimed as more suitable to assess more realistic scenario analyses. However, the robustness and reproducibility of this method are compromised as the same group of experts could suggest different strengths and relationships according to current land system dynamics and environmental policies agenda. Even though the expert-FCM was useful to reveal spatial data limitations as autocorrelation, its structure mirrored the data-FCM structure and is under the influence of similar limitations as data availability, scaling issues and literature availability. Therefore, the expert-FCM could be used as a complementary step to the proposed data-FCM to diminish data limitation issues.

Appendix A.5

Table A.5 – Cross-analysis between correlation values (among coded variables) and literature review of expert knowledge (N=140000). Correlations are considered relevant when larger than 0.100 and significant at the 0.01 level (2-tailed).

Relationship	Correlation	Relationship cited by relevant literature	data-FCM and expert-FCM
Acces ↔ Infra	Significant	Aguiar et al. (2007); Alves et al. (1999); Arima et al. (2008); Soler et al. (2009)	X
Agrop ↔ DrySv		Aragão et al. (2008); Chomitz and Thomas (2003); Sombroek (2001)	X
Agrop ↔ Lpri		Arima et al. (2005a); Browder (1988); Browder et al. (2008); Fujisaka et al. (1996); Margulis (2004a); Sills and Caviglia-Harris (2009)	X
Agrop ↔ Hfert		Hughes et al. (2002); Moraes et al. (1996); Numata et al. (2003); Roberts et al. (2002)	X
Agrop ↔ Acces		Aguiar et al. (2007); Arima et al. (2008); Soler et al. (2009)	X
Agrop ↔ Fire		Aragão et al. (2008); Laurance and Williamson (2001)	X
Agrop ↔ Cred		Andersen and Reis (1997); Arima et al. (2005a)	X
Agrop ↔ OldSet		Alves et al. (1999); Brandão and Souza (2006a); Escada (2003)	X
Agrop ↔ CHerd		Arima et al. (2005a); Fujisaka et al. (1996); Margulis (2004a)	X
Agrop ↔ Incap		Browder et al. (2008); Margulis (2004a); Soler et al. (2009)	X
Cred↔ CHerd		Arima et al. (2005a); Faminow (1997)	X
CHerd ↔ AgeH		Brondizio and Moran (2008); Moran et al. (2003); Perz (2001)	X
DrySv ↔ Fire		Aragão et al. (2008); Aragao et al. (2007); Nepstad et al. (2001)	X
Fire ↔ FoRes		Nepstad et al. (2006a)	X
Hfert ↔ Fire		Hughes et al. (2002)	X
Hfert ↔ Cred		Arima et al. (2008); Fearnside (1986)	X

Hfert ↔ CHerd	Significant	Fearnside (1980); Hecht (1985); Margulis (2004a)	X
Infra↔ OldSet		Alves (2002); Alves et al. (1999); Brandão and Souza (2006b); Brandão et al. (2007); Soler et al. (2009); Soler and Verburg (2010)	X
Infra ↔ SptCol		Brandão et al. (2007)	X
Inhab ↔ AgeH		Brondizio and Moran (2008); Moran et al. (2003); Perz (2001)	X
Lpri ↔ Hfert		Sills and Caviglia-Harris (2009)	X
Lpri ↔ Acces		Sills and Caviglia-Harris (2009)	X
Lpri ↔ Cred		Sills and Caviglia-Harris (2009)	X
DrySv ↔ Hfert		Indirect indications: Aragao et al. (2007); Hughes et al. (2002)	X (sensitivity analysis & scenarios)
Acces ↔ FoRes	NOT Significant	Pedlowski et al. (2005)	X (sensitivity analysis & scenarios)
Infra ↔ NewSet		Soler et al. (2009)	X (sensitivity analysis)
CHerd ↔ Inhab		Faminow (1997)	X (sensitivity analysis)

Note: Agrop (Agro-pasture expansion), DrySv (Dry season severity), Lpri (Land prices), Cred (Subsidized Credits), Hfert (High fertility), Acces (Accessibility), Infra (Infrastructure), Fire (Fire spots), CHerd (Cattle herd), FoRes (Forest reserves), OldSet (Old settlements), NewSet (New settlements), SptCol (Spontaneous colonization), Incap (*Per capita* income), Inhab (Number of inhabitants), AgeH (Age of householders).

Chapter 6 – Synthesis

6.1 Introduction

The core objective of my dissertation was to analyze Amazonian land use and land cover pattern dynamics in order to identify the underlying system dynamics. By combining static and dynamic methodologies, I was able to explore system feedbacks within this non-linear human-environmental system for more sustainable development pathways. Here in chapter 6, a synthesis of the previous chapters is provided. It is an analysis of how chapters 2 to 5 together address the overall objectives and contribute to land use science. Additionally, I will explore how relevant feedback loops can be reinforced by public policies in order to improve the sustainability of both land use systems and the living conditions in the region. For that, I focused on three main subjects: 1) identification of location factors and drivers of land dynamic patterns; 2) patterns and processes of land use system changes; and 3) interactions and relevant feedbacks within human-environmental systems in the Brazilian Amazon.

6.2 Location factors and drivers of land dynamics

The analyses of location factors and drivers of land cover change operating at local and regional scales in Rondônia State are detailed in chapters 2 and 3 respectively (see Figures 2.1 and 3.1). The results showed that proximate causes of land dynamics, underpinned mainly by spatial policies (*i.e.* inappropriate occupation planning), have driven land cover change at both local and regional spatial scales. The analysis in chapter 2, after accounting for the age of settlements, revealed that location factors such as soil fertility could explain both the scarcity of forest assets in old settlements as well as secondary forest assets in newer settlements. The influence of underlying causes on deforestation concerning accessibility to facilities (*i.e.* roads, towns, sawmills or farms) did not change significantly over different spatial scales, but rather followed subsequent steps over time in official and spontaneous colonization areas in Rondônia State.

The land use patterns were either analyzed through a snapshot (chapter 2) or dynamically in time (chapter 3). Both types of analysis indicated similar roles of biophysical location factors and accessibility measures based on roads at local and regional scales. This observation supports the often used space for time analogy for quantifying land use/cover systems within the CLUE modeling approach (Veldkamp and Fresco, 1996b). The adoption of spatial zoning concerning property size at the regional scale was able to capture the indirect influence of socioeconomic organization in land use systems. This results clarified the role of small farms (< 240 ha) in the deforestation processes at local scale in Rondônia State, which caused relevant land cover change as indicated by both household level and spatial data analysis at the regional scale. As described in the literature and observed during fieldwork, it is also important to account for socioeconomic processes that lead to spatial aggregation of lots. These processes are important because they can result in an expansion of the number of medium and large properties, which is most noticeable in old settlements. Spatial zoning in Rondônia, however, differed significantly from other states such as Mato Grosso and Pará. In those states, the rates of deforestation are generally attributed to large farms, and are still reported as the highest ones within the Brazilian Amazon (INPE, 2013b).

The methodologies used in the first chapters helped explaining similarities and differences among location factors and drivers of forest and secondary forest change across different spatial extents at the local scale, especially accessibility through roads, spatial policies and biophysical variables. However, the description of spatially diverse processes of land cover change at the local scale through statistical models is limited when using variables that represent socioeconomic underlying causes (e.g. income per capita, population density) that act at regional levels. This is likely because for these data this is no the appropriate spatial scale of their use. The statistical methods have limitations in identifying and exploring the relevant interactions and feedbacks within the land use systems and human decisions, irrespective of the spatial scale. Thus, complementary tools as presented in chapters 4 and 5 were adopted.

6.3 Patterns and processes of land systems

We investigated to what extent the analytical and empirical methods shown in chapters 2 to 4 can explain the complexity of land use systems in the Brazilian Amazon, regarding spatial-temporal patterns and processes occurring at different spatial scales. Insights on interactions and feedbacks occurring at/within different spatial scales were systematically taken from the results of chapters 2, 3 and 4. Such insights came up from the holistic view of empirical statistical behavior of drivers, changing patterns and processes, and household level interviews to landholders of different farm sizes in Rondônia and Mato Grosso states (Soler, 2011; Soler et al., 2007). That allowed to gather sufficient information to identify interactions and associated feedbacks within specific coupled human-environmental systems. The term *coupled human-environment system* is used to acknowledge the fact that humans, as users, actors and managers are not external, but an integral elements of the studied system (Schröter et al., 2004). The importance of actor diversity on land change is also acknowledged by the explicit consideration of different farm types. This section is divided in two parts where I discuss: 1) Patterns and processes of land use/cover change at different spatial scales, and; 2) The links between land use intensification and land tenure issues.

6.3.1 Pattern-process description at different spatial scales

The outputs of chapter 3 indicated that household level data, when compared to remote sensing, spatial and/or census data, point to similar patterns of land cover change for Rondônia State, but also demonstrate some divergent land change processes across local and regional spatial scales. Census data, remote sensing and interviews with key informants during fieldwork in Rondônia and Mato Grosso indicate heterogeneous land cover change patterns and processes during the last decades. Each data source represents a slightly different reality.

In order to understand patterns and processes of land dynamics in the Brazilian Amazon we have to consider the heterogeneity of location factors and drivers of deforestation and secondary forest change, as well as the interactions among them that can act diversely across spatial scales. Indications of these interactions were provided during fieldwork campaigns and they were confirmed in distinct patterns and processes analyses of land cover/use change in chapters 2, 3 and 4. Particularly, the description of patterns and processes shows that: a) interactions at local and regional scales are similar regarding drivers of accessibility to infrastructure and indirect socioeconomic causes; b) biophysical variables (*i.e.* location factors) and policy aspects (*i.e.* underlying causes such as spatial zoning) tend to act differently between the spatial scales adopted.

In terms of location factors, the differences across scales are either due to the distinct level of influence of biophysical aspects to deforestation processes (e.g. soil fertility, soil types or geomorphology) better perceivable when confronting results within scales, or to the coarser level of spatial data compared to land use/cover patterns. In terms of policy aspects, their stronger influence at the regional scale are likely due to land use history and land distribution, which indirectly underpin the extent of fertile soils within small and larger farms. This output reveals that similar process over regional and local patterns of soil fertility influencing deforestation depending on land use history (*i.e.* the spatial zoning or aggregation of lots in older settlements). On the other hand, despite land use history and land distribution might act similarly within extents at local scale in Rondônia. Their influence on deforestation processes are very dissimilar at the regional scale compared to Rondônia and Mato Grosso states (further discussed in the next section).

These analyses indicate that empirical statistical descriptions with regression analysis are capable to identify similarities and divergences of patterns and processes across different spatial scales, a result also obtained for Central America (Kok, 2001). Despite this ability, these statistical methods cannot identify and explore interactions within location factors, drivers and processes that act across scales.

6.3.2 Land use intensification links to land distribution issues

It is generally understood that land use system investigation in the Brazilian Amazon must take into account land use intensification and the associated land tenure and land distribution issues (Alves, 2002; Fearnside, 1993; Vosti et al., 2002). In chapter 4, some of these underlying causes were tackled by investigating how processes acting at the household level (e.g. land distribution issues) act from local to broader scales throughout interactions with location factors (e.g. soil fertility) and drivers of land use change (e.g. infrastructure and accessibility based on roads).

The results in chapter 4 indicate that land distribution influences land use intensification processes in different ways in time and space in the Amazonian states of Rondônia and Mato Grosso. National and international demands for beef and soybean, accessibility to beef/milk markets and technological improvement through machinery as well as labor force concentration have contributed to land use intensification among medium to large farms. The same processes have occurred among small farms, but instead they have been more driven by stocking rates, improvement of accessibility and demand to milk markets. Despite diverse, all interactions are connected to the fact that all farm size categories share the same natural resources, but the existing socioeconomic system provides distinct and usually unbalanced benefits between these categories of farm sizes. Such social and environmental issues among small farms also depend on land use systems that can succeed to sustainable alternative trajectories or fail due to land degradation. The lack of land management together with badly-driven investments can explain the failure of usual pasture after slash-and-burn land systems among small farms in less fertile spots. The influence of land speculation by large landholders seems also to be a determinant of such failure.

The analyses summarized in sections 6.2 and 6.3 lead to the conclusion that using regressions I was able to identify similarities and divergences of patterns and processes across different spatial scales. Nevertheless, associations between land use patterns and process of land cover change do not provide satisfactory comprehension of the identified coupled human-environmental systems. In other words, the interactions between human actions and the environment identified at different spatial scales in the Brazilian Amazon that might end up in relevant feedbacks cannot be explored using standard statistical methods. Thus, in the next section I discuss the outcomes of chapter 5 in which a simple system dynamics model is used to help describing and understanding feedback loops of decision-making processes. This understanding might contribute towards a more sustainable management of the human-environmental system.

6.4 Interactions and feedbacks

In chapter 5, a simple system dynamic Fuzzy Cognitive Map (FCM) model is used to explore interactions and feedbacks between drivers and other factors that influence land use. Importantly, the FCM model is parameterized with the results of chapters 2, 3 and 4. The interactions between drivers and other factors that influence land use/cover change were identified from the previously described analyses of the local factors, drivers and underlying causes of land change. Similarly, the identification of feedback loops was based on observed patterns and processes of land cover change, especially regarding the dependence of land use intensification on land distribution. The discussion below is structured along the benefits and limitations of using spatial data to structure and parameterize Fuzzy Cognitive Maps to explore feedbacks. This section is divided into two parts where I discuss: 1) Identification of interactions at local and regional spatial scales that can reveal feedbacks, and; 2) Relevant feedback loops.

6.4.1 Interactions at local and regional scales

The interactions identified within proximate and underlying causes of land use/cover change were explored in distinct Fuzzy Cognitive Maps linked to spatial data at two spatial scales, according to the methodology proposed in chapter 5. The spatial-temporal investigation of deforestation and secondary forest patterns (chapters 2 and 3), and agro-pasture expansion (chapter 4) indicate that most relevant interactions are mainly between soil fertility, accessibility to towns/markets, land prices, fires, dry season severity and land use/cover types. These interactions were related to the age of establishment, property size and land distribution regime.

In addition to the information presented in chapter 5, I constructed additional FCMs to represent a personal system´s understanding at local and regional scales, and better comprehend these interactions. In this way, I could structurally explore existing interactions within coupled human-environmental systems at two scales. As these FCMs were predominantly constructed as a secondary aid to explore interactions, only the model at local scale is illustrated here (see Figure 6.1). This model shows the interactions of land use/cover patterns to their location factors and direct/indirect drivers of change in old and new rural projects in Machadinho and Vale do Anari municipalities in Rondônia State. In Figure 6.1, the thickness of arrows represent the intensity of interactions among location factors, drivers and land use/cover changes, while weights are represented by the gray scale attributed to their respective boxes. The assumptions made for the causal relationships, *i.e.* the direction of arrows were done based on fieldwork interviews from 2006 and 2008, expert knowledge and the literature review (for details see Table 2.1 in chapter 2 and Table A.1 in chapter 5).

The representation of interactions in a system´s model allows a logical comprehension of the system´s complexity. The example given in Figure 6.1 indicates that secondary forest patterns are directly determined by soil data (soil type and soil fertility) and slope, while these location factors indirectly influence the feedback loops occurring in old and new rural settlements among relevant drivers of change (accessibility to towns, fires, dry season severity) and secondary forest/deforestation patterns. Also relevant drivers and underlying causes of deforestation at the local scale are the existence of forest reserves, credits to agro-pasture activities, population density and income *per capita*. These aforementioned drivers and underlying causes can indirectly reinforce feedbacks at both scales.

Two FCMs were constructed for the regional scale considering the age of rural settlements in the northeast of Rondônia State and the different farm sizes in both states Rondônia and Mato Grosso. The results indicated that the complexity of feedbacks loops within human-environmental systems tends to increase together with the heterogeneity of land use/cover change patterns. The exploration of interactions within these FCMs demonstrates that the level of complexity of the human-environmental systems increases considerably from the local to the regional scale. This is because of the heterogeneity of land use/cover change patterns as well as the number of interactions and feedback loops are higher at the regional scale. At the regional scale, the interactions can be analyzed regarding their influence on interactions at local scale, *i.e.* whether there are interactions (and even feedbacks) across scales.

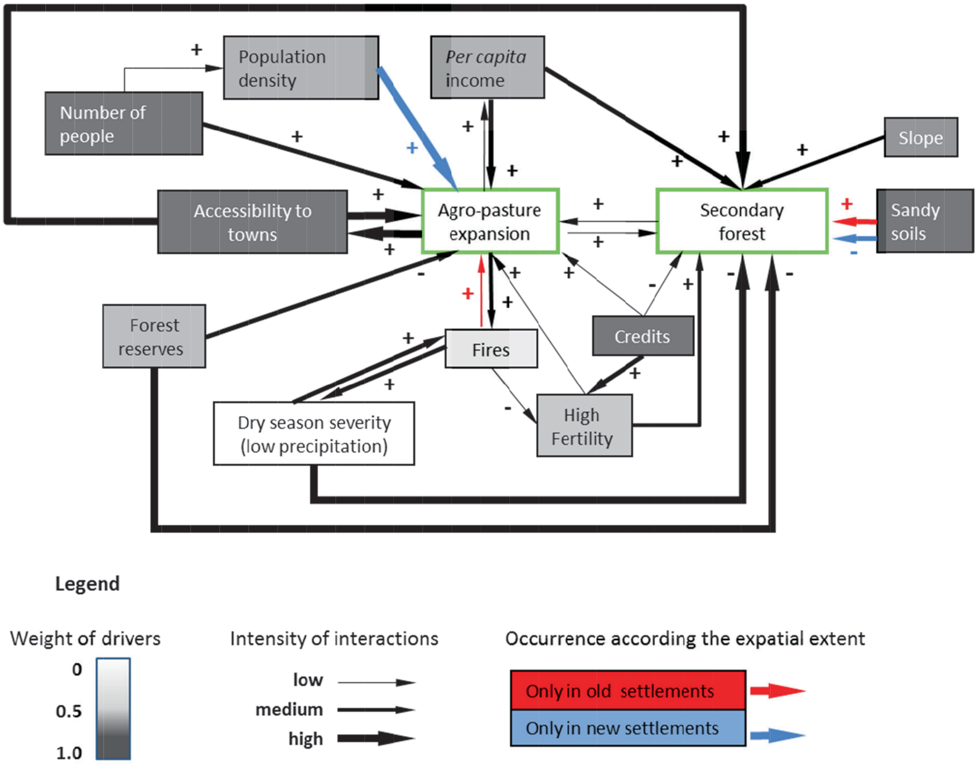


Figure 6.1 – System´s model representing the interactions and feedback loops retrieved from the Fuzzy Cognitive Map at the local scale in old and new rural settlements in Rondônia State. The weights and intensity of interactions between land cover change patterns to location factors, direct and indirect drivers of change are represented by arrow thickness and gray scale of boxes, as shown in the legend.

6.4.2 Relevant feedback loops

The interactions identified in FCMs at the local and regional scales indicated the existence of feedback loops, which are listed in Table 6.1. These feedbacks were explored taking into account the interactions identified as sensitive, according to the sensitivity analysis executed in chapter 5 (for details see section 5.5.2 and Table 5.5).

Figure 6.1 clearly shows the feedback loops within accessibility, agro-pasture expansion (deforestation) and secondary forest patterns are important interactions both in old or new settlements. This feedback loop appears to be of overriding importance in the human-environment system at the local scale, and is more important than the feedback loop within deforestation, fires, dry season severity and secondary forest occurring in old settlements. This feedback loop is observed to be rather more relevant at regional scale.

Table 6.1 – Relevant feedback loops revealed by linking cognitive methods and spatial data listed in order of importance at local and regional scales considering three different spatial extents listed in the first column.

Spatial extent at which feedback loop was identified	**Spatial scale a which feedback loops act**
	Local scale
Old settlements in two municipalities in Rondônia	1) accessibility +➔ secondary forest +➔deforestation +➔ accessibility 2) deforestation +➔ fires +➔ dry season severity -➔ secondary forest +➔ deforestation
New settlements in two municipalities in Rondônia	1) accessibility +➔ secondary forest +➔ deforestation +➔ accessibility
	Regional scale
Old or new settlements in the northeast of Rondônia (30 municipalities)	1) deforestation +➔ fires +➔ dry season severity +➔ deforestation 2) land prices +➔ deforestation +➔ accessibility +➔ land prices 3) land prices +➔ deforestation -➔ land prices 4) land prices +➔ deforestation +➔ fires -➔ soil fertility +➔ land prices
Groups of farm sizes in Rondônia & Mato Grosso states (157 municipalities)	1) deforestation +➔ fires+➔ dry season severity+➔ deforestation 2) annual crops+➔ number of tractors per farm +➔ labor availability +➔ annual crops 3) accessibility to beef/milk markets +➔ land prices +➔ deforestation +➔ accessibility to beef/milk markets 4) accessibility to beef markets +➔ beef revenue +➔ pasture +➔ deforestation +➔ accessibility to beef markets 5) accessibility to milk markets +➔ milk production +➔ milk revenue +➔ pasture +➔ deforestation +➔ accessibility to milk markets 6) accessibility to milk markets +➔ milk production +➔ agricultural revenue +➔ perennial crops +➔ deforestation +➔ accessibility to milk markets

According to experts and literature, fires and dry season severity tend to intensify over time regardless of their role in the feedback loop with deforestation. This result can be interpreted as processes occurring at larger scales that are not uniquely affected by land dynamics at the local scale. In other words, the feedback loop within deforestation, fires, dry season severity and secondary forest act from the regional (or even broader) to the local scale. As a result, the coupled human-environmental system at local scale appears to be mainly determined by the feedback loop within agro-pasture expansion, with fires and dry season severity acting at broader scales (Cardoso et al., 2003).

Relevant feedback loops acting at the local and regional scales regarding rural settlements were related to the increase of accessibility to towns leading to further deforestation. The importance of accessibility (roads) in determining the overall pattern of deforestation in the Amazon is well known (Aguiar et al., 2007; Alves et al., 2003; Alves et al., 1999; Brandão and Souza, 2006b; Cardille and Foley, 2003; Fearnside and Ferreira, 1984; Fearnside and Graca, 2006). At the local scale, such feedbacks were linked to processes of lots aggregation, where older rural settlements (originally occupied by small farms) have a higher chance to turn into a pasture landscape. Such pasture landscapes tend to be much similar to land always dominated by large cattle farms, except from the lack of technology (see detailed discussion in chapter 4). Although not included in these feedback loops, population growth can drive deforestation while income *per capita* can drive secondary forest, reinforcing the feedback loop at local scale within secondary forest, deforestation and accessibility. This might explain the recent increase in deforestation as most landholders have had an increase in income *per capita*. Additionally, at regional scale forest reserves could dampen the occurrence of fires, negatively reinforcing the feedback loop within deforestation, fires, dry season severity and secondary forest.

Regional differences between Rondônia and Mato Grosso states are marked by the distinct importance in these states of the feedback loops among changes in land cover patterns, land use types, accessibility to markets, land prices, labor availability and technological level (tractors per farm). In general, these feedbacks reflect historical land occupation politically constrained by land markets, which guarantee the socioeconomic differentiation and technological level of crops between small and large landholders. Such feedback loops seem to be very strong, and their functioning and alteration is not only a social, but also a sustainability issue to be tackled by policy makers, local people, the private sector and the traditional communities (Brondizio, 2004; Browder et al., 2008; Hecht, 1985; Perz and Walker, 2002).

This analysis indicates that feedbacks regarding land prices and dry season severity act differently between different scales, and they were identified as more relevant at regional than at local scale. However, feedbacks among deforestation and accessibility seemed to have similar influence at all spatial scales. The results indicate that when going from the finest to the broadest scale it becomes more difficult to understand and explore interactions within drivers acting at local scale as deforestation and individual land use types. We see thus different feedback loops nested within others at higher scale levels. This observation denotes a direct consequence of the increase in land use system´s complexity, which is a similar conclusion to the one taken in the previous section regarding the exploration of FCMs system´s models.

These results show that detailed conclusions regarding interactions and feedbacks are only possible within data limitations of land systems analyses. The most important limitation is the fact that existing data at distinct spatial scales were only available either at the property level or at the municipality level. Data at the property level supported the analysis of deforestation/secondary forest regrowth (chapters 2 and 3), while data at the municipality level supported the analysis of land use change in terms of land distribution (chapters 3 and 4). As a consequence, the adopted methodology of building FCM linked to spatial data is also at risk of explanatory fallacies, which can be only partially avoided by taking into account expert knowledge and meta-analysis of case studies available in the literature.

6.5 Learning from statistic-cognitive approaches

In this section I discuss two main contributions of this thesis in relation to the proposed method of linking cognitive approaches to spatial-temporal analysis of land use/cover change. First, the feedbacks are discussed regarding their possible utility to support sustainable land systems. Secondly, the associated lessons learned on how the new insights of the revealed feedbacks can be used to indicate successful sustainable alternatives.

6.5.1 Feedbacks to support sustainable land systems

Ultimately, my drive to study land use and land cover dynamics was linked to the broader aim of advancing the sustainability land use/cover change. Successful research should then not only be measured by scientific merit, but also by the usefulness of resulting products and recommendations (Kates et al., 2001). In that context, research outputs and recommendations can be considered useful only if they help stakeholders to improve their decision making, *i.e.,* if improved decision-making can lead to more sustainable management of the human-environment system. Considering the importance of sustainable development, I exemplify and discuss the relevant feedback loops that might help sustainable practices observed in the field among small farms regarding drivers, patterns and processes of changes in land systems.

The intensive fieldwork campaign in 2008 provided sufficient material at the household level for the analyses described in chapters 3 and 4. Beyond that, fieldwork interviews revealed examples of small farming practices that can lead to sustainable land use systems. The most relevant cases (named here sustainable cases) were linked to: 1) agro-forestry with native species associated to cocoa or coffee plantations underneath; 2) reforestation with native (*Hevea brasiliensis*) or exotic species (*Tectona grandis*) from Southeastern Asian tropical forests and; 3) ananas plantation on poor fertile soils. The core drivers of land use identified in these examples were, in order of importance: agricultural background of landholders, diversification and profitability of land use system at regional/national markets, labor force within the family and finally soil fertility (except for ananas plantation). Because the number of samples of such sustainable cases is very small (with only one sample in the ananas plantation), a statistical analysis was not performed. These sustainable cases could nonetheless support the discussion below on the feasibility of reproducing already existing sustainable practices among small landholders in the Brazilian Amazon.

This overview regarding the main drivers and processes of specific land use systems considered as sustainable cases indicate that feedback loops that reinforce accessibility to markets, perennial crops, agricultural revenue, soil fertility and labor force can determine or undermine decision-making processes that allow for more sustainable land use systems in the Brazilian Amazon. Also, specific land use types such as ananas plantation can be an alternative in poor fertile areas that has been mistakenly planned for small farming. The implementation of educational and financial incentives to small landholders could likely dampen feedbacks of deforestation where land speculation pressures further lots aggregation. Such actions can improve living conditions of small farmers who struggle to keep their land, and usually have no sponsorships and little knowledge to choose for alternative and more sustainable plantations.

The analysis of feedback loops of forest change in the context of recent political actions is an interesting and relevant subject. Two main established and on-going changes in legislation are considered. Firstly, the modification of the Brazilian Forestry Code that affected the rules of obliged reserves along rivers and on the top of hills. Secondly, the recent legislation and governmental subsidizing programs to sustainable land use/cover practices (the National Policy for Ecosystem Services and the Federal Payment for Ecosystems Services Program). Among the most relevant initiatives of sustainable agriculture in the Brazilian Amazon are: the subsidized incentives for small landholders to agriculture/pasture practices who follow the Forestry Code; the subsides to the development of agro-forest systems; and finally the regulation for projects of Payment for Ecosystems Services (PES), sometimes associated to Reducing Emissions from Deforestation and Forest Degradation (REDD) (Metzger, 2010; Moraes, 2012).

The feedback loop at the local scale that reinforces secondary forest and the one at the regional scale that reinforces agricultural revenue and perennial crops could be directly affected by such policies, especially regarding PES and REDD policies. Conversely, the feedback loops at the regional scale including deforestation, dry season severity and fires, or within land prices, deforestation, fires and soil fertility could be dampened in the long term if changes in the Forestry Code are enforced among large farms. Thus, under the auspicious human-environmental interactions, such recent changes in both land cover trends in the Brazilian Amazon and the Brazilian environmental legislation and sustainability policies indicate that small, medium and large landholders can all foresee and start applying more sustainable land use practices that are economically feasible. Despite that, the cultural barriers are still strong in keeping the usual slash-and-burn for agriculture and/or pasture expansion. However, I believe this paradigm can be replaced by governmental campaigns spreading news of successful stories and with the private sector recognizing that the market niche of sustainable practices can not only keep gains, but also guarantee sellers and buyers survival in the long term.

This overall logic and main conclusions of this thesis when assembling all chapters together are shown in Figure 6.2.

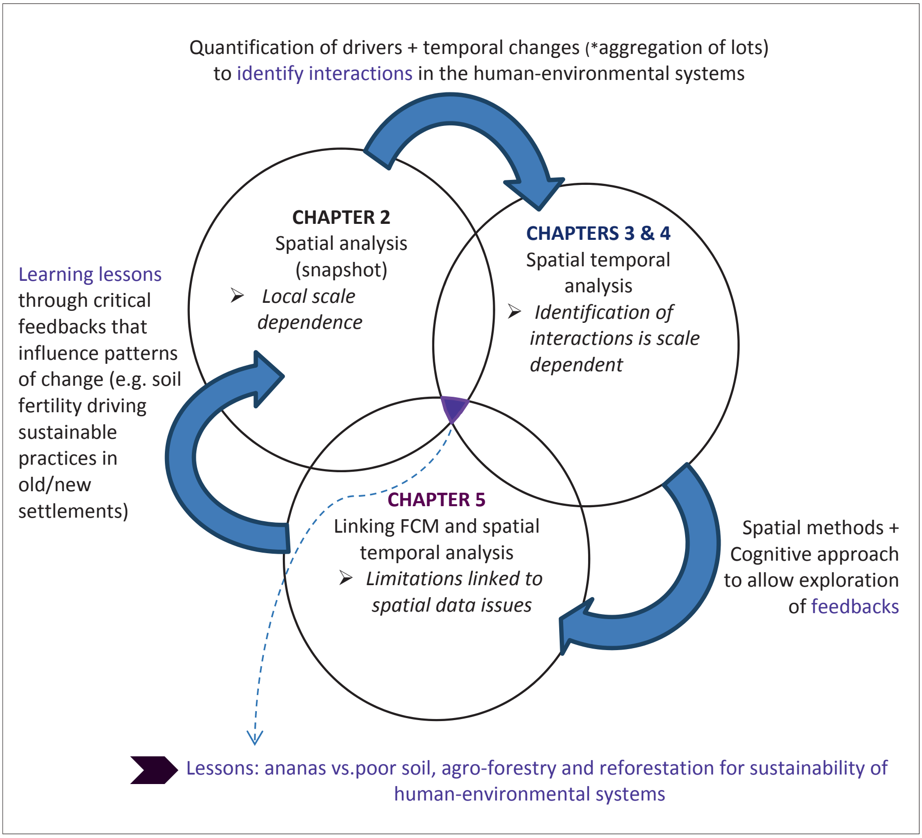


Figure 6.2 – System diagram indicating the main conclusions of this thesis in understanding land systems dynamics. Text inside the circles indicate methods and achievements obtained in different chapters, the text next to blue arrows indicate the gains when adding new methods at each step, and finally the purple intersection within circles indicates the lessons learnt only possible when assembling together results from all chapters.

The system illustrates the methods and the achievements of individual steps taken in different chapters to understand land use systems dynamics (text inside circles), as well as the gains when adding new methods at each step of thesis (text along blue arrows). In the last step between chapter 5 and chapter 2, the gain loop is completed with the associated learnt lessons taken from feedbacks regarding local choices of landholders that might lead to more sustainable pathways. The intersection among the circles (in purple) indicates that lessons can only be learnt when assembling outputs of all chapters together.

Besides the lessons regarding sustainability of land use systems, the need of high resolution data on soil fertility, as well as of agrarian structure at the property level (including records of aggregation of lots) to the extent of the whole Brazilian Amazon can be taken as important lessons for appropriate land use planning. There is one limitation to the used feedbacks, namely that they do not take market saturation into account. The ananas plantations can only grow to a limited extent as the local market will be limited.

Fortunately, there is now a new governmental effort lead by the Environmental Ministry to produce high resolution mapping of agricultural, pasture and forest assets at the property level to the whole country. This SiCAR (Rural and Environmental National Database System) has been built by information provided by landholders and organized by local governments of Brazilian states. Most states are already committed to produce data at the property level helping land use planning. Landholders who do not join the SiCAR might be prevented to get rural credits or subsides. Despite that, soil fertility data at local scale at large extents is still an issue to be tacked, as detailed data can only be found to small extents of Brazil.

6.6 Key conclusions

This thesis shows that there is added value in analyzing land system changes in the Brazilian Amazon by accounting for the processes operating across different scales. Insights obtained at different scales and with different methods can be combined in a single framework that allows an integrated view of human-environmental interactions. The key conclusions of this thesis are:

1) Statistical and cognitive methods can, together, provide better insight in the human-environmental interactions enclosing aspects of socioeconomic development, historical land distribution issues, land use intensification and sustainability of land use systems;
2) Through the description of drivers with statistical regression models, it is possible to explain similarities and differences among drivers of forest and secondary forest change patterns across different spatial extents in the Brazilian Amazon. This method has

limitations in revealing the causality of relations between drivers and land use patterns. The results of this method are scale dependent;

3) Spatial analysis using statistical methods to associate between location factors and patterns of land use change can be used to identify differences between spatial scales and regions. The statistical associations between drivers and land use/cover change are limited in their capability to explore the relevant feedbacks among deforestation, secondary forest regrowth, drivers and actors of land use change;
4) There are different feedback loops acting at different scales, but the results indicate an overall dominance of infrastructure (accessibility), followed by land prices as major drivers of these feedbacks;
5) Feedback loops that reinforce secondary forest growth and/or agricultural revenue from perennial crops can lead to a sustainable human-environment system among small farms, but *Payment for Ecosystems Services* (PES) and *Reducing Emissions from Deforestation and Forest Degradation* (REDD) policies must be enforced. Feedback loops within dry season severity, fires and land prices can reduce deforestation in the Brazilian Amazon if land market regulations and the Forestry Code be enforced, especially among large farms;
6) Policy effectiveness can be evaluated by analyzing the feedbacks identified with the FCM methodology.

References

Aguiar, A.P. D., G. Câmara and M. I. S. Escada 2007. Spatial statistical analysis of land-use determinants in the Brazilian Amazonia: Exploring intra-regional heterogeneity. Ecological Modelling 209: 169 -188.

Aguiar, A.P.D. 2006. Modeling land use change in the Brazilian Amazon: Exploring intra-regional heterogeneity. Remote Sensing, National Institute for Space Research (INPE).

Alves, D. S. 2007a. Cenários de cobertura e uso da terra e dimensões humanas no LBA. In Dimensões Humanas da Biosfera-Atmosfera na Amazônia, eds. W Costa, Becker; B. and Alves; D.S.. 39-63. São Paulo: EDUSP.

Alves, D. S. 2007b. Science and technology and sustainable development in Brazilian Amazon. In Stability of Tropical Rainforest Margins, 491-510.

Alves, D. S. 2002. Space-time dynamics of deforestation in Brazilian Amazonia. International Journal of Remote Sensing 23: 2903-2908.

Alves, D. S. 2008. Taking things public: a contribution to address human dimensions of environmental change. Philosophical Transactions of the Royal Society B-Biological Sciences 363: 1903-1909.

Alves, D. S., M. I. S. Escada, J. L. G. Pereira and C. D. Linhares 2003. Land use intensification and abandonment in Rondonia, Brazilian Amazonia. International Journal of Remote Sensing 24: 899-903.

Alves, D. S., D. C. Morton, M. Batistella, D. A. Roberts and C. Souza Jr. 2009. The changing rates and patterns of deforestation and land use in Brazilian Amazonia. In Amazonia and Global Change, eds. Michael Keller, M. Bustamante, J. Gash and P. S. Dias, 11-23. Washington, DC: American Geophysical Union.

Alves, D. S., J. L. G. Pereira, C. L.de Sousa, J. V. Soares and F. Yamaguchi 1999. Characterizing landscape changes in central Rondonia using Landsat TM imagery. International Journal of Remote Sensing 20: 2877-2882.

Andersen, L.E., W.J. Granger, E. J. Reis, D. Weinhold and S. Wunder 2002. The economics of deforestation: Dynamic modeling of Amazonia. Cambridge, UK: Cambridge University Press.

Andersen, L.E. and E. J. Reis 1997. Deforestation, development and government policy in the Brazilian Amazon: an econometric analysis. In Deforestation, development and government policy in the Brazilian Amazon: an econometric analysis, 27: Institudo de Pesquisa Econômica Aplicada (IPEA).

Aragão, L. E. O. C., Y. Malhi, N. Barbier, A. Lima, Y. Shimabukuro, L.O. Anderson and S. Saatchi 2008. Interactions between rainfall, deforestation and fires during recent years in the Brazilian Amazonia. Philosophical Transactions of the Royal Society B-Biological Sciences 363: 1779-1785.

Aragao, L. E. O. C., Y. Malhi, R. M. Roman-Cuesta, S. Saatchi, L. O. Anderson and Y. E. Shimabukuro 2007. Spatial patterns and fire response of recent Amazonian droughts. Geophysical Research Letters 34: -.

Arima, E. Y., P. Barreto and M. Brito 2005a. Cattle Ranching in the Amazon: trends and implications for environmental conservation. Belém: IMAZON.

Arima, E. Y., R. T. Walker, S. G. Perz and M. Caldas 2005b. Loggers and forest fragmentation: Behavioral models of road building in the Amazon basin. Annals of the Association of American Geographers 95: 525-541.
Arima, E. Y., R. T. Walker, M. Sales, C. Souza and S. G. Perz 2008. The fragmentation of space in the Amazon basin: Emergent road networks. Photogrammetric Engineering and Remote Sensing 74: 699-709.
Asner, Gregory P., Eben N. Broadbent, Paulo J. C. Oliveira, Michael Keller, David E. Knapp and João N. M. Silva 2006. Condition and fate of logged forests in the Brazilian Amazon. Proceedings of the National Academy of Sciences 103: 12947-12950. doi: 10.1073/pnas.0604093103
Axelrod, R. 1976. Structure of decision : the cognitive maps of political elites. Princeton: Princeton University Press.
Barona, Elizabeth, Navin Ramankutty, G. Hyman and Oliver T. Coomes 2010. The role of pasture and soybean in deforestation of the Brazilian Amazon. Environmental Research Letters 5: 024002-024009. doi: 10.1088/1748-9326/5/2/024002
Barreto, P., C. Souza Jr., A. Anderson, R. Salomão, J. Wiles and R. Noguerón 2005. Human Pressure in the Brazilian Amazon. In Human Pressure in the Brazilian Amazon, ed. IMAZON, State of the Amazon, 6. Belém: IMAZON.
Batistella, M. 2001. Landscape change and land-use/land-cover dynamics in Rondônia, Brazilian Amazon. Center for the study of institutions, population and enviromental change, Indiana University.
Batistella, M., S. Robeson and E. F. Moran 2003. Settlement design, forest fragmentation, and landscape change in Rondonia, Amazonia. Photogrammetric Engineering and Remote Sensing 69: 805-812.
Becker, B. 1997. Amazônia. São Paulo: Ática.
Becker, B. 2004. Amazônia: Geopolítica na virada do III milênio. Rio de Janeiro: Garamond.
Becker, B. 2005. Geopolítica da Amazônia. Estudos Avançados 19: 71-86.
Becker, B. 1995. Undoing Myths: the Amazon - an urbanized forest. In Brazilian perpectives on sustainable development for the Amazon region, eds. M. Clüsener-Godt and I. Sachs, 53-89. Paris, France: UNESCO.
Becker, B.; 2010. Novas territorialidades na Amazônia: desafio às políticas públicas. Boletim Museu Paraense Emílio Goeldi: Ciências Humanas 5: 17-23.
Bialoskorski Neto, S. 2001. Virtual Cooperatives in Brazil and the Globalization Process. Journal of Rural Cooperation 29: 153-165.
Borner, J. and S. Wunder 2008. Paying for avoided deforestation in the Brazilian Amazon: from cost assessment to scheme design. International Forestry Review 10: 496-511.
Brandão, A. O. and C. Souza 2006a. Deforestation in Land Reform Settlements in the Amazon. In Deforestation in Land Reform Settlements in the Amazon, ed. IMAZON, State of the Amazon, 4. Belém: IMAZON.
Brandão, A. O. and C. M. Souza 2005. Avaliação de imagens Landsat para identificação e extração de estradas madeireiras. In Avaliação de imagens Landsat para identificação e extração de estradas madeireiras, ed. INPE, XII Brazilian Remote Sensing Simposium, 3503-3509. Goiânia, Brazil: INPE.
Brandão, A. O. and C. M. Souza 2006b. Mapping unofficial roads with Landsat images: a new tool to improve the monitoring of the Brazilian Amazon rainforest. International Journal of Remote Sensing 27: 177-189.

Brandão, A. O., C. M. Souza, J. G. F. Ribeiro and M. H. R. Sales 2007. Deforestation and unofficial roads in the Amazon. In Deforestation and unofficial roads in the Amazon., XIII Brazilian Simposium of Remote Sensing, 2357-2364. Florianópolis, Brazil.
Brasil 2007. Anuário estatístico do crédito rural 2000-2007. In Anuário estatístico do crédito rural 2000-2007: Banco Central do Brasil.
Brasil 2008. Brazilian National Plan on Climate Change. In Brazilian National Plan on Climate Change, ed. Comitê Insterminiterial sobre Mudança do Clima, 154. Brasília: Governo Federal.
Brasil 1971. I Plano Nacional de Desenvolvimento. In I Plano Nacional de Desenvolvimento, ed. Secretaria de Imprensa da Presidência da República, 7. Brasília: Presidência da República.
Brasil 2002. Instrução Normativa n.51. Approved technical regulations for prodution, identity and quality standards of milk types A, B, C, Pasteurized and cooled raw milk, and technical regulations for raw milk collection, storage in cooling tanks and transportation in bulk. In Instrução Normativa n.51. Approved technical regulations for prodution, identity and quality standards of milk types A, B, C, Pasteurized and cooled raw milk, and technical regulations for raw milk collection, storage in cooling tanks and transportation in bulk., ed. Pecuária e Abastecimento Ministério da Agricultura.
Brasil 2012. Plan of Action for the Protection and Control of Deforestation in the Amazon region - PPCDAm.
Brasil 2009. Provisional Measure (MP) 458/09. In Provisional Measure (MP) 458/09, ed. Federal Government, 14.
Briassoulis, H. 2000. Analysis of land use change: theoretical and modeling approaches In The Web Book of Regional Science, ed. S. Loveridge. Morgantown: West Virginia University.
Brondizio, E. S. 2004. Agriculture intensification, economic identity, and shared invisibility in Amazonian peasantry: caboclos and colonists in comparative perspective. Culture and Agriculture 26: 1-24.
Brondizio, E. S., S.D. McCracken, E. F. Moran, A.D. Siqueira, D.R. Nelson and C. Rodrigues-Pedraza 2002. The Colonist Footprint: Toward a Conceptual Framework of Deforestation Trajectories Among Small Farmers in Frontier Amazônia. . In Deforestation and Land Use in the Amazon, eds. C. Wood and R Porros, 133-161. Gainesville: Florida University Press.
Brondizio, E. S. and E. F. Moran 2008. Human dimensions of climate change: the vulnerability of small farmers in the Amazon. Philosophical Transactions of the Royal Society B-Biological Sciences 363: 1803-1809.
Browder, J. O. 1988. Public policy and deforestation in the Brazilian Amazon. In Public policies and the misuse of forest resources eds. R. Repetto and M. Gillis, 247-283. Cambridge: Cambridge University Press.
Browder, J. O. 1994. Surviving In Rondonia - The Dynamics Of Colonist Farming Strategies In Brazil Northwest Frontier. Studies In Comparative International Development 29: 45-69.
Browder, J. O., M. A. Pedlowski and P. M. Summers 2004. Land use patterns in the Brazilian Amazon: Comparative farm-level evidence from Rondonia. Human Ecology 32: 197-224.
Browder, J. O., M. A. Pedlowski, R. Walker, R. H. Wynne, P. M. Summers, A. Abad, N. Becerra-Cordoba and J. Mil-Homens 2008. Revisiting theories of frontier expansion in

the Brazilian Amazon: A survey of the colonist farming population in Rondonia's post-frontier, 1992-2002. World Development 36: 1469-1492.
Brown, J. Christopher, Matthew Koeppe, Benjamin Coles and Kevin P. Price 2005. Soybean Production and Conversion of Tropical Forest in the Brazilian Amazon: The Case of Vilhena, Rondônia. AMBIO: A Journal of the Human Environment 34: 462-469.
Câmara, G., A. Paula, D. Aguiar, M. I. Escada, S. Amaral, T. Carneiro, A. M. V. Monteiro, R. Araujo, I. Vieira and B. Becker 2005. Amazonian deforestation models. Science 307: 1043-1044.
Cardille, J. A. and J. A. Foley 2003. Agricultural land-use change in Brazilian Amazonia between 1980 and 1995: Evidence from integrated satellite and census data. Remote Sensing of Environment 87: 551-562.
Cardoso, M. F., C. A. Nobre, G. Sampaio, M. Hirota, Dalton. Valeriano and Gilberto Câmara 2009. Long-term potential for tropical-forest degradation due to deforestation and fires in the Brazilian Amazon. Biologia 64: 433-437. doi: 10.2478/s11756-009-0076-9
Cardoso, Manoel F., George C. Hurtt, Berrien Moore, Carlos A. Nobre and Elaine M. Prins 2003. Projecting future fire activity in Amazonia. Global Change Biology 9: 656-669. doi: 10.1046/j.1365-2486.2003.00607.x
Carley, K. and M. Palmquist 1992. Extracting, Representing, and Analyzing Mental Models. Social Forces 70: 601-636.
Carvalho, G., A. C. Barros, P. Moutinho and D. Nepstad 2001. Sensitive development could protect Amazonia instead of destroying it. Nature 409: 131-131.
Celentano, D. and A. Verissimo 2007. The Amazon frontier advance: from boom to bust. In The Amazon frontier advance: from boom to bust., ed. IMAZON, The State of the Amazon: Indicators, 43. Belém: IMAZON.
Chen, P. Y. and P. M. Popovich 2002. Correlation: Parametric and nonparametric measures. Thousand Oaks, CA: Sage Publications.
Chomitz, K.M. and T.S. Thomas 2003. Determinants of land use in Amazonia: A fine-scale spatial analysis. American Journal of Agricultural Economics 85: 1016-1028.
Chomitz, K.M. and T.S. Thomas 2001. Geographic patterns of land use and land intensity in the Brazilian Amazon. World Bank Policy Research Working Paper No. 2687. Available at SSRN: Available at SSRN: http://ssrn.com/abstract=632755.
Claessens, L., J. M. Schoorl, P. H. Verburg, L. Geraedts and A. Veldkamp 2009. Modelling interactions and feedback mechanisms between land use change and landscape processes. Agriculture Ecosystems & Environment 129: 157-170.
Cleary, David 1993. After the Frontier: Problems with Political Economy in the Modern Brazilian Amazon. Journal of Latin American Studies 25: 331-349. doi: doi:10.1017/S0022216X00004685
Cochrane, T.T. and T. A. Cochrane 2006. Diversity of the land resources in the Amazonian State of Rondônia, Brazil. Acta Amazonica 36: 91-102.
Cossette, P. and M. Audet 1992. Mapping of an Idiosyncratic Schema. Journal of Management Studies 29: 325-347.
Costa, F.A. 2010. Market and production of lands in Amazon:evaluation referred to technological trajectories. Boletim do Museu Paraense Emílio Goeldi de Ciencias Humanas 5: 25-39.
Costa, F.A. 2009. Trajetórias tecnológicas como objeto de política de conhecimento para a Amazônia: uma metodologia de delineamento. Revista Brasileira de Inovação 8: 35-86.

Costa, W.M. 2007. Tendências recentes na Amazônia: os sistemas produtivos emergentes. In Dimensões humanas da biosfera-atmosfera na Amazônia, eds. B.; Becker, D. S.; Alves and W. M. Costa, 81-112. São Paulo: EDUSP.
Cox, P. M., R. A. Betts, C. D. Jones, S. A. Spall and I. J. Totterdell 2000. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. Nature 408: 750-750.
Coy, M. 1987. Rondônia: frente pioneira e o programa polonoroeste. O processo de diferenciação sócioeconômica na periferia e os limites do planejamento público. Tubinguen Geographische Studien 95: 253-270.
CPRM 2004. Carta Geológica do Brasil ao Milionésimo, folha SC-20. In Carta Geológica do Brasil ao Milionésimo, folha SC-20, ed. CPRM, Programa Geologia do Brasil. Rio de Janeiro: CPRM.
Cunha, M.C. and M.W.B. Almeida 2001. Populações tradicionais e conservação ambiental. In Biodiversidade na Amazônia Brasileira, eds. J.P. Capobianco, A. Veríssimo, A. Moreira, D. Sawyer, I. Santos and L.P. Pinto, 184-193. São Paulo: Estação Liberdade & ISA.
Dale, V. H., R. V. Oneill, F. Southworth and M. Pedlowski 1994a. Modeling effects of land management in the Brazilian settlement of Rondonia. Conservation Biology 8: 196-206.
Dale, V. H., S. M. Pearson, H. L. Offerman and R. V. Oneill 1994b. Relating patterns of land-use change to faunal biodiversity in the Central Amazon. Conservation Biology 8: 1027-1036.
de Espindola, Giovana M., Ana Paula D. de Aguiar, Edzer Pebesma, Gilberto Câmara and Leila Fonseca 2012. Agricultural land use dynamics in the Brazilian Amazon based on remote sensing and census data. Applied Geography 32: 240-252. doi: http://dx.doi.org/10.1016/j.apgeog.2011.04.003
EMATER-RO 2006. Information extracted from EMATER database (Sistema de Informações ATER). In Information extracted from EMATER database (Sistema de Informações ATER). Machadinho d'Oeste: EMATER.
Escada, M. I. S., A. M. V. Monteiro, A.P. D. Aguiar, T.G.S. Carneiro and G. Câmara 2005. Análise de padrões e processos de ocupação para a contrução de modelos na Amazônia: Experimentos em Rondônia. In Análise de padrões e processos de ocupação para a contrução de modelos na Amazônia: Experimentos em Rondônia, XII Simpósio Brasileiro de Sensoriamento Remoto, 2973-2983. Goiânia, Brazil.
Escada, M.I.S. 2003. Evolução de padrões da terra na região Centro-Norte de Rondônia. Remote Sensing, National Institute for Space Research (INPE).
Evans, T. P., A. Manire, F. de Castro, E. Brondizio and S. McCracken 2001. A dynamic model of household decision-making and parcel level landcover change in the eastern Amazon. Ecological Modelling 143: 95-113.
Faminow, M. D. 1998. Cattle, deforestation and development in the Amazon. New York: CAB International.
Faminow, M. D. 1997. Spatial economics of local demand for cattle products in Amazon development. Agriculture Ecosystems & Environment 62: 1-11.
Fearnside, P. M. 2008a. Amazon forest maintenance as a source of environmental services. Anais Da Academia Brasileira De Ciencias 80: 101-114.
Fearnside, P. M. 2003. Conservation policy in Brazilian Amazonia: Understanding the dilemmas. World Development 31: 757-779.

Fearnside, P. M. 2005. Deforestation in Brazilian Amazonia: History, rates, and consequences. Conservation Biology 19: 680-688.
Fearnside, P. M. 1993. Deforestation in Brazilian Amazonia: The effect of population and land tenure. Ambio 22: 537-545.
Fearnside, P. M. 1980. The effect of cattle pasture on soil fertility in the Brazilian Amazon: consequences for beef production sustainability. Tropical Ecology 21: 125-137.
Fearnside, P. M. 1997. Limiting factors for development of agriculture and ranching in Brazilian Amazonia. Revista Brasileira de Biologia 57: 531-549.
Fearnside, P. M. 2008b. The Roles and Movements of Actors in the Deforestation of Brazilian Amazonia. Ecology and Society 13: -.
Fearnside, P. M. 1986. Settlement In Rondonia And The Token Role Of Science And Technology In Brazil Amazonian Development-Planning. Interciencia 11: 229-236.
Fearnside, P. M. 2001. Soybean cultivation as a threat to the environment in Brazil. Environmental Conservation 28: 23-38.
Fearnside, P. M. and G. D. Ferreira 1984. Roads In Rondonia - Highway Construction And The Farce Of Unprotected Reserves In Brazils Amazonian Forest. Environmental Conservation 11: 358-360.
Fearnside, P. M. and P. M. L. D. Graca 2006. BR-319: Brazil's manaus-porto velho highway and the potential impact of linking the arc of deforestation to central Amazonia. Environmental Management 38: 705-716.
Ferraz, S. F. D., C. A. Vettorazzi, D. M. Theobald and M. V. R. Ballester 2005. Landscape dynamics of Amazonian deforestation between 1984 and 2002 in central Rondonia, Brazil: assessment and future scenarios. Forest Ecology and Management 204: 67-83.
Foweraker, J. 1981. The struggle for land: a political economy of the pioneer frontier in Brazil from 1930 to the present day. Cambridge: Cambrigde University Press.
Fox, J., R.R. Rindfuss, S.J. Walsh and V. Mishra 2002. People and the Environment; Approaches for Linking Household and Community Surveys to Remote Sensing and GIS. Boston: Kluwer Academic Publishers.
Fujisaka, S., W. Bell, N. Thomas, L. Hurtado and E. Crawford 1996. Slash-and-burn agriculture, conversion to pasture, and deforestation in two Brazilian Amazon colonies. Agriculture Ecosystems & Environment 59: 115-130.
Futema, C. and E. Brondizio 2003. Land reform and land-use changes in the lower Amazon: Implications for agricultural intensification. Human Ecology 31: 369-402.
Gallagher, Paul, Guenter Schamel, Hosein Shapouri and Heather Brubaker 2006. The international competitiveness of the U.S. corn-ethanol industry: A comparison with sugar-ethanol processing in Brazil. Agribusiness 22: 109-134. doi: 10.1002/agr.20072
Gastwirth, Joseph L. 1972. The Estimation of the Lorenz Curve and Gini Index. The Review of Economics and Statistics (The MIT Press) 54: 306–316. doi: 10.2307/1937992
Geist, H. J. and E. F. Lambin 2001. What drives tropical deforestation? : a meta-analysis of proximate and underlying causes of deforestation based on subnational case study evidence. Louvain la Neuve: LUCC International Project Office.
Geist, H., W. J. McConnell, E. F. Lambin, E. F. Moran, D. S. Alves and T. Rudel 2006. Causes and trajectories of land-use/cover change. In Land-use and land-cover change: local processes and global impacts, eds. E. F. Lambin and H. Geist,
222. Berlin: Springer.

Geurs, K. T. and J. R. Ritsema van Eck 2001. Accessibility measures: review and applications. Evaluation of accessibility impacts of land-use transport scenarios, and related social and economic impacts. In Accessibility measures: review and applications. Evaluation of accessibility impacts of land-use transport scenarios, and related social and economic impacts, ed. Netherlands Environmental Assessment Agency, 265. Bilthoven: National Institute of Public Health and the Environment.

Gibson, C. C., E. Ostrom and T. K. Ahn 2000. The concept of scale and the human dimensions of global change: a survey. Ecological Economics 32: 217-239.

Gullison, Raymond E., Peter C. Frumhoff, Josep G. Canadell, Christopher B. Field, Daniel C. Nepstad, Katharine Hayhoe, Roni Avissar, Lisa M. Curran, Pierre Friedlingstein, Chris D. Jones and Carlos Nobre 2007. Tropical Forests and Climate Policy. Science 316: 985-986. doi: 10.1126/science.1136163

Hecht, S. B. 2007. Factories, forests, fields and family: Gender and neoliberalism in extractive reserves. Journal of Agrarian Change 7: 316-347.

Hecht, S. B. 2005. Soybeans, development and conservation on the Amazon frontier. Development and Change 36: 375-404.

Hecht, S. and A. Cockburn 1989. Defenders of the Amazon - Deforestation Is Not Just About Ecological Destruction but Social and Political Injustice. New Statesman & Society 2: 16-20.

Hecht, Susanna B. 1985. Environment, development and politics: Capital accumulation and the livestock sector in Eastern Amazonia. World Development 13: 663-684.

Helfand, S.M. and L.F. Brunstein 2001. The Changing Structure of the Brazilian Agricultural Sector and the Limitations of the 1995/96 Agricultural Census. Revista de Economia e Sociologia Rural 39: 41-66.

Hughes, R. F., J. B. Kauffman and D. L. Cummings 2002. Dynamics of aboveground and soil carbon and nitrogen stocks and cycling of available nitrogen along a land-use gradient in Rondonia, Brazil. Ecosystems 5: 244-259.

Hughes, R. F., J. B. Kauffman and D. L. Cummings 2000. Fire in the Brazilian Amazon 3. Dynamics of biomass, C, and nutrient pools in regenerating forests. Oecologia 124: 574-588.

IBAMA 2005. Online database. In Online database, ed. Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis. Brasília: MMA (Ministério do Meio Ambiente).

IBGE 2008. Banco de dados agregados - Pesquisas Municipais Pecuária, Agrícola e Industrial. In Banco de dados agregados - Pesquisas Municipais Pecuária, Agrícola e Industrial.: IBGE.

IBGE 2007a. Banco de dados agregados - Pesquisas Municipais Pecuária, Agrícola e Industrial. In Banco de dados agregados - Pesquisas Municipais Pecuária, Agrícola e Industrial.: IBGE.

IBGE 1970. Censo agropecuário 1970. In Censo agropecuário 1970. Rio de Janeiro: Instituto Brasileiro de Geografia e Estatística (IBGE).

IBGE 1975. Censo agropecuário 1975. In Censo agropecuário 1975. Rio de Janeiro: Instituto Brasileiro de Geografia e Estatística (IBGE).

IBGE 1980. Censo agropecuário 1980. In Censo agropecuário 1980. Rio de Janeiro: Instituto Brasileiro de Geografia e Estatística (IBGE).

IBGE 1985. Censo agropecuário 1985. In Censo agropecuário 1985. Rio de Janeiro: Instituto Brasileiro de Geografia e Estatística (IBGE).

IBGE 1996. Censo agropecuário 1996. In Censo agropecuário 1996. Rio de Janeiro: Instituto Brasileiro de Geografia e Estatística (IBGE).

IBGE 2006. Censo agropecuário 2006. In Censo agropecuário 2006. Rio de Janeiro: Instituto Brasileiro de Geografia e Estatística (IBGE).

IBGE 1991. Censo demográfico 1991. In Censo demográfico 1991. Rio de Janeiro: Instituto Brasileiro de Geografia e Estatística (IBGE).

IBGE 2000. Censo demográfico 2000. In Censo demográfico 2000. Rio de Janeiro: Instituto Brasileiro de Geografia e Estatística (IBGE).

IBGE 2007b. Contagem da população 2007. In Contagem da população 2007. Rio de Janeiro: Instituto Brasileiro de Geografia e Estatística (IBGE).

IBGE 1981. Crescimento e distribuição da população brasileira: 1940-1980. Rio de Janeiro: Instituto Brasileiro de Geografia e Estatística (IBGE).

IBGE 2004. Mapa de Biomas e de Vegetação In Mapa de Biomas e de Vegetação Rio de Janeiro: IBGE.

IDARON 2006. Fieldwork reports of vaccination campaigns against aftosa fever from 1999 to 2006. Porto Velho: Agência de Defesa Sanitária Agrosilvopastoril do Estado de Rondônia.

INCRA 2006. Plans of agrarian projects in Machadinho d'Oeste and Vale do Anari. In Plans of agrarian projects in Machadinho d'Oeste and Vale do Anari. Porto Velho: INCRA.

INCRA 2008. Plans of agrarian projects in the north of Rondônia State. In Plans of agrarian projects in the north of Rondônia State. Ariquemes: INCRA.

INCRA 2007. Statistical data per category of rural property. In Statistical data per category of rural property: National Institute of Colonization and Land Reform.

INPE 2013a. DETER - Near Real Time Deforestation Detection System <http://www.obt.inpe.br/deter/>. In DETER - Near Real Time Deforestation Detection System <http://www.obt.inpe.br/deter/>. São José dos Campos, São Paulo: Instituto Nacional de Pesquisas Espaciais.

INPE 2007. Monitoramento da Floresta Amazônica Brasileira por Satélite (Monitoring the Brazilian Amazonia Forest by Satellite). . In Monitoramento da Floresta Amazônica Brasileira por Satélite (Monitoring the Brazilian Amazonia Forest by Satellite). . São José dos Campos, São Paulo: INPE (Instituto Nacional de Pesquisas Espaciais).

INPE 2008. Monitoring the Brazilian Amazonian forest by satellite - PRODES, DETER and DEGRAD projects. In Monitoring the Brazilian Amazonian forest by satellite - PRODES, DETER and DEGRAD projects. São José dos Campos, São Paulo: INPE (Instituto Nacional de Pesquisas Espaciais).

INPE 2009a. PRODES - Monitoring the Brazilian Amazonian forest by satellite images. In PRODES - Monitoring the Brazilian Amazonian forest by satellite images. São José dos Campos, São Paulo: Instituto Nacional de Pesquisas Espaciais.

INPE 2011. PRODES - Monitoring the Brazilian Amazonian forest by satellite images <http://www.obt.inpe.br/prodes/index.html>. In PRODES - Monitoring the Brazilian Amazonian forest by satellite images <http://www.obt.inpe.br/prodes/index.html>. São José dos Campos, São Paulo: Instituto Nacional de Pesquisas Espaciais.

INPE 2009b. PRODES - Monitoring the Brazilian Amazonian forest by satellite images <http://www.obt.inpe.br/prodes/index.html>. In PRODES - Monitoring the Brazilian Amazonian forest by satellite images <http://www.obt.inpe.br/prodes/index.html>. São José dos Campos, São Paulo: Instituto Nacional de Pesquisas Espaciais.

INPE 2013b. PRODES - Monitoring the Brazilian Amazonian forest by satellite images <http://www.obt.inpe.br/prodes/index.html>. In PRODES - Monitoring the Brazilian Amazonian forest by satellite images <http://www.obt.inpe.br/prodes/index.html>. São José dos Campos, São Paulo: Instituto Nacional de Pesquisas Espaciais.

INPE/CPTEC 2005. Burns monitoring. In Burns monitoring: National Institute for Space Research (INPE).

INPE/EMBRAPA 2011. TerraClass 2008 - Levantamento das informações de uso e cobertura da terra na Amazônia. In TerraClass 2008 - Levantamento das informações de uso e cobertura da terra na Amazônia. Belém: INPE (Instituto Nacional de Pesquisas Espaciais).

INPE/EMBRAPA 2013. TerraClass 2010 - Levantamento das informações de uso e cobertura da terra na Amazônia. In TerraClass 2010 - Levantamento das informações de uso e cobertura da terra na Amazônia. Belém: INPE (Instituto Nacional de Pesquisas Espaciais).

Jenkins, C.N. and L. Joppa 2009. Expansion of the global terrestrial protected area system. Biological Conservation 142 2166–2174.

Kates, Robert W., William C. Clark, Robert Corell, J. Michael Hall, Carlo C. Jaeger, Ian Lowe, James J. McCarthy, Hans Joachim Schellnhuber, Bert Bolin, Nancy M. Dickson, Sylvie Faucheux, Gilberto C. Gallopin, Arnulf Grübler, Brian Huntley, Jill Jäger, Narpat S. Jodha, Roger E. Kasperson, Akin Mabogunje, Pamela Matson, Harold Mooney, Berrien Moore, Timothy O'Riordan and Uno Svedin 2001. Sustainability Science. Science 292: 641-642. doi: 10.1126/science.1059386

Kok, K. 2001. Scaling the land use system. Wageningen: Wageningen Universiteit.

Kok, Kasper 2009. The potential of Fuzzy Cognitive Maps for semi-quantitative scenario development, with an example from Brazil. Global Environmental Change 19: 122-133.

Koomen, E., J. Stillwell, A. Bakema and H.J. Scholten 2007. Modelling land-use change: progress and applications. Dordrecht: Springer.

Kosko, B. 1986. Fuzzy Cognitive Maps. International Journal of Man-Machine Studies 24: 65-75.

Lambin, E. F. and H. J. Geist 2003. Regional differences in tropical deforestation. Environment 45: 22-36.

Lambin, E. F., B. L. Turner, H. J. Geist, S. B. Agbola, A. Angelsen, J. W. Bruce, O. T. Coomes, R. Dirzo, G. Fischer, C. Folke, P. S. George, K. Homewood, J. Imbernon, R. Leemans, X. B. Li, E. F. Moran, M. Mortimore, P. S. Ramakrishnan, J. F. Richards, H. Skanes, W. Steffen, G. D. Stone, U. Svedin, T. A. Veldkamp, C. Vogel and J. C. Xu 2001. The causes of land-use and land-cover change: moving beyond the myths. Global Environmental Change-Human and Policy Dimensions 11: 261-269.

Laurance, W. F., A. K. M. Albernaz, P. M. Fearnside, H. L. Vasconcelos and L. V. Ferreira 2004. Deforestation in Amazonia. Science 304: 1109-1109.

Laurance, W. F., A. K. M. Albernaz, G. Schroth, P. M. Fearnside, S. Bergen, E. M. Venticinque and C. Da Costa 2002. Predictors of deforestation in the Brazilian Amazon. Journal of Biogeography 29: 737-748.

Laurance, W. F. and G. B. Williamson 2001. Positive feedbacks among forest fragmentation, drought, and climate change in the Amazon. Conservation Biology 15: 1529-1535.

Lemos, M. C. and J. T. Roberts 2008. Environmental policy-making networks and the future of the Amazon. Philosophical Transactions of the Royal Society B-Biological Sciences 363: 1897-1902.

Lesschen, J-P., P.H. Verburg and S.J. Staal 2005. Statistical methods for analysing the spatial dimension of changes in land use and farming systems. In Statistical methods for analysing the spatial dimension of changes in land use and farming systems, ed. LUCC report series no. 7., 81. Wageningen: ILRI & Wageningen University. .

Liu, Jianguo, Thomas Dietz, Stephen R. Carpenter, Marina Alberti, Carl Folke, Emilio Moran, Alice N. Pell, Peter Deadman, Timothy Kratz, Jane Lubchenco, Elinor Ostrom, Zhiyun Ouyang, William Provencher, Charles L. Redman, Stephen H. Schneider and William W. Taylor 2007. Complexity of Coupled Human and Natural Systems. Science 317: 1513-1516. doi: 10.1126/science.1144004

Lorena, R.B. 2008. Linking spatial patterns of land-use to agents of deforestation in the Brazilian Amazon. Département de Géographie Université Catholique de Louvain.

Ludewigs, T., A. D. D'Antona, E. S. Brondizio and S. Hetrick 2009. Agrarian Structure and Land-cover Change Along the Lifespan of Three Colonization Areas in the Brazilian Amazon. World Development 37: 1348-1359.

Macedo, Marcia N., Ruth S. DeFries, Douglas C. Morton, Claudia M. Stickler, Gillian L. Galford and Yosio E. Shimabukuro 2012. Decoupling of deforestation and soy production in the southern Amazon during the late 2000s. Proceedings of the National Academy of Sciences. doi: 10.1073/pnas.1111374109

Machado, L. 1998. A fronteira agrícola na Amazônia. In A fronteira agrícola na Amazônia, eds. A. Cristofoletti, B. Becker, F. Davidovich and P.P. Geiger, Geografia e Meio Ambiente no Brasil, 181-217. São Paulo: Cia das Letras.

Machado, L.O. 1989. Mytos y realidade de la Amazônia Brasileña en el contexto geopolítico mundial (1540-1912). Ph.D., Barcelona University.

Malhi, Yadvinder, Luiz E. O. C. Aragão, David Galbraith, Chris Huntingford, Rosie Fisher, Przemyslaw Zelazowski, Stephen Sitch, Carol McSweeney and Patrick Meir 2009. Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. Proceedings of the National Academy of Sciences. doi: 10.1073/pnas.0804619106

MAPA 2008. List of slaughterhouses and diary industries certified by the Federal Inspection Agency. In List of slaughterhouses and diary industries certified by the Federal Inspection Agency. Brasilia: Serviço de Inspeção Federal - Ministério da Agricultura, Pecuária e Abastecimento.

Marengo, J. A., C. A. Nobre, J. Tomasella, M. F. Cardoso and M. D. Oyama 2008. Hydro-climatic and ecological behaviour of the drought of Amazonia in 2005. Philosophical Transactions of the Royal Society B-Biological Sciences 363: 1773-1778.

Margulis, S. 2004a. Causes of deforestation in the Brazilian Amazon. In Causes of deforestation in the Brazilian Amazon, ed. World Bank Working Paper. Washington: World Bank.

Margulis, S. 2004b. Causes of deforestation in the Brazilian Amazon. 22.

Matricardi, E. A. T., D. L. Skole, M. A. Cochrane, M. Pedlowski and W. Chomentowski 2007. Multi-temporal assessment of selective logging in the Brazilian Amazon using Landsat data. International Journal of Remote Sensing 28: 63-82.

Mello, A. Yu Iwama and D. S. Alves 2011. Secondary vegetation dynamics in the Brazilian Amazon based on thematic mapper imagery. Remote Sensing Letters 2: 189 - 194.

Mello, A.J.H. and D.S. Alves 2005. Padrões de desflorestamento no regime fundiário de fronteira da Amazônia brasileira. In Padrões de desflorestamento no regime fundiário

de fronteira da Amazônia brasileira, XII Simpósio Brasileiro de Sensoriamento Remoto, 3053-3060. Goiânia, Brazil.
Menard, S. 2001. Applied logistic regression analysis. Sage: Sage University Papers.
Mertens, B. and E. F. Lambin 1997. Spatial modelling of deforestation in southern Cameroon - Spatial disaggregation of diverse deforestation processes. Applied Geography 17: 143-162.
Mertens, B., R. Poccard-Chapuis, M. G. Piketty, A. E. Lacques and A. Venturieri 2002. Crossing spatial analyses and livestock economics to understand deforestation processes in the Brazilian Amazon: the case of Sao Felix do Xingu in South Para. Agricultural Economics 27: 269-294.
Messina, J. P., S. J. Walsh, C. F. Mena and P. L. Delamater 2006. Land tenure and deforestation patterns in the Ecuadorian Amazon: Conflicts in land conservation in frontier settings. Applied Geography 26: 113-128.
Metzger, Jean Paul 2010. O Código Florestal tem base científica? Natureza & Conservação 8: 1-5.
Millikan, B. H. 1992. Tropical deforestation, land degradation, and society - lessons from Rondonia, Brazil. Latin American Perspectives 19: 45-72.
Milne, Eleanor, Richard Aspinall and Tom Veldkamp 2009. Integrated modelling of natural and social systems in land change science. Landscape Ecology DOI 10.1007/s10980-009-9392-2.
Miranda, E. E. de, J.A.C. Mangabeira, E. G. Gomes, M. Batistella and J.R. Miranda 2002. Café e coragem: 13 anos de colonização agrícola em Rondônia. In Café e coragem: 13 anos de colonização agrícola em Rondônia, ed. Embrapa Monitoramento por Satélite, Embrapa Monitoramento por Satélite - Documentos, 120. Campinas: EMBRAPA.
Miranda, E. E. and C. Mattos 1992. Brazilian rain forest colonization and biodiversity. Agriculture Ecosystems & Environment 40: 275-296.
Miranda, E. E., O. T.; Oshiro, D. C.; Victoria, F. E.; Torressan and C. A. Carvalho 2009. O alcance da legislação ambiental e territorial. Agroanalysis 28: 25 - 31.
MMA 2005. Base de dados sobre exploração dos recursos naturais. In Base de dados sobre exploração dos recursos naturais. Brasilia: Ministério do Meio Ambiente.
Monbeig, Pierre 1984. Pioneiros e fazendeiros de São Paulo. São Paulo: Hucitec-Polis.
Montazemi, A. R. and D. W. Conrath 1986. The Use of Cognitive Mapping for Information Requirements Analysis. Mis Quarterly 10: 45-56.
Moraes, J. F. L. de 2012. Pagamento por Serviços Ambientais (PSA) como instrumento de política de desenvolvimento sustentável dos territórios rurais: o projeto protetor das águas de Vera Cruz, RS. Sustainability in Debate 3: 43-56.
Moraes, J. F. L. de, B. Volkoff, Carlos C. Cerri and M. Bernoux 1996. Soil properties under Amazon forest and changes due to pasture installation in Rondônia, Brazil. Geoderma 70: 63-81.
Moran, E. F. 1993. Deforestation and Land-Use in the Brazilian Amazon. Human Ecology 21: 1-21.
Moran, E. F., E. S. Brondizio, J. M. Tucker, M. C. da Silva-Forsberg, S. McCracken and I. Falesi 2000. Effects of soil fertility and land-use on forest succession in Amazonia. Forest Ecology and Management 139: 93-108.
Moran, E. F., A. Siqueira and E. S. Brondizio 2003. Household demographic structure and its relationship to deforestation in the Amazon Basin. In People and the Environment

Approaches for Linking Household and Community Surveys to Remote Sensing and GIS eds. J. Fox, R.R. Rindfuss, S.J. Walsh and V. Mishra, 61-89. Dordrecht: Kluwer Academic Publishers.

Morton, Douglas C., Ruth S. DeFries and Yosio E. Shimabukuro 2009. Cropland expansion in cerrado and transition forest ecosystems: Quantifying habitat loss from satellite-based vegetation phenology. . In Cerrado Land Use and Conservation, Advanced Applied Biodiversity Science., ed. C. A. Klink. Washington, D.C.: Conservation International.

Morton, Douglas C., Ruth S. DeFries, Yosio E. Shimabukuro, Liana O. Anderson, Egidio Arai, Fernando del Bon Espirito-Santo, Ramon Freitas and Jeff Morisette 2006. Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. Proceedings of the National Academy of Sciences 103: 14637-14641. doi: 10.1073/pnas.0606377103

Muchagata, Marcia and Katrina Brown 2003. Cows, colonists and trees: rethinking cattle and environmental degradation in Brazilian Amazonia. Agricultural Systems 76: 797-816.

Mueller, C.C. 2003. Expansion and modernization of agriculture in the Cerrado – the case of soybeans in Brazil’s Center-West. In Expansion and modernization of agriculture in the Cerrado – the case of soybeans in Brazil’s Center-West, The ECO/ UnB Working papers, 28. Brasília: University of Brasília, Departament of Economics.

NASA/USGS 2000. Shuttle radar topography mission data (SRTM). In Shuttle radar topography mission data (SRTM): National Aeronautics and Space Administration and United States Geological Survey.

Nepstad, D. C., A. Verissimo, A. Alencar, C. Nobre, E. Lima, P. Lefebvre, P. Schlesinger, C. Potter, P. Moutinho, E. Mendoza, M. Cochrane and V. Brooks 1999. Large-scale impoverishment of Amazonian forests by logging and fire. Nature 398: 505-508.

Nepstad, D., G. Carvalho, A. C. Barros, A. Alencar, J. P. Capobianco, J. Bishop, P. Moutinho, P. Lefebvre, U. L. Silva and E. Prins 2001. Road paving, fire regime feedbacks, and the future of Amazon forests. Forest Ecology and Management 154: 395-407.

Nepstad, D., S. Schwartzman, B. Bamberger, M. Santilli, D. Ray, P. Schlesinger, P. Lefebvre, A. Alencar, E. Prinz, G. Fiske and A. Rolla 2006a. Inhibition of Amazon deforestation and fire by parks and indigenous lands. Conservation Biology 20: 65-73.

Nepstad, D., C. Stickler and O. Almeida 2006b. Globalization of the Amazon beef and soy industries: opportunities for conservation. Conservation Biology 20(6): 1595-1603. Conservation Biology 20: 1595-1603.

Nobre, C. A., P. J. Sellers and J. Shukla 1991. Amazonian Deforestation and Regional Climate Change. Journal of Climate 4: 957-988.

Numata, I., J. V. Soares, D. A. Roberts, F. C. Leonidas, O. A. Chadwick and G. T. Batista 2003. Relationships among soil fertility dynamics and remotely sensed measures across pasture chronosequences in Rondonia, Brazil. Remote Sensing of Environment 87: 446-455.

Ostrom, Elinor, Marco A. Janssen and John M. Anderies 2007. Going beyond panaceas. Proceedings of the National Academy of Sciences 104: 15176-15178. doi: 10.1073/pnas.0701886104

Otsuki, T., I. W. Hardie and E. J. Reis 2002. The implication of property rights for joint agriculture-timber productivity in the Brazilian Amazon. Environment and Development Economics 7: 299-323.

Overmars, K. P., G. H. J. de Koning and A. Veldkamp 2003. Spatial autocorrelation in multi-scale land use models. Ecological Modelling 164: 257-270.
Overmars, K. P. and P. H. Verburg 2005. Analysis of land use drivers at the watershed and household level: Linking two paradigms at the Philippine forest fringe. International Journal of Geographical Information Science 19: 125-152.
Overmars, K. P. and P. H. Verburg 2006. Multilevel modelling of land use from field to village level in the Philippines. Agricultural Systems 89: 435-456.
Ozesmi, U. and S. Ozesmi 2003. A participatory approach to ecosystem conservation: Fuzzy cognitive maps and stakeholder group analysis in Uluabat Lake, Turkey. Environmental Management 31: 518-531.
Pacheco, P. 2009. Agrarian Reform in the Brazilian Amazon: Its Implications for Land Distribution and Deforestation. World Development 37: 1337-1347.
Padoch, C., E. S. Brondizio, S. Costa, M. Pinedo-Vasquez, R. R. Sears and A. Siqueira 2008. Urban forest and rural cities: multi-sited households, consumption patterns, and forest resources in Amazonia. Ecology and Society 13: 16.
Pan, W. K. Y., S. J. Walsh, R. E. Bilsborrow, B. G. Frizzelle, C. M. Erlien and F. Baquero 2004. Farm-level models of spatial patterns of land use and land cover dynamics in the Ecuadorian Amazon. Agriculture Ecosystems & Environment 101: 117-134.
Parker, D. C., A. Hessl and S. C. Davis 2008. Complexity, land-use modeling, and the human dimension: Fundamental challenges for mapping unknown outcome spaces. Geoforum 39: 789-804.
Parker, D. C., S. M. Manson, M. A. Janssen, M. J. Hoffmann and P. Deadman 2003. Multi-agent systems for the simulation of land-use and land-cover change: A review. Annals of the Association of American Geographers 93: 314-337.
Pedlowski, M. A. and V. H. Dale 1992. Land-use practices in Ouro Preto do Oeste, Rondonia, Brazil. In Land-use practices in Ouro Preto do Oeste, Rondonia, Brazil, ed. Environmental Sciences Division Publication, 41: OAK Ridge National Laboratory.
Pedlowski, M. A., V. H. Dale, E. A. T. Matricardi and E. P. da Silva 1997. Patterns and impacts of deforestation in Rondonia, Brazil. Landscape and Urban Planning 38: 149-157.
Pedlowski, M. A., E. A. T. Matricardi, D. Skole, S. R. Cameron, W. Chomentowski, C. Fernandes and A. Lisboa 2005. Conservation units: a new deforestation frontier in the Amazonian state of Rondonia, Brazil. Environmental Conservation 32: 149-155.
Pedlowski, M., V. Dale and E. A. T. Matricardi 1999a. A criação de áreas protegidas e os limites da conservação ambiental em Rondônia. Ambiente & sociedade: 93-107.
Pedlowski, Marcos, Virginia Dale and Eraldo Matricardi 1999b. A criação de áreas protegidas e os limites da conservação ambiental em Rondônia. Ambiente & sociedade: 93-107.
Pereira, L.M., M. I. S. Escada and C.D. Rennó 2007. Análise da evolução do desmatamento em áreas de pequenas, médias e grandes propriedades na região centro-norte de Rondônia, entre 1985 e 2000. In Análise da evolução do desmatamento em áreas de pequenas, médias e grandes propriedades na região centro-norte de Rondônia, entre 1985 e 2000, XIII Simpósio Brasileiro de Sensoriamento Remoto, 6905-6912. Florianópolis, Brazil.
Perz, S. G. 2005. The effects of household asset endowments on agricultural diversity among frontier colonists in the Amazon. Agroforestry Systems 63: 263-279.
Perz, S. G. 2001. Household demographic factors as life cycle determinants of land use in the Amazon. Population Research and Policy Review 20: 159-186.

Perz, S. G. and D. L. Skole 2003. Social determinants of secondary forests in the Brazilian Amazon. Social Science Research 32: 25-60.
Perz, S. G. and R. T. Walker 2002. Household life cycles and secondary forest cover among small farm colonists in the Amazon. World Development 30: 1009-1027.
Pfaff, A., J. Robalino, R. Walker, S. Aldrich, M. Caldas, E. Reis, S. Perz, C. Bohrer, E. Arima, W. Laurance and K. Kirby 2007a. Roads and deforestation in the Brazilian Amazon. Journal of Regional Science 47: 109-123.
Pfaff, A., J. Robalino, R. Walker, S. Aldrich, M. Caldas, E. Reis, S. Perz, C. Bohrer, E. Y. Arima, W. F. Laurance and K. Kirby 2007b. Road investments, spatial spillovers, and deforestation in the Brazilian Amazon. Journal of Regional Science 47: 109-123.
Pinho, P. F. , B. Orlove and M. Lubell 2012. Overcoming Barriers to Collective Action in Community-Based Fisheries Management in the Amazon. Human Organization 71: 99-109
Pinto, E. P. 1993. Rondônia, Evolução Histórica, A Criação do T. F.G Fator de Integração Nacional Rio de Janeiro: Expressão e Cultura.
Pontius, R. G. and L. C. Schneider 2001. Land-cover change model validation by an ROC method for the Ipswich watershed, Massachusetts, USA. Agriculture Ecosystems & Environment 85: 239-248.
RADAMBRASIL 1978. Folha SC.20 – Porto Velho. In Folha SC.20 – Porto Velho, Levantamento de Recursos Naturais. Rio de Janeiro: IBGE.
Ribeiro, D. and C.A. Moreira Neto 1992. A fundação do Brasil: testemunhos, 1500-1700. Petrópolis, Brazil: Vozes.
Rindfuss, R. R., S. J. Walsh, B. L. Turner, J. Fox and V. Mishra 2004. Developing a science of land change: Challenges and methodological issues. Proceedings of the National Academy of Sciences of the United States of America 101: 13976-13981.
Rindfuss, R.R., S.J. Walsh, V. Mishra, J. Fox and G.P. Dolcemascolo 2003. Linking household and remotely sensed data, methodological and practical problems. In People and the Environment. Approaches for linking houeshold and community surveys to remote sensing and GIS, eds. J. Fox, R.R. Rindfuss, S.J. Walsh and V. Mishra, 1-31. Boston: Kluwer Academic Publishers.
Rindfuss, Ronald R., Barbara Entwisle, Stephen J. Walsh, Li An, Nathan Badenoch, Daniel G. Brown, Peter Deadman, Tom P. Evans, Jefferson Fox, Jacqueline Geoghegan, Myron Gutmann, Maggi Kelly, Marc Linderman, Jianguo Liu, George P. Malanson, Carlos F. Mena, Joseph P. Messina, Emilio F. Moran, Dawn C. Parker, William Parton, Pramote Prasartkul, Derek T. Robinson, Yothin Sawangdee, Leah K. Vanwey and Peter H. Verburg 2008. Land use change: complexity and comparisons. Journal of Land Use Science 3: 1 - 10.
Roberts, D. A., I. Numata, K. Holmes, G. Batista, T. Krug, A. Monteiro, B. Powell and O. A. Chadwick 2002. Large area mapping of land-cover change in Rondonia using multitemporal spectral mixture analysis and decision tree classifiers. Journal of Geophysical Research-Atmospheres 107: LBA 40: 41-18.
Roberts, F. S. 1973. Building and Analyzing an Energy Demand Signed Digraph. Environment and Planning A 5: 199-221.
Rodrigues, A. S. L., R. M. Ewers, L. Parry, C. Souza, A. Verissimo and A. Balmford 2009. Boom-and-Bust Development Patterns Across the Amazon Deforestation Frontier. Science 324: 1435-1437.

Rondonia 2004. Boletim climatológico de Rondônia ano 2004. In Boletim climatológico de Rondônia ano 2004, ed. Secretaria de Estado do Desenvolvimento Ambiental (SEDAM). Porto Velho: Governo do Estado de Rondônia.

Rondonia 2000. Zoneamento socioeconômico-ecológico. In Zoneamento socioeconômico-ecológico., ed. SEDAM, PLANAFORO, 18. Porto Velho: Governo de Rondonia.

Rondônia 2000. Zoneamento socioeconômico-ecológico. In Zoneamento socioeconômico-ecológico., ed. SEDAM, PLANAFORO, 18. Porto Velho: Governo de Rondonia.

Santana, A.C. 2003. Descrição e análise da cadeia produtiva de leite no Estado de Rondônia. Movendo Idéias 8: 24-36.

Santos Jr., R. A. O. and P. Lena 2010. Da predação à sustentabilidade na Amazônia: a difícil metamorfose. In Desenvolvimento sustentável e sociedades na Amazônia., eds. R. A. O. Santos Jr. and P. Lena, 11-50. Belém: MPEG-PPG7.

Sawyer, D. 1984. Frontier expansion and retraction in Brazil. In Frontier Expansion in Amazonia, eds. M. Schmink and C. Wood, 180-203. Florida: University Press of Florida.

Schneider, R.R., E. Arima, A. Veríssimo, P. Barreto and C. Jr. Souza 2000. Sutainable Amazon: Limitations and oportunities for rural development. Brasília: World Bank and IMAZON.

Schröter, Dagmar, Marc J Metzger, Wolfgang Cramer and Rik Leemans 2004. Vulnerability assessment–analysing the human-environment system in the face of global environmental change. Environmental Science Section Bulletin 2: 11-17.

Scouvart, M., R. T. Adams, M. Caldas, V. Dale, B. Mertens, V. Nedelec, P. Pacheco, B. Rihoux and E. F. Lambin 2007. Causes of deforestation in the Brazilian Amazon: a qualitative comparative analysis. Journal of Land Use Science 2: 257 - 282.

SEPLAN 2002. Zoneamento socioeconômico-ecológico. In Zoneamento socioeconômico-ecológico, ed. SEPLAN, Secretaria de Estado de Planejamento e Coordenação Geral. Cuiaba: Governo de Rondonia.

Siegmund-Schultze, M., B. Rischkowsky, J. B. da Veiga and J. M. King 2010. Valuing cattle on mixed smallholdings in the Eastern Amazon. Ecological Economics 69: 857-867.

SIF 2006. Informations obtained from SIF technicians regarding local and regional milk production chain in the northeast of Rondônia State. In Informations obtained from SIF technicians regarding local and regional milk production chain in the northeast of Rondônia State. Jaru: Serviço de Inspeção Federal - Ministério da Agricultura.

Sills, Erin O. and Jill L. Caviglia-Harris 2009. Evolution of the Amazonian frontier: Land values in Rondônia, Brazil. Land Use Policy 26: 55-67.

Soares-Filho, B., A. Alencar, D. Nepstad, G. Cerqueira, M. D. V. Diaz, S. Rivero, L. Solorzano and E. Voll 2004. Simulating the response of land-cover changes to road paving and governance along a major Amazon highway: the Santarem-Cuiaba corridor. Global Change Biology 10: 745-764.

Soares-Filho, B., R. M. Assuncao and A. E. Pantuzzo 2001. Modeling the spatial transition probabilities of landscape dynamics in an amazonian colonization frontier. Bioscience 51: 1059-1067.

Soares-Filho, B., D. C. Nepstad, L. M. Curran, G. C. Cerqueira, R. A. Garcia, C. A. Ramos, E. Voll, A. McDonald, P. Lefebvre and P. Schlesinger 2006. Modelling conservation in the Amazon basin. Nature 440: 520-523.

Soares Filho, B., D. C. Nepstad, L. M. Curran, G. C. Cerqueira, R. A. Garcia, C. A. Ramos, E. Voll, A. McDonald, P. Lefebvre and P. Schlesinger 2006. Modelling conservation in the Amazon basin. Nature 440: 520-523.

Soares Filho, Britaldo, A. Alencar, D. Nepstad, G. Cerqueira, M. D. V. Diaz, S. Rivero, L. Solorzano and E. Voll 2004. Simulating the response of land-cover changes to road paving and governance along a major Amazon highway: the Santarem-Cuiaba corridor. Global Change Biology 10: 745-764.
Soares Filho, Britaldo, R. M. Assuncao and A. E. Pantuzzo 2001. Modeling the spatial transition probabilities of landscape dynamics in an amazonian colonization frontier. Bioscience 51: 1059-1067.
Soler, L. de S. 2011. Land use and land cover dynamics in the Brazilian Amazon: understanding human-environmental interactions. In Land use and land cover dynamics in the Brazilian Amazon: understanding human-environmental interactions, Association of American Geographer - Annual Meeting. Seattle, Washington: AAG.
Soler, L. de S., M.I.S. Escada and P. H. Verburg 2009. Quantifying deforestation and secondary forest determinants for different spatial extents in an Amazonian colonization frontier (Rondonia). Applied Geography 29: 182-193 doi: 10.1016/j.apgeog.2008.09.005
Soler, L. de S., P. Verburg, Gilberto Câmara and A. Veldkamp 2007. Statistical analysis and feedback exploration of land use change determinants at local scale in the Brazilian Amazon. In Statistical analysis and feedback exploration of land use change determinants at local scale in the Brazilian Amazon, International Geoscience and Remote Sensing Symposium (IGARSS 2007), 3462 – 3465. Barcelona, Spain: IEEE.
Soler, L. de S. and P.H. Verburg 2010. Combining remote sensing and household level data for regional scale analysis of land cover change in the Brazilian Amazon. Regional Environmental Change 10: 371-386.
Sombroek, W. 2001. Spatial and temporal patterns of Amazon rainfall - Consequences for the planning of agricultural occupation and the protection of primary forests. Ambio 30: 388-396.
Southworth, F., V. H. Dale and R. V. Oneill 1991. Contrasting patterns of land-use in Rondonia, Brazil - simulating the effects on carbon release. International Social Science Journal 43: 681-698.
Souza Jr., C. and A. Verissimo 2007. Boletim transparência florestal. In Boletim transparência florestal, 5. Estado do Pará: IMAZON.
Sunderlin, William D. and Jacques Pokam 2002. Economic Crisis and Forest Cover Change in Cameroon: The Roles of Migration, Crop Diversification, and Gender Division of Labor. Economic Development and Cultural Change 50: 581-606.
Tardin, A.T., D.C.L. Lee, R.J.R. Santos, O.R. Assis, M.P.S. Barbosa, M.T. Moreira, D. Silva and C.P. Santos Filho 1980. Subprojeto desmatamento. Convênio IBDF/CNPq - INPE. In Subprojeto desmatamento. Convênio IBDF/CNPq - INPE, ed. INPE. São José dos Campos: National Institute for Space Research (INPE).
Turner, F. J. 1893. The Significance of the Frontier in American History. In The Significance of the Frontier in American History, ed. American Historical Association, Annual report: American Historical Association.
Turner II, B. L., Emilio F. Moran and R.R. Rindfuss 2004. Integrated land-change science and its relevance to the human sciences. In Land change science. Observing, monitoring and understanding trajectories of change on the earth's surface, eds. Garik Gutman, Anthony C. Janetos, Christopher O. Justice, Emilio F. Moran and John F. Mustard, 431-447. Dorcrecht/London: Kluwer Academic Publishers.

Veiga, J. B. da , M. G. Piketty, J. F. Tourrand, A. M. Alves, R. Poccard-Chapuis and M. Thales 2005. Determinantes da expansão da pecuaria na Amazônia Oriental: Conseqüências para as politicas publicas. In Determinantes da expansão da pecuaria na Amazônia Oriental: Conseqüências para as politicas publicas., ed. Embrapa Amazônia Oriental, Cadernos de Ciência e Tecnologia, 221-234. Brasília: Embrapa.
Veiga, J. B. da, J. F. Tourrand, M. G. Piketty, R. Poccard-Chapuis, A. M. Alves and M. Thales 2004. Expansão e trajetórias da pecuaria na Amazônia: Pará, Brasil. In Expansão e trajetórias da pecuaria na Amazônia: Pará, Brasil., ed. Editora Universidade de Brasília. Brasília: Universidade de Brasília.
Veldkamp, A. and L. O. Fresco 1996a. CLUE-CR: An integrated multi-scale model to simulate land use change scenarios in Costa Rica. Ecological Modelling 91: 231-248.
Veldkamp, A. and L. O. Fresco 1996b. CLUE: A conceptual model to study the conversion of land use and its effects. Ecological Modelling 85: 253-270.
Veldkamp, A. and L. O. Fresco 1997. Exploring land use scenarios, an alternative approach based on actual land use. Agricultural Systems 55: 1-17.
Veldkamp, A., K. Kok, G. H. J. De Koning, J. M. Schoorl, M.P.W. Sonnenveld and P. H. Verburg 2001a. Multi-Scale system approaches in agronomic research at the landscape level. Soil And Tillage Research 58: 129-140.
Veldkamp, A. and P. H. Verburg 2004. Modelling land use change and environmental impact. Journal of Environmental Management 72: 1-3.
Veldkamp, A., P. H. Verburg, K. Kok, G. H. J. de Koning, J. Priess and A. R. Bergsma 2001b. The need for scale sensitive approaches in spatially explicit land use change modeling. Environmental Modeling & Assessment 6: 111-121.
Velho, Otávio Guilherme 1976. Capitalismo autoritário e campesinato. São Paulo: DIFEL.
Verburg, Peter H. 2006. Simulating feedbacks in land use and land cover change model. Landscape Ecology 21: 1171-1183.
Verburg, Peter H., Kasper Kok, Robert Gilmore Pontius Jr. and A. Veldkamp 2006. Modeling land-use and land-cover change. In Land-use and land-cover change: local processes and global impacts, eds. E. F. Lambin and H. Geist, 222. Berlin: Springer.
Verburg, Peter H., Koen P. Overmars and Nol Witte 2004. Accessibility and land-use patterns at the forest fringe in the northeastern part of the Philippines. The Geographical Journal 170: 238-255. doi: doi:10.1111/j.0016-7398.2004.00123.x
Verburg, Peter H. and A. Veldkamp 2004. Projecting land use transitions at forest fringes in the Philippines at two spatial scales. Landscape Ecology 19: 77-98.
Vliet, M., Kasper Kok and A. Veldkamp 2010. Linking stakeholders and modellers in scenario studies; the use of Fuzzy Cognitive Maps as a communication and learning tool. Futures 42: 1-14.
Vosti, S. A., J. Witcover and C. L. Carpentier 2002. Agricultural Intensification by small-holders in the western Brazilian Amazon: from deforestation to sustainable land use. In Agricultural Intensification by small-holders in the western Brazilian Amazon: from deforestation to sustainable land use, Research report, 135. Washington, DC: International Food Policy Research Institute.
Walker, R., S. A. Drzyzga, Y. L. Li, J. G. Qi, M. Caldas, E. Arima and D. Vergara 2004. A behavioral model of landscape change in the Amazon Basin: The colonist case. Ecological Applications 14: S299-S312.

Walker, R., N.J. Moore, E. Arima, S. Perz, C. Simmons, M. Caldas, D. Vergara and C. Bohrer 2009. Protecting the Amazon with protected areas. Proceedings of the National Academy of Sciences: 10582-10586.
Walker, R., E. F. Moran and L. Anselin 2000. Deforestation and cattle ranching in the Brazilian Amazon: external capital and household processes. World Development 28: 683-699.
Walker, R., S. Perz, M. Caldas and L. G. T. Silva 2002. Land use and land cover change in forest frontiers: The role of household life cycles. International Regional Science Review 25: 169-199.
Walsh, S. J., T. P. Evans, W. F. Welsh, B. Entwisle and R. R. Rindfuss 1999. Scale-dependent relationships between population and environment in northeastern Thailand. Photogrammetric Engineering and Remote Sensing 65: 97-105.
Werth, D. and R. Avissar 2004. The regional evapotranspiration of the Amazon. Journal of Hydrometeorology 5: 100-109.
Witcover, J., S. A. Vosti, C. L. Carpentier and T. C. D. A. Gomes 2006. Impacts of soil quality differences on deforestation, use of cleared land, and farm income. Environment and Development Economics 11: 343-370.

Summary

The Amazon forest is the world's most important hot spot of deforestation that can compromise environmental services for both regional and global population. Three main points of view characterize the scientific efforts in studying the environmental and human aspects of the Brazilian Amazon. First, there is the concern on how deforestation affects the regulation of biogeochemical, water and climatic cycles. Second, sociological and anthropological studies have shown the importance in understanding how forest conservation is related to cultural and ethnical diversity, and how forest conversion can be explained by socioeconomic issues and human occupation hierarchies. Finally, there is the investigation of viable and rather sustainable land use practices engaged to keep Amazonian ecosystems resilient to changes, which is the context of this thesis.

Land use and land cover dynamics are considered a result of the interactions between human activities and the environment. Feedback mechanisms of land use/cover are a particular type of interaction that can be relevant to the investigation of sustainable land use practices. In this thesis, Rondônia and Mato Grosso states, located in the deforestation frontier of the Brazilian Amazon, were selected as case study to investigate such mechanisms. The relevance of studying the role of feedback mechanisms in the Amazonian deforestation frontier lies in the fact that the standing forests pose a number of constraints to economic development, but at the same time provide the ideal configuration for sustainable practices of land occupation, depending mostly on past and present policy history. A combination of empirical statistical models (representing state-of-the-art in spatial modeling) with fuzzy cognitive methods (developed from social studies) was used. This proposed combination can help us to cognitively understand feedback loops within local population and land cover changes considering current and historical socioeconomic aspects, land distribution issues and biophysical terrain conditions. Thus, the main objective of this thesis is to analyze Amazonian land use and land cover pattern dynamics in order to identify the underlying system dynamics. By combining static and dynamic methodologies, system feedbacks within this non-linear human-environmental system can be explored for more sustainable development pathways.

Land use and land cover modeling is a powerful learning tool for policy making. However, limitations in modeling feedbacks due to computational problems are enhanced by the conceptual difficulties to equalize approaches from modelers and social scientists in describing land use/cover change. To face these issues, the methodology adopted links empirical models based on statistical analysis to fuzzy cognitive methods. It is motivated by the fact that human's response to changes are rather subjective and, therefore, require new frameworks that tackle this subjectivity and can still be robust and reproducible by spatial modelers. This combination of methods can help land scientists to cognitively understand feedback loops within local population and land cover changes considering current and historical socioeconomic aspects, land distribution issues and biophysical terrain conditions.

The thesis is organized in six chapters. Chapter 1 gives an overall introduction of the relevance and subject of this thesis, while the discussion presented in Chapter 6 aims to synthesize and link in a single framework the different outcomes of articles presented in Chapters 2 to 5, which are the foundation of this work. Together the chapters allow us to discuss human-environmental interactions that may prevent deforestation and enhance sustainable land use practices in the Brazilian Amazon, both at local and regional scale.

In Chapter 2, deforestation and secondary forest patterns are statistically modeled at the local scale while in Chapter 3 surveys at the household level are compared to remote sensing data stratified according to zoning areas at the regional scale, but both methods take into account the land use planning in Rondônia state, in the south-western part of the Brazilian Amazon. In Chapter 2, the main drivers of deforestation and secondary forest are quantified at the local scale. At this scale, distinct characteristics of agrarian projects are adopted based on their different periods of establishment in two municipalities, Vale do Anari and Machadinho d´Oeste. Drivers of change are quantified using an exploratory analysis based on land cover maps retrieved from remote sensing data, as well as spatial data from several sources regarding biophysical and socioeconomic characteristics, accessibility measures and public policies of forest conservation. In Chapter 3, deforestation patterns and processes are analyzed by using multi-temporal remote sensing data at the regional scale (to build land cover maps), and household level data organized in questionnaires applied to farmers from 30 municipalities in the northeast of Rondônia.

Since the statistical models obtained from Chapter 2 and Chapter 3 are built at local and regional scales respectively, they are analyzed together to analyze whether key drivers of land cover change at the local scale have similar or divergent influence at the regional scale. Results from Chapter 2 show that secondary forest is determined by high soil fertility and steep areas in young settlements at local and regional spatial scales, although soil influence is less pronounced at local scale. Results from Chapter 3 show that land use planning history and property size are key variables to capture the importance of socioeconomic differentiation, also they indicate that land distribution issues are connected to deforestation at the regional scale. Results from both Chapters 2 and 3 indicate that soil fertility and slope determine the scarcity of forest assets in older settlements. Accessibility to facilities and infrastructure do not show significant changes over spatial scales, but rather over time being highly determined by land use planning. Biophysical and accessibility drivers act similarly over spatial scales, and also over time considering the three years analyzed (1996, 2000 and 2006).

In Chapter 4, the central theme is the investigation of the interactions between market chain dynamics and the evolution of land systems. By identifying land use changes in relation to the land distribution structure, we infer different levels of agricultural intensification that could drive favorable scenarios for family farming and/or agro-industrial systems. The results indicate that land use intensification among medium to large farms are due to demand for beef and soybean, accessibility to markets, machinery and labor force concentration. Among small farms, land use intensification is mainly driven by stocking rates, accessibility and demand from milk markets. Milk and beef demands have influenced infrastructure improvement, with indications of a vertical integration of milk markets, which requires market regulation and land use policies to guarantee sustainable land use practices. Despite sharing the same natural resources, the existing socioeconomic system provides unbalanced benefits, once small farms sizes depend on land use systems that can succeed to sustainable alternative trajectories or do not fail due to land degradation. The lack of land management together with poorly-driven investments can explain the failure of usual pasture after slash-and-burn land systems among small farms in less fertile spots. The influence of land speculation by large landholders seems also to be a determinant of such failure.

In Chapter 5, the method of Fuzzy Cognitive Maps (FCMs) is used as an innovative approach to reveal relevant feedback loops by exploring identified human-environmental interactions. The chapter aims to study feedback mechanisms by constructing FCMs based on spatial data and expert knowledge, which allows a semi-quantification of hard and soft interactions in alternative development scenarios. Spatial databases at local/regional scales described in Chapters 2 and 3, literature review and insights from fieldwork interviews are taken as the starting point for the development of FCMs. A sensitive analysis of the outputs of the resulting FCMs is done based on empirical knowledge of renowned researchers in land cover change in the Brazilian Amazon. The resulting FCM based on spatially explicit data was proved to be useful to explore land cover change scenarios and to compare them to scenarios developed from spatial models. Feedbacks between deforestation, land prices and dry season severity showed coherent responses in the sensitivity analysis. However, the important feedback between accessibility and land prices was undervalued due to poor data quality and spatial autocorrelation. The results support the argument that by incorporating the proposed method to spatially explicit models, the consistency between demand and spatial allocation can be endorsed. In addition, this might prevent the potential incongruence of considering divergent realities from stakeholders or too different backgrounds given by experts' consensus.

Finally, in Chapter 6 I explore how relevant feedback loops can be reinforced by public policies in order to improve the sustainability of both land use systems and the living conditions in the region. Interactions were particularly analyzed to identify relevant feedback loops that can be reinforced by such policies and possibly improve sustainability of land use systems. A list of relevant feedback loops of land use/cover change is given according to the spatial scale and spatial extent of data adopted to build the FCMs. Feedback loops within accessibility, deforestation and secondary forest patterns determine changes in old and new settlements at both spatial scales. Feedback loops among land use/cover change, accessibility, land prices, labor availability and machinery reflect land occupation differences between Rondônia and Mato Grosso, politically constrained by land markets. Concluding, I discuss the utility of feedbacks to support sustainable land systems, and how associated lessons learned can be used to indicate successful sustainable alternatives.

Overall, this thesis shows that statistical and cognitive methods can, together, provide better insight in the human-environmental interactions enclosing aspects of socioeconomic development, historical land distribution issues, land use intensification and sustainability of land use systems. Feedback loops that reinforce secondary forest growth and/or revenue from perennial crops can lead to a sustainable human-environment system in the Brazilian Amazon, but policies such as PES (Payment for Ecosystems Services) and REDD (Reducing Emissions from Deforestation and Forest Degradation) must be enforced. On the other hand, the feedback loops within dry season severity, fires and especially land prices can reduce deforestation if land market regulations and the Forestry Code are enforced especially among large farms. These results lead to a key conclusion that policy effectiveness of sustainable land use practices can be evaluated by analyzing the feedbacks identified with the FCM methodology. In summary, this thesis shows that there is added value in analyzing land system changes in the Brazilian Amazon by accounting for the processes operating across different scales and that the insights obtained at different scales and with different methods can be combined in a single framework that allows an integrated view of human-environmental interactions.

The research described in this thesis was financially supported by the Foundation for the Advancement of Tropical Research (WOTRO) of the Netherlands Organization for Scientific Research (NWO). It was conducted as part of the integrated project called “Vulnerability and resilience of the Brazilian Amazon forests and human environment to changes in land use and climate”, funded by WOTRO/NWO that ran from 2005 to 2010 and was supported by the Soil Geography and Land Dynamics Group at Wageningen University, Alterra Institute, VU University Amsterdam and the Brazilian National Institute for Space Research (INPE).

Samenvatting

Het Amazoneregenwoud is ’s werelds grootste hot-spot van ontbossing, wat ecosysteemdiensten voor zowel de regionale als de mondiale bevolking in gevaar kan brengen. Wetenschappelijk onderzoek gerelateerd aan het bestuderen van de menselijke en milieuaspecten van het Braziliaanse Amazonegebied heeft drie belangrijke kenmerken. Ten eerste is er de zorg over hoe ontbossing de regulering van biogeochemische, water- en klimaatcycli beïnvloedt. Ten tweede hebben sociologische en antropologische studies het belang aangetoond van een beter begrip van de relatie tussen het behoud van bos en culturele en etnische diversiteit, en hoe ontbossing verklaard kan worden door sociaaleconomische vraagstukken en menselijke bewoning. Ten slotte is er onderzoek naar praktisch uitvoerbaar en duurzaam landgebruik, wat nauw gerelateerd is aan het veerkrachtig houden van ecosystemen in het Amazonegebied. Dit is de context van dit proefschrift.

De dynamiek van landgebruik en landbedekking wordt gezien als een gevolg van de interacties tussen menselijke activiteiten en omgevingsfactoren. Terugkoppelingsmechanismen van landgebruik en landbedekking zijn een bijzondere vorm van zo’n interactie die voor het onderzoek naar duurzaam landgebruik relevant kunnen zijn. In dit proefschrift zijn Rondônia en Mato Grosso geselecteerd als studiegebieden om dergelijke mechanismen te onderzoeken omdat het ontbossingsfront door deze staten in de Braziliaanse Amazone heen loopt. Het belang van het bestuderen van de rol van terugkoppelingsmechanismen in de frontlijn van ontbossing ligt in het feit dat de bestaande bossen een beperking zijn voor economische ontwikkeling, maar tegelijkertijd de ideale configuratie bieden voor duurzame landontwikkeling. Er is gebruik gemaakt van een combinatie van empirische statistische modellen (die de meest actuele ruimtelijke modellering vertegenwoordigen) en ‘fuzzy’ cognitieve methoden (ontwikkeld op basis van sociale studies). De voorgestelde combinatie kan helpen om terugkoppelingslussen tussen de lokale bevolking en veranderingen in landgebruik en landbedekking beter te begrijpen Hierbij is gebruik gemaakt van de huidige en historische sociaaleconomische factoren, landverdelingskwesties en biofysische omstandigheden. De belangrijkste doelstelling van dit proefschrift is om patronen van veranderingen in landgebruik en landbedekking in de

Amazone te analyseren om zo de dynamiek van het onderliggende systeem te kunnen identificeren. Door de combinatie van statische en dynamische methoden, kunnen terugkoppelingen worden verkend in dit niet-lineaire sociaalecologische systeem ten behoeve van de ontwikkeling van duurzame ontwikkelings trajecten.

Het modelleren van landgebruik en landbedekking is een krachtig leermiddel, ook in relatie tot beleidsvorming. Echter, de beperkingen in het modelleren van terugkoppelingen vanwege problemen met rekencapaciteit worden versterkt door de conceptuele moeilijkheden om benaderingen van modelleurs en sociale wetenschappers in het beschrijven van veranderingen van landgebruik/bedekking te verenigen. Om deze problemen aan te pakken, is een methodologie gevolgd die empirische modellen op basis van statistische analyses verbindt aan fuzzy cognitieve methoden. Dit wordt ingegeven door het feit dat de menselijke reacties op veranderingen deels subjectief zijn en daarom nieuwe kaders vereisen die deze subjectiviteit aan kunnen pakken, zodanig dat onderzoek gedaan door ruimtelijke modelleurs robuust en reproduceerbaar blijft. Deze combinatie van methoden kan helpen om terugkoppelingslussen tussen de lokale bevolking en landgebruikveranderingen beter te begrijpen, uitgaande van de huidige en historische sociaaleconomische factoren, landverdelingskwesties en biofysische omstandigheden.

Dit proefschrift is verdeeld in zes hoofdstukken. Hoofdstuk 1 geeft een algemene introductie van het belang en het onderwerp van dit proefschrift, terwijl de discussie in Hoofdstuk 6 is bedoeld als synthese en als presentatie van een overkoepeld raamwerk met de verschillende uitkomsten gepresenteerd in Hoofdstukken 2 tot en met 5, die de basis van het proefschrift vormen. Alle hoofdstukken samen geven ons de mogelijkheid om de interacties tussen mens en milieu die ontbossing kunnen voorkomen en duurzaam landgebruik in de Braziliaanse Amazone kunnen versterken te bespreken, zowel op lokaal als op regionaal niveau.

In Hoofdstuk 2 worden patronen van ontbossing en secundaire bossen statistisch gemodelleerd op lokale schaal, terwijl in Hoofdstuk 3 huishoudonderzoek wordt vergeleken met remote sensing data op regionale schaal. Beide methoden houden rekening met landgebruiksplannen in de deelstaat Rondônia, in het zuidwestelijke deel van het Braziliaanse Amazonegebied. In Hoofdstuk 2 worden de belangrijkste drijvende krachten achter ontbossing en secundaire bossen gekwantificeerd op lokale schaal. Op deze schaal zijn specifieke ruimtelijke begrenzingen gekozen gerelateerd aan karakteristieken van agrarische projecten die in verschillende periodes zijn gestart in twee gemeentes, Vale do Anari en Machadinho d'Oeste. Drijvende krachten van landgebruikveranderingen worden gekwantificeerd aan de hand van een verkennende analyse op basis van de landbedekkingskaarten gebaseerd op remote sensing data. Hierbij wordt ook gebruik gemaakt van ruimtelijke gegevens uit verschillende andere bronnen met betrekking tot biofysische en socio-economische kenmerken, maten van bereikbaarheid, en overheidsbeleid op het gebied van bosconservering. In Hoofdstuk 3 worden patronen en processen van ontbossing geanalyseerd door het gebruik van multi-temporele remote sensing beelden op regionale schaal (om een landbedekkingskaart te maken) en gegevens op huishoudniveau verkregen uit vragenlijsten voorgelegd aan boeren uit 30 gemeenten in het noordoosten van Rondônia.

Aangezien de statistische modellen verkregen uit de Hoofdstukken 2 en 3 zijn ontwikkeld voor respectievelijk de lokale en de regionale schaal, worden ze samen geanalyseerd om vast te stellen of de belangrijkste drijvende krachten van landbedekkingsverandering op lokale schaal een gelijkwaardige of verschillende invloed hebben op de regionale schaal. Resultaten uit Hoofdstuk 2 laten zien dat aanwezigheid van secundair bos wordt bepaald door hoge bodemvruchtbaarheid en steile gebieden in jonge nederzettingen op zowel lokale als regionale schaal, met een minder uitgesproken invloed van de bodem op lokale schaal. Resultaten uit Hoofdstuk 3 laten zien dat de geschiedenis van ruimtelijke planning en grootte van de boerderij belangrijke variabelen zijn om het belang van sociaaleconomische differentiatie vast te stellen. Ook geven de resultaten aan dat er een verband is tussen problemen met verdeling van stukken grond en ontbossing op regionale schaal. De resultaten van zowel Hoofdstuk 2 als 3 geven aan dat bodemvruchtbaarheid en reliëf de schaarste van bos in oudere nederzettingen bepalen. Toegang tot faciliteiten en infrastructuur laten geen significante veranderingen over ruimtelijke schalen zien, maar wel over temporele schalen, waar veranderingen in sterke mate worden bepaald door ruimtelijke ordening. Drijvende krachten gerelateerd aan biofysische factoren en toegankelijkheid hebben dezelfde invloed over de verschillende ruimtelijke en temporele schalen in de drie onderzochte jaren (1996, 2000 en 2006).

In Hoofdstuk 4 is het onderzoek naar de interacties tussen de dynamiek van de afzetketen en de ontwikkeling van landsystemen het centrale thema. Door landgebruiksveranderingen in relatie tot de structuur van landdistributie te identificeren, konden we verschillende niveaus van intensivering van de landbouw vaststellen die het uitgangspunt zouden kunnen zijn voor gunstige scenario's voor de familiale landbouw en/of agro-industriële systemen. De resultaten geven aan dat de intensivering van landgebruik bij middelgrote tot grote bedrijven het gevolg is van een groeiende vraag naar rundvlees en soja, en een toenemende toegankelijkheid van markten en tot machines, en een concentratie van arbeidskrachten. Bij kleine boerderijen wordt intensivering van landgebruik vooral gedreven door de veebezetting, bereikbaarheid en de vraag vanuit de markt voor melk. De vraag naar melk en rundvlees hebben de verbetering van de infrastructuur beïnvloed, met aanwijzingen dat dit ook geleid heeft tot een verticale integratie van markten voor melk. Dit laatste maakt marktregulering en landgebruiksbeleid noodzakelijk om zo ook duurzaam landgebruik te garanderen. Ondanks dat natuurlijke hulpbronnen worden gedeeld, biedt het bestaande sociaaleconomische systeem onevenwichtige voordelen. Succes van kleine boeren is afhankelijk van systemen van landgebruik die kunnen slagen door het volgen van duurzame alternatieve trajecten of die niet kunnen mislukken door landdegradatie. Het gebrek aan landbeheer samen met slechte investeringen kan het mislukken van de poging om productieve graslanden te behouden verklaren. Dit is vooral een probleem voor kleine boeren die gebruik maken van de techniek van kappen en branden (“slash-and-burn”) op minder vruchtbare plekken. De invloed van landspeculatie door grootgrondbezitters lijkt ook een belangrijke factor in relatie tot deze mislukking.

In Hoofdstuk 5 wordt de zogeheten “Fuzzy Cognitive Maps” methode (Fuzzy Cognitieve Diagrammen; FCM's) gebruikt als een innovatieve benadering om relevante terugkoppelingslussen aan het licht te brengen door het verkennen van interacties tussen mens en natuur. Doel van dit hoofdstuk is terugkoppelingsmechanismen te bestuderen door FCM’s te construeren op basis van harde ruimtelijke gegevens en ‘zachtere’ kennis van experts. Dit maakt een semi-kwantificering van interacties mogelijk, ook onder verschillende ontwikkelingsscenario's. Ruimtelijke databases op lokale/regionale schaal zoals in de Hoofdstukken 2 en 3 beschreven, een literatuurstudie, en inzichten uit veldwerk-interviews vormden het uitgangspunt voor de ontwikkeling van FCM's. Een gevoeligheidsanalyse van de uitkomsten van de resulterende FCM’s is uitgevoerd op basis van empirische kennis van gerenommeerde onderzoekers naar landbedekkingsverandering in het Braziliaanse Amazonegebied. De resulterende FCM gebaseerd op ruimtelijk expliciete gegevens bleken nuttig om scenario’s van landbedekkingsverandering te verkennen en ze te vergelijken met scenario's ontwikkeld op basis van ruimtelijke modellen. Terugkoppelingen tussen ontbossing, grondprijzen en de mate van droogte tijdens het droge seizoen waren consistent belangrijk tijdens de gevoeligheidsanalyse. Echter, de belangrijke terugkoppeling tussen bereikbaarheid en grondprijzen werd onderschat vanwege de lage kwaliteit van de gegevens en vanwege een hoge ruimtelijke autocorrelatie. De resultaten ondersteunen het argument dat door het opnemen van FCM's in ruimtelijk expliciete modellen, de samenhang tussen de vraag naar landbouwproducten en de ruimtelijke verdeling daarvan kan worden verbeterd. Bovendien zou dit mogelijke problemen kunnen voorkomen bij het in ogenschouw nemen van uiteenlopende perspectieven van verschillende belanghebbenden en/of experts.

Tenslotte ga ik in Hoofdstuk 6 na hoe relevante terugkoppelingslussen kunnen worden versterkt door overheidsbeleid te richten op het verbeteren van de duurzaamheid van zowel landgebruiksystemen als de levensomstandigheden in de regio. Een lijst met relevante terugkoppelingslussen van verandering van landgebruik/bedekking werd vastgesteld op basis van de ruimtelijke schaal en het ruimtelijk bereik van de gebruikte gegevens om de FCM’s te bouwen. Terugkoppelingslussen tussen bereikbaarheid, ontbossing, en patronen van secundaire bossen bepalen veranderingen in oude en nieuwe nederzettingen op beide ruimtelijke schalen. Terugkoppelingslussen tussen verandering van landgebruik/bedekking, bereikbaarheid, grondprijzen, en beschikbaarheid van arbeid en machines weerspiegelen verschillen in landbewoning tussen Rondônia en Mato Grosso, wat verder beperkt wordt door het grondmarktenbeleid. Afsluitend bespreek ik het nut van onderzoek naar terugkoppelingen om ontwikkeling van duurzame landsystemen te ondersteunen, en hoe de opgedane ervaringen kunnen worden gebruikt om succesvolle duurzame alternatieven te verkennen.

Kortom, dit proefschrift laat zien dat statistische en cognitieve methoden samen kunnen zorgen voor een beter inzicht in de interacties tussen mens en milieu, inclusief aspecten van sociaaleconomische ontwikkelingen, historische land verdelingsvraagstukken, landgebruik-intensivering, en duurzaamheid van landgebruiksystemen. Terugkoppelingslussen die de groei van secundair bos en/of de inkomsten uit meerjarige gewassen versterken kunnen leiden tot een duurzaam sociaalecologisch systeem in het Braziliaanse Amazonegebied, maar beleid, zoals PES (betaling voor ecosysteemdiensten) en REDD (vermindering van broeikasgasemissies als gevolg van ontbossing en bosdegradatie), moet worden afgedwongen. Aan de andere kant, de terugkoppelingslussen tussen de mate van droogte tijdens het droge seizoen, branden, en vooral de grondprijzen kan ontbossing verminderen als regelgeving van grondmarkten en de boswetgeving worden afgedwongen, vooral voor grote bedrijven.

Deze resultaten leiden tot de belangrijke conclusie dat de doeltreffendheid van het beleid gerelateerd aan duurzaam landgebruik kan worden geëvalueerd door het analyseren van de terugkoppelingen geïdentificeerd door gebruik van de FCM methodologie. Samenvattend laat dit proefschrift zien dat er een toegevoegde waarde is in het analyseren van veranderingen in het landsysteem in het Braziliaanse Amazonegebied door rekening te houden met processen die op verschillende schalen opereren. De resultaten verkregen op verschillende schalen en met verschillende methoden kunnen worden gecombineerd in één enkel kader dat het mogelijk maakt om een geïntegreerde visie te geven op de interacties tussen mens en milieu.

Citation and dedicatory

“A culture is no better than its woods”
W.H. Auden

“Indeed, the only truly serious questions are ones that even a child can formulate. Only the most naive of questions are truly serious. They are the questions with no answers. A question with no answer is a barrier that cannot be breached. In other words, it is questions with no answers that set the limits of human existence.”
Milan Kundera, [In] The unbearable lightness of being

“…all my destinations will accept the one that’s me so I can breathe (…)
A mind full of questions and a teacher in my soul and so it goes (…)
Holding me like gravity are places that pull
If ever there was someone to keep me at home it would be you…
I know all the rules, but the rules do not know me ”
E. Vedder

A meus pais, aos mestres memoráveis e aos amigos verdadeiros, a quem devo tudo que sou e tudo o que sei. Obrigada por iluminarem meu caminho e sempre me fortalecerem na luta pelos homens que cuidam da Terra.

To my parents, my memorable teachers and my true friends… to whom I owe what I´ve become and everything I´ve learned. Thank you all for brighten my way and for supporting my struggle for people who care for the Earth.

†Em memória de meus avós Alzira, Franço, Chico e Irene, que apesar das agruras de suas vidas sempre me mostraram motivos para continuar.†Em memória de Orlando Guedes e Neuza Motta, que nos alegraram com sua espontaneidade, e do herói Breitner Bender que será sempre um menino em nossas lembranças..***pois só se vive por um triz***!

Acknowledgments

I would like to thank my promotors Tom Veldkamp and Peter Verburg as well as my co-promotor Kasper Kok for their research support, for sharing their experience and ideas, but mostly for their patience and trust on my personal development as a PhD student.

Thanks to Diógenes Alves for sharing his wise thoughts and relevant knowledge during the fieldwork campaign of 2008, for co-authoring the article in which Chapter 4 is based and mostly for his friendship and consideration. A thanks also goes to my Brazilian supervisor Gilberto Câmara for his constructive ideas and for research, institutional and personal support. Thanks to Isabel Escada for her ideas while co-authoring the article in which Chapter 2 is based, and sharp opinion that even tough to handle, they helped me to see things different in both my personal and professional life.

Special thanks to Bart Kruijt, coordinator of the Amazonian Resilience integrated project, for his constant support and trust.

Thanks to Ana Paula Dutra Aguiar, Tiago Carneiro, Emilio Moran, José Simeão Medeiros, Eraldo Matricardi, Dalton Valeriano, Roberto Araújo, Ângelo Mansur, Mateus Batistella, Gustavo Valladares, Ênio Fraga, Pedro de Andrade, Arnaldo Carneiro, João Roberto dos Santos and Cláudio Almeida for sharing ideas, information and knowledge.

Agradecimento especial ao técnico do INCRA Wilson Pagani (Longarina), por compartilhar seu imenso conhecimento nos processos de uso e ocupação da terra na Amazônia, por sua bravura, apoio, sugestões e constante bom humor durante as missões de campo em Rondônia e Mato Grosso.

Gostaria também de agradecer em especial a todas as famílias entrevistadas, pela hospitalidade e pelo carinho durante a pesquisa de campo, e principalmente pelas informações compartilhadas fundamentais para a realização dessa tese.

Also, I would like to show my appreciation to a number of Brazilian institutes and governmental organizations whose technicians and researchers made their database available, and without which this research could never be done, to mention: Instituto Nacional de Pesquisas Espacias (INPE) Secretaria de Desenvolvimento Ambiental de Rondônia (SEDAM/RO), Companhia Brasileira de Recursos Minerais (CPRM), Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA), Instituto Nacional de Colonização e Reforma Agrária (INCRA), Instituto Nacional de Geografia de Estatística (IBGE) and Associação de Assistencia Tecnica e Extensão Rural do Estado de Rondônia (EMATER-RO).

Thanks to Dr. Claudius van de Vijver and all collaborators from Production Ecology & Resource Conservation Graduation School, as well as to the most efficient secretaries of SGL Group: Henny van den Berg and Mieke Hannink as well as to Luciana Moreira from DPI-INPE. You were all crucial to the proper development of my PhD research.

Thanks to Fabrício Zanchi and Rita von Randow, my fellows on the PhD journey, for their friendship and for taking the lead in the toughest fieldwork campaigns of the Amazonian Resilience integrated project.

Also, I would like to thank to important colleagues and friends who somehow supported my PhD project to mention Corina da Costa Freitas, Sidnei Sant'Anna, João Vassallo, Fernando Pellon de Miranda, Liana Anderson, Félix Carrielo, Isabel Vega, Luciana Spinelli, Marcos Pereira (grande Marquito!), Camille Nolasco, also to Cláudio Couto for being the person who was the first to tell me to go ahead with this project . For all of you, among many others from Brazil and abroad, who helped me somehow in achieving my goals my big thanks.

To my PhD fellows from SGL Group specially to my officemates and good friends (in temporal order) Alejandra Vallejo and Arnaud Temme (Mr. President and the first lady!), José Alvarez , Nicia Giva, Eke Buis, Koen Overmars, Kathleen Neumann, Diego Valbuena and last, but definitely not least, to my ‘corner office’ mates Wouter van Gorp (Mr. DJ) and Monique Gulickx (Sport Spicy)! The time spent with you guys is unforgettable! Thank you for the friendship, countless laughs as well as creative and thoughtful ideas.

I would like to express my gratefulness to my friends Saulo Alves, Vanja Viana, Vicky Maaskant, Vassilis Pagmantidis, Glaciela Kaschuk, Odair Alberton, Michael Daamen, Celso von Randow, Vânia de Souza, Flávia Talarico, Érica Duarte, Danuta Chmielewska, Lucia Yanez, Monica Hernandez, Lilian Lima, Haíssa Cardelli, Dulce da Silva, Priscilla Sabadin and many others with whom I shared blissful moments during my stay in Wageningen.

Special thank goes to my unique group of friends Cath, Mo, Mr. DJ and Erez the great!! You’ve made my days in Wageningen much warmer, funnier, crazier and very anarchical!!!! Thanks for the nihilist discussions and for sharing some wonderful wine, beers, cheese, apple pies, Brazilian/Dutch/Swiss food, barbecues, music, dancing, seeding and harvesting of delicious vegetables! You will always have a home in my heart and in my country!

Many special credits go to my eternal friends Valquíria Oliveira, Natasha Andrade, Claire Thienpont, Catherine Pfeifer, Monique Gulickx, Fernanda Ledo and Alessandra Gomes who have always supported me unconditionally. Thanks for your friendship that goes beyond our lifetime.

Por fim, gostaria de agradecer à minha família, meus pais Nelson e Terezinha, meu irmão Wilson e sua família linda, minhas queridas primas Bel, Lalá, Cris e a tia Dó pelo apoio e constante torcida, pela compreensão, e por me fortalecerem com suas mensagens sempre divertidas que ajudaram a encurtar a enorme distância de um oceano inteiro. Agradeço ao meu amor Manoel Cardoso, por sempre me apoiar, pela paciência, compreensão, conhecimentos divididos, relevantes sugestões e principalmente por suportar minha angústia na etapa final deste trabalho.

Agradeço às forças que regem nosso Universo por esta benção e privilégio de me tornar PhD após tantas dúvidas e desvios ao longo do caminho!

Curriculum Vitae

Luciana de Souza Soler was born on January 14, 1976 in Guaratinguetá, São Paulo. Since 1994, when she initiated her Bachelor in Physics, she has focused her research in nature conservation particularly in land use practices in Pantanal ecosystem. In 2000, she finished her M.Sc. on Remote Sensing at the National Institute for Space Research (INPE). During her Master her research contribution was centered on radar (SAR) images processing and classification applied to offshore pollution monitoring along the Brazilian Coast in Campos Basin. From 2002 to 2004, she worked for the University of Rio de Janeiro as part of a World Bank project to support operational actions of the Brazilian Petroleum Agency and the Brazilian Navy in oils spill surveillance along the Brazilian coast. However, inherent aims to contribute to forest conservation led her to develop parallel research on land cover change in the Brazilian Amazon along with the private sector as well as with INPE researchers. In 2005, the author started her PhD research in Wageningen University whose results are presented in this document. In 2010 the author became a collaborator to INPE and the Planetary Skin Institute (CISCO/NASA) in large scale land use modelling and carbon emission estimates from deforestation; and since 2012 she has been working with applied research on natural disasters at the National Early Warning and Monitoring Centre of Natural Disasters (Cemaden) in Brazil.

List of publications

SOLER, L.S., VERBURG, P.H, ALVES, D.S. Evolution of Land Use in the Brazilian Amazon: From Frontier Expansion to Market Chain Dynamics. LAND 3(3), 981-1014, 2014 (doi:10.3390/land3030981).

OMETTO, J. P. ; AGUIAR, A.P. ; ASSIS, T. ; SOLER, L.S. ; VALLE, P.; TEJADA, G. ; LAPOLA, D. M. ; MEIR, P.. Amazon forest biomass density maps: tackling the uncertainty in carbon emission estimates. Climatic Change (online), v. 00, p. February 2014, 2014. (doi: 10.1007/s10584-014-1058-7).

SOLER, L.S., KOK, K., CÂMARA, G., VELDKAMP, A. . Using Fuzzy Cognitive Maps to describe current system dynamics and develop land cover scenarios: a case study in the Brazilian Amazon, Journal of Land Science, v.7, n. 2 , pp. 149–175, 2012. (doi:10.1080/1747423X.2010.542495).

SOLER, L.S., KOK, K. , CÂMARA, G., VELDKAMP, A. Land use and land cover dynamics in the Brazilian Amazon: understanding human-environmental interactions In: Planet under pressure Conference, 26-29 março, 2012, Londres (Poster presentation).

CARDOSO, M., SOLER, L.S., AGUIAR, A.P.D., SAMPAIO, G. Relations between fires and connection to markets. In: Planet under pressure Conference, 26-29 março, 2012, Londres (Poster presentation).

OMETTO, J. P, AGUIAR, A.P.D., SOLER, L.S., ASSIS, T.de O, OLIVEIRA, P.V.. Amazon deforestation and regional carbon balance. In: Planet under pressure Conference, 26-29 março, 2012, Londres (Oral presentation).

AGUIAR, A.P.D., OMETTO, J. P, SOLER, L.S., ASSIS, T.de O, ANDRADE, P., LAPOLA, D. M., DALLA NARA, E. Scenarios for the Amazonia 2050: combining emission reductions and social development. In: Planet under pressure Conference, 26-29 março, 2012, Londres (Poster presentation).

OMETTO, J. P, SOLER, L.S., ASSIS, T.de O, OLIVEIRA, P.V., AGUIAR, A.P.D. Carbon emissions risk map from deforestation in the tropical Amazon. In: American Geophysical Union, Fall Meeting 2011, AGU, San Francisco, California, USA, 5-9 December, 2011. (Oral presentation).

ASSIS, T.de O, SOLER, L.S., AGUIAR, A.P.D., OMETTO, J. P. Assessing risk maps of deforestation to the Brazilian Amazon using LuccME framework. In: XV Simpósio Brasileiro de Sensoriamento Remoto, INPE, Curitiba, Brazil, May 2011, Conference paper (Oral presentation).

SOLER, L S. Land use and land cover dynamics in the Brazilian Amazon: understanding human-environmental interactions. In: AAG Annual Meeting 2011, Seattle, Washington, 12-16 April, 2011. (Oral presentation).

SOLER, L.S., VERBURG, P.H.. Combination of remote sensing and household level data for regional scale analysis of land use change trajectories in the Brazilian Amazon.

Regional Environmental Change , v.10, n. 4 , pp. 371–386, 2010. (doi: 10.1007/s10113-009-0107-7).
SOLER, L S., VERBURG, P.H.; ESCADA, M.I.S.. Quantifying deforestation and secondary forest determinants for different spatial extents in an Amazonian colonization frontier (Rondônia). Applied Geography, v.29 , pp. 182–193, 2009. (doi: 10.1016/j.apgeog.2008.09.005).
FREITAS C.C.; SOLER L.S. SANT'ANNA S.J.S.;DUTRA L.V.; SANTOS J.R.; MURA, J.C.; CORREIA, A.H. Land Use and Land Cover Mapping in Brazilian Amazônia Using Polarimetric Airborne P-Band Radar Data. IEEE Transactions on Geoscience and Remote Sensing. IGARSS'2007 Special Issue, v. 46, n. 10, pp.2953-2970, 2008. (doi: 10.1109/TGRS.2008.2000630).
SOLER, L S.; VERBURG, P.H.; VELDKAMP, A.; ESCADA, M.I.S.; CÂMARA, G. Quantifying land use/cover determinants under the role of official colonization areas at different spatial extents in Rondônia. In: Proceedings of the International Scientific Conference - Amazon in Perspective, Integrated Science for a Sustainable Future, Manaus, Brazil, 17-20 November 2008. (Poster presentation).
SOLER, L S.; VERBURG, P.H.; VELDKAMP, A.; ESCADA, M.I.S.; CÂMARA, G. Statistical analysis and feedback exploration of land use change determinants at local scale in the Brazilian Amazon. In: Conference Proceedings of the IEEE International Geoscience and Remote Sensing Symposium (IGARSS 2007), Barcelona, Spain, 23-28 July 2007. IEEE. pp. 3462 – 3465, Conference paper. (doi:10.1109/IGARSS.2007.4423591).
KRUIJT, B.; L., F.; NOBRE, A.; TOMASELLA, J.; HUTJES, R.W.A.; WATERLOO, M.; NOBRE, C.A.; VERBURG, P.; CÂMARA, G.; KOK, K.; ZANCHI, F.B.; SILVA, R. C.; SOLER, L. S.; ESCADA, I. How resilient may the Amazon rain forest carbon balance be to climate change? In: Integrated land ecosystem-atmosphere processes study; proceedings of the 1st iLEAPS science conference, Helsinki (Finland), January 21-26, 2006. - Helsinki (Finland): Yliopistopaino, - p. 80 – 81, 2006. Conference paper.(Poster presentation).
SOLER, S.L.; VERBURG, P.; ESCADA, M.I.S.; CÂMARA, G., 2005. Analysis of deforestation processes in the Brazilian Amazon and their interactions with the human-environmental system. In: 6th Open Meeting of the Human Dimensions of Global Environmental Change Research Community, 9-13 October, 2005,IHDP, University of Bonn, Bonn, Germany. (Poster presentation).

PE&RC PhD Training Certificate

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities).

Review of literature (4.5 ECTS)

- A review of deforestation processes in Brazilian Amazon: a starting point to analyze land use and land cover dynamics on human-environmental system

Writing of project proposal (4 ECTS)

- Local resilience of the human-environmental system in the Brazilian Amazon under conditions of global climate change and large-scale deforestation

Post-graduate courses (5 ECTS)

- Land science: concepts, tools and uncertainties in land use studies and landscape dynamics; PE&RC (2005)
- Multivariate statistics; INPE, Brazil (2006)
- Global changes; INPE, Brazil (2006)
- Land use change modelling using TerraME; INPE/ GEOMA, Brazil (2007)

Laboratory training and working visits (4.5 ECTS)

- Discussion on land use change processes, gathering soil data, land suitability and rural settlements limits; EMBRAPA, Campinas, (2005)
- Geology and geomorphology data, drainage, mineral resources and sites of exploration; Companhia de Pesquisa de Recursos Mineirais, CPRM (2005)
- Visit to flux tower ZF2 from LBA/INPA near Manaus to discuss ongoing projects among WUR, INPE and INPA (Instituto Nacional de Pesquisas da Amazonia), (2006)
- Fieldwork in Rondônia State, visit to various governmental and non-governmental institutions exploratory fieldwork view, GPS data collection and interview to farmers; Porto Velho (CPRM, EMBRAPA, INCRA, SEDAM, SIPAM), Machadinho d'Oeste and Vale do Anari (City Halls, industries, slaughterhouse, sawmills), Jaru (INCRA, dairy industries slaughterhouse), (2007)
- Visit to gather data building, soil fertility map; Port Velho SEDAM (2007)
- Visit to flux tower ZF2, ZF3 and Fazenda Jaru from LBA/INPA near Manaus for a project meeting to discuss the current status and next steps; (2007)
- Fieldwork in Rondônia State, household level survey with 100 farmers in the study area, visit to governmental and non-governmental institutions, GPS data collection, interviewing farmer states (2008)

Invited review of (unpublished) journal manuscript (2 ECTS)

- IEEE Transactions on Geoscience and Remote Sensing: Remote sensing application on land use and land cover change (2009)
- Philosophical Transactions of the Royal Society A: People vulnerability to natural disasters and its relation to human occupation (2012)

Competence strengthening / skills courses (3,5 ECTS)

- PhD Competence assessment; PE&RC (2005)
- Scientific writing; CENTA, WUR (2005)
- The art of writing; CENTA, WUR (2007)

PE&RC Annual meetings, seminars and the PE&RC weekend (3 ECTS)

- How resilient is the Amazon; Studium Generale, WUR (2005)
- PE&RC Day (2005, 2008)
- Dimensões humanas do uso e cobertura das terras na Amazônia, uma contribuição do LBA; INPA / LBA (2005)
- PE&RC Weekend (2007, 2008)
- How design contributes to effective knowledge for sustainable landscape development; scientific symposium (2009)
- Symposium: pathways to a sustainable and robust Amazon (2010)

Discussion groups / local seminars / other scientific meetings (4.5 ECTS)

- Statistics , maths and modelling in Production Ecology and Resource Conservation (2005, 2007)
- Modelling methods in ecology (2006)
- Integration seminars presented at INPE (2005, 2006, 2007)
- Spatial modelling discussion group (2007 / 2008)
- Stakeholder participation discussion group (2008)

International symposia, workshops and conferences (9 ECTS)

- The 6th Open Meeting of the Human Dimensions of Global, IHDP, UNESCO (2005)
- International Geoscience and Remote Sensing Symposium; Barcelona (2007)
- AAG Annual meeting; Seattle, Washington (2011)
- Planet under pressure conference; International Geosphere-Biosphere Program; London (2012)

Lecturing / supervision of practical 's / tutorials (3 ECTS)

- Spatial dynamics modelling at INPE; Sao José dos Campos, Brazil (2006)
- Multivariate statistics applied to remote sensing at INPE; Sao José dos Campos, Brazil (2006)
- Modelling land use and land cover change with CLUE-S at INPA; Manaus, Brazil (2006)
- Modelling land use and land cover change with CLUE-S at EMBRAPA, Sao Carlos, Brazil (2010)