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MODELING LAND USE CHANGE IN THE BRAZILIAN AMAZON: EXPLORING INTRA-REGIONAL HETEROGENEITY

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“Nothing is less real than realism… Details are confusing. It is only by selection, by elimination, by emphasis that we get at the real meaning of things”.

Georgia O'Keeffe, 1922

Dedico a meus filhos,
José Guilherme e Ana Elisa.
Tudo é uma questão de saber escolher,
dar ênfase às coisas certas.
E transformar pedras e ossos em arte...

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MODELAGEM DE MUDANÇA DO USO DA TERRA NA AMAZÔNIA: EXPLORANDO A HETEROGENEIDADE INTRA-REGIONAL

RESUMO

Este trabalho descreve os resultados da aplicação de um arcabouço de modelagem dinâmica para explorar como fatores alternativos, políticas públicas e condições de mercado influenciam o processo de ocupação da Amazônia. Trabalhos anteriores na Amazônia enfatizaram aspectos como distância a estradas, e desconsideraram a enorme heterogeneidade biofísica e sócio-econômica da região. A análise estatística apresentada usa um banco de dados espacial (células de 100 x 100 km^2 e 25 x 25 km^2) com 40 variáveis organizadas em células de ambientais, demográficas, de estrutura agrária, tecnológicas, e indicadores de conectividade a mercados como variáveis independentes, e variáveis de uso e cobertura (pastagem, agricultura temporária e permanente, floresta) como variáveis dependentes. Os fatores determinantes dos padrões de uso foram identificados usando modelos de regressão (*spatial lag* e regressão linear múltipla) para toda a região e três sub-regiões. Os resultados dos modelos de regressão demonstram quantitativamente que a importância relativa dos fatores determinantes apresenta grande variação na região. Modelos de regressão enfatizam fatores associados a conexão a mercados, conexão a portos e áreas protegidas. Os modelos foram utilizados para realizar diferentes explorações de cenários de mudança de uso até 2020. Explorações incluem a análise da influência de diferentes fatores na dinâmica das novas fronteiras na Amazônia, de possíveis impactos políticas públicas, e aumento e diminuição da demanda. As principais conclusões são: (a) conexão a mercados nacionais é o fator mais importante para capturar os padrões espaciais das novas fronteiras; (b) a interação entre os fatores de conexão e demais fatores biofísicos e sócio-econômicos que influencia a dinâmica intra-regional heterogênea; (c) estas diferenças levam a impactos diferenciados de políticas públicas na região. Este trabalho reflete a importância da exploração de cenários como uma ferramenta para auxiliar o entendimento do processo de ocupação da Amazônia.

MODELING LAND USE CHANGE IN THE BRAZILIAN AMAZON: EXPLORING INTRA-REGIONAL HETEROGENEITY

ABSTRACT

This work describes the results of applying a dynamical LUCC modeling framework to explore how alternative determining factors, policies and market constraints influence the process of land occupation in Amazonia. Previous work regarding deforestation in Amazonia has emphasized aspects such as distance to roads, and has disregarded the region's enormous biophysical and socio-economical heterogeneity. The statistical analysis uses a spatially-explicit database (cells of 100 x 100 km^2 and 25 x 25 km^2) with 40 environmental, demographical, agrarian structure, technological, and market connectivity indicators as independent variables, and land-use (pasture, temporary and permanent crops, non-used agricultural land) patterns as dependent variables. The determinant factors of land patterns were identified regression models (spatial lag and multiple linear regressions) at multiple spatial resolutions for the whole region and for three sub-regions. Regression models results showed quantitatively that the relative importance and significance of land use determining factors greatly vary across the Amazon. Models emphasize policy-relevant factors, especially those related to connection to national markets, connection to ports, and protected areas. The models were used to build different exploration scenarios of land use change until 2020. Explorations include an analysis of the influence of different factors in the new Amazon frontiers dynamics, the possible impacts public policies, and increasing or decreasing demand. The main conclusions drawn from the scenario explorations are: (b) connection to national markets is the most important factor for capturing the spatial patterns of the new Amazonian frontiers; (b) it is the interaction between connectivity and other factors that influence the heterogeneous intra-regional dynamics; (c) these differences led to heterogeneous impact of policies across the region. This work reflects the importance of scenario exploration as a tool to understand the process of occupation in the Brazilian Amazonia.

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ABBREVIATION LIST

CPRM – Brazilian Geological Service

FUNAI – Brazilian National Foundation for Indigenous Peoples

G7 - Group of Seven (Canada, France, Germany, Italy, Japan, United Kingdom, United States of America)

GEOMA – Rede Temática de Modelagem Ambiental na Amazônia

IBAMA – Brazilian Institute of Environment and Natural Resources

IBGE – Brazilian Institute of Geography and Statistics

INCRA – Brazilian Institute of Colonization and Homestead

INMET – Brazilian Institute of Meteorology

LUCC - Land use and cover change

MMA – Brazilian Ministry for the Environment

PPG7 - Pilot Program for the Protection of Tropical Forests

CHAPTER 1

INTRODUCTION

1.1 Introduction

The Brazilian Amazonia rain forest covers an area of 4 million km2. Due to the intense human occupation process in the last decades, about 16% of the original forest has been removed, and the current rates are still very high (INPE, 2005). Deforestation in Amazonia is one of largest single contributors to CO2 emissions worldwide (Santilli et al., 2005). Amazonia possesses valuable biodiversity resources threatened by deforestation. The process of human occupation in the region during the last decades has also been associated with a concentration of land ownership, social inequalities, land conflicts, violence, and illegal activities (Brito, 1995; GEOMA, 2003; Machado, 1998). Growing regional and external demand for beef (Arima et al., 2005; Faminow, 1997; Margulis, 2004), and the potential expansion of mechanized crops are the main threats to the forest (Becker, 2005; Fearnside, 2001).

The process of human occupation in Brazilian Amazonia is heterogeneous in space and time. According to Becker (2001), sub-regions with different speed of change coexist in the Amazon, due to the diversity of ecological, socio-economic, political and accessibility conditions. Until the 1960s human occupation was concentrated along the rivers and coastal areas (Becker, 1997; Machado, 1998). The biggest changes in the region started in the 1960s and 1970s during the military regime, due to an effort to populate the region and integrate it into the rest of the country (Becker, 1997; Costa, 1997; Machado, 1998). After the 1990s, occupation continued intensely, but more driven by regional economic interests than subsided by the Federal Government (Becker, 2005).

According to (Alves, 2001; Alves, 2002), deforestation tends to occur close to previously deforested areas, showing a marked spatially-dependent pattern, most of it concentrated within 100 km from major roads and 1970´s development zones, as illustrated in Figure 1.1. Roads that offer an easier access to other parts of Brazil concentrate a greater proportion of deforestation, indicating that deforestation was initially associated with the creation of development zones and roads during the military government, but continued more intensely in areas that established productive systems connected to more prosperous areas of Brazil (Alves, 2001; Alves, 2002). Figure 1.1 also shows the three macro-regions proposed by (Becker, 2005) with distinct characteristics regarding the human occupation process: *Densely Populated Arch, Central Amazonia,* and *Occidental Amazonia.*

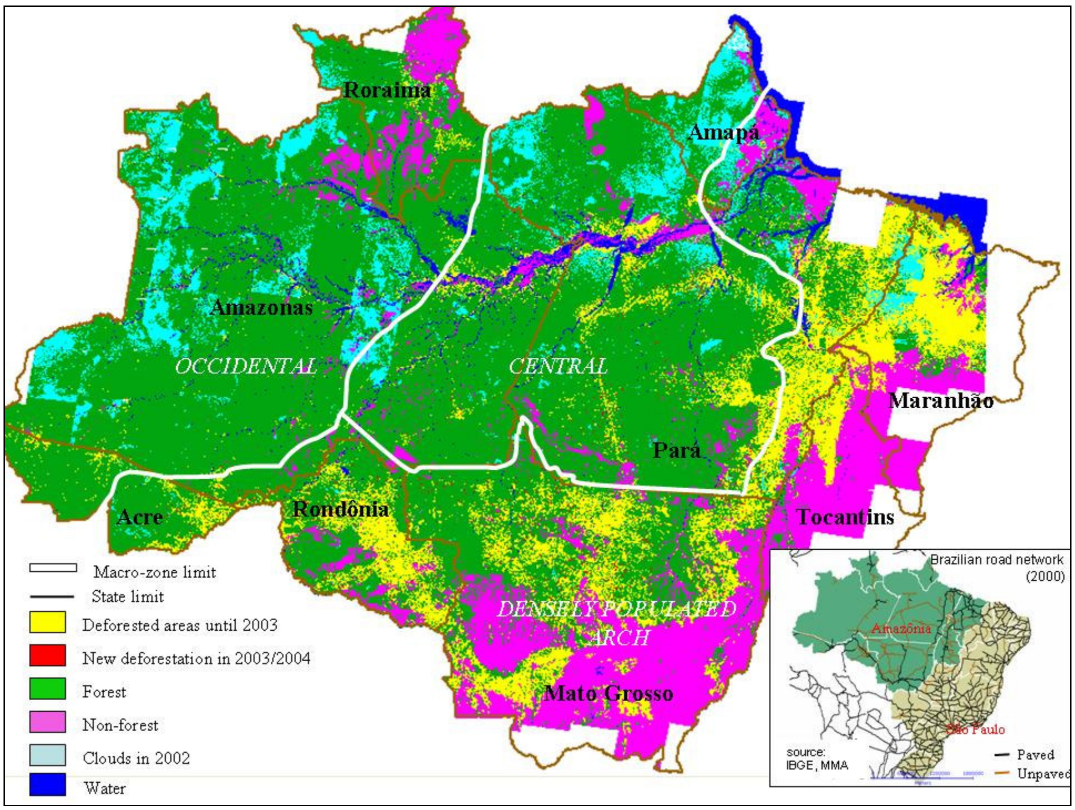

FIGURE 1.1 – Amazonia deforested areas and three macro-zones (source: (Becker, 2005; INPE, 2005))

As Figure 1.1 illustrates, most of the deforested areas concentrate in the south-eastern part of the Amazonia, the area usually known as the "Deforestation Arch", or the

Densely Populated Arch as proposed by Becker (2005), where most urban centres, roads and core activities are located. Currently, however, the more vulnerable area is the *Central Amazonia*. This is the area crossed by the new axes of development, from the centre of the Pará state to the eastern part of the Amazonas state, where the new occupation frontiers are located (Becker, 2005; GEOMA, 2003). The *Occidental Amazonia* is the most preserved region outside the influence of the main road axes (Becker, 2005).

Given the importance of the Brazilian Amazonia region, both at the national and international scales, it is important to derive sound indicators for public policy making. Informed policymaking requires a quantitative assessment of the factors that bring about change in Amazonia, and should take this intra-regional heterogeneity into account. As stated by Becker (2000): "understanding the differences is the first step to appropriate policy actions". Quantifying deforestation and, in a broader sense, *land use and land cover change*[1] (LUCC) determinant factors, is also a requirement for the development of LUCC models. Computational models are useful tools to supplement our mental modeling capabilities, in order to make more informed decisions (Costanza and Ruth, 1998). LUCC models can help the evaluation of possible impacts of alternative policies through scenario building, and contribute to the decision making process. That is the scope of this thesis: the use of LUCC models in the Brazilian Amazonia to explore intra-regional heterogeneity and the policy impacts.

The remainder of this section is organized as follows. Section 1.2 presents a brief review about LUCC models, and discusses the main issues regarding their application in Amazonia. Section 1.3 presents the hypothesis and goals of this thesis. Section 1.4 presents the structure of the document.

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[1] Land cover refers to the land's physical attributes (for instance, forest, water, grassland, desert, built areas, etc.). Land use refers to the human use of such attributes (for instance, recreation, protection, pasture, residential areas). Land use and cover change refers both to conversion between classes (e.g., deforestation or desertification processes), and to alterations (such as agricultural intensification, and forest degradation). Briassoulis, H., 2000, Analysis of Land Use Change: Theoretical and Modeling Approaches, Regional Research Institute, West Virginia University presents a broad discussion about these concepts and related theories.

1.2 LUCC models and the Amazonia

A great variety of LUCC models can be found in the literature, with distinct goals, approaches, theoretical background and modeling traditions. An extensive review of land use theories and modeling approaches is provided by Briassoulis (2000). Irwin (2001) present a review of land use models based on economic theory. Agent-based model reviews are found in Parker (2001). Brown and Pearce (1994), Lambin (1997), Kaimowitz and Angelsen (1998) and Barbier and Burgess (2001) present reviews of deforestation models. A technical comparison of the internal mechanisms of nine land use change models is found in (Eastman et al., 2005). Lambin (2000) discusses the application of LUCC models in land use intensification studies. (Veldkamp and Lambin, 2001) and (Verburg et al., 2004) discuss LUCC modeling research priorities, focusing on projective spatially-explicit models. (Veldkamp et al., 2001) discusses scale issues also on spatially-explicit models.

In the scope of this thesis, we focus on spatially-explicit LUCC models with the following aims:

- Explain and test hypothesis about past changes, through the identification of determining factors of land use change;
- Envision which changes will happen, and their intensity, location and time;
- Assess how choices in public policy can influence change, by building different scenarios considering different policy options.

In this section, we discuss five issues related to LUCC models and their application in the Amazon: selection of driving factors; the distinction between models that project quantity and location; the approaches to quantify the relationships between land use change and driving forces; and finally scale issues.

The selection and assessment of driving forces of change is one of the main issues in LUCC modeling (Geist and Lambin, 2001; Lambin and Geist, 2003; Lambin and Geist, 2001; Lambin et al., 2001). Current understanding moves away from simplifying single factor explanations (such as population growth), and points out that land use and cover changes are determined by a complex web of biophysical and socio-economic factors that interact in time and space, in different historical and geographical contexts, creating different trajectories of change. It is people's response to economic opportunities mediated by institutional factors that drives changes. Such opportunities and constraints are created by local, national and international markets and policies (Lambin et al., 2001).

In the Amazon, few studies analyzed intra-regional differences on driving factors. Several econometric models[2] were developed (Andersen et al., 2002; Andersen and Reis, 1997; Pfaff, 1999; Reis and Guzmán, 1994; Reis and Margulis, 1991), using municipal level data for the whole Amazonia, to analyze the importance of deforestation factors such as credit, population pressure, presence of roads, biophysical factors, etc. Spatially explicit analyses of 10 deforestation determining factors were conducted by Kirby (2006) and Laurance (2002) using regular cells as the unit of analysis at two spatial resolutions: 50 x 50 km^2 and 20 x 20 km^2. Of the previous studies, only Perz (2003) conducted a comparative analysis in three space partitions (*remote, frontier, consolidated*), but focusing specifically on social determinants of secondary growth.

Besides, most previous works focus on deforestation as a unified measure, disregarding the heterogeneity of actors and agricultural uses, which may have different driving forces and develop specific trajectories of change. An exception is the work of Margulis (2004), which presents an econometric model that quantifies the relationships in space and time of the main agricultural activities (wood extraction, pasture and crops).

[2] Econometric models explain land use changes using one or more equations that express the relationship between demand and/or supply and their determinant factors, normally through multiple regression models, with an emphasis on economic factors (Briassoulis, 2000).

Another relevant aspect in LUCC modeling is the distinction between models that project the quantity of change and models that identify possible location of change (Lambin et al., 2000; Veldkamp and Lambin, 2001). This requires the clear differentiation between spatial determinants of change, i.e., local *proximate causes* directly linked to land use changes (in the case of deforestation, soil type, distance to roads, for instance) from *underlying driving forces*, which are normally remote in space and time, and operate at higher hierarchical levels, including macro-economic changes and policy changes. Projecting the temporal distribution of change (how much and when changes will happen) requires a deeper understanding of underlying forces, including demand for land-based commodities. Possible location of change is simpler to project, and basically requires the identification of the spatial determinants of change (proximate causes). The confusion between spatial determinants and underlying causes has led to an over-emphasis in factors such as roads, soil types or topography as *causes* of deforestation (Veldkamp and Lambin, 2001).

Previous spatially-explicit projective deforestation models in Amazonia (Laurance et al., 2001; Nepstad et al., 2001) mixed both concepts, using spatial patterns of deforestation close to roads in the Arch to project future quantity of deforestation in other areas. Recent work of Soares-Filho (2006) uses two separate models to project location and quantity of change. But underlying and proximate causes are also mixed: the quantity model uses spatial factors (such as road paving) to increase the rate, based on past spatial patterns of deforestation in the Arch.

A third relevant aspect related to LUCC modeling is the approach to quantify relations between land use change and its driving forces. According to Verburg (2004) three distinct approaches can be adopted: (a) process theories and physical laws; (b) empirical methods, especially regression analysis; (c) and expert knowledge. When modeling the whole Amazon, due to the complexity of processes and actors across the region, and the lack of theories that would explain such heterogeneous occupation process, the use of empirical data is the most indicated approach. However, LUCC models could potentially verify hypotheses about the Amazonia occupation process, by combining such approaches, for instance, combining alternative regression models, or modifying regression coefficients by using expert knowledge.

Empirical relationships can be obtained in two ways (Verburg et al., 2004): (a) using *cross-section* data (one point in time) to analyze the relationships between determining factors and land use/cover *structure* (or *pattern*); (b) using panel data (several points in time) to analyze the relationship between determining factors and land use/cover *change* in that period. The relationships established through empirical methods cannot be taken for causal relationships and should not be applied to long term projections, as processes are non-stationary (Veldkamp and Lambin, 2001; Veldkamp et al., 2001). However, cross-section analyses of the land use system result in more stable relationships, as they relate to the resulting structure a long history of changes, not of a specific period (Verburg et al., 2004).

Finally, the last aspect to be discussed is the scale of analysis and regional interactions. The scale[3] on which a process is studied affects the explanation found to the phenomenon. Relationships between land use change and driving forces established in local studies cannot directly be extrapolated to regional scales, due to properties such as non-linearity, emergence and collective behaviour (Verburg et al., 2004). At different scales, a different process may have a dominant influence on the land use system (Gibson et al., 2000). Regional dynamics affect (and are affected by) local conditions in top-down and bottom-up interactions (Verburg et al., 2004). According to Becker (2005): "it is impossible today, more than ever, to understand what happens in one place, and consequently, to conceive and implement adequate public policies, without considering the interests and conflicting actions at different geographical scales".

Latest evidence from deforestation data (INPE, 2005) indicates the existence of intra-regional *interaction* in relation to the effects of policies. Governance policies applied to

[3] According to Gibson, C.; Ostrom, E.; Ahn, T. K. The concept of scale and the human dimensions of global change: a survey. Ecological Economics, 32: 217–239, 2000., scale is "the spatial, temporal, quantitative, or analytical dimension used to measure and study any phenomenon". All scales have extent and resolution. In the case of spatial scales, extension refers to the dimension of the study area, and resolution to the measurement precision (e.g., pixel resolution, administrative unit in the case of census data).

one region, such as the creation of protected areas or command and control actions, (BRASIL, 2005) might induce the *occupation of another area*. Thus, the creation of a protected area does not necessarily result in an overall decrease of deforestation rates, since there are pristine areas to be occupied. On the other hand, the improvement of conditions in a given area, such as the paving of roads and the strengthening of productive chains, can favor occupation of that area *in detriment of another*. No previous work about the Amazonia has explored such intra-regional interactions, resulting from processes that act on different hierarchical levels, including demand for land. In fact, previous works (Laurance et al., 2001; Nepstad et al., 2001; Soares-Filho et al., 2006) adopted such rigid premises about positive or negative impacts of local policies on the *overall regional quantity of change* that such interactions are not possible in their models.

Given these considerations, next section presents the hypotheses and specific goals of this thesis and its contribution in relation to previous works.

1.3 Thesis hypotheses and objectives

This thesis explores two main *hypotheses* about the human occupation process in the Amazonia using quantitative spatial modeling approaches:

1. The heterogeneity of land use spatial determining factors and policy effects across the Amazonia.

2. The importance of measures of connectivity to markets to explain intra-regional differences in the Amazonia occupation process.

The hypothesis of heterogeneity of factors is based on the macro-regions proposed by Becker (2005). In the second hypothesis, connectivity to markets is a proxy to insertion in the national productive system. This hypothesis is derived from the conclusions of Alves (2001; 2002)).

The *specific goals* of this work are:

1. *Quantify the intra-regional heterogeneity in the relative importance of determining factors using spatial statistical analysis methods*. This work comparatively quantifies the determining factors of deforestation and main land uses (pasture, temporary agriculture and permanent agriculture) in the whole Amazonia and in the three macro-regions.

2. *Explore how alternative determining factors, policies and market constraints could potentially influence the process of human occupation in Amazonia using a dynamic LUCC modeling framework*. Alternative regression models are compared to assess the relative importance of different factors in capturing the new Amazonia frontiers. Policies analyzed include the paving of roads, the creation of protected areas and actions of law enforcement. Scenarios of increasing and decreasing demand allow the analysis of the impact of alternative market constraints on the occupation process.

In order to achieve the second goal, the CLUE modeling framework was selected and adapted to the Amazon characteristics. This modeling framework was selected for the following reasons:

a) the projected changes are spatially explicit;

b) the framework allows the incorporation of a broad range of determining factors, with relationships to land use patterns based on empirical methods;

c) it was conceived for large-area applications and low-resolution data, such as census data;

d) the use of a multi-scale allocation approach, in which the changes projected in a coarser resolution influence changes in the finer resolution;

e) in each scale, different statistical relationships and factors may be used; and

f) the clear separation of the aspects of temporal and spatial change projections.

The main modification added in this thesis to the original CLUE model is the inclusion of indicators of the non-uniform governance levels across the region, which allows the exploration of law enforcement scenarios. The premise incorporated in the model is that active presence of the government in an area inhibits illegal activities, and thus can slow down the forest conversion pace in those areas.

In summary, this thesis adds to previous LUCC modeling efforts in the Amazonia:

- The broad category of biophysical and socio-economic spatially explicit factors we used, including connectivity measures and agrarian structure indicators;
- The analysis of heterogeneity of land-use determinant factors across the region;
- The use of a dynamic modeling framework to refine the understanding of the contribution of different factors in the occupation process, through the comparison of projections using alternative regression models;
- The inclusion of indicators of the presence of the state in the dynamic model to explore law enforcement police scenarios;
- The adoption of flexible premises regarding the distribution of change in scenario explorations to allow the emergence of intra-regional interaction effects.

The next section describes the document structure.

1.4 Document structure

This thesis is structured as follows:

- Chapter 2 presents an overview of the Amazonia occupation process, and a more detailed review of previous LUCC works in the Amazonia, already mentioned in this introduction.
- Chapter 3 presents the study area and the spatially-explicitly database constructed to support the analyses presented in Chapters 4 and 5.

- Chapter 4 presents the spatial statistical analysis methods and results. The statistical analysis part corresponds to the first goal stated above;
- Chapter 5 presents the CLUE modeling methods and results, corresponding to the second goal stated above;
- Chapter 6 presents the conclusions of this thesis and suggestions for future work.

CHAPTER 2

BRAZIAN AMAZONIA: REVIEW OF HUMAN OCCUPATION PROCESS AND PREVIOUS LUCC MODELING

2.1 Human occupation and new frontiers

2.1.1 Occupation history: 1950-2000

Up to the 1950s, human presence in Amazonia was limited to the coastal areas, and to the riverside areas in the main navigable rivers, and to the large settlement in the city of Manaus. Migration from other Brazilian regions to Amazonia increased in the 1950's, due to government-induced actions such as the building of the Belém-Brasilia (BR 153) and Cuiabá-Porto Velho (BR 364) roads. From 1950 to 1965 the population in Amazonia increased from 1 to 5 million people (Becker, 1997). The biggest changes occurred from 1965 to 1985 (Becker, 1997; Costa, 1997; Machado, 1998), during the military regime, which consider occupation in Amazonia a national priority and included the region in its national plans. The government carried out major public projects in the region, through three major strategic axes (Becker, 1997):

- *Establishment of integrative connections*: a large road network, a communications infrastructure, and large hydroelectric plants.
- *Induced migratory and capital flows*: the government established many colonization programs, which led to large migration flows and to the establishment of new urban centres; tax breaks and capital subsidies induced major private investments in the region.
- *Creation of federal lands*: the government determined that a buffer of 100 km around all federal roads were publicly-owned, and used this land to induce colonization projects.

The extent of human occupation in this period is illustrated in Figure 2.1. After the end of the military regime, state intervention was reduced and the occupation in Amazonia has been more driven by regional economical interests (Becker, 2005).

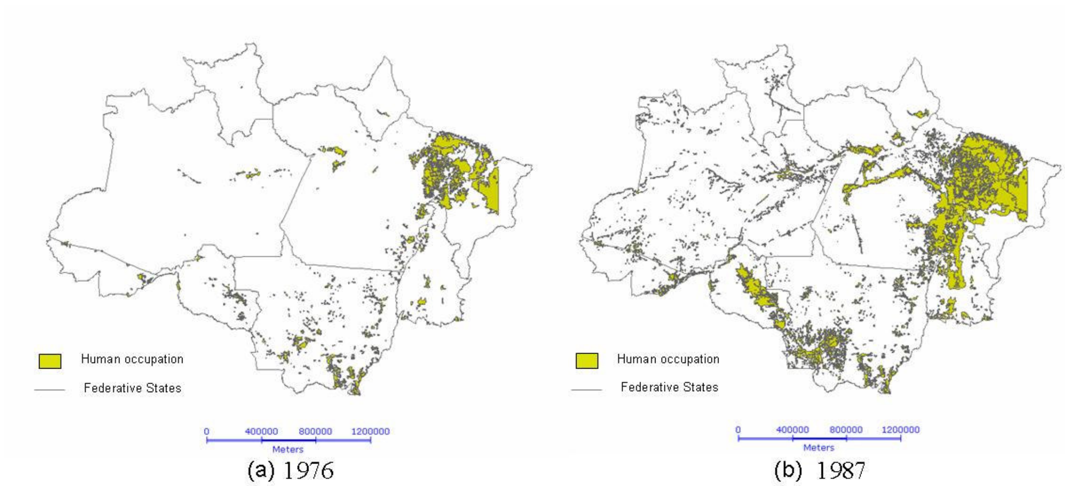


FIGURE 2.1 - Human occupation in 1976 and 1987 (source: IBGE).

To understand the recent process of land use change in Amazonia, the regions' biophysical and socio-economic heterogeneity has to be considered. Regional society includes indigenous and traditional populations, urban and rural workers, small, medium and large farmers, and capitalized agribusiness entrepreneurs, in a complex mosaic of actors, economic activities and conflicting interests (Becker, 2005; Brito, 1995). According to the last census, Amazonia population reached 21 million people in 2000, most of them living in urban areas (IBGE, 2000). In the last 20 years, four major activities related to the land use change have been: timber extraction, cattle rising, large-scale and small-scale agriculture. These activities have occurred in different parts of the region. Each type of activity is induced by a combination of occupation history, geophysical conditions, connection to markets, and a mix of government and private actions.

Timber extraction is associated mostly with predatory forest exploitation. According to (Schneider, 2000), the timber extraction sector is a major economical activity in the region, and accounts for 15% of the economy of the states of Pará, Mato Grosso e

Rondônia, and generates 500 thousand jobs. According to Lentini (2005), at least 5% of the economic active population in the Brazilian Amazon works either directly or indirectly in the logging activity. According to Nepstad (1999), 90% of timber extraction is illegal and contributes to the impoverishment of the forest and makes it more susceptible to fire. After exhaustion of the forest in a region, the timber extraction industries migrate to the new areas. In the early 1990s, the timber industry was concentrated in Southern Pará, North of Mato Grosso state, and Rondônia. Lately, there has been a migration to the West of Pará and to the South of Amazonas. According to recent surveys (Lentini et al., 2005), 36% of the wood production was sold to the international market.

After the forest has been cut, the resulting land is often appropriated for private ownership, mostly by using corruption in the land cadastral system (GEOMA, 2003). It was only very recently, in 2005, that the Brazilian government started to act to avoid misuses of the cadastral system. When the forest is removed, it is mostly used for cattle rising. Margulis (2004) points out that cattle raising accounts for 70% of converted forest areas after clear cut, due to the high private profitability of cattle rising associated with reasonable transportation costs. From 1990 to 2003, Amazonia cattle herd rise went from 26.6 million to 64 million (IBGE, 2006b). National market absorbs most of the meet produced in Amazonia, especially the Northeast and Southeast regions (Arima et al., 2005). Faminow (1997) showed that the local demand for cattle products such as beef and milk is also a cause of cattle production increase. Until the early 1990s, when the forest was converted to small farms, the settlers used it for temporary agriculture and later for pasture. Lately, there is a tendency of even small farmers convert clear cut forest directly into pasture.

From the 1990s onwards, capitalized agriculture also expanded into the region (especially soybeans). The initial expansion of large-scale agriculture occurred in the cerrado areas in the South of Amazonia. Lately, the expansion moved into the forest area. According to Margulis (2004) agriculture does not compete with cattle rising for forest conversion. There geographical and ecological barriers for the expansion of large-scale agriculture. Areas with annual rainfall greater than 2000 mm are not suitable for soybeans. Large-scale agriculture tends to occupy regions with better soils and flat terrain.

Small scale agriculture occurs in old occupation areas such as the North-east of Pará, and Maranhão, and in the areas of Pará (especially along the Transamazônica road) Mato Grosso and Rondonia that have been colonized by government land reform projects.

2.1.2 Government policies for Amazonia: 1995-2005

After a decade of non direct involvement in Amazonia, the significant extent of deforestation from 1985 to 1995 (circa 200,000 km2) forced the Brazilian federal government to take action to organize development and to protect endangered areas. In 1996, the "Avança Brasil" plan established corridors of production flow in the region, including paving the Cuiabá-Santarém road, new hydroelectric dams, and a combination of road and waterways in the region of the Madeira river. The basic motivation was to stimulate grain exports for the North Hemisphere. These plans fuelled major land speculation in some areas, and also a strong reaction from the environmental sector. The "Avança Brasil" plans ended up being delayed, but are still part of current government plans (PPA 2004-2007) as discussed in Becker (2004) and Thery (2005).

Meanwhile, the Ministry for the Environment set up a strong policy for forest preservation, including the creation of 170,000 km2 of protected areas (BRASIL, 2005), many in regions where rapid land use change is occurring. Currently, indigenous lands and conservation units comprise, respectively, 22% and 8% of Amazonia. A network of socio-environmental initiatives was also established in the region, based on local populations, sustainable alternative activities and international support. The PPG7 (Pilot Program for the Protection of Tropical Forests) projects, financed by the Word Bank, the G7 (Group of Seven) and the Brazilian government, are examples of such initiatives. Currently, he environmental sector, including NGO, religious organizations, national and international scientists, and governmental institutions, have active voice and are able to influence public policies in the Amazonia (Becker, 2005).

The combined action of these global, national and local processes, and contradiction between environmental and development government polices, are expressed by three main land-uses: (a) the reproduction of the wood extraction and cattle rising expansion cycle; (b) protected forest areas and alternative uses experiences; (c) expansion of capitalized agriculture (Becker, 2004). The challenge for land use models is to include these forces in the model.

2.1.3 New expansion areas and future axes of development

This section presents a summary of current deforestation process in Amazonia, focusing on the spatial distribution of new expansion areas and future possible axes of development, (INPE, 2005). Currently, the main area of deforestation is the Densely Populated Arch, especially in the north of Mato Grosso state and southeast of Pará States (INPE, 2005). However, as the availability of land decreases in the Arch and societal controls and protected reserves increase in the region, the deforestation process tends to migrate to new occupation areas. These new occupation areas are mostly concentrated in Central Amazonia, as illustrated in Figure 4. Figure 4 also illustrates more consolidated areas still active in the Arch, and future possible axes of development, as initially presented in Escada (2005b), combining recent deforestation data (INPE, 2005) to the new frontiers assessment of (Becker, 2004, , 2005).

These new frontiers are different from the ones in the 1960s and 1970s (Becker, 2004, , 2005). They are promoted by private actors (timber industry, cattle raisers and soybean producers) installed in the region. The three main new expansion areas are (Becker, 2005):

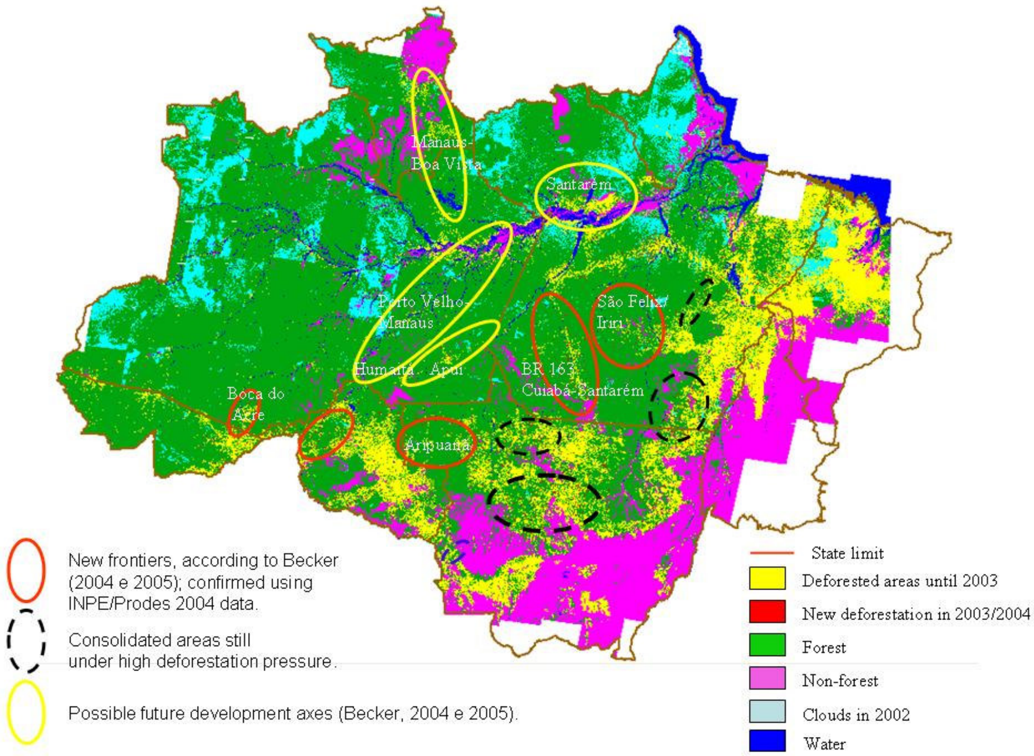


FIGURE 2.2 - New frontiers and future axes of development in the Brazilian Amazonia (source: adapted (Escada et al., 2005b)).

- *Cuiabá-Santarém*: consists of the area in Pará-State crossed by BR 163 road, an extension of the timber/cattle frontiers coming from Mato Grosso state that has been intensified in the last years by the perspective of paving the road, since the Avança-Brasil plan, as discussed in Section 2.2. There is also a convergence of cattle raisers from Pará coming from the Transamazônica road. In 2003, the announcement of the Federal Government's intention to pave the BR 163 road led to a land speculation process. Large tracts of area were appropriated for soybean production. There was a strong reaction from the environmental sector. This debate lead to the proposal of a set of integrated polices for the area. Other factors, such as soybean prices in external markets may also have contributed to the decrease of deforestation rates in this area.

- *Iriri/SãoFelix*: cattle raisers from São Felix do Xingu, Tocantins State and Goiás state lead this expansion process into the area know as "Terra do Meio", an area surrounded by indigenous lands, between the Iriri and Xingu rivers. Roads are opened by farmers themselves, with support of local municipality, including a link with the Cuiabá-Santarém road. The local perspective is more towards beef production than soybeans. In the municipalities of São Felix, Tucumã and Ourilândia, a well organized beef market chain is already installed (Escada et al., 2005a; GEOMA, 2003; Mertens et al., 2002; Poccard-Chapuis, 2004). Fertile soils and humid climate are pointed out by cattle raisers as the main attractive of this area (Escada et al., 2005a). Cattle herd has increased 780% from 1997 to 2004 (Escada et al., 2005a), and currently has 10% of total Pará State herd. São Felix do Xingu presented one of the highest deforestation rates in the last years, but in 2005 a decrease in rate was also felt in this area (INPE, 2005). Controlling measures have been taken in the region (BRASIL, 2005), including the creation of a mosaic of protected areas.

- *Madeira Corridor*: includes the whole area under influence of the Madeira River, an important waterway that connects the Rondônia State to Manaus, in the heart of the Amazon. This new frontier does not consist of single locality, but of several areas in the South of Amazonas State combining multiple actors and processes. Those localities jointly form a significant expansion area (Becker, 2004, , 2005), and include: (a) the Rio Branco-Boca do Acre road, the south of Labrea municipality, and the Humaitá-Labrea area occupied by pasture; (b) Manicoré, where groups from Rondônia and Mato Grosso are appropriating land for soybean production; (c) Apuí, with strong illegal timber production; and (d) Porto-Velho Manaus road, especially in Humaitá and Cassutana municipality, that constitutes the newer, more technologically advanced and faster area, where capitalized farms from the south are forming large farms for mechanized soybean production. The process in the Madeira Corridor expansion areas has not been as strong as in the two other frontiers in the previous years. However, there was a significant increase in 2005 Porto-Velho Manaus deforestation rates (INPE, 2005).

Another aspect that should be emphasized in Figure 2.2 is the heterogeneity of new frontiers in terms of stage of occupation and deforestation intensity. This indicates a temporal heterogeneity in the new frontiers, and the existence of differentiated local conditions in the different areas.

As mentioned above, in 2005 the government executed several localized "command and control" actions in Amazonia, to illegal deforestation ((BRASIL, 2004, , 2005)). Deforestation rates had increased from 2001 to 2004 from 18.165 km2 to 27.971 km2. In 2005, the estimated rate dropped to 18.900 km2. The federal policy actions in the region and lower soybeans prices in the international market may explain the 2005 decrease, which does not necessarily imply in decreasing trend. The command and control actions were mostly concentrated in the Cuiabá-Santarém road, in the north of Mato Grosso, in the São Felix/Iriri area, and also in some areas in the south of Amazonas. According to (INPE, 2005), a decrease in the intensity of deforestation was identified in such areas, but pressure increased in other areas, such as in the south of Pará, as illustrated in Figure 2.3.

Other area in Central Amazon that deserves attention is the riverbanks of the Amazon river close to Santarém, where a new soybean production area is being organized (Becker, 2005). The knowledge about new frontiers and future axes of development will be used in our modeling approach to select and refine statistical models that correctly capture areas more susceptible to change. Models that best capture this new region dynamics will be adopted for alternative police action analysis, as discussed in Chapter 5.

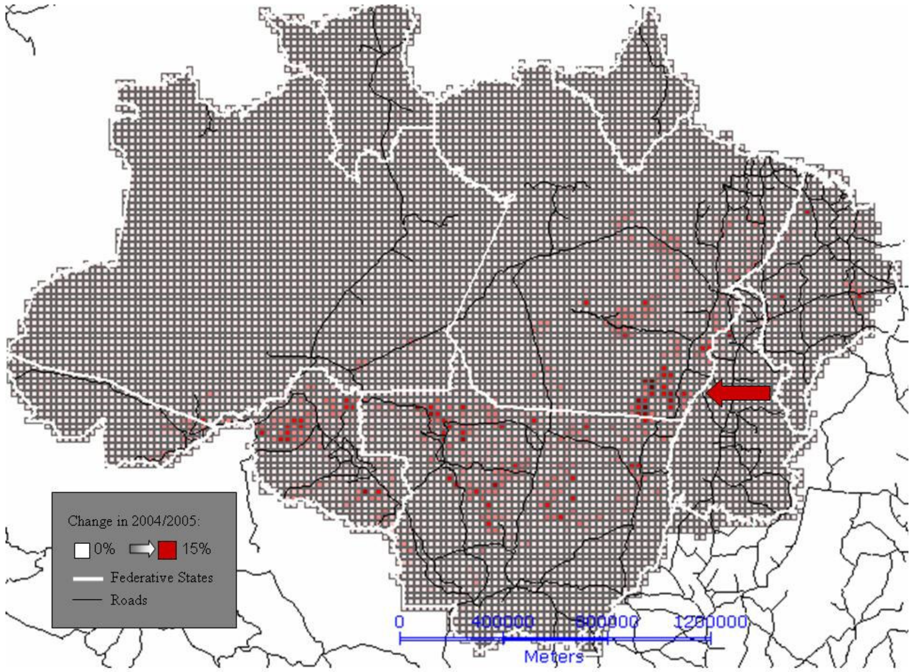


FIGURE 2.3 - Deforestation hot-spots in 2005 (source: (INPE, 2005)).

2.2 Review of previous LUCC modeling in the Brazilian Amazonia

2.2.1 Land use factors statistical analyses

This section considers previous work on assessment of factors associated to land use change in Amazonia, focusing mainly on studies that cover the whole region. For other tropical forest areas, Kaimowitz and Angelsen (1998) present a broad review of deforestation models. One of the approaches reviewed is the use of *econometric methods*. Along this line, Reis and Guzmán (1994) developed a non-spatial econometric analysis of deforestation at the region wide level using municipal data. They found out that *population density, road network density and extension of cultivated areas* were the most important factors.

Also using econometric methods, Andersen and Reis (1997) analyzed the determining factors of deforestation from 1975 to 1995, using municipal data at a region-wide level. Results indicate that deforestation started by a governmental action associated to road construction and establishment of development programs. Later on, local market forces turned out to be the more important factor, replacing government action as the main drivers for deforestation. Their model indicates that land use change is caused by eleven factors: *distance to the federal capital, road length, earlier deforestation in the area, earlier deforestation in neighboring municipalities, rural population density, land prices, urban GDP growth, size of cattle herd, change in the size of cattle herd, change in agricultural production, and change in land prices*.

Pfaff (1999) analyzed the determining factors of deforestation using an econometric model based on municipal data from 1978 to 1988, associated to deforestation data obtained from remote sensing surveys, covering the whole region. His results indicate the relevance of biophysical variables (*soil quality and vegetation type*), transportation-related variables (*road network density in the area and in its neighbours*), and government-related variables (*development policies*). *Population density* was only considered a significant factor when the model used a non-linear (quadratic) formulation. The author concluded that, in a newly occupied area, earlier migration has a stronger impact on deforestation than latter settlements.

Margulis (2004) presents an econometric model that analyses the Amazon occupation quantifying the relationships in space and time of the main agricultural activities (wood extraction, pasture and crops), and their effects in the region deforestation. He also considers the *ecological and economic factors* conditioning these relationships. Models are based on municipal panel data from five agricultural census, from 1970 to 1996, complemented by geo-ecological information (*vegetal cover, relief, average rainfall and rainfall in June*), and transport costs (*transport cost to São Paulo by roads*). Results indicate: (a) no evidence of precedence between the wood extraction and pasture activities; (b) rainfall seems to be the major agro-ecological determinant; (c) reducing transportation cost induces intensification, but results were not conclusive in relation to intensification increasing or decreasing deforestation.

The second type of research on causes of land use change in Amazonia studies social factors based on municipal data and remote sensing. Perz and Skole (2003) developed a spatial regression model for secondary vegetation using *social indicators* as determining factors. They used demographic (1980 and 1991) and agricultural (1980 and 1985) census data, aggregated at the municipal level. The results show that the factors have a significant spatial variation among the three sub-regions considered by the authors (*remote, frontier, consolidated*). Their study points out that analysis of factors that influence land use change in Amazonia should consider regional differences.

A third line of work use regular cells as analysis units. Laurance et al. (2002) performs statistical analysis to assess the relative importance of 10 factors at two spatial resolutions: 50 x 50 km2 and 20 x 20 km2. Their main conclusions were that, both at the coarser and finer scales, three factors are most relevant for deforestation: *population density, distance to roads and dry season extension*. Kirby et al. (2006) refines this analysis, and reinforce that both paved and non-paved roads are the main factor determining deforestation.

A fourth like of work are sub-regional analysis that consider specific areas and localized factors. Soares-Filho et al. (2002) analyzed a small colonist's area in North Mato Grosso during two time periods: 1986-1991 e 1991-1994. He constructed logistic regression models to analyze the determining factors for the following transitions: forest to deforested, deforested to secondary vegetation, and secondary vegetation to removal of secondary vegetation. The factors considered were: *vegetation type, soil fertility, distance to rivers, distance to main roads, distance to secondary roads, distance to deforestation, distance to secondary vegetation, urban attractiveness factor*. Mertens et al. (2002) studied the deforestation patterns in the São Felix do Xingu region (Pará State). He divided the study area in sub-regions according to patterns identified by remote sensing and identified different types of social actors. Then he applied logistic regression to analyze deforestation determining factors by type of actor in three time periods (before 1986, 1986-1992, 1992-1999). The factors analyzed were: *presence of colonization areas, presence of protected areas, presence of relief, distance to cities, distance to villages, distance to dairy industries, distance to main roads, distance to secondary roads, and distance to rivers*.

The statistical analysis performed in this thesis adds to these efforts in three aspects. Most studies in Amazonia are restricted to deforestation factors, while this work goes a step further, decomposing deforestation patterns into pasture, temporary and permanent agriculture. The Amazonian region is divided into three macro-regions to assess intra-regional differences in the relative importance of determining factors. In addition to the socio-economic and biophysical factors adopted in previous works, the model includes measures of connectivity to national markets and to ports, and introduces agrarian structure indicators that have not been used before. The approach will be fully described in Chapter 4.

2.2.2 Recent projective modeling and scenario building

In this section we focus on recent LUCC modeling efforts aiming at projecting land use change for the next decades in Amazonia. These studies analyze the impacts of the Federal Government infra-structure plans and include work by (Laurance et al., 2001), (Nepstad et al., 2001), (Andersen et al., 2002) and (Soares-Filho et al., 2006). For each model, we review the factors considered, the scenarios constructed, and the main results. We also discuss their different projective approaches.

Laurance et al. (2001) discuss the future of the Amazon using a simple GIS model based on the assumption that road infrastructure is the prime factor driving deforestation. Two alternative scenarios are considered, according to: (1) the extent of estimated degraded areas around existing and planned infra-structure; (2) the estimated impact of protected areas. The authors extrapolate linearly the empirical relationship between past spatial patterns of deforestation and distance to roads into the medium term future (2020). The model does not consider Amazonia's biophysical and socio-economic heterogeneity. Projected maps show uniform buffer shapes around existing and planned roads and other infra-structure across the whole region. Model results that included planned roads indicate that in 2020, 28% of the Amazon will be deforested or highly degraded in the optimist scenario, and 42% in the non-optimist scenario. The new infra-structure plans are responsible for an increase in the deforestation rate of 2,690 km2 per year in the optimist scenario, and 5,060 km2 per year in the pessimist scenario. The work is an example of confusing spatial determinants of land-use patterns with subjacent factors that condition the quantity of change.

Nepstad et al. (2001) also extrapolate past spatial patterns of deforestation to predict future rates, taking roads as the single predictor of deforestation. Based on corridors of 100 km centered at roads, the model predicts that the 6,245 km of planned federal roads would cause additional deforested area between 120,000 km2 (supposing the lower deforestation historical rates along major paved highways, 29%) and 270,000 km2 (supposing the lower deforestation historical rates along major paved highways, 58%) in the next 20 to 30 years.

Andersen et al. (2002) developed an econometric model of the deforestation dynamics in Amazonia, also employed to analyze the impacts of planned federal infrastructure. Using municipality level data from 1970 to 1999, the authors propose a dynamic spatial econometric model with six endogenous (dependent) variables: land clearing, rural and urban GDP growth, rural and urban population growth and cattle herd growth. The model uses socio-economic data and federal credit as independent variables. The results are different from those of Laurance et al. (2001) and Nepstad et al. (2001). Model results indicate that the planned federal infrastructure will encourage agricultural intensification and urban growth, and reduce the total cleared area compared to the situation when the plan is not implemented. The main differences between Andersen et al. (2002) and the other two models are: (a) the inclusion of socio-economic variables, such as population, income and land prices; and (b) the clear separation of the effects of road building and the effects of subsided credit. Inclusion of existing cleared land in the equations enables a distinction between infra-structure impact in pristine areas and in settled areas. The model results point out that the improvement of existing roads drives up land prices, encourages more intensive land use, and thus leads to economic gains. The main disadvantage of such modeling approach is not being spatially-explicit.

A different approach was adopted by Soares-Filho et al (2006, 2005). The authors developed a two component model, separating the computation of deforestation rates from the allocation of such rates in space. The authors analyzed six scenarios representing different levels of governance. Scenarios differ through the impact of law enforcement in private areas and expansion of protected areas. There are two extreme scenarios: the total governance scenario and the business as usual one. The total governance scenario hypothesizes a gradual decrease in deforestation rates and that deforestation in private lands is limited to 50% of forest areas. This scenario also envisages the expansion of protected areas to 41% of the total forest area and that 100% of the forest in protected areas is kept intact. In the extreme business as usual scenario, protected areas lose up to 40% of their forest areas. Intermediary scenarios incorporate a subset of the governance measures into a business as usual scenario.

To *compute the deforestation rates*, the Amazon basin was subdivided into 40 sub-regions. The model projects deforestation rates for each sub-region using historical trends and an additional positive factor to incorporate the effect of new infrastructure. Rates vary according to the scenario assumption regarding the expected trend (increasing or decreasing) and the level of law enforcement in private and protected areas. Overall rates for the whole Amazonia are a composition of individual sub-region rates. The *allocation model* considers that proximity to urban centers increase deforestation. Deforestation is smaller closer to low flooded terrain and elevated and steep slopes. It is not influenced by soil quality and vegetation type, and does not necessarily follow the major river networks. Distance to previously deforested land and distance to roads (including both paved and non-paved) are the strongest predictors of deforestation, and indigenous reserves are important in hindering deforestation.

Model results indicate that paving the Manaus–Porto Velho road, which traverses a region with few protected areas and little human settlements, promotes more deforestation than paving the Cuiabá–Santarém road. The business as usual model predicts removal of 40% of total forest cover by 2050; around 250,000 km2 of this deforestation would be credited to new paving projects. The intermediary governance scenarios indicate that expansion and enforcement of protected areas could avoid one-third of projected deforestation, but private land conservation is also necessary to reduce deforestation. The authors suggest that international community can play a role in reducing deforestation, through international market pressures for ecological sound land management for beef, soybeans and other food commodities. This work is a step forward, since it incorporates the concept of governance in the scenario modeling. From a modeling perspective, the authors use the same assumption as Laurance (2001) and Nepstad (2001), about the effects of local spatial determinants of change (roads and the existence protected areas) into overall deforestation rates, as will be discussed below.

In summary, the projection of quantity of change presented by Laurance (2001) and Nepstad (2001) assumes that past *spatial* patterns of deforestation will occur again in pristine areas. They also assume that spatial determinants are a cause per se of deforestation. Soares-Filho et al. (2005) also adopt as a premise that the overall deforestation rate increases when roads are paved, according to past spatial patterns, and decreases as a overall measure when protected areas are created. On the other hand, Andersen (2002) and Margulis (2004) indicate that paving roads does not always cause an increase in deforestation rates, since this might cause intensification of land use in more consolidated areas. The model of Soares-Filho et al. (2005) assumes that the impact of road paving is stronger in pristine areas, but does not account for intensification and possible negative feedbacks on deforestation rates in more consolidated areas.

Using past patterns to determine the amount of change does not take into consideration that new Amazon frontiers are different from the frontiers of the 1970s (Becker, 2005). The amount of change over the whole region is conditioned by a web of subjacent factors, including international, national and local demand for beef, wood and soybeans, that act as a counterforce to institutional, law enforcement, monitoring and control measures. Local political and economical forces are also important players (Becker, 2004). Latest evidence from deforestation data (INPE, 2005) indicates the existence of intra-regional interaction. Governance policies applied to one region, such as the creation of protected areas, might induce the occupation of another area. Thus, the creation of protected areas does not necessarily result in an overall decrease of deforestation rates, since there are pristine areas to be occupied. Improving conditions in a given area, such as paving roads and strengthening productive chains, can *favour occupation of that area in detriment of another*. Previous studies do not capture these processes, as they are based on rigid premises regarding the effects of public policies. Such intra-regional interactions need to be better understood. In our model, the intra-regional interactions emerge as a result of the following premises:

- *The Amazonian region is divided into three large macro-regions*: the Densely Populated Arch, the Central Amazonia and Occidental Amazonia (Becker, 2005). The three macro-regions are used to explore the non-uniform temporal and spatial distribution of change across the region, through regionalized demand scenarios. (Soares-Filho et al., 2006) divides their study area into 40 sub-regions, thus limiting the possible spatial interactions to smaller areas. The use of larger regions also allows the emergence of internal differences in terms of speed of change, not constrained by past trends.

- *The demand for deforestation is an exogenous variable for the model.* The model considers that the demand for deforestation is related to external market forces. Demand increase and decrease are proxies of market constraints, representing higher or lower pressure for forest conversion determined by the national and international agribusiness. This premise contrasts with previous work (Laurance et al., 2001) (Nepstad et al., 2001), where the demand for deforestation is calculated based on road expansion and impact on protected areas.

- *Separation between the spatial aspects of change and the temporal distribution of the amount of change.* In the model of Soares-Filho et al. (2005), the deforestation rates are calculated based on a combination of external market forces and the effects of road paving, law enforcement and creation of protected areas. By contrast, in this work, roads and protected areas are incorporated only as spatial determinants of location of change. They do not influence overall deforestation rates. This approach allows the analysis of both local and regional effects related to road paving and law enforcement across the different regions.

This thesis analyzes the impact on projected deforestation patterns of accessibility factors, alternative policies, and market constraints in five alternative scenario explorations. Each exploration emphasizes a different aspect of the Amazonia occupation process. The modeling approach is presented in Chapter 5.

CHAPTER 3

STUDY AREA AND DATABASE CONTRUCTION

3.1 Study Area

The study area is the whole Brazilian Amazonia rain forest area. All variables representing land use patterns and their potential determining factors are decomposed into regular cells of 25 x 25 km^2 (*fine scale resolution*) and 100 x 100 km^2 (*coarse scale resolution*) covering the whole study area, as illustrated in Figure 3.1. The study area excludes cells with a major proportion of non-forest vegetation, outside the Brazilian Amazon, and clouded areas, according to the 1997 deforestation map compiled by INPE (INPE, 2005)). The fine scale resolution has 5.682 cells of 625 km^2 each, and the coarse resolution 363 cells of 10.000 km^2 each.

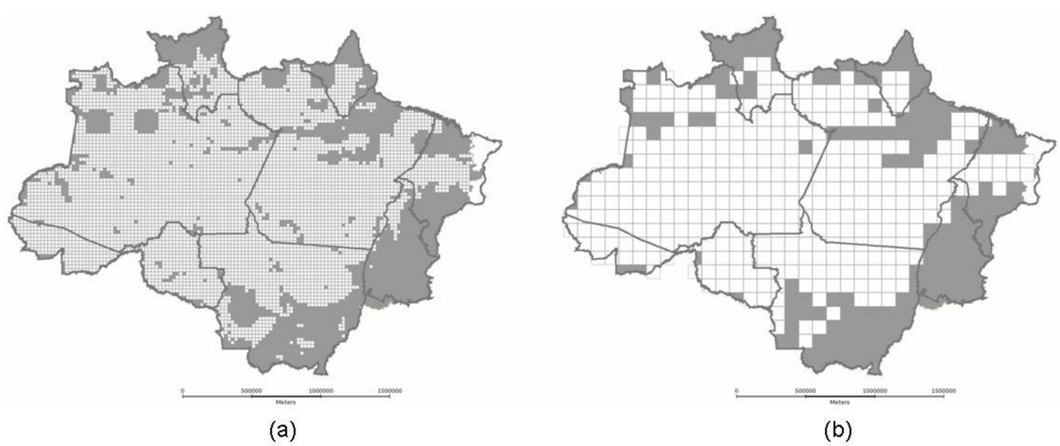


FIGURE 3.1 – Study area: (a) 25 x 25 km^2; (b) 100 x 100 km^2 cells.

The remaining of this section is organized as follow. Section 3.2 presents the land use data sources and the process of combining them into the regular cells. Section 3.3 presents the potential determinant factor data sources and the process of computing the cell values.

3.2 Land use patterns

3.2.1 Deforested area patterns

Using a map that presents the accumulated deforestation until 1997 derived by INPE using LANDSAT TM images (INPE, 2005), the proportion of forest and deforested for each 25 x 25 km^2 and 100 x 100 km^2 cells were computed. Figure 3.2 illustrates the fine resolution resulting patterns.

3.2.2 Agricultural land use patterns

The deforested area pattern of were decomposed into the main agricultural uses (pasture, temporary agriculture, permanent agriculture, non-used agricultural areas, and planted forest), combining the remote sensing based data from INPE (INPE, 2005) and census information from Agricultural Census of 1996 (IBGE, 1996). Municipality based census data was converted from polygon-based data to the cell space of 25 x 25 km^2. Comparison between agricultural areas reported by census data and measured by remote sensing showed disagreements in total area (INPE, 2005). The total agricultural area for each municipality was taken from the remote sensing survey, and the proportion of each agricultural land-use category was taken from the census. The conversion process assumed that the proportion of land-use types is uniformly distributed over the deforested areas of the municipality. Figures 3.3, 3.4 and 3.5 present the resulting pasture, temporary agriculture and permanent agriculture patterns, respectively.

Pasture is spread over the whole deforested area, being the major land use in 1996/1997. It covers approximately 70% of total deforested area, in agreement with the estimates presented by Margulis (2004). Temporary crops represent approximately 13% of the deforested area, and permanent crops approximately 3% of the deforested area. Agricultural patterns are considerably more concentrated than pasture. Table 3.1 presents quantitative indicators of the heterogeneity of distribution of the three land use patterns across the region, considering different Federative States.

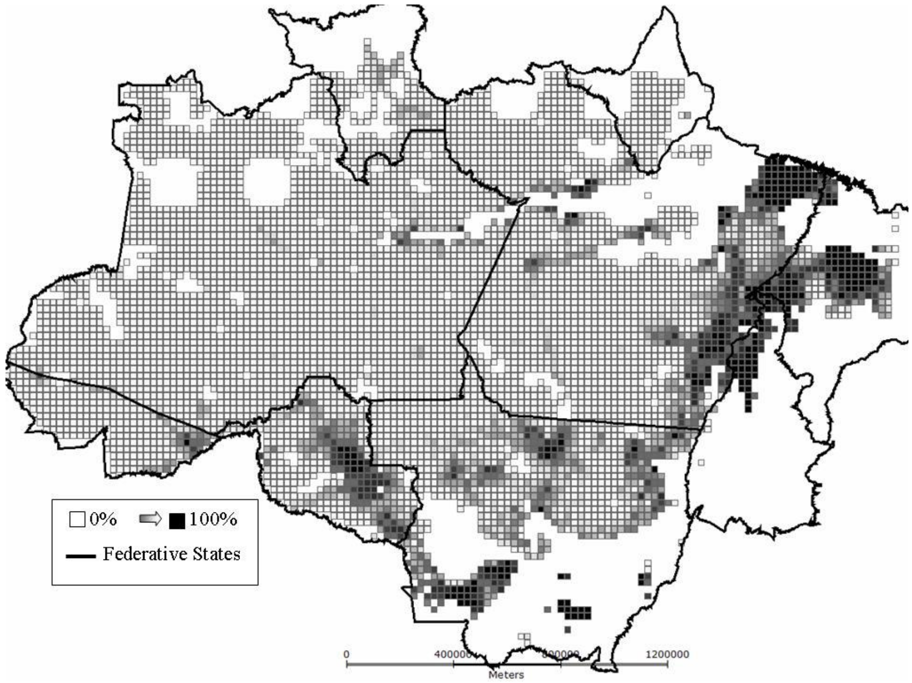


FIGURE 3.2 – Deforested areas spatial pattern in 1997 (25 x 25 km^2).

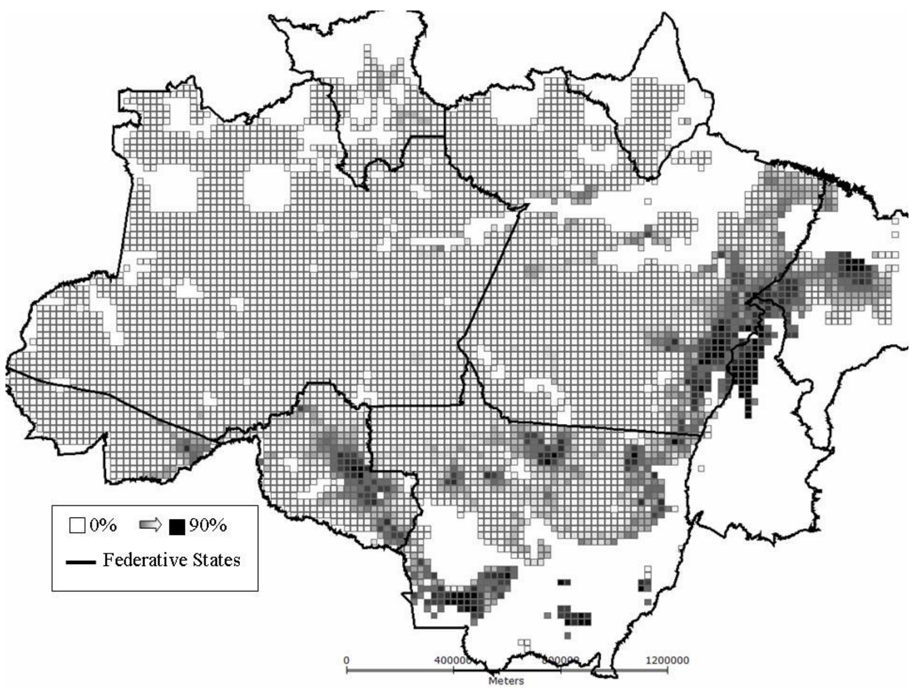


FIGURE 3.3 – Pasture pattern in 1996/1997 (25 x 25 km^2).

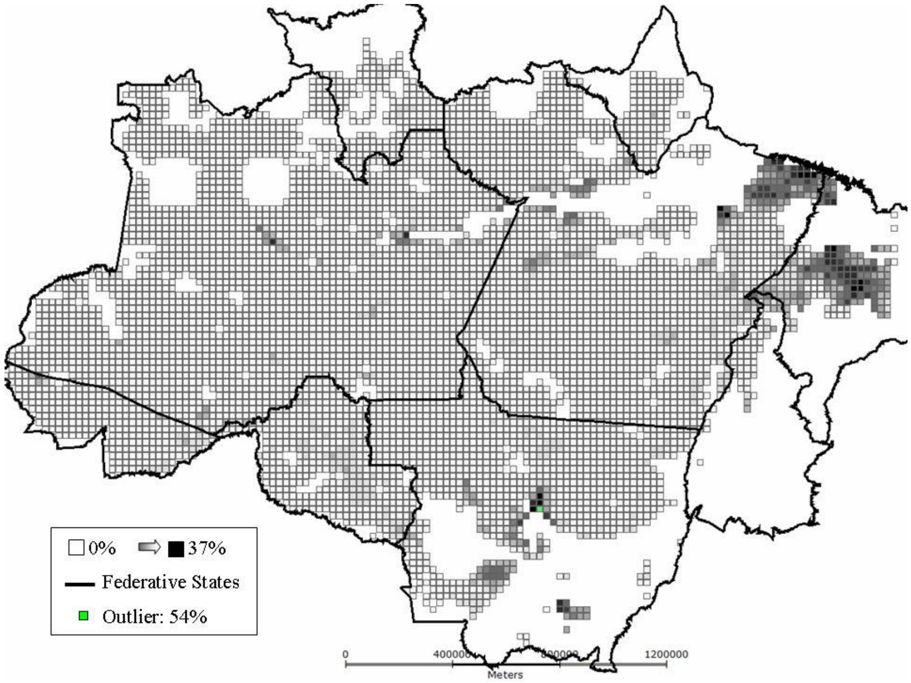


FIGURE 3.4 – Temporary agriculture pattern in1996/1997 (25 x 25 km^2).

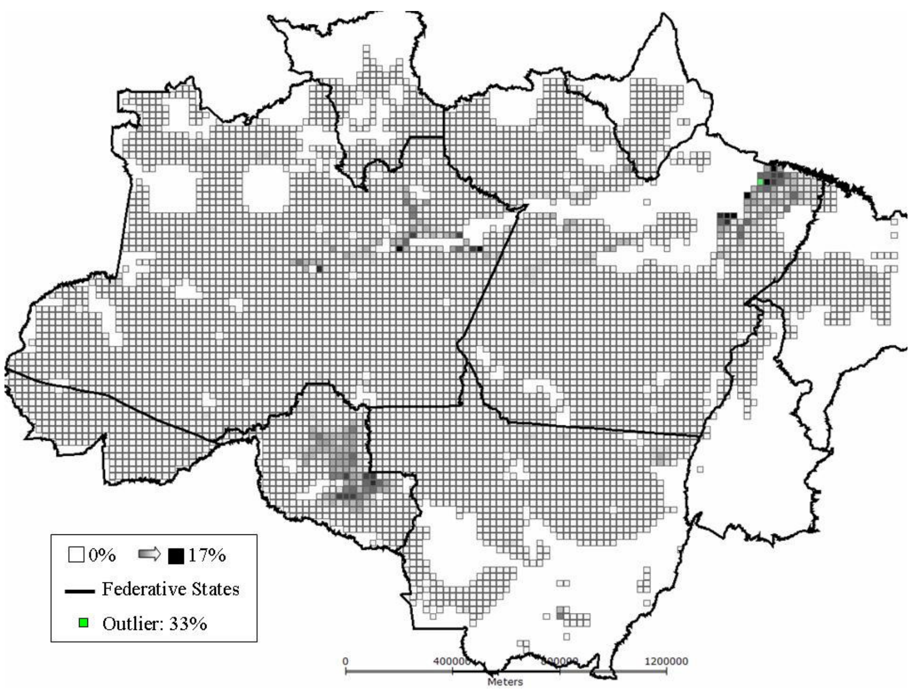


FIGURE 3.5 Permanent Agriculture pattern in 1996/1997 (25 x 25 km^2).

TABLE 3.1 - Comparison of quantitative indicators of land use heterogeneity across the region. The indicator is the number of 25 x 25 km^2 cells occupied by different land uses.

State	Number of valid cells	Number of cells with more than 10% deforested	Number of cells with more than 10% pasture	Number of cells with more than 10% temporary agriculture	Number of cells with more than 10% permanent agriculture
Amazonas	2117	102	25	19	6
Pará	1559	485	407	99	13
Mato Grosso	842	507	450	54	0
Rondônia	348	186	166	1	9
Acre	232	43	36	0	0
Maranhão	170	153	140	104	0
Roraima	156	31	21	0	0
Amapa	99	6	1	0	0
Tocantins	59	56	56	6	0
Total	5582	1569	1302	283	28

Temporary crops are mostly concentrated the north-eastern area of the Pará and in Maranhão states. The state of Mato Grosso and the areas along the main rivers in the Amazonas state also present a significant area proportion of the temporary agriculture pattern. The temporary agriculture class we adopted encompasses around 80 types of temporary crops, and includes both subsistence and capitalized agriculture. According to the 1996 IBGE census information (IBGE, 1996), the temporary agriculture pattern seen in the south border of Mato Grosso is already related to the capitalized agriculture (especially soybeans) expansion in forest areas (Becker, 2001). On the other hand, in old occupation areas such as the North-east of Pará and Maranhão, and also in some municipalities in the north of Mato Grosso, agrarian structure is dominated by small holders. According to IBGE database (IBGE, 1996), dominant temporary crops were manioc and corn in 1996. Permanent crops occupy a smaller area than the other two land uses, concentrated in the old occupation areas of the north-eastern of Pará state and along the Amazon River, and in Rondônia, where most occupation is related to official settlement projects (Becker, 2005). These specific characteristics of the distribution of the temporary and permanent agriculture patterns reinforced the need to include agrarian structure indicators in our analysis, as discussed in the next section.

3.3 Potential determinant factors

The spatially explicit database includes 50 environmental and socio-economic variables that could potentially explain macro and intra-regional differences in land use patterns. The complete list of variables is shown in Table 3.1 . These variables are grouped into seven categories:

- *Accessibility to markets*: distance to roads, rivers and urban centres, connection to national markets and ports, derived from IBGE (Brazilian Institute for Geography and Statistics) cartographic maps.

- *Economic attractiveness*: capacity to attract new occupation areas, measured as distance to timber-production facilities and to mineral deposits. Timber-production facility data was provided by IBAMA (Brazilian Institute of Environment and Natural Resources) and mineral deposit data by CPRM (Brazilian Geological Service).

- *Demographical*: population density and recent migration, based on the 1991 municipal census and the 1996 municipal population count by IBGE.

- *Technological*: technological level of farmers, using indicators such as density of tractors per area and quantity of fertilizers per area. These measures use the IBGE 1996 agricultural census.

- *Agrarian Structure*: land distribution indicators, indicating the proportion (in terms of number of properties and in terms of area inside the municipality) of small (less than 200 ha), medium (200 ha to 1000 ha) and large (greater than 1000 ha) farms. These measures use the IBGE 1996 agricultural census.

- *Public Policy*: factors related to governmental actions, such as indicators associated to planned settlements, and protection areas. Settlements information is provided by INCRA (Brazilian Institute of Colonization and Homestead). Protected areas combine information from IBAMA, regarding Conservation

Units, and FUNAI (Brazilian National Foundation for Indigenous Peoples), regarding Indigenous Lands.

- *Environmental*: variables related to land conditions such as soil fertility and climate. Fertility data is derived from IBGE natural resources maps, integrating soil type, morphology, texture, and drainage information. Climate data source is INMET (Brazilian Institute of Meteorology).

TABLE 3.2 – Potential land use determining factors in the cellular database (25 x 25 km^2 cells and 100 x 100 km^2 cells)

Category	Cellular database variable	Description	Source
Accessibility to Markets	`dist_non_paved_road`	Euclidean distance to nearest non-paved road	IBGE
	`dist_paved_roads`	Euclidean distance to nearest paved road	IBGE
	`dist_roads`	Euclidean distance to nearest road	IBGE
	`dist_rivers`	Euclidean distance to nearest large river	IBGE
	`dist_urban`	Euclidean distance to nearest urban centre	IBGE
	`conn_sp_noweight`	Connection to SP (national market) though the road network	
	`conn_sp`	Connection to SP (national market) though the road network considering the type pf road	IBGE
	`conn_ne_noweight`	Connection to Northeast (national market) though the road network	IBGE
	`conn_ne`	Connection to the Northeast (national market) though the road network considering the type pf road	IBGE
	`conn_mkt_noweight`	Maximum connection to one of the two markets: SP or Northeast	IBGE
	`conn_mkt`	Maximum connection to one of the two markets: SP or Northeast, considering the type of road	IBGE
	`conn_ports noweight`	Maximum connection to ports	IBGE
	`conn_ports`	Maximum connection to port considering the type of road	IBGE
Economical	`dist_wood`		IBAMA
attractiveness	`dist_mineral`	Euclidean distance to all types of mineral deposits	CPRM
Demographical	`demo_dens_91`	Population density in 1991	IBGE
	`demo _dens_96`	Population density in 1996	IBGE
	`demo _migr_91`	Percentage of migrants in 1991	IBGE
	`demo _migr_96`	Percentage of migrants in 1996	IBGE
	`demo _tx_urban_96`	Proportion of urban population in 1996	IBGE
Technological	`tec_trat_prop`	Number of tractor per number of property owners	IBGE
	`tech_trat_area_plan t`	Number of tractor per total planted area in the municipality	IBGE
	`tech_ass_prop`	Number of properties that receive technical assistance per number of property owners	IBGE
	`tech_ass_area_plant`	Number of properties that receive technical assistance per total planted area in the municipality	IBGE
Agrarian	`agr_small`	Percentage of small, medium and large properties	IBGE
Structure	`agr_medium`	in terms of municipalities area	IBGE
	`agr_large`		IBGE
	`agr_nr_small`	Percentage of small, medium and large properties	IBGE
	`agr_nr_medium`	in terms of number of properties in the municipalities	IBGE
	`agr_nr_large`		IBGE
Political	`settl_nfamilies_70_ 99`	Number of settled families until 1999	INCRA
	`setl_area_70_99`	Area of settlements until 1999	INCRA
	`prot_all`	Percentage of protected area (any type of CU or IL)	IBAMA FUNAI
	`prot_il`	Percentage of indigenous lands area	

	prot_cu	Percentage of Conservation Units	
Environmental	soil_fert	Percentage of soils of high and medium fertility	IBGE
	soil_fert_low	Percentage of soils of low fertility	IBGE
	soil_wet	Percentage of soils of "várzea"	IBGE
	clima_q1_temp	Jan, Feb, Mar, Apr temperature average	INMET
	clima_q2_temp	May, Jun, Jul, Aug temperature average	INMET
	clima_q3_temp	Sep, Oct, Nov, Dec temperature average	INMET
	clima_q1_umidade	Jan, Feb, Mar, Apr humidity average	INMET
	clima_q2_umidade	May, Jun, Jul, Aug humidity average	INMET
	clima_q3_umidade	Sep, Oct, Nov, Dec humidity average	INMET
	clima_q1_precip	Jan, Feb, Mar, Apr precipitation total	INMET
	clima_q2_precip	May, Jun, Jul, Aug precipitation total	INMET
	clima_q3_precip	Sep, Oct, Nov, Dec precipitation total	INMET
	clima_precip	Average precipitation in the three drier subsequent months of the year	INMET
	clima_humid	Average humidity in the three drier subsequent months of the year	INMET
	clima_temp	Average humidity in the three lowest temperature subsequent months of the year	INMET

Sections 3.3.1 to 3.3.7 present the process of aggregating such variables into the regular 25 x 25 km^2 cells, and illustrate graphically the main factors in each category. Once computed in the fine resolution, all the variables were aggregated to the coarse resolution. For each variable, each 100 x 100 km^2 cell receives the average value of sixteen fine resolution 25 x 25 km^2 cells.

These variables were compiled initially to support the statistical analysis of land use determining factors. As land use data relates to the 1996/1997 period, the data sources used to construct the cellular database are compatible with theses dates, according to availability. However, some of the variables are multi-temporal to support the dynamic modeling and scenario construction discussed in Chapter 5. These dynamic variables are: *connection to markets, connection to ports, distance to roads, distance to paved roads, distance to unpaved roads and protected areas*. Section 5.2.5.3 presents the temporal changes in these variables, in the scope of the scenarios explored in this thesis.

3.3.1 Accessibility to market factors

The measures of accessibility to markets include *connections to markets and ports*. These variables deserved special attention, as they allow exploration of one of the basic hypotheses of this paper: insertion in the Brazilian productive system is essential to explain deforestation patterns and intra-regional heterogeneity. Each cell has connectivity indicators that are inversely proportional to the minimum path distance from each cell to national markets and to ports, using the roads network. We distinguished paved from non-paved roads (non-paved roads are supposed to double the distances). Figure 3.6 illustrate the connection to markets variable. Figure 3.7 illustrates the connection to ports variable. These measures were computed using the generalized proximity matrix (GPM), described in (Aguiar et al., 2003). The GPM is an extension of the spatial weights matrix used in many spatial analysis methods (Bailey and Gattrel, 1995) where the spatial relations are computed taking into account not only absolute space relations (such as Euclidean distance), but also relative space relations (such as topological connection on a network). Currently, most spatial data structures and spatial analytical methods used in GIS, and also in LUCC modeling, embody the notion of space as a set of absolute locations in a Cartesian coordinate system, thus failing to incorporate spatial relations dependent on topological connections and network fluxes. The connectivity measures incorporate topological spatial relations and fluxes in road networks in the analysis of land use determining factors. As pointed by Verburg et al., (2004), understanding the role of networks is essential to understanding land-use structure.

Additional measures of accessibility to markets include Euclidean *distances to paved and unpaved roads, rivers and urban centres*. Distance to urban centres is a proxy of accessibility to local markets and basic services. As illustrated in Figure 3.8, most urban centres concentrate in the Arch macro-region, and along the main rivers. In the Central area, few localities are identified. Figures 3.7 to 3.9 illustrate, respectively, the distance to road, distance to paved roads and distance to main rivers variables.

3.3.2 Economical attractiveness factors

Distance to timber-production facilities and to mineral deposits the minimum are measured as Euclidean distance from each cell to the nearest timber-production facilities. Distances from each cell to mineral deposits were measured in the same way. Figures 3.10 and 3.13 illustrate these two factors. Timber production sites were concentrated in Rondônia, Mato Grosso and northeast Pará States. Mineral deposits present a more intense concentration in southeastern Pará and Rondônia States.

3.3.3 Demographical factors

Demographical derived from municipality level data. Variable values in the 25 km^2 cells were computed taking the average of the corresponding values in each municipality weighted by the area intersection between the municipalities and the cell. Figure 3.14 illustrates the population density according to the 1996 IBGE census. Cells with population density *higher than 3 people per* km^2 are highlighted. Population densities are low, as Figure 3.14, with concentration in Belém and Manaus, in old occupation areas (such as in the north-eastern part of Pará and Maranhão States), and areas of governmental settlement projects (Rondônia, for instance).

3.3.4 Technological factors

Technological variables are also derived from municipality level data. Variable values in the 25 km^2 cells were computed taking the average of the corresponding values in each municipality (e.g., average number of tractors per farm) weighted by the area intersection between the municipalities and the cell. Figures 3.15 illustrate average number of tractors per farm variable and 3.16 illustrate the technical assistance variable. They highlight, respectively, areas in which the average number of tractors per farm is greater than 0.50, and areas in which more than 30% of the farms received technical assistance in 1996. As the figures show, according to 1996 data, both conditions hold in the southern part of Mato Grosso State.

3.3.5 Agrarian Structure factors

The agrarian structure indicators are based on municipality level information. The percentage of small, medium and large farms in area was computed in relation to the total area of farms inside the municipality. It disregards non-farm areas inside the municipality such as protected areas, or land owned by the Federal government. Thus the small, medium and large categories sum 100%. Alternative variables were also computed giving the proportion of the number small, medium and large farms in relation to the total number of farms in the municipality. These six variables are indicators of the dominance of a certain type of actor in a certain region.

Figure 3.17 and 3.18 illustrate two of these variables: percentage of small farms in area and number. Analyzed together they are also indicators the land concentration. Figure 3.17 highlights areas with less than 40% of small farms in relation to the *area of farms* in the municipality. Figure 3.18 highlights areas with less than 40% of small farms in relation *the number* of farms in the municipality. In the Arch, in general, only in Rondônia and north-eastern Pará small farms have a major proportion of the land. On the other hand, only in the south of Mato Grosso State they are minority in number.

3.3.6 Public Policy factors

Settlements variables are also derived from municipality level data. Variable values in the 25 km2 cells were computed taking the average of the corresponding values in each municipality (e.g., number of settled families, area of settled families) weighted by the area intersection between the municipalities and the cell. Figure 3.19 illustrates the number of settled families' variable, highlighting areas in which more than 50 families were settled from 1970 to 1999.

The measure of environmental protection areas uses the percentage of each cell that intercepts a protected area. Protected areas includes: Indigenous Lands and Federal and State Conservation Units. Figure 3.20 illustrate the protected areas variable.

3.3.7 Environmental factors

Soil variables use a fertility classification based on IBGE (Brazilian Institute for Geography and Statistics) soils map that considers soil type, morphology, texture, and drainage information. Based on this classification, we grouped the soils into three categories: fertile soils, non-fertile soils, and wetland soils. The soil variables considered in our analysis represent the proportion of each of these categories in the 25 km^2 cells. Figure 3.20 illustrate the fertile soils variable, and Figure 3.21 the wet soils variable. Fertile soils are concentrated on Mato Grosso, Rondônia, and several parts of Pará (including the Transamazônica, São Felix, and the old occupation area in the north-eastern part of the State,). In the Amazonas State, Apuí has better soils. Wet soils are mostly located in the Occidental Amazonia.

Climate data uses monthly averages of precipitation, humidity and temperature from 1961 to 1990, on a grid with a spacing of 0.25 degrees of latitude and longitude. The humidity and precipitation data was converted into 25 km2 cells by computing the intensity of the dry season in each cell. The dry season does not occur at the same period in each cell, and varies from June-July-August in the state of Mato Grosso region to November-December-January on the state of Roraima. The climate indicator for each cell is a measure that accounts for these differences, by taking the average of the three drier and consecutive months in each cell. Figure 3.23 and 3.24 illustrate the humidity and precipitation variables computed this way.

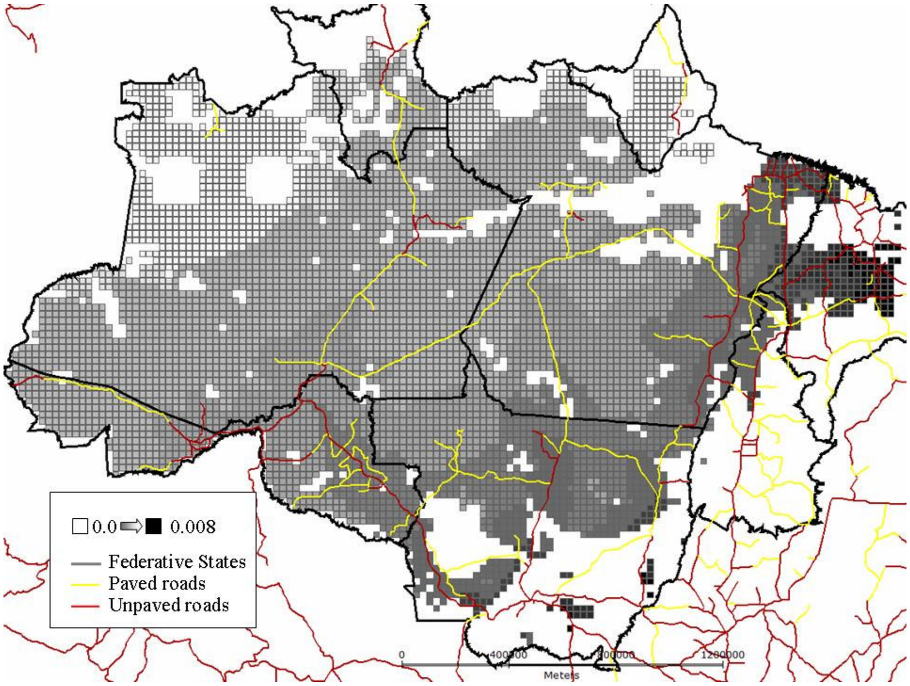


FIGURE 3.6: Indicator of connectivity to national markets (São Paulo and Northeast) in 1997 (source of road network: IBGE).

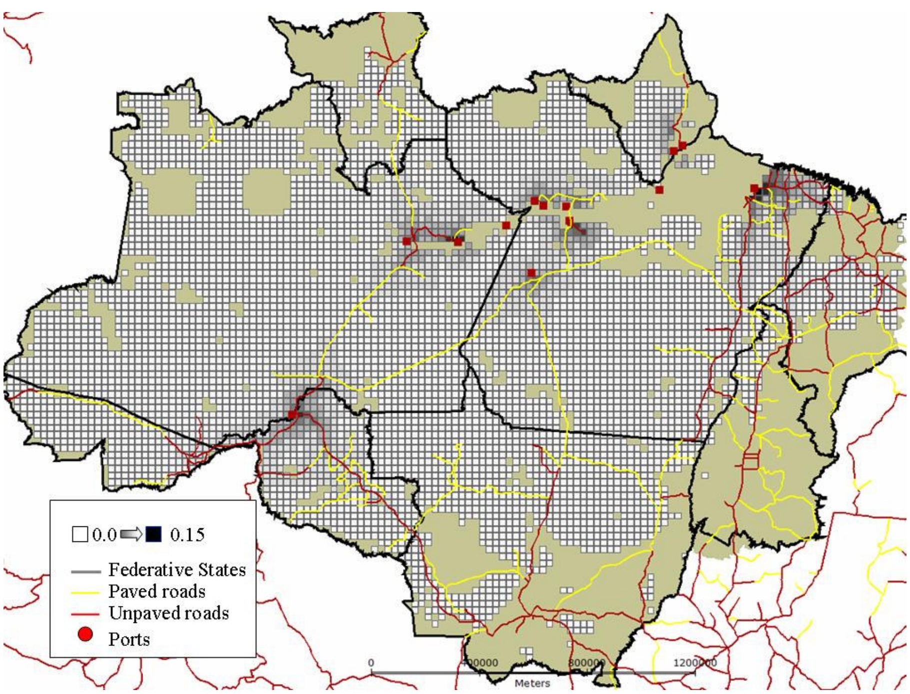


FIGURE 3.7 – Indicator of connectivity to Amazonia ports in 1997 (source of road network: IBGE).

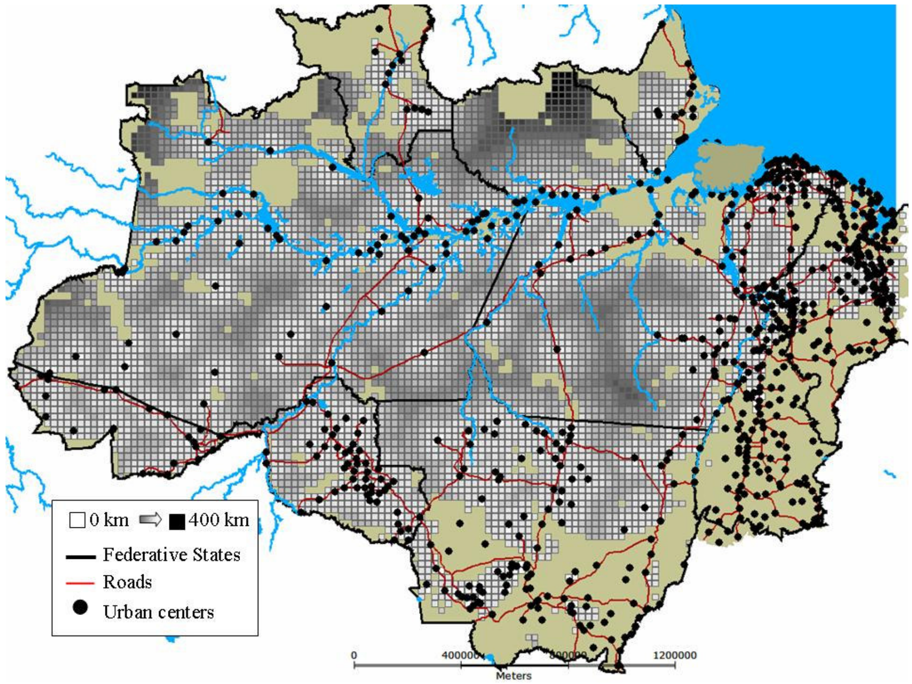


FIGURE 3.8 – Distance to urban centres in 1997 (data source: IBGE).

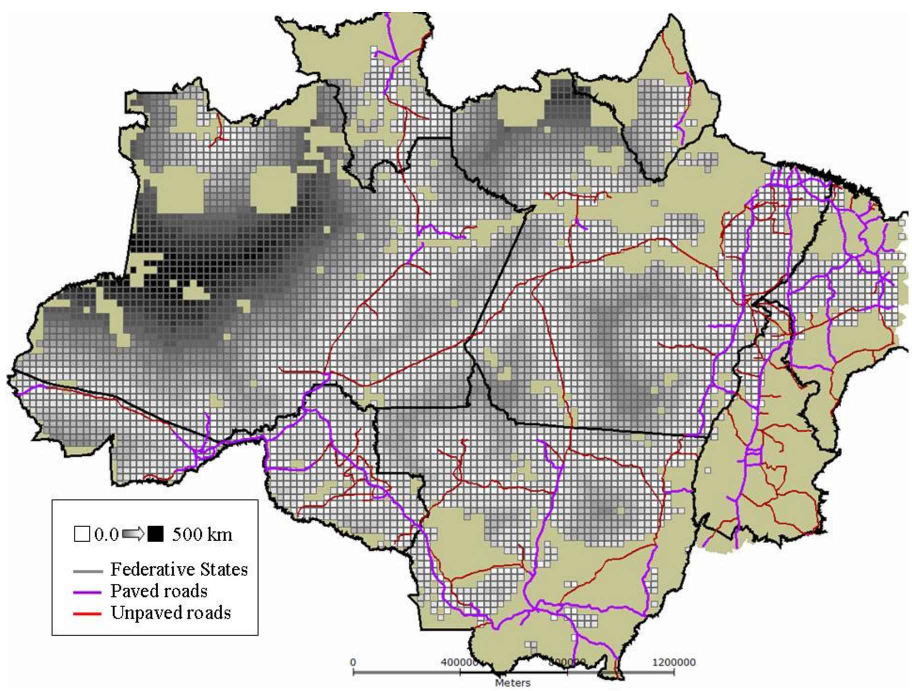


FIGURE 3.9 – Distance to roads in 1997 (data source: IBGE).

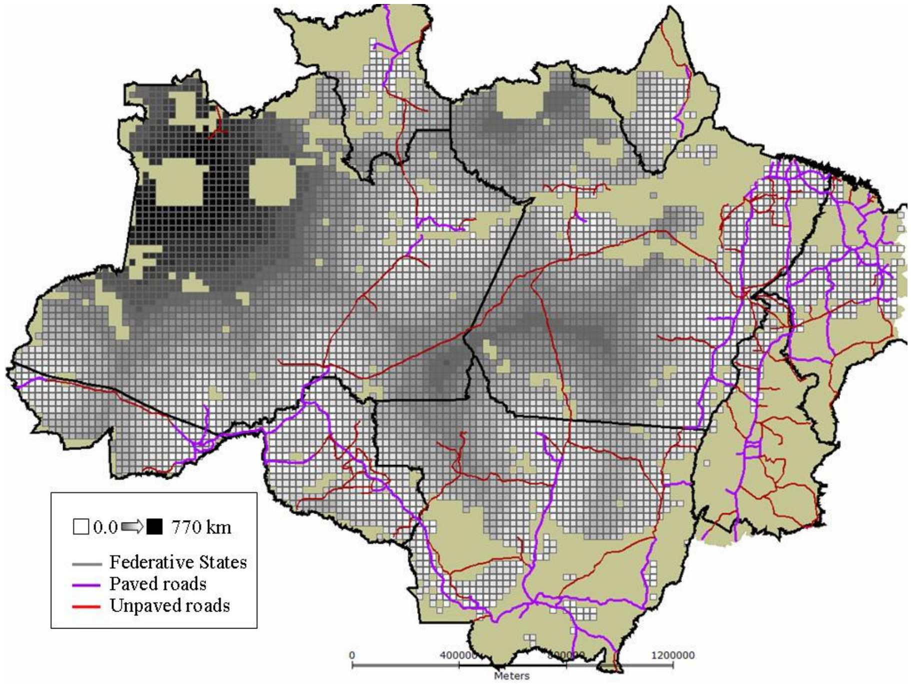


FIGURE 3.10 – Distance to paved roads in 1997 (data source: IBGE).

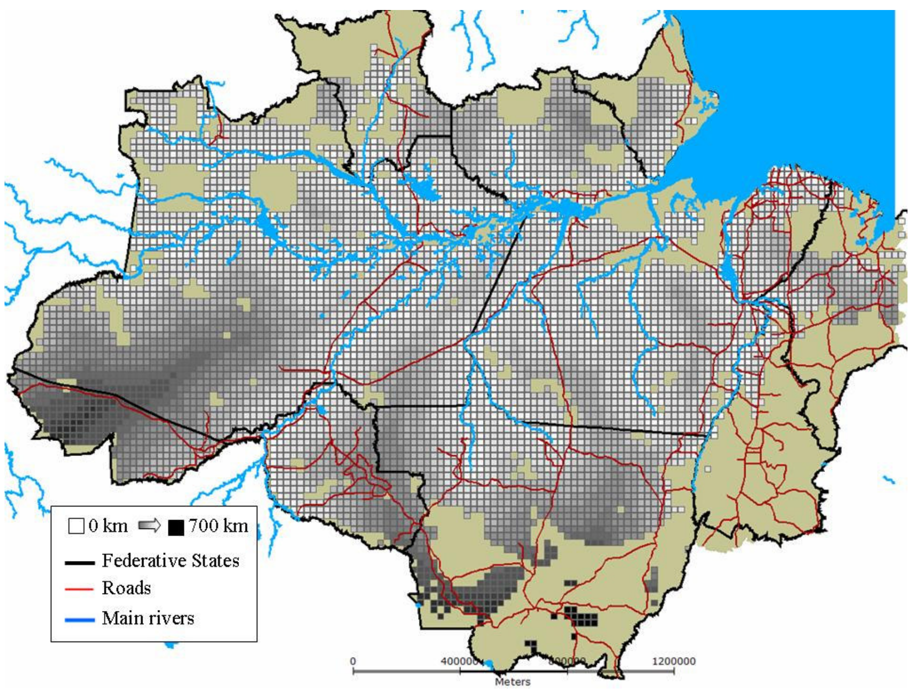


FIGURE 3.11 – Distance to main rivers (data source: IBGE).

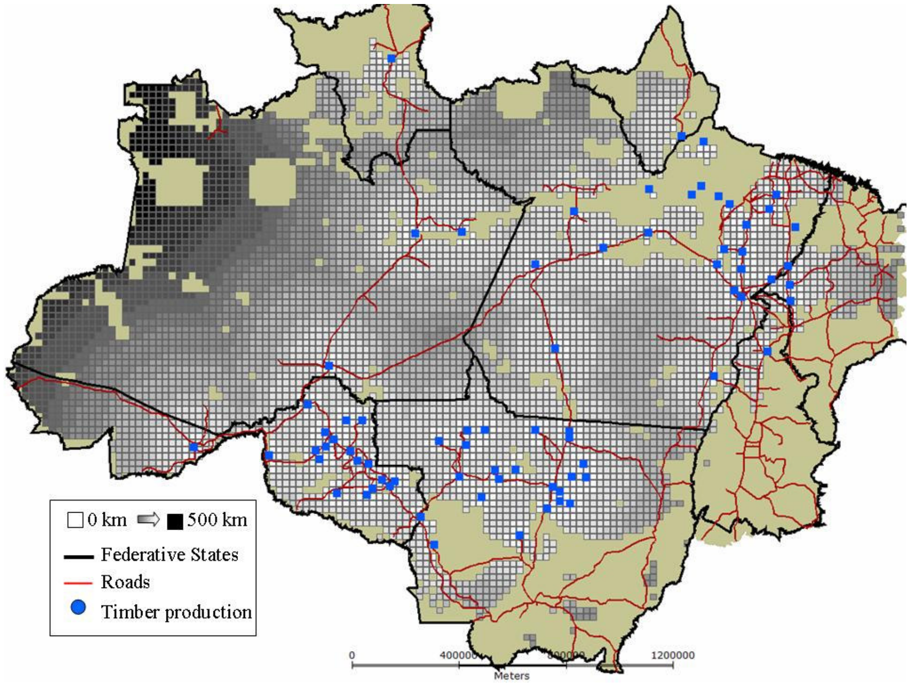


FIGURE 3.12 –Distance to timber production sites in 1997 (data source: MMA)

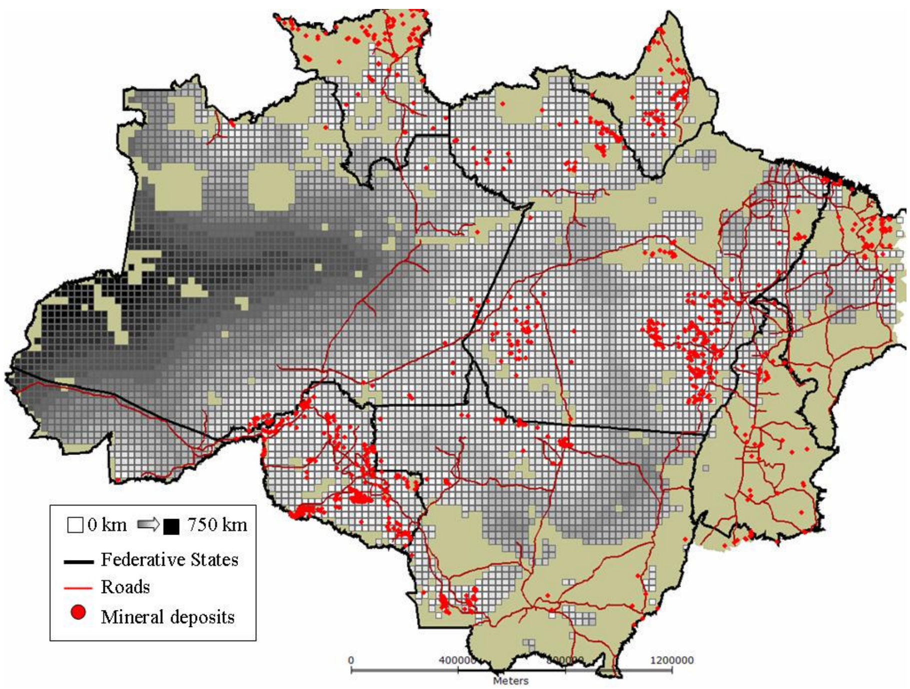


FIGURE 3.13 – Distance to mineral deposits (data source: CPRM).

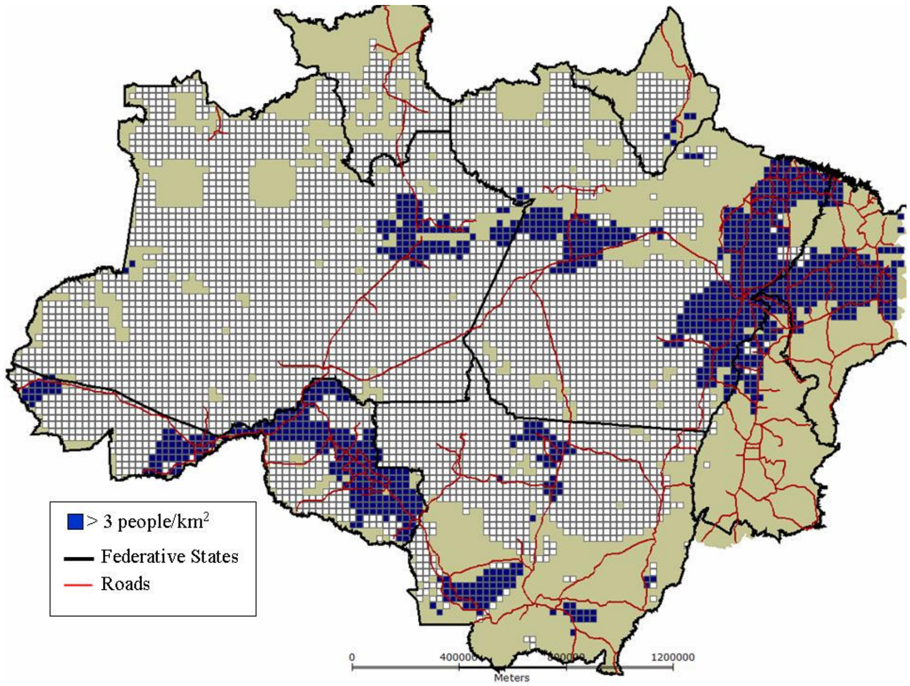


FIGURE 3.14 - Population density in 1996 (data source: IBGE Population Counting 1996).

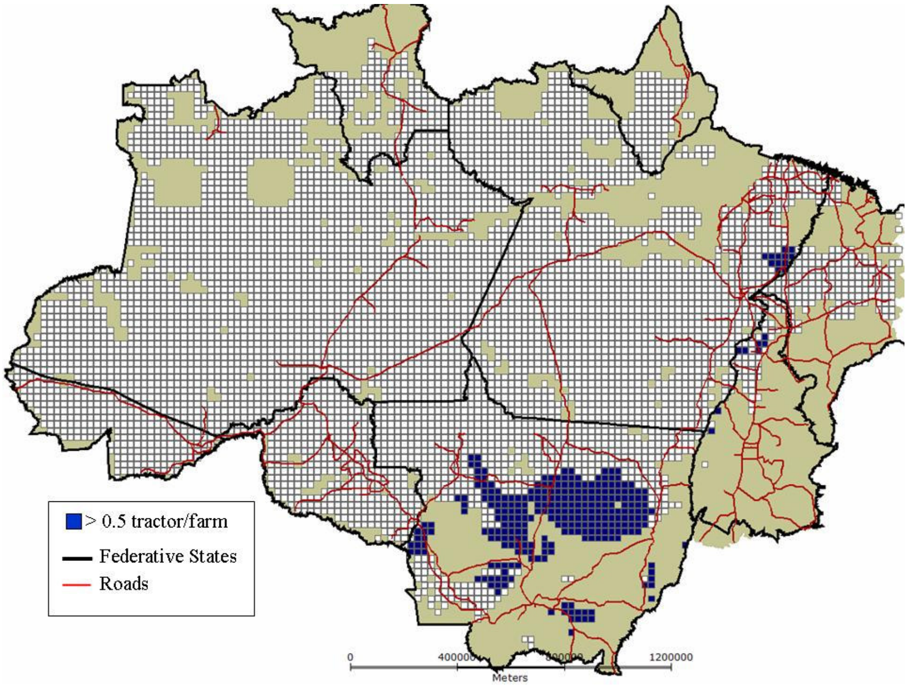


FIGURE 3.15 – Technological indicator: average number of tractors per property in 1996 (data source: IBGE Agricultural Census 1996).

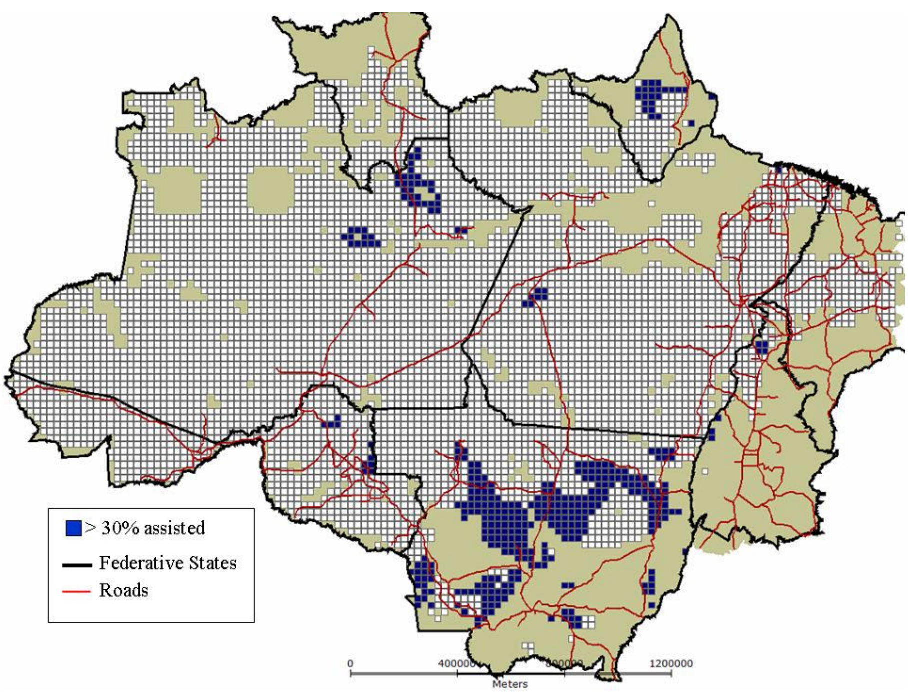


FIGURE 3.16 - Technological indicator: percentage of farms that received technical assistance in 1996 (data source: IBGE Agricultural Census 1996).

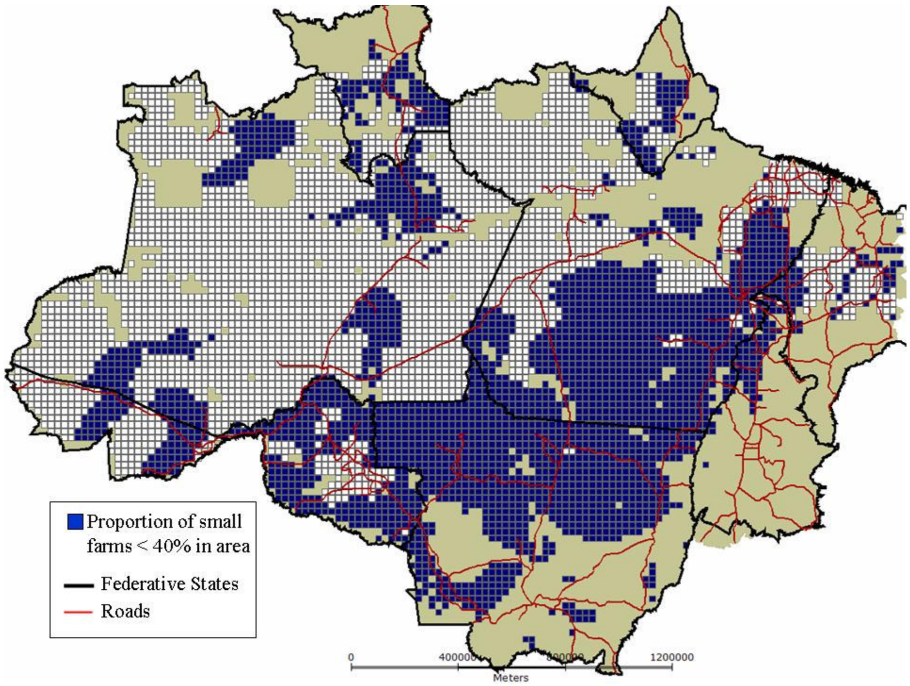


FIGURE 3.17 – Agrarian structure indicator: percentage of small farm area in relation *to the area* of farms (data source: IBGE Agricultural Census 1996).

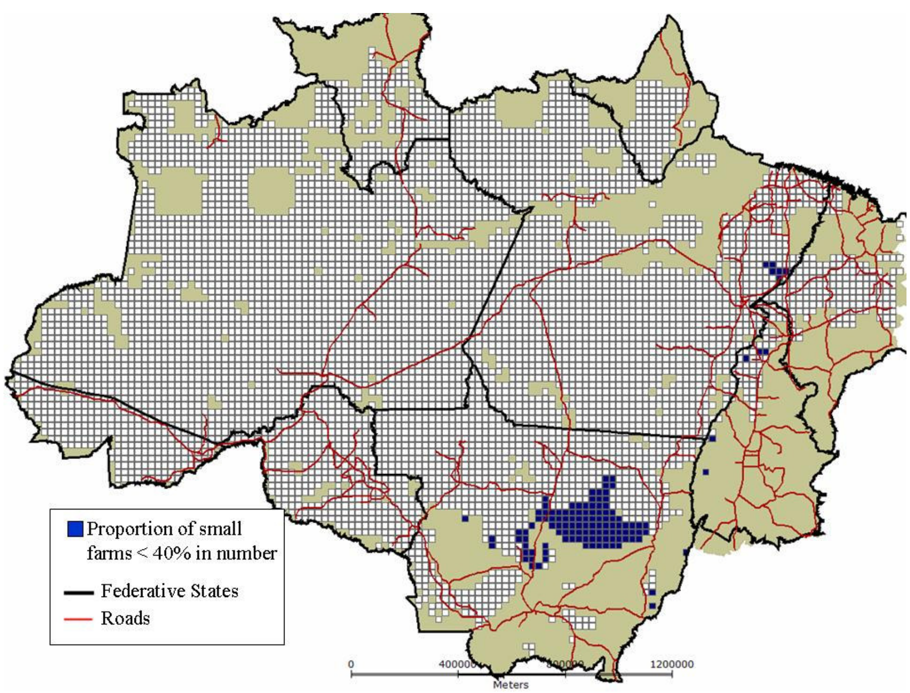


FIGURE 3.18 - Agrarian structure indicator: percentage of small farms in relation *to the number* of farms (data source: IBGE Agricultural Census 1996).

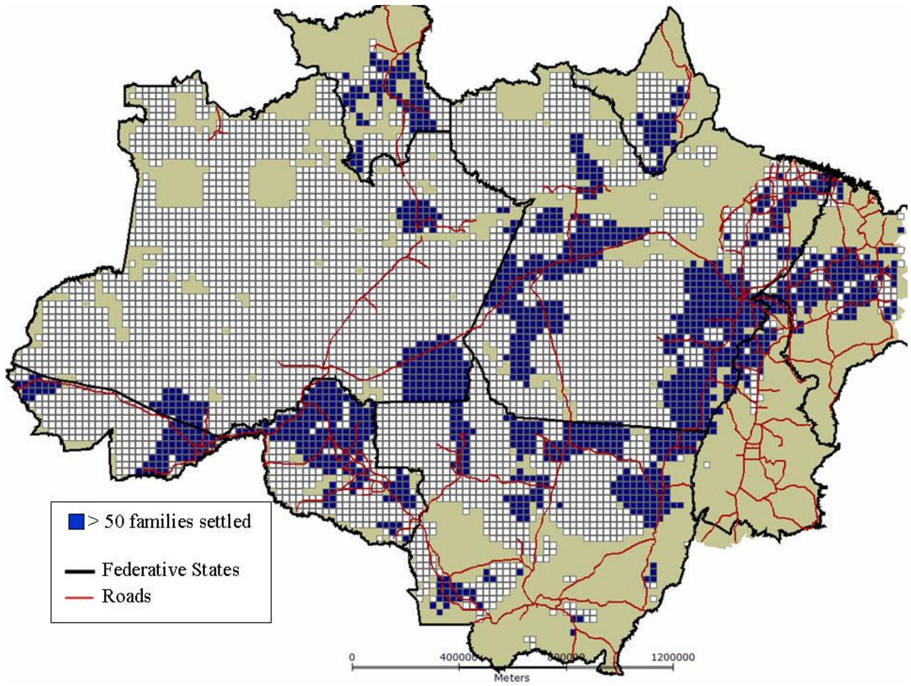


FIGURE 3.19 – Number of settled families from 1970 to 1999 (data source: INCRA).

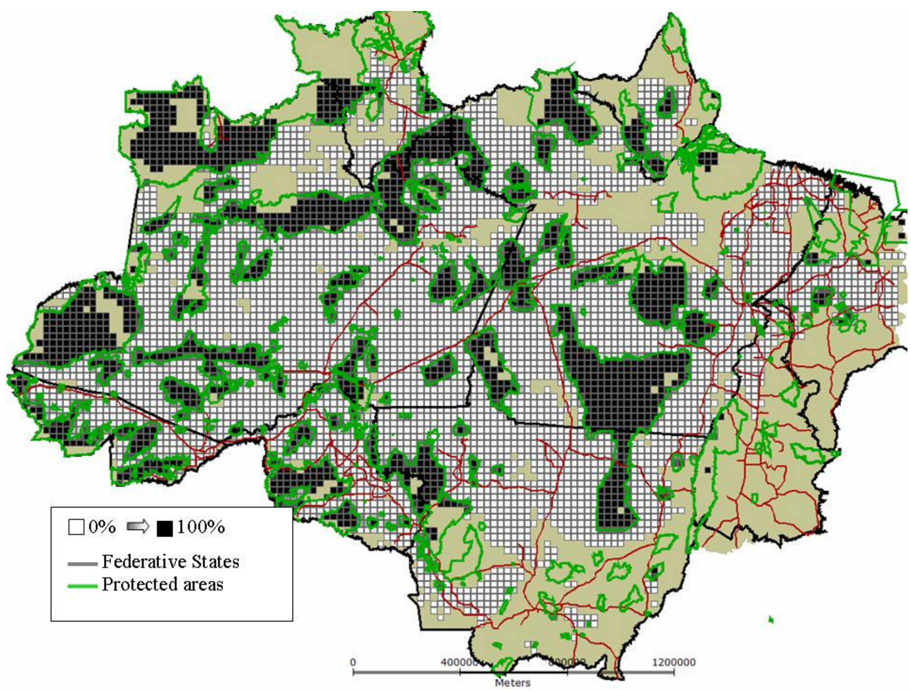


FIGURE 3.20 – Percentage of protected areas in 1997: Indigenous Lands and Federal and State Conservation Units (data sources: MMA and FUNAI).

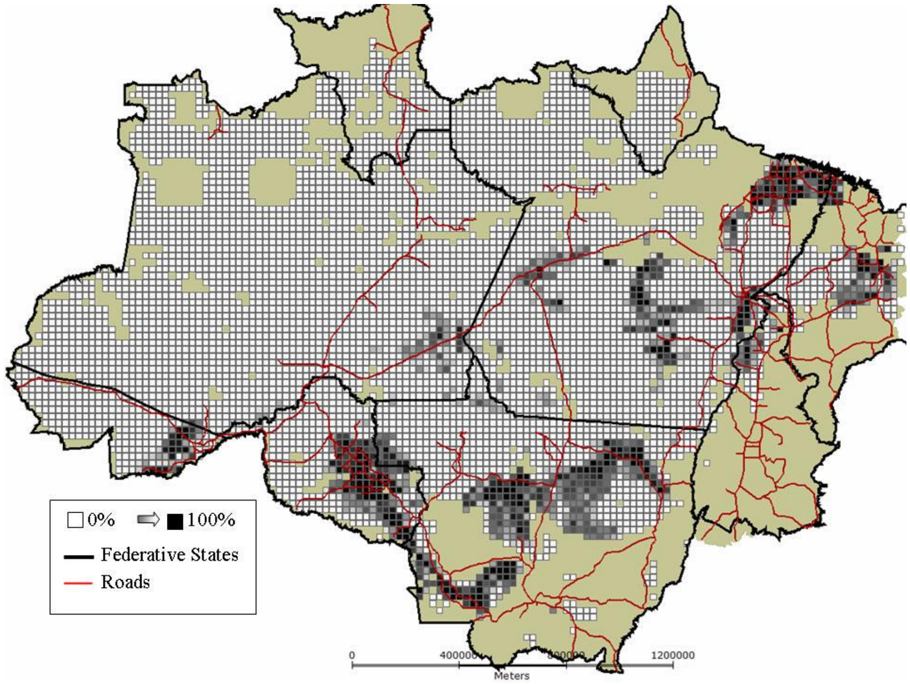


FIGURE 3.21 – Percentage of fertile soils (data source: IBGE).

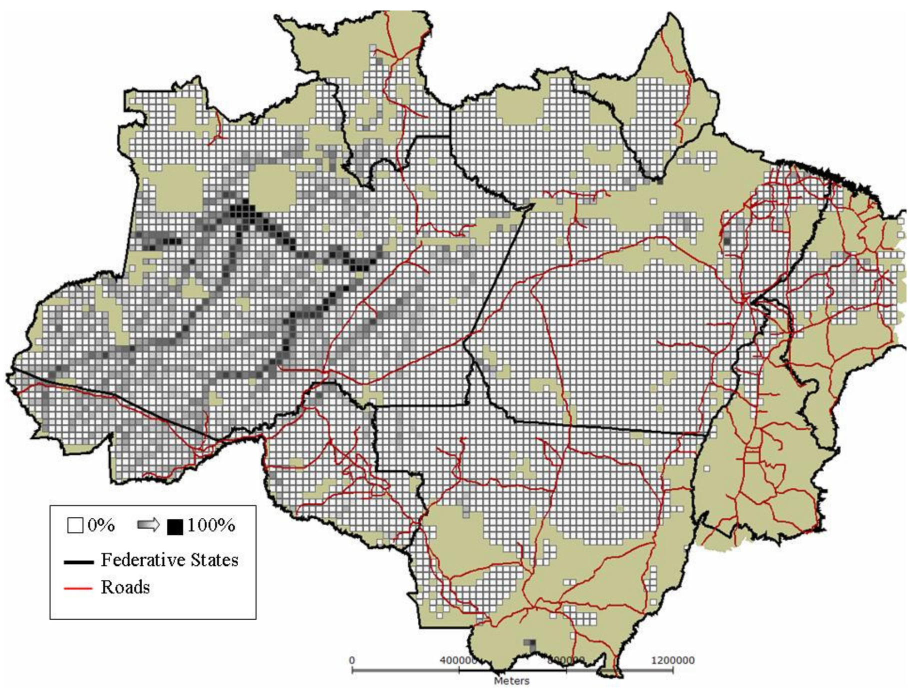


FIGURE 3.22 – Percentage of wet soils (data source: IBGE).

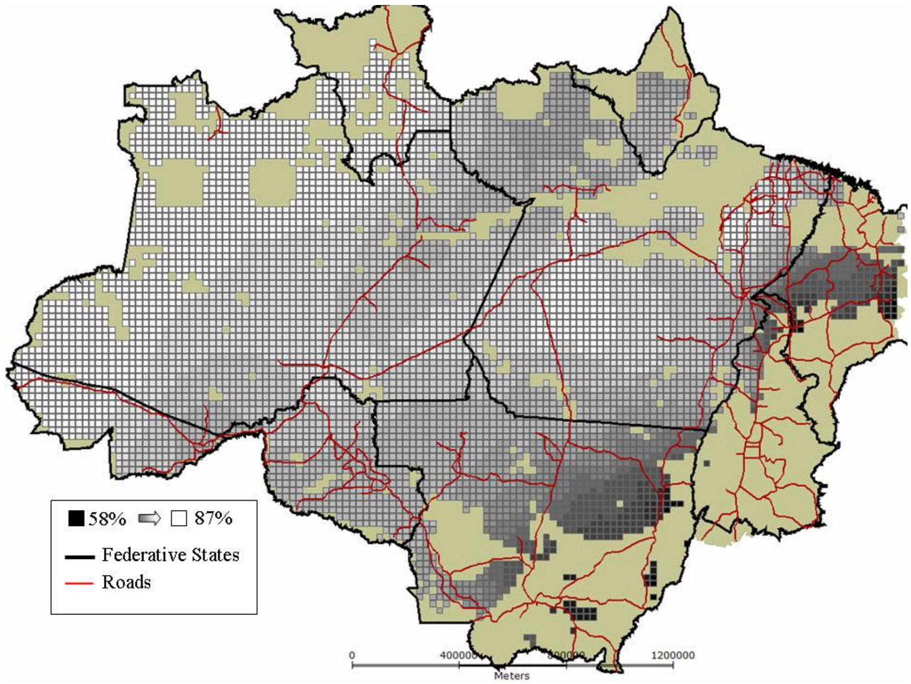


FIGURE 3.23 - Average humidity in the three driest consecutive months of the year (data source: INMET).

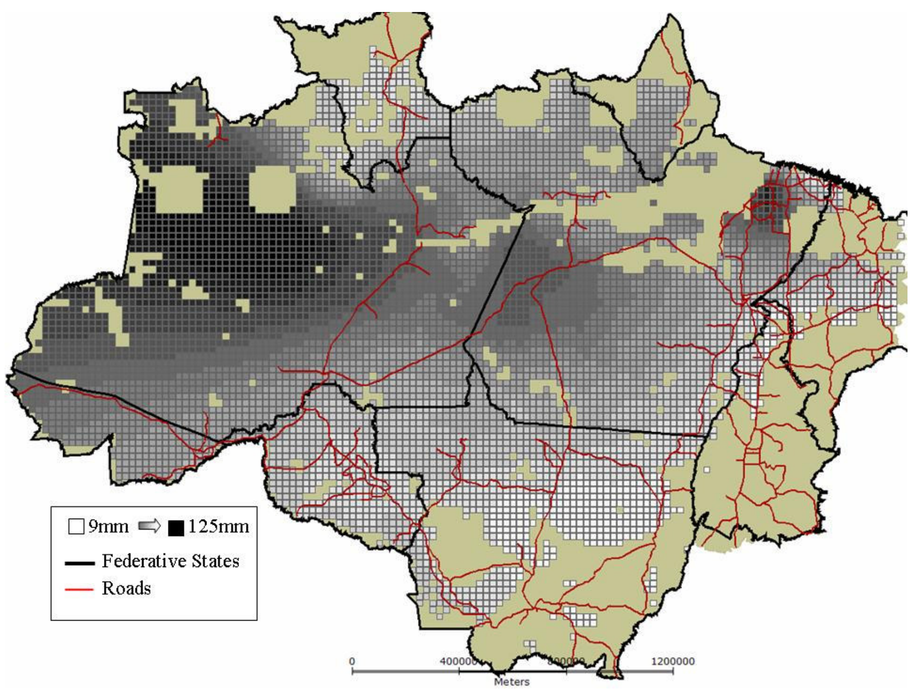


FIGURE 3.24 - Average precipitation in the three less rainy consecutive months of the year (data source: INMET).

CHAPTER 4

SPATIAL MODELING OF LAND-USE DETERMINANTS IN THE BRAZILIAN AMAZONIA

4.1 Introduction

This chapter presents the development of a spatial explicit model of the determinants associated to land use change in Amazonia, using the 25 x25 km^2 cells of the database presented in Chapter 3.

The model explores the relative importance of the determining factors related to *deforestation, pasture, temporary and permanent agriculture patterns*, and the intra-regional differences between these factors. Four spatial partitions are compared: the whole Brazilian Amazonia and three macro-regions defined by Becker (2005), namely the Densely Populated Arch, the Central Amazonia and the Oriental Amazonia (Figure 1.1). Results are consistent with the hypothesis of heterogeneity adopted in this thesis.

This chapter is organized as follows. Section 4.2 presents the methods used in the assessment of determinant factors for land use patterns in Amazonia. Section 4.3 presents the results and discusses them.

4.2 Methods

4.2.1 Exploratory analysis and selection of variables

In the statistical models of this chapter, dependent variables are those associated to land use (deforestation, pasture, temporary and permanent agriculture). The potential explanatory variables were grouped into seven types: *accessibility to markets, economical attractiveness, demographical, technological, agrarian structure, public policies,* and *environmental*, as described in Chapter 3.

An initial exploratory statistical analysis showed that some of the relationships between potential explanatory variables and the land use variables were not linear. We applied a logarithmic transformation to the land use variables and to some explanatory variables. The log transformation improved the regression results significantly. This improvement suggests that the explanatory variables are related to the initial choice of areas to be occupied. After the initial choice, land use change behaves as a spatial diffusion process because deforestation tends to occur close to previously deforested areas (Alves, 2002).

There was a high degree of correlation among potential explanatory factors. This led to the selection of a subset of the initial 50 potential variables. When choosing between highly correlated variables, those related to accessibility and public policies had preference. For the same category, alternative possibilities were tested. For instance, out of the many environmental variables, we chose the average humidity in the drier months. The final choice of explanatory variables for regression analysis does not include demographical or technological factors, which are captured indirectly by other variables. As a result, the statistical analysis used only a representative subset of all variables, as shown in Table 4.1. This subset was selected to cover the broadest possible range of categories, while minimizing correlation problems.

TABLE 4.1 – Subset of potential explanatory variables selected for the spatial statistical analysis.

Category	Variable	Description	Unit	Source
Accessibility to markets	conn_mkt	Indicator of strength of connection to national markets (SP and NE) through roads network	-	IBGE
	conn_ports	Indicator of strength of connection to ports through roads network	-	IBGE
	log_dist_rivers	Euclidean distance to large rivers (log)	km	IBGE
	log_dist_roads	Euclidean distance to roads (log)	km	IBGE
	log_dist_urban	Euclidean distance to urban centers (log)	km	IBGE
Economic Attractiveness	log_dist_wood	Euclidean distance to wood extraction poles (log)	km	IBAMA
	log_dist_mineral	Euclidean distance to mineral deposits (log)	km	CPRM
Public policies	prot_area	Percentage of protected areas	% of cell area	IBAMA FUNAI
	log_settl	Number of settled families from 1970 to 1999 (log)	Number of families (log)	INCRA
Agrarian Structure	agr_small	Percentage of area of small properties	% of cell area	IBGE
Environmental	soil_fert	Percentage of high and medium to high fertility soils in	% of cell area	IBGE
	soil_wet	Percentage of wetland soils ("*várzea*" soils)	% of cell area	IBGE
	clim_humid	Average humidity in the three drier months of the year	%	INMET

Even in the subset of variables presented above, there was still a high degree of correlation, which varied across the spatial partitions. We decided to build different spatial regression models, where each model had potentially explanatory variables with less than 50% correlation between them. To build the regression models, we selected as primary variables those with potentially greater explanatory power in relation to deforestation: *distance to urban centres, distance to roads, climatic conditions and connection to markets*. Then we tested these three variables for correlation to select the leading variables for each model. Distance to urban centres and distance to roads were correlated in all spatial partitions, except in the Occidental one. Distance to roads and connection to national markets could not be placed in the same subgroup for the whole Amazon. Climatic conditions and connection to national markets were also highly correlated, except in the Central region. This cross-correlation analysis between the potentially explanatory variables led to the models summarized in Table 4.2. An automatic linear forward stepwise regression was applied to refine the models and discard non-significant variables. Some variables were found to be significant in some of the models and non-significant in others, as shown in Table 4.2. The resulting models are:

1. *Amazonia*: for the whole region, three models were considered: one including distance to urban centres and connection to markets (*urban+connection*), one including distance to urban centres and climatic conditions (*urban+climate*), and a third one including distance to roads and climatic conditions (*roads+climate*).

2. *Densely Populated Arch*: for this region, two models are considered. The first is lead by distance to urban centres and connection to markets (*urban+connection*) and the second includes distance to roads and connection to markets (*roads+connection*).

3. *Central Amazonia*: for this region, two models are considered. The first is lead by distance to urban centres and connection to markets (*urban+connection*) and the second includes distance to roads and connection to markets (*roads+connection*).

4. *Central Amazonia*: for this region, a single model that includes distance to urban centres, distance to roads, and connection to markets (*urban+roads+connection*) was considered.

TABLE 4.2 - Groups of non-correlated explanatory variables for the spatial statistical analysis.

	Amazonia			Arch		Central		Occidental
	urban+connection	urban+climate	roads+climate	urban+climate	roads+connection	urban+climate+connection	roads+climate+connection	urban+roads
log_dist_urban	x	x		x		x		x
log_dist_roads			x		x		x	x
conn_mkt	x				x	x	x	n/s
clima_humid		x	x	x		x	x	n/s
conn_ports	x	x	x	n/s	n/s	x	x	n/s
log_dist_rivers	x	x	x	n/s	n/s	x	x	x
log_dist_wood				x	x			
log_dist_mineral		x		x	x	x	x	
prot_area	x	x	x	x	x	x	x	x
agr_small	x	x	x	x	x	x	n/s	n/s
log_settl	x	x	x	x	x	x	x	x
soil_fert	x	x	x	x	x	x	x	n/s
soil_wet	x	n/s	x	n/s	n/s	x	x	n/s

4.2.2 Spatial regression modeling

Spatial regression models were used to establish the relative importance of the determining factors for different land-uses. One of the basic hypotheses in linear regression models is that observations are not correlated, and consequently the residuals of the models are not correlated too. In land use data, this hypothesis is frequently not true. Land use data has the tendency to be spatially autocorrelated. The land use changes in one area tend to propagate to neighbouring regions. Spatial dependence could be seen as a methodological disadvantage, as it interferes on linear regression results, but on the other hand is exactly what gives us information on spatial pattern and structure and process (Overmars et al., 2003). This work applies a spatial lag regression model (Anselin, 2001) to assess the relative importance of potential explanatory factors. In this method, the spatial structure is supposed to be captured in one parameter.

The linear regression model formulation can be described as:

$$\boldsymbol{Y} = \boldsymbol{X\beta} + \varepsilon,\ \varepsilon \sim N(0, \sigma^2)\text{, or} \tag{4.1}$$

$$\begin{bmatrix} y_1 \\ y_2 \\ .. \\ .. \\ y_n \end{bmatrix} = \begin{bmatrix} 1 & x_{11} & .. & x_{1k-1} \\ 1 & x_{21} & .. & x_{2k-1} \\ .. & .. & .. & .. \\ .. & .. & .. & .. \\ 1 & x_{n1} & .. & x_{nk-1} \end{bmatrix} \begin{bmatrix} \beta_0 \\ \beta_1 \\ .. \\ .. \\ \beta_{k-1} \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ .. \\ .. \\ \varepsilon_n \end{bmatrix} \tag{4.2}$$

where $\boldsymbol{Y}$ is an (*n x 1*) vector of observations on a dependent variable taken at each of n locations, $\boldsymbol{X}$ is an (*n x k*) matrix of exogenous variables, $\boldsymbol{\beta}$ is an (*k x 1*) vector of parameters, and $\boldsymbol{\varepsilon}$ is (*n x 1*) an vector of disturbances. The spatial lag model includes a spatial dependence term, through a new term that incorporates the spatial autocorrelation as part of the explanatory component of the model:

$$\boldsymbol{Y} = \rho \boldsymbol{WY} + \boldsymbol{X\beta} + \varepsilon \tag{4.3}$$

where $\boldsymbol{W}$ is the spatial weights matrix, and the product $\boldsymbol{WY}$ expresses the spatial dependence on $\boldsymbol{Y}$, where ρ is the *spatial autoregressive coefficient*. The spatial autoregressive lag model aims at exploring the global patterns of spatial autocorrelation in the data set. This spatial model considers that the spatial process whose observations are being analyzed is stationary. This implies that the spatial autocorrelation patterns can be captured in a single regression term. This method was employed by Overmars et al. (2003) in a study in Equador. In the Brazilian Amazon, Perz and Skole (2003) used a spatial lag model, focusing on social factors related to secondary vegetation.

In this work, we compare the results of the spatial lag models with those of a non-spatial linear regression model for the whole Amazonia. This helps to understand how explanatory factors contribute to spatial dependence in this case. These results will be presented in the next section. In order to compare the models, we will present the R^2 value (coefficient of multiple determination) and the Akaike information criteria (*AIC*). As stated by Anselin (2001), the R^2 value is not a reliable indicator of goodness of fit when the data is spatially autocorrelated. The Akaike information criteria (Akaike, 1974) is a more suitable performance measure than the R^2 value for spatially correlated data. The model with the highest AIC absolute value is the best. To compare the determining factors relative importance in each model, the standardized regression coefficients (*beta*) and associated significance level (*p-level*) for each variable will be presented.

4.3 Results and discussion

This section summarizes the main findings, organized as follows. Section 4.1 presents the deforestation determining factors for whole Amazonia. It compares the results obtained by linear regression to those of spatial regression. The comparison shows how determinants change their importance when spatial autocorrelation is considered, and what this indicates in terms of spatial dependence and land-use structure. Section 4.2 presents a comparison of deforestation factors across the four spatial partitions (Amazonia, Densely Populated Arch, Central and Occidental macro-zones), using spatial regression models. Section 4.3 presents a comparison of the main land-use (pasture, temporary and permanent agriculture) determinants, also using spatial regression models. The results of pasture and agriculture determinants are presented only for the Arch macro-zone, where occupation is more consolidated.

4.3.1 Deforestation factors in the whole Amazonia

This section presents and discusses the regression models for whole Amazonia. A pre-processing step maintained in the models only variables less than 50% correlated to each other, and eliminated those non-significant according to an automatic forward stepwise procedure (see Table 4.2). The three models have the following explanatory variables:

- *urban+connection*: distance to urban centres (log), connection to markets, connection to ports, distance to rivers (log), protected areas, percentage of small farmers, number of families in settlements (log), soil fertility, and soil wetness.

- *urban+climate*: distance to urban centres (log), humidity, connection to ports, distance to rivers (log), distance to mineral deposits (log), protected areas, percentage of small farmers, number of families in settlements (log), soil fertility, and soil wetness.

- *roads+climate*: distance to roads (log), humidity, connection to ports, distance to rivers (log), protected areas, percentage of small farmers, number of families in settlements (log), soil fertility, and soil wetness.

Table 4.3 presents the statistical analysis results for the three models and compares the non-spatial linear regression model with the spatial lag model, where the dependent variable is the *log percentage of deforestation* for each 25 x 25 km^2 cell. The spatial lag model includes one additional variable (`w_log_def`) that measures the extent of spatial autocorrelation in the deforestation process. In Table 4.3, we present the R^2 value (coefficient of multiple determination) and the Akaike information criteria (AIC) for all models. In both indicators, the spatial regression models showed a better performance than the non-spatial linear model. The spatial coefficient of the spatial lag models is significant and higher than 0.70 in all models. This is a quantitative evidence that corroborates of earlier assessments that deforestation is a diffusive process in the Amazon, and tends to occur close of previously opened areas (Alves, 2002). The other variables found to be important (with higher *betas*) are distance to urban centres (log), distance to roads (log), connection to markets, humidity, and protected areas.

TABLE 4.3 - Linear and spatial lag regression models of (log) deforestation determining factors in the whole Amazon.

Subgroup urban+connection			*Subgroup urban+climate*			*Subgroup roads+clima*		
Linear Regression								
R-squared:		0.66	R-squared:		0.65	R-squared:		0.58
AIC:		-39144.50	AIC:		-38944.9	AIC:		-37928.6
	Beta	p-level		Beta	p-level		Beta	p-level
log_dist_urban	-0.45	0.00	log_dist_urban	-0.48	0.00	log_dist_road	-0.39	0.00
conn_mkt	0.26	0.00	clim_humid	-0.18	0.00	clim_humid	-0.24	0.00
prot_area	-0.14	0.00	log_settl	0.12	0.00	prot_area	-0.19	0.00
log_settl	0.10	0.00	prot_area	-0.15	0.00	soil_fert	0.16	0.00
soil_fert	0.09	0.00	soil_fert	0.12	0.00	log_settl	0.13	0.00
conn_ports	0.07	0.00	agr_small	-0.10	0.00	soil_wet	0.10	0.00
agr_small	-0.09	0.00	conn_ports	0.07	0.00	log_dist_rivers	-0.07	0.00
log_dist_rivers	-0.04	0.00	log_dist_mineral	-0.05	0.00	conn_ports	0.05	0.00
soil_wet	-0.02	0.02	log_dist_rivers	-0.03	0.00	agr_small	-0.06	0.00
Spatial Lag								
R-squared:		0.81	R-squared:		0.81	R-squared:		0.81
AIC:		-41876.2	AIC:		-41871	AIC:		-41781.5
	Beta	p-level		Beta	p-level		Beta	p-level
w_log_def	0.73	0.00	w_log_def	0.74	0.00	w_log_def	0.78	0.00
log_dist_urban	-0.15	0.00	log_dist_urban	-0.16	0.00	log_dist_road	-0.13	0.00
conn_mkt	0.05	0.00	clim_humid	-0.04	0.00	clim_humid	-0.05	0.00
prot_area	-0.07	0.00	log_settl	0.03	0.00	prot_area	-0.07	0.00
log_settl	0.03	0.00	prot_area	-0.07	0.00	soil_fert	0.04	0.00
soil_fert	0.03	0.00	soil_fert	0.03	0.00	log_settl	0.02	0.01
conn_ports	0.02	0.00	agr_small	-0.03	0.00	soil_wet	0.05	0.00
agr_small	-0.03	0.00	conn_ports	0.02	0.00	log_dist_rivers	-0.03	0.00
log_dist_rivers	-0.03	0.00	log_dist_mineral	-0.02	0.01	conn_ports	0.01	0.14
soil_wet	0.01	0.05	log_dist_rivers	-0.02	0.00	agr_small	-0.01	0.18

We also compared the strength of the most important factors considering the linear regression model and the spatial lag model, as shown in Table 4.4. It groups the distance to urban centres and distance to roads variables that are highly correlated, and then connection to markets and climate variables, also highly correlated. As expected, using the spatial lag regression model, all betas get lower, but not in a uniform way. When considering the intrinsic spatial dependence of deforestation, the 'connection to markets' variable (and the climate one) decreases proportionally more than the others, although it is still one of the main factors. Therefore, these variables carry a large part of the spatial dependence. This corroborates with earlier assessments (Alves, 2002) that showed that deforestation tends to occur along roads that provide an easier connection to the more developed areas in Brazil. These areas also present the driest climate in Amazon, with more favourable conditions to agriculture (and also to infra-structure construction and maintenance) than the more humid areas in the western Amazonia, in accordance with previous results (Schneider, 2000). Our statistical results indicate that these factors (the diffusive nature of deforestation, distance to roads and to urban centres, climate and connection to markets), and the interaction among them, contributed significantly for the pattern of deforestation in 1996/1997. The existence of protected areas also plays an important role in avoiding deforestation in high pressure areas, as will be further discussed in the next section.

TABLE 4.4 - Main deforestation determining factors comparison (whole Amazonia).

Variable	**Subgroup**	**Beta**		**% of decrease**
		Linear	**Spatial lag**	
w_log_def	*urban+connection*	-	0.73	-
w_log_def	*urban+climate*	-	0.74	-
w_log_def	*roads+climate*	-	0.78	-
log_dist_urban	*urban+connection*	-0.45	-0.15	67%
log_dist_urban	*urban+climate*	-0.48	-0.16	67%
log_dist_roads	*roads+climate*	-0.39	-0.13	67%
conn_mkt	*urban+connection*	0.26	0.05	81%
clim_humid	*urban+climate*	-0.18	-0.04	78%
clim_humid	*roads+climate*	-0.24	-0.05	79%
prot_area	*urban+connection*	-0.14	-0.07	50%
prot_area	*urban+climate*	-0.15	-0.07	53%
prot_area	*roads+climate*	-0.19	-0.07	63%

Previous studies of causes of land-use change in Amazonia tended to emphasize distance to roads as the main determinant (Kirby et al., 2006; Laurance et al., 2002). The results from this paper indicate that distance to urban centres is as important as distance to roads as a determinant factor for land-use change. Distance to urban centres is a population indicator and also a proxy of local markets. In 1996, 61% of the approximately 20 million people lived in Amazonian urban areas; in 2000, 69% of the total population (Becker, 2004). Urban population growth rates increase faster in Amazonia than in other parts of Brazil, not only in the larger cities but also in those with less than 100.000 people (Becker, 2001). Faminow (1997) showed that the local demand for cattle products such as beef and milk is an overlooked cause of cattle production increase, and consequently, deforestation. Our results reinforce the need to further understand the relationship between land use change and this process of urban population growth in Amazônia.

In summary, our results indicate that strong spatially concentrated pattern of deforestation in Amazonia is related to the diffusive nature of the land use change process. The concentration of this pattern in the Southern and Eastern parts of the Amazonia is related to proximity to urban centres and roads, reinforced by the higher connectivity to the more developed parts of Brazil, and more favourable climatic conditions in comparison to the rest of the region. Therefore, more favourable production conditions in terms of climate, connection to national markets, and proximity to local markets seem to be the key factors in explaining the deforestation process.

4.3.2 Comparison of deforestation determining factors across space partitions

This section presents and discusses the regression models for three spatial partitions: Densely Populated Arch, Central Amazonia and Occidental Amazonia. For each space partition, two alternative models were considered, one including the *distance to urban centres* variable, and one with the *distance to roads* variable (except in the Occidental partition where they were allowed to be in the same model). A pre-processing step maintained in the models only variables less than 50% correlated to each other, and eliminated those non-significant according to an automatic forward stepwise procedure (see Table 4.2). The models have the following explanatory variables:

- Arch: *urban+climate*: distance to urban centres (log), climate, distance to timber production (log) distance to mineral deposits (log), protected areas, percentage of small farmers, number of families in settlements (log), and soil fertility;

- Arch: *roads+connection*: distance to roads (log), connection to markets, distance to timber production (log), distance to mineral deposits (log), protected areas, percentage of small farmers, number of families in settlements (log), and soil fertility.

- Central: *urban+climate+connection*: distance to urban centres (log), connection to markets, humidity, connection to ports, distance to rivers (log), distance to timber production (log), distance to mineral deposits (log), protected areas, percentage of small farmers, number of families in settlements (log), soil fertility, and soil wetness;

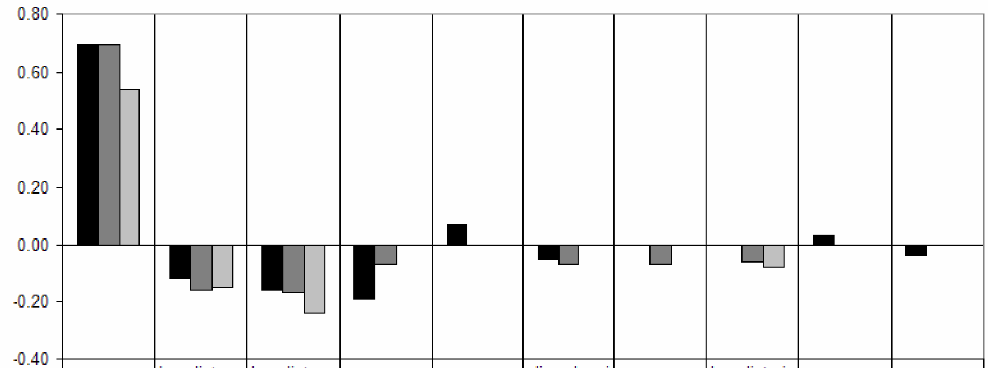
- Central: *roads+climate+connection*: distance to roads (log), connection to markets, humidity, connection to ports, distance to rivers (log), distance to timber production (log), distance to mineral deposits (log), protected areas, number of families in settlements (log), soil fertility, and soil wetness.

- Occidental: *urban+roads*: distance to urban centres (log), distance to roads (log), distance to rivers (log), protected areas, and number of families in settlements (log).

Table 4.5 presents the statistical analysis results for these models, including the R^2 and the Akaike information criteria (AIC). Both criteria indicate that the Arch models are the best fit. The spatial autoregressive coefficient (`w_log_def`) is significant and higher than 0.67 in all models of the Arch and Central regions. In the Occidental region, it is also significant, but presents a lower value (0.54), indicating a less marked spatial pattern. The Occidental region is still quite undisturbed, except by the areas close to the main rivers, and around Manaus. As stated by Becker (2001) the Amazonia presents regions with different speeds of modification. The lower spatial dependence is an indicator that occupied areas in the Occidental region do not spread to the neighbouring cells at the same pace as the ones in the main axes of development in the Arch and Central region. The other variables found to be important (with higher *betas*) - or that present some relevant variation among the spatial partitions - are: distance to urban centres (log), distance to roads (log), protected areas, connection to markets, connection to ports, distance to large rivers, soil fertility, number of settled families, and agrarian structure. Figure 4 illustrates graphically the most important differences found among these eight factors.

TABLE 4.5 - Spatial lag regression models of deforestation determining factors across space partitions.

ARCH			**CENTRAL**			**OCCIDENTAL**		
Distance to roads models								
R-squared:		0.80	R-squared:		0.71	R-squared:		0.50
AIC :		-14783.70	AIC :		-12413.10	AIC :		-12023.00
	Beta	p-level		Beta	p-level		Beta	p-level
w_log_def	0.71	0.00	w_log_def	0.72	0.00	w_log_def	0.54	0.00
conn_mkts	0.07	0.00	log_dist_roads	-0.16	0.00	log_dist_urban	-0.24	0.00
prot_areas	-0.19	0.00	conn_ports	0.07	0.00	log_dist_roads	-0.15	0.00
log_dist_roads	-0.12	0.00	log_dist_rivers	-0.07	0.00	log_dist_rivers	-0.08	0.00
log_dist_wood	-0.04	0.00	log_settl	0.04	0.01	prot_area	-0.02	0.17
soil_fert	0.04	0.00	prot_area	-0.06	0.00	log_settl	0.00	0.81
log_settl	0.02	0.05	soil_wet	0.07	0.00			
agr_small	-0.03	0.01	log_dist_mineral	-0.05	0.00			
log_dist_mineral	-0.01	0.20	conn_mkt	0.03	0.06			
			clim_humid	-0.07	0.00			
			soil_fert	0.03	0.06			
Distance to urban models								
R-squared:		0.80	R-squared:		0.71			
AIC :		-13942.20	AIC :		-12405.10			
	Beta	p-level		Beta	p-level			
w_log_def	0.70	0.00	w_log_def	0.67	0.00			
log_dist_urban	-0.16	0.00	log_dist_urban	-0.17	0.00			
prot_areas	-0.19	0.00	conn_ports	0.09	0.00			
clim_humid	-0.05	0.00	conn_mkt	0.07	0.00			
log_settl	0.03	0.00	prot_area	-0.07	0.00			
soil_fert	0.03	0.00	log_dist_mineral	-0.05	0.00			
log_dist_mineral	-0.03	0.02	log_settl	0.04	0.00			
agr_small	-0.03	0.01	soil_wet	0.05	0.00			
log_dist_wood	-0.02	0.05	clim_humid	-0.06	0.00			
			log_dist_rivers	-0.05	0.00			
			soil_fert	0.03	0.04			
			agr_small	0.01	0.68			



	w_log_def	log_dist_roads	log_dist_urban	prot_all	conn_mkt	clima_humid	conn_ports	log_dist_rivers	fert_soils	agr_small
Arch	0.70	-0.12	-0.16	-0.19	0.07	-0.05			0.04	-0.04
Central	0.70	-0.16	-0.17	-0.07		-0.07	-0.07	-0.06		
Occidental	0.54	-0.15	-0.24					-0.08		

FIGURE 4.1 - Graphical comparison of main deforestation factors across macro-regions. Values shown are the average of significant beta coefficients. Empty values are non-significant coefficients in any of the models for that partition.

The first main difference is the relative higher values of the protected areas variable (% of all types of protected areas in each cell, including Indigenous Lands and Federal and State Conservation Units). In the Arch, it is the second most important factor (after the spatial autocorrelation coefficient), preceding distance to roads and distance to urban centers. Indigenous lands and conservation units correspond, respectively, to 22% and 6% of the Amazon region (Becker, 2001), spread over the region (see Figure 3.20). Our results indicate quantitatively that protected areas can be important instruments in avoiding deforestation in high pressure areas such as the Arch. This is in accordance with earlier results that showed that protected areas are in general effective in refraining deforestation even if some level of deforestation is found inside of them Ferreira et al. (2005). Their efficacy depends on the clear demarcation of its limits, on the socio-economic context in which they are created, and on appropriate monitoring and controlling measures, as discussed by Ribeiro et al. (2005) and Escada et al. (2005a).

Distance to roads and distance to urban centers are not the most important determinants in all macro-regions. Also, they do not explain intra-regional differences, as they are both similarly important in all macro-zones, except in the Occidental macro-zone, where distance to urban centers is considerably more important. In the Occidental macro-zone, distance to large rivers also plays an important role. This result is coherent with the small disturbance of the area, concentrated mostly in Manaus and close to the rivers.

On the other hand, connection measures (connection to markets and connection to ports) play different roles across the partitions. Connection to markets is important in explaining Arch deforestation patterns, but not in the other macro-regions. In the Central macro-region it looses significance in one of the models, when distance to roads is also used. Connection to ports is important only in the Central region, whose historical occupation process is related to the rivers. Climate (intensity of dry season) is also important in explaining deforestation in the Arch and Central partitions. In the Central spatial partition, the climate variable did not present correlation to the connection to markets variable, and both could be placed in the same regression model. In the Arch, climate and connection to markets are correlated, and were analyzed in different models, both presenting significant coefficient values. This indicates that both factors created favourable conditions to occupation in the Eastern part of the Amazon.

The differences between the models for the Arch and the Central regions are important. They point out to an occupation process in the Arch that uses roads as its main connections. In the Arch, the existence of protected areas is the main factor that is statistically significant as an impediment to deforestation. A second deterrent is unfavourable climatic conditions, in areas where the dry season is more intense. Since the area on the south of the Arch still has a considerable extension of primary forest areas outside protected areas, close to the mechanized agriculture belt in the south of Mato Grosso, and also benefits from drier climate, the creation of protected areas in that region would be an important factor for deterrence of the deforestation process.

In the Central region, due to its historical occupation process, connection to national markets is not significant in one of the models. There is a stronger influence of rivers connections (variables distance to rivers and connection to ports). The Central region is currently the most vulnerable region, where new frontiers are located (Becker, 2004).

As the agricultural production systems of the new occupied areas in the Central region became stronger, these statistical relationships will be modified to reflect the new reality, but *not necessarily replicating the Arch relationships*. For instance, connection to ports may continue to be important in the Central region due to the presence of exportation ports in the Amazon River, but road connection to the rest of the country may also gain importance, linking productive areas to their markets. In relation to protected areas, the statistical relationship was not as strong as in the Arch in the period of analysis. However, the creation of protected areas in the Central region, in appropriate socio-economic contexts (Escada et al., 2005a), would also be an important instrument for conservation of areas that may become threatened by the new frontiers.

In the next paragraphs we discuss results related to other significant variables: soils fertility, number of settled families and agrarian structure indicators. The soils fertility indicator (percentage of fertile soils in each cell) has a positive relationship to deforestation in the Arch and in the whole Amazonia models. Comparing the deforestation patterns and the patterns of medium and high fertility soils in the 25 x 25 km^2 cell space shown 3.21, one can notice the existence of better quality soils in Rondônia and the Transamazônica, where most colonization programs were placed. Better soils are also found in Mato Grosso. Federal Government possibly took into consideration existing soil surveys when planning the development projects and colonization settlements of the 70's and 80's (the RADAM project in the 70's mapped vegetation, soils, geology and geomorphology).

As expected, the number of settled families by official colonization programs (accumulated from 1970 to 1999) has a positive and significant relationship in the Arch and Central regions (and also in the whole Amazonia, as Table 4.3 shows). On the other hand, the agrarian structure indicator (percentage in area of farms smaller than 200 ha) is also significant in the Arch, but presents a negative signal, indicating that deforestation is more associated with areas with a greater proportion of medium and large farms, than areas occupied by small farms. This relationship is also significant in the whole Amazonia.

Many authors have presented diverse estimates of the share of small and large farmers in relation to deforestation (for instance, Fearnside (1993); Walker et al. (2000). As stated by Walker et al. (2000) and Margulis (2004), the relative importance of small, medium and large farms on deforestation varies from one region to the other, as the dynamics of deforestation are very distinct at different localities. However most of previous works show that when considering the overall deforestation extent in the Amazon a more significant impact is caused by large farms (Margulis, 2004). Our results provide further evidence that areas occupied by large and medium farms have a higher impact on deforestation than areas occupied by small farms, when the whole Arch macro-region is analyzed. This can be explained by the relative contribution of Pará, Tocantins and Mato Grosso states. As Figure 4.2 illustrates, small farm areas are concentrated in Rondônia, northeast of Pará and Maranhão. In most of the Arch area, the agrarian structure is predominantly of medium and large farms. For instance, in Mato Grosso the mean value for the agrarian structure indicator is 0.07 (0.07 standard deviation), meaning that in average only 7% of the farm lands are occupied by properties with less than 200 ha.

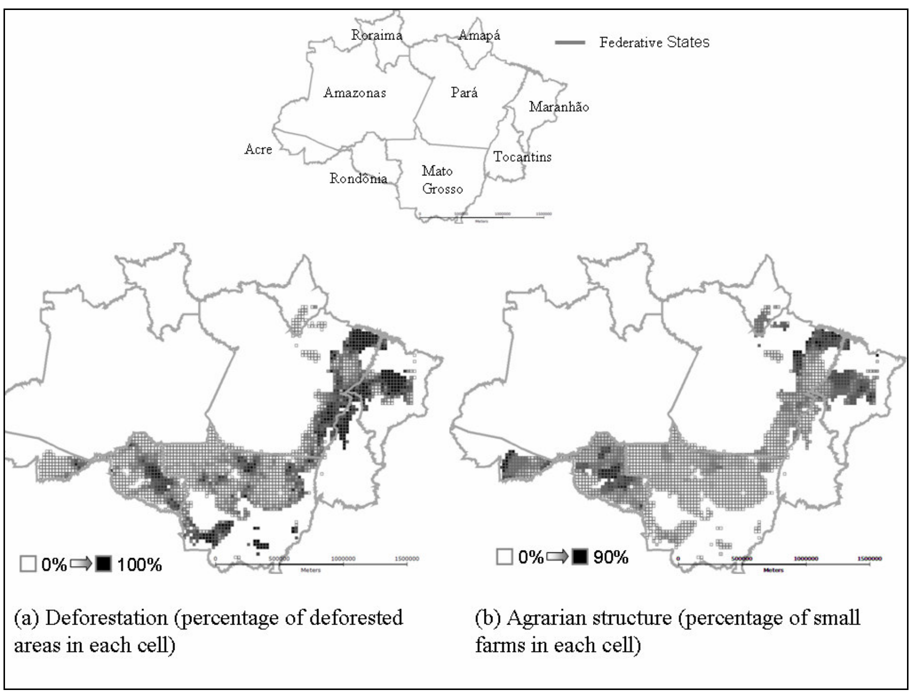


FIGURE 4.2 - Agrarian structure and deforestation patterns in the Arch.

4.3.3 Comparison of land-use determining factors in the Arch partition

This section presents and discusses the results of the spatial lag models for the Arch partition, in which the dependent variables are the *log percentage of pasture, temporary agriculture and permanent agriculture* in each 25 x 25 km^2 cell. For each of these three types of land use, we consider two alternative models, one including the distance to urban centres variable, and one with the distance to roads:

- *urban+climate:* distance to urban centres (log), climate, distance to timber production (log) distance to mineral deposits (log), protected areas, percentage of small farmers, number of families in settlements (log), and soil fertility;

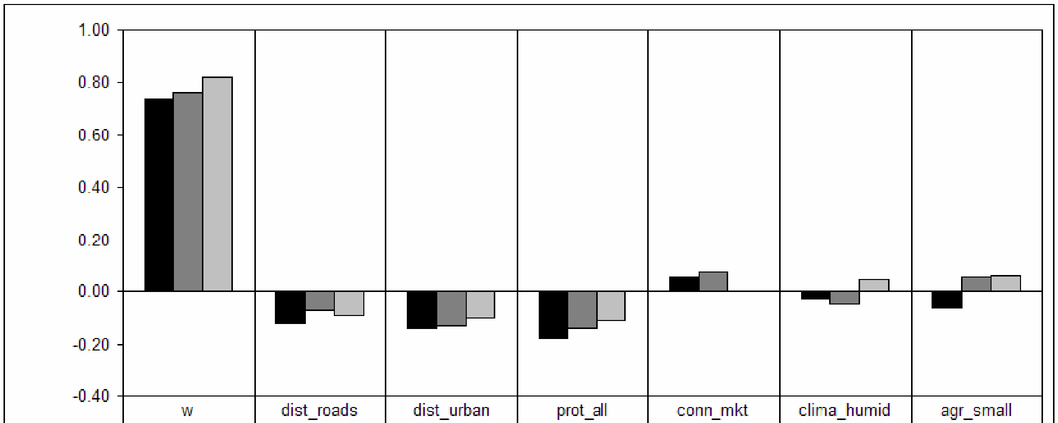
- *roads+connection:* distance to roads (log), connection to markets, distance to timber production (log), distance to mineral deposits (log), protected areas, percentage of small farmers, number of families in settlements (log), and soil fertility.

Table 4.6 presents the statistical analysis results for the six models. The R^2 and the Akaike information criteria (AIC) are presented as measures of goodness of fit to compare the models. All indices are similar, but temporary agriculture models perform slightly better according to the log likelihood. The spatial auto-regressive coefficient of the spatial lag models is significant and higher than 0.70 in all models, presenting the higher values in the permanent agriculture models (above 0.80), indicating a stronger clustering of such use (see Figure 2). The other relevant factors that will be analyzed in this section are: distance to urban centres (log), distance to roads (log), protected areas, connection to markets, and agrarian structure. Figure 4.3 illustrates graphically the most important differences found among these eight factors.

As with deforestation in the Arch macro-region, protected areas, distance to roads and distance to urban centres are the most important variables in explaining the distribution of land-use patterns. Connection to markets is significant to temporary agriculture and pasture, but not to permanent agriculture. The main difference is the signal in relation to agrarian structure variable (percentage in area of farms smaller than 200 ha). The beta value for the agrarian structure has a positive value in both temporary agriculture and permanent agriculture models. In the pasture model, the beta is negative.

TABLE 4.6 - Spatial lag regression models of pasture, temporary and permanent agriculture in the Arch.

ARCH			**CENTRAL**			**OCCIDENTAL**		
Distance to roads models								
R-squared:		0.80	R-squared:		0.71	R-squared:		0.50
AIC :		-14783.70	AIC :		-12413.10	AIC :		-12023.00
	Beta	p-level		Beta	p-level		Beta	p-level
w_log_def	0.71	0.00	w_log_def	0.72	0.00	w_log_def	0.54	0.00
conn_mkts	0.07	0.00	log_dist_roads	-0.16	0.00	log_dist_urban	-0.24	0.00
prot_areas	-0.19	0.00	conn_ports	0.07	0.00	log_dist_roads	-0.15	0.00
log_dist_roads	-0.12	0.00	log_dist_rivers	-0.07	0.00	log_dist_rivers	-0.08	0.00
log_dist_wood	-0.04	0.00	log_settl	0.04	0.01	prot_area	-0.02	0.17
soil_fert	0.04	0.00	prot_area	-0.06	0.00	log_settl	0.00	0.81
log_settl	0.02	0.05	soil_wet	0.07	0.00			
agr_small	-0.03	0.01	log_dist_mineral	-0.05	0.00			
log_dist_mineral	-0.01	0.20	conn_mkt	0.03	0.06			
			clim_humid	-0.07	0.00			
			soil_fert	0.03	0.06			
Distance to urban models								
R-squared:		0.80	R-squared:		0.71			
AIC :		-13942.20	AIC :		-12405.10			
	Beta	p-level		Beta	p-level			
w_log_def	0.70	0.00	w_log_def	0.67	0.00			
log_dist_urban	-0.16	0.00	log_dist_urban	-0.17	0.00			
prot_areas	-0.19	0.00	conn_ports	0.09	0.00			
clim_humid	-0.05	0.00	conn_mkt	0.07	0.00			
log_settl	0.03	0.00	prot_area	-0.07	0.00			
soil_fert	0.03	0.00	log_dist_mineral	-0.05	0.00			
log_dist_mineral	-0.03	0.02	log_settl	0.04	0.00			
agr_small	-0.03	0.01	soil_wet	0.05	0.00			
log_dist_wood	-0.02	0.05	clim_humid	-0.06	0.00			
			log_dist_rivers	-0.05	0.00			
			soil_fert	0.03	0.04			
			agr_small	0.01	0.68			



	w	dist_roads	dist_urban	prot_all	conn_mkt	clima_humid	agr_small
Pasture	0.74	-0.12	-0.14	-0.18	0.06	-0.03	-0.06
Temporary	0.77	-0.07	-0.13	-0.14	0.08	-0.05	0.06
Permanent	0.82	-0.09	-0.10	-0.11		0.05	0.07

FIGURE 4.3 - Graphical comparison of main land-use factors in the Arch macro-region. Values shown are the average of significant beta coefficients. Empty values are non-significant coefficients in any of the models for that partition.

Pasture is spread over the region (see Figure 3.3), and its determining factors are very similar to deforestation ones, discussed in previous section. Our results indicate that medium and large farms have a larger proportion of pasture areas *when considering the whole Arch extent*. The relative share of small, medium and large farms in terms of pasture area varies according different localities. Rondônia, for instance, have a significant pasture area (see Table 3.1) and an agrarian structure related to small farmers. The negative signal our model captures is related to the *proportionally larger area* of Mato Grosso and Pará States, in which the agrarian structure is predominantly of large farms.

On the other hand, temporary and permanent agriculture present differentiated and concentrated patterns, as discussed in Section 3.2. Our results indicate a tendency for temporary and permanent agriculture to occupy areas associated to small farms, when considering the whole Arch, in our period of analysis. Permanent crops are present in North-eastern Pará, Rondônia and along the Amazon River. These three areas have a land structure related mostly to small properties, what explains the positive signal in the permanent agriculture model. In the temporary agriculture model, the positive signal can be explained by the fact that the temporary agriculture practiced in Pará and Maranhão by small farmers occupy a larger area than the mechanized agriculture found in the south of Mato Grosso (see Table 3.1). Although this statistical relationship may change with the expansion of mechanized agriculture into forest areas (Becker, 2005), that requires large tracts of plain land, and is practiced by a capitalized type of actor, our results indicate the existence of a land use system based on temporary agriculture practiced by small farms, especially in old occupation areas such as Maranhão and Northeast Pará.

This land use pattern analysis we conducted provide further evidence of the heterogeneity of the region, both in terms of agrarian structure and land use trajectories adopted in different localities. For instance, both Rondônia and the north-eastern part of Pará State have a dominance of small farms. However, in Rondônia temporary crops are not as significant as in north-eastern Pará. On the other hand, there is a significant pattern of permanent crops in Rondônia. Soybean expansion may change the statistical relationship with the agrarian structure as we obtained for temporary crops, but not the fact that these other land use systems exist, and that effective policy action may take this heterogeneity into consideration.

CHAPTER 5

EXPLORING SCENARIOS OF LAND-USE CHANGE IN THE BRAZILIAN AMAZONIA

5.1 Introduction

In this chapter a dynamic spatially explicit model (the CLUE model (Kok et al., 2001; Veldkamp and Fresco, 1996; Verburg et al., 1999a)) is applied to explore possible scenarios of land use change in the Brazilian Amazonia. The concept of "*scenario exploration*" is introduced. Each exploration emphasizes a different aspect of the Amazonia occupation process. Out of many possibilities, this work presents the results of five explorations which analyze the effects on future deforestation patterns of *alternative accessibility factors, policies and market constraints*, as follows.

The two first explorations analyze the use of alternative regression models in the CLUE framework to identify factors that best capture the new Amazon frontiers and future possible axes of development. This comparison aims at understanding the importance of different accessibility determining factors in process of land use change. In the first exploration, the focus is on connectivity factors. In the second, accessibility to local markets (distance to urban centres). Then, the impacts of alternative public policies are analyzed in two other explorations. Two types of policies are considered: (a) policies that influence intra-regional conditions for agricultural use, such as road paving and the creation of protected areas; and (b) law enforcement policies, such as deforestation limits inside private properties. Last exploration analyzes scenarios of increasing and decreasing demand for land in Amazonia, corresponding to higher or lower pressure for forest conversion determined by the national and international agribusiness.

From each of the five explorations very different patterns may emerge. Each exploration comprises two or three alternative results (hot-spots of change from 1997 to 2020) to be compared. Together, the results of the five explorations are complementary, and contributing to the understanding of different aspects of the occupation process.

This chapter is organised as follows. Section 5.2 presents the methodology. Section 5.3 presents the results and discussion of the different scenario explorations.

5.2 Methods

5.2.1 The CLUE framework and its adaptation to Amazonia

This paper uses the CLUE framework adapted to the Amazonia characteristics. The CLUE framework consists of two main components, as illustrated in Figure 5.1 6: (1) the *Demand module*, that projects the amount of change for each land-use class; (2) the *Allocation module*, the spatial component that acts in two scales (a coarse and a fine resolution grid) to localize such changes. The demand module is application specific (see, for instance, previous CLUE applications in Ecuador (De Koning et al., 1999) China (Verburg and Veldkamp, 2001; Verburg et al., 1999b), and Central America (Kok and Veldkamp, 2001.)). Demand calculation is based either on trend analysis of past change rates, scenario constructions, or more elaborate economical models. The amount of change for each land use is passed on to the allocation module. The allocation module uses one cellular space consisting of fixed size cells for each spatial scale. Allocation of changes depends on the suitability of each cell, defined by empirical relationships between land use patterns and determining factors.

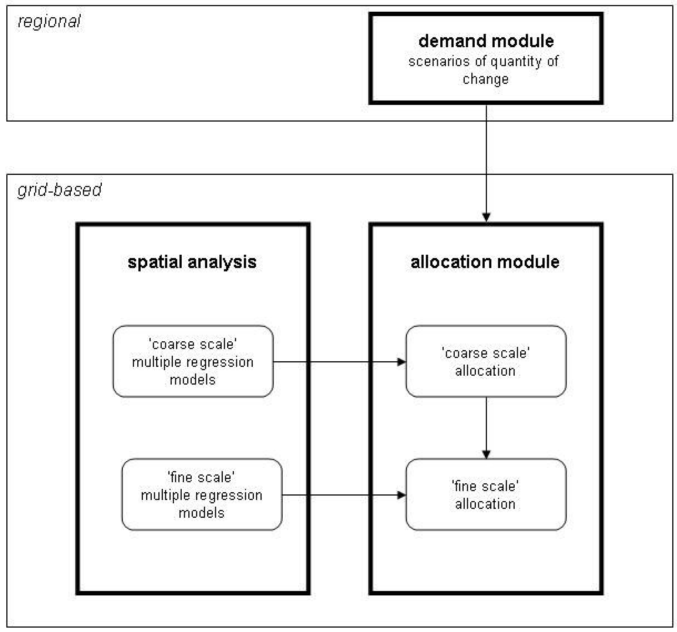


FIGURE 5.1 - Structure of the main components of the CLUE modeling framework (source: adapted from Verburg et al. (1999b)).

The CLUE multi-scale allocation module works as follows. Relations between land uses and explanatory factors are quantified by multiple regressions based on land use patterns in a given date. Different regression models are adopted at the coarse and fine resolution. Such regression models are used to establish the suitability of each cell in relation to a certain land use. The model first allocates changes at coarse resolution cells trying to reach the total amount of change determined by the demand module for each land-use in each year. Then the same process is repeated at fine scale. The difference, besides the use of different regression models, is that the amount of change in each cell at fine scale is also influenced by the change projected at the corresponding cell at coarse scale. Details about the allocation mechanism can be found in Verburg et al. (1999a).

Adapting the CLUE framework to Amazonia required: (a) initial modeling decisions, such as the choice of land use classes, potential determining factors, spatial and temporal scales of analysis; (b) statistical analysis for both resolutions; (c) changes in the internal CLUE allocation model; and (d) establishment of a combination of demand and allocation scenarios that would allow exploration of how alternative determining factors, policies and market constraints influence the Amazonia occupation process. These steps are described in the next sections.

5.2.2 Basic modeling decisions

Land use classes (dependent variables) are the percentage of forest and main agricultural uses (pasture, temporary agriculture, permanent agriculture, planted forest, and non-used agricultural areas) in each 25x25 km^2 and 100x100 km^2 cell, as discussed in Section 3.2.2. The potential explanatory variables compiled to support this work are described in Section 3.3, and include *accessibility to markets, economical attractiveness, demographical, technological, agrarian structure, public policies,* and *environmental* factors.

In the fine scale resolution, four spatial partitions are considered for the statistical analysis: the whole Brazilian Amazonia and three macro-zones, namely the Densely Populated Arch, the Central Amazonia and the Oriental Amazonia. In the coarse resolution, only the whole Amazonia is considered. The time frame of analysis is 1997 to 2020. Temporal resolution is one year.

5.2.3 Statistical analysis

5.2.3.1 Adequacy of Linear Regression models in LUCC models

The statistical analysis aims at establishing the relationship between the land use patterns (dependent variables) and their determining factors (independent variables), obtained though a linear regression analysis. The adequacy of conventional linear multiple regressions models was analyzed. One of the basic hypotheses in linear regression models is that observations are not correlated, and consequently the residuals of the models are not correlated as well. In land use data, this hypothesis is usually not true. Land use data has the tendency to be spatially autocorrelated, as land use changes in one area tend to propagate to neighboring regions. Spatial dependence could be seen as a methodological disadvantage, as it interferes on linear regression results, but on the other hand is exactly what gives us information on spatial pattern and structure and process (Overmars et al., 2003).

Chapeter 4 presents a statistical analysis using the spatial lag regression model (Anselin, 2001), a modified linear regression model in which the spatial dependence is captured in one parameter (the auto-regressive coefficient). We compared the results of the spatial lag models with those of a non-spatial linear regression model for the whole Amazonia to understand how explanatory factors contribute to spatial dependence. Results show that the spatial coefficient of the spatial lag models is significant and higher than 0.70 in all models, a quantitative evidence that corroborates of earlier assessments that deforestation is a diffusive process in the Amazon, and tends to occur close of previously opened areas (Alves, 2002). Results also show that when using the spatial lag regression model, the determining factors coefficients in the regression equation get lower, but not in a uniform way. Connectivity to markets factors carry a larger part of the spatial dependence, and reinforce the diffusive pattern of deforestation (see Table 4.4).

There is a risk of using the spatial lag model for dynamical LUCC modeling. The spatial autocorrelation parameter is related to the previous deforestation in the neighborhood. The resulting model would have a tendency to concentrate changes in previously occupied areas, not allowing new patterns to emerge. Thus, we considered more appropriate to tie the diffusive aspect of deforestation to scenario-dependent variables such as connectivity to markets and distance to roads. New patterns could emerge as connectivity characteristics are changed. Similar considerations are presented by Overmars et al. (2003). In this way, we chose to use the linear regression model coefficients to feed the CLUE model.

5.2.3.2 Statistical analysis procedure

An initial exploratory statistical analysis showed that some of the relationships between potential explanatory variables and the land use variables were not linear. We applied a logarithmic transformation to the land use variables and to some explanatory variables. The log transformation improved the regression results significantly. This improvement suggests that the explanatory variables are related to the initial choice of areas to be occupied. After the initial choice, occupation tends to concentrate close to previously opened areas (Alves, 2002).

The explanatory analysis identified a high degree of correlation among the potential explanatory factors presented in Chapter 3. A subset of 15 variables was selected for the regression analysis required to run the CLUE model. This subset is presented in Table 5.1. These variables cover the broadest possible range of categories, while minimizing correlation problems. Within the same category, alternative possibilities were tested. For instance, out of the many climate variables, we selected the average humidity in the drier months of the year in each cell. The final choice of explanatory variables does not include any variables from the *demographical* or *technological* categories, which are captured indirectly by other correlated variables. We gave preference to variables in the *accessibility to markets* and *public policy* categories that could be used for policy scenario analysis.

TABLE 5.1 – Subset of potential explanatory variables selected to run the CLUE model.

Category	Variable	Description	Unit	Source
Accessibility to markets	conn_mkt	Indicator of strength of connection to national markets (SP and NE) through roads network	-	IBGE[1]
	conn_ports	Indicator of strength of connection to ports through roads network	-	IBGE
	log_dist_rivers	Euclidean distance to large rivers (log)	km	IBGE
	log_dist_roads	Euclidean distance to roads (log)	km	IBGE
	log_dist_pav_roads	Euclidean distance to paved roads (log)	km	IBGE
	log_dist_unpav_roads	Euclidean distance to unpaved roads (log)	km	IBGE
	log_dist_urban	Euclidean distance to urban centers (log)	km	IBGE
Economic Attractiveness	log_dist_wood	Euclidean distance to wood extraction poles (log)	km	IBAMA[2]
	log_dist_mineral	Euclidean distance to mineral deposits (log)	km	CPRM[3]
Public policies	prot_area	Percentage of protected areas	% of cell area	IBAMA FUNAI[4]
	log_settl	Number of settled families from 1970 to 1999 (log)	Number of families (log)	INCRA[5]
Agrarian Structure	agr_small	Percentage of area of small properties	% of cell area	IBGE
Environmental	soil_fert	Percentage of high and medium to high fertility soils in	% of cell area	IBGE
	soil_wet	Percentage of wetland soils ("*várzea*" soils)	% of cell area	IBGE
	clim_humid	Average humidity in the three drier months of the year	%	INMET[6]

Even in the subset of variables presented in Table 5.1, there was still a high degree of correlation, which varied across the spatial partitions and resolution. For instance, at both scales, distance to urban centres and distance to roads were highly correlated in all spatial partitions, except in the Occidental one. Climatic conditions and connection to national markets were also highly correlated, except in the Central region. Distance to roads and connection to national markets were highly correlated in the whole Amazon. We decided to build different regression models, where each model had potentially explanatory variables with less than 50% correlation between them.

Several alternative models were constructed for each spatial partition. To build the regression models, we selected as primary variables those with potentially greater explanatory power in relation to deforestation: distance to urban centres and distance to roads, followed by connection to markets and climate variables. This led to the models summarized in Table 5.2:

- *Coarse resolution*: We consider two models, one including distance to urban centres (*amazon_urban_100*) and another including distance to roads (*amazon_roads_100*). Both models were derived considering the whole Amazonia.

- *Fine resolution*:

    - One model for the whole Amazonia, including distance to roads (*amazon25*).

    - Three models for three different sub-regions (the Arch, Central and Occidental macro-zones), all including by distance to roads (*arch25, central25, occidental25*).

TABLE 5.2 - Groups of non-correlated explanatory variables used to construct the regression models.

	Coarse resolution		**Fine resolution**			
	amazon_urban100	amazon_roads100	amazon25	arch25	central25	occidental25
log_dist_urban	x					x
log_dist_roads		x			x	x
log_dist_paved_roads			x	x		
log_dist_unpaved_roads			x	x		
conn_mkt				x	x	x
clima_humid	x	x	x		x	x
conn_ports	x	x	x	x	x	x
log_dist_rivers	x	x	x	x	x	x
log_dist_wood				x		
log_dist_mineral		x		x	x	
prot_area	x	x	x	x	x	x
agr_small	x	x	x	x	x	x
log_settl	x	x	x	x	x	x
soil_fert	x	x	x	x	x	x
soil_wet	x	x	x	x	x	x

An automatic linear forward stepwise regression was applied to refine the models and discard non-significant variables for all land uses. In the fine resolution models, we attempted to distinguish between distance to paved and unpaved roads in all spatial partitions. However, in the Central and Occidental regions, paved roads were not significant, as few paved roads existed in 1997. In these cases, we used the variable distance to roads (that aggregates both paved and unpaved roads).

The relative importance of different factors varies in the resulting regression models derived for different spatial partitions. These differences are explored to understand the impact of different factors on the deforestation process, as described in Section 5.2.5.

5.2.4 Allocation module modifications

Three main modifications were added to the CLUE allocation module (Verburg et al., 1999a) to adapt it to specific Amazonia characteristics. These modifications allow the analysis of law enforcement scenarios, as follows:

1. *Adoption of an alternative allocation procedure after forest cover reaches a minimum threshold in each cell.* After a given limit, only very small and slow changes are allowed to occur in the forest cover. This parameter can be used in scenario explorations regarding obedience (or not) to the Federal law that imposes that 80% of forest inside private properties must be preserved. This law is currently largely disrespected. Scenario alternatives regarding the possible impacts of the law enforcement can be constructed through a new parameter (`forest_threshold`) added to the allocation module.

2. *Control of the maximum amplitude of change in a single cell in a given time step.* We calibrated the allocation parameters using 2003 deforestation data (INPE, 2005), and concluded that the CLUE model had a tendency to concentrate changes on a few cells, which presented higher levels of suitability than the others. This was leading to unrealistic large forest removal concentrated on a few cells. We imposed an upper limit to the amplitude of change in each cell through a new parameter (`change_max_lim`). By controlling this parameter we can also impose different levels of forest conversion pace in each cell. This can be used to construct scenarios regarding the possible effects of government actions to control illegal deforestation and land appropriation practices.

3. *Heterogeneity of parameter values representing different levels of control.* We created a mechanism to allow these two parameters (`forest_threshold` and `change_max_lim`) to assume unique values for the whole Amazonia or

regionalized values. Regionalized values can be used to simulate "command and control" actions to inhibit illegal activities at selected locations, or non-uniform levels of governance across the region.

5.2.5 Scenario building

5.2.5.1 Overview

The paper proposes five alternative scenario explorations summarized in Table 3. Each exploration emphasizes a different aspect of the occupation process: the importance of determining factors, the effects of policies and the effect of market constraints. Exploration A and B analyze the relative importance of accessibility to markets factors in capturing the new Amazonia frontiers. These explorations compare alternative regression models. Exploration A compares models based only on distance to roads to models that include connectivity factors. Exploration B analyzes the effects of using distance to urban centres in the coarse resolution. Explorations C and D analyze the effects of public policies in the projected deforestation patterns. Exploration C analyzes the impacts of road paving and creation of protected areas. Exploration D considers law enforcement polices. Finally, Exploration E analyzes the effects of increasing or decreasing the demand, to understand how market constraints can alter the projected deforestation patterns.

Explorations use a combination of alternative regression models, demand and allocation scenarios. Allocation scenarios encompass changes in dynamic spatial determining factors (due to road paving and creating protected areas). Law enforcement scenarios refer to possible values of the allocation parameters described in Section 5.2.4.

TABLE 5.3 - Scenario exploration summary

EXPLORATION		REGRESSION MODELS				SCENARIOS		
		100km	***25km***					
			Arco	***Central***	***Ocidental***	***Allocation***	***Demand***	***Law enforcement***
A	Alternative factors:	amazon_roads100	amazon25	amazon25	amazon25	No-change	Baseline	No
	Accessibility	amazon_roads100	arch25	central25	occidental25	No-change	Baseline	No
		amazon_roads100	arch25	arch25	arch25	No-change	Baseline	No
B	Alternative factors:	amazon_roads100	arch25	arch25	arch25	No-change	Baseline	No
	Local markets	amazon_urban100	arch25	arch25	arch25	No-change	Baseline	No
C	Policy analysis: Road paving	amazon_roads100	arch25	arch25	arch25	Paving and Protection	Baseline	No
	and protected areas	amazon_urban100	arch25	arch25	arch25	Paving and Protection	Baseline	No
D	Policy analysis: Law enforcement	amazon_roads100	arch25	arch25	arch25	No-change	Baseline	Private reserves 50%
		amazon_roads100	arch25	arch25	arch25	No-change	Baseline	Local command and control
E	Market constraints	amazon_roads100	arch25	arch25	arch25	Paving and Protection	Decrease	No
		amazon_roads100	arch25	arch25	arch25	Paving and Protection	Increase	No
		amazon_urban100	arch25	arch25	arch25	Paving and Protection	Decrease	No
		amazon_urban100	arch25	arch25	arch25	Paving and Protection	Increase	No

This remainder of section is organized as follows. Section 5.2.5.2 presents the premises regarding the demand scenarios used in the explorations. Section 5.2.5.3 describes the alternative allocation scenarios. Section 5.2.5.4 describes the alternative law enforcement scenarios.

5.2.5.2 Demand scenarios

The CLUE demand module for this study is based on past and current deforestation rates (INPE, 2005). Actual deforestation rates are used from 1997 to 2004 (INPE, 2005). The baseline scenario assumes the current level of deforestation (approximately ~25,000 km^2) will be maintained until 2020. The baseline scenario is used for Explorations A, B, C and D. Exploration E uses two alternative demand scenarios. In the first demand scenario, the rate decreases until 15,000 km^2 per year in 2015, and then stabilizes at this level until 2020. In the second demand scenario, deforestation rate increases to 35,000 km^2 in 2015, and then stabilizes until 2020. Other premises adopted in the demand scenarios include:

- *The relative percentages of the different land-use classes* (IBGE, 1996) are maintained until 2020. Pasture represents 68% of the deforested area, and temporary agriculture, 14%. Although there is a reported increase in soybean in forest areas in the last years, cattle herd in the Amazonia is also increasing (IBGE, 2006a). Changes in these assumptions are left for future work, as the new agricultural census is planned for 2006.

- *To distribute the quantity of change in the three macro-regions*, we assume that the annual deforestation rates will significantly decrease in the Arch and increase in the Central area, according to the percentages shown in Figure 5.2. The premise behind the demand regionalization is that the Amazonian new frontiers are driven by regional forces acting in the Central Amazon (Becker, 2005). In the Occidental region, a smaller demand increase than in the Central area is assumed. The projected distributed rates in each spatial partition were checked against 2003 deforestation data (INPE, 2005) to assure compatibility with current land use process.

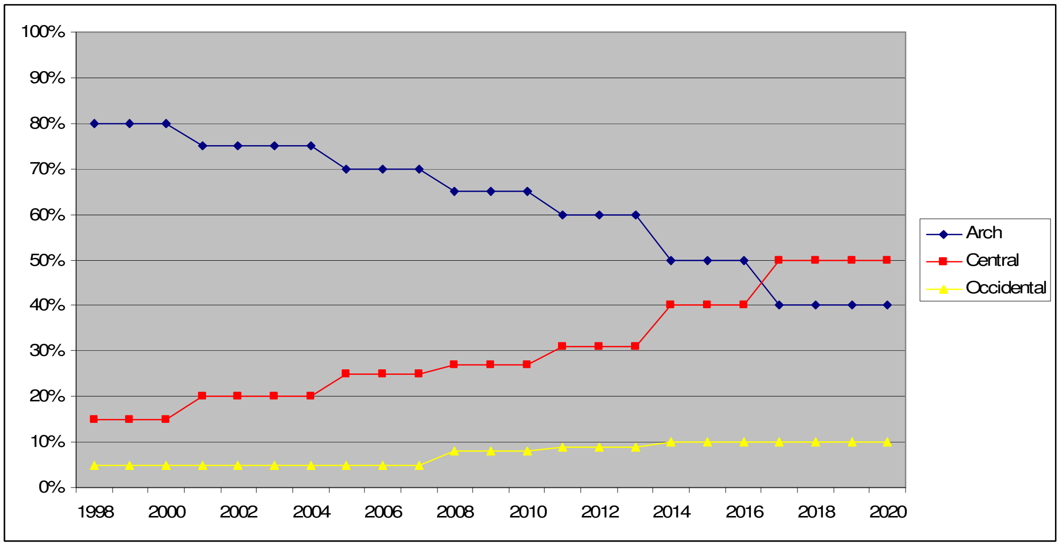


FIGURE 5.2 - Temporal deforestation rate distribution among macro-regions.

5.2.5.3 Allocation scenarios

Allocation scenarios account for the temporal change in factors influenced by road paving and creation of protected areas. These factors are connection to markets, connection to ports, distance to roads, distance to paved roads, distance to unpaved roads and protected areas. These factors take different values in the cellular database in both fine and coarse scales, according to two different allocation scenarios:

- *No change* in roads and protected areas, except the inclusion of some unpaved roads after 2000 (the Canopus unpaved road in São Felix do Xingu (Escada et al., 2005a), and three new unpaved roads in the north-western part of Mato Grosso state).
- *Paving and protection scenario*: five roads are paved according to the schedule shown in Table 5.4, and new protected areas are created in 2004. Figure 5.3 illustrates the changes in the protected areas and road network in this scenario.

TABLE 5.4 - Paving and protecting allocation scenario schedule.

Road	Segment to be paved	State	Year of completion
BR 163 (Cuiabá-Santarém)	Itaúba-Santarém	Pará	2007
BR 364	Bujari-Cruzeiro do Sul	Acre	2007
PA 279	Xinguara-São Felix doXingu	Pará	2007
BR 230 (Transamazônica)	Humaitá-Labrea	Amazonas	2007
BR 319 (Porto Velho-Manaus)	Humaitá-Careiro	Amazonas	2010

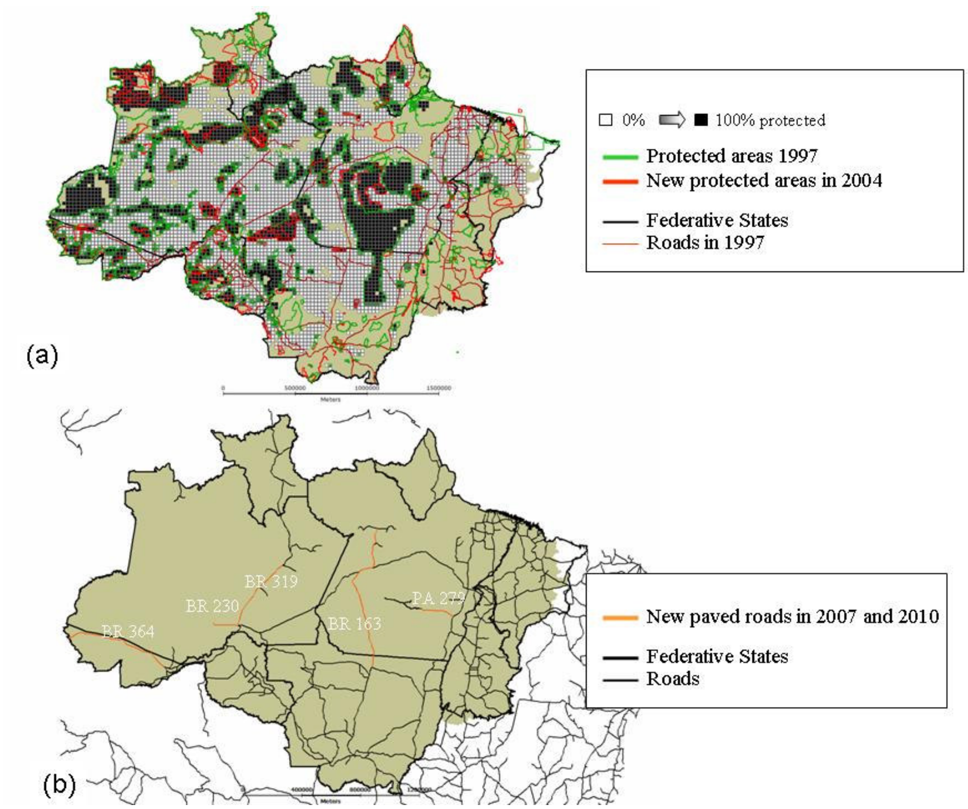


FIGURE 5.3 - Paving and protecting scenario changes in: (a) protected areas; (b) road network.

Figures 5.4 and 5.5 illustrate, respectively, the temporal evolution (1997, 2010) of the connection to markets and ports variables in the "Paving and Protecting" scenario.

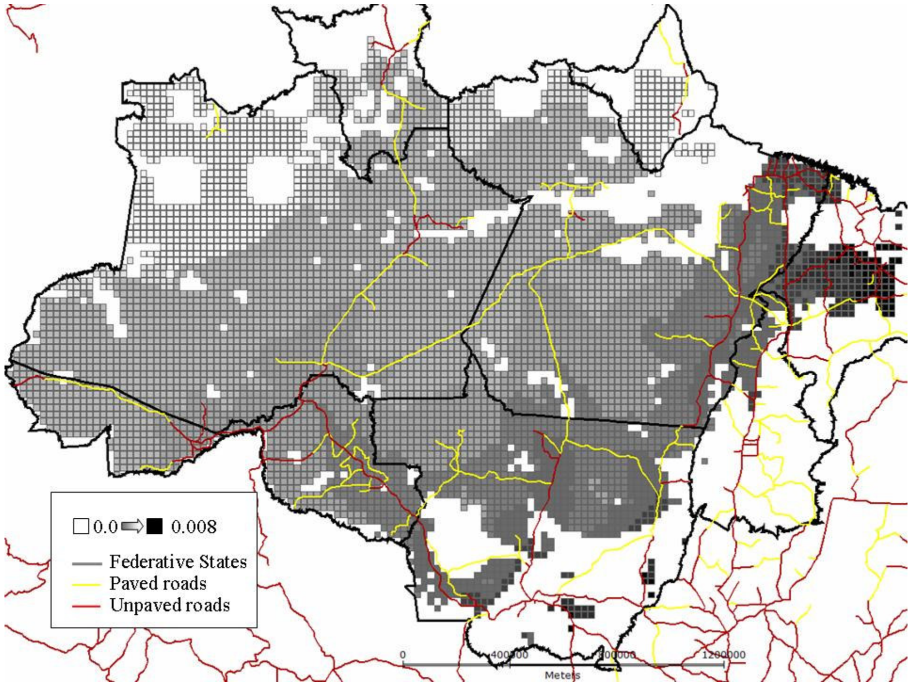


FIGURE 5.4 – Connection to national markets (São Paulo and Northeast) in 1997.

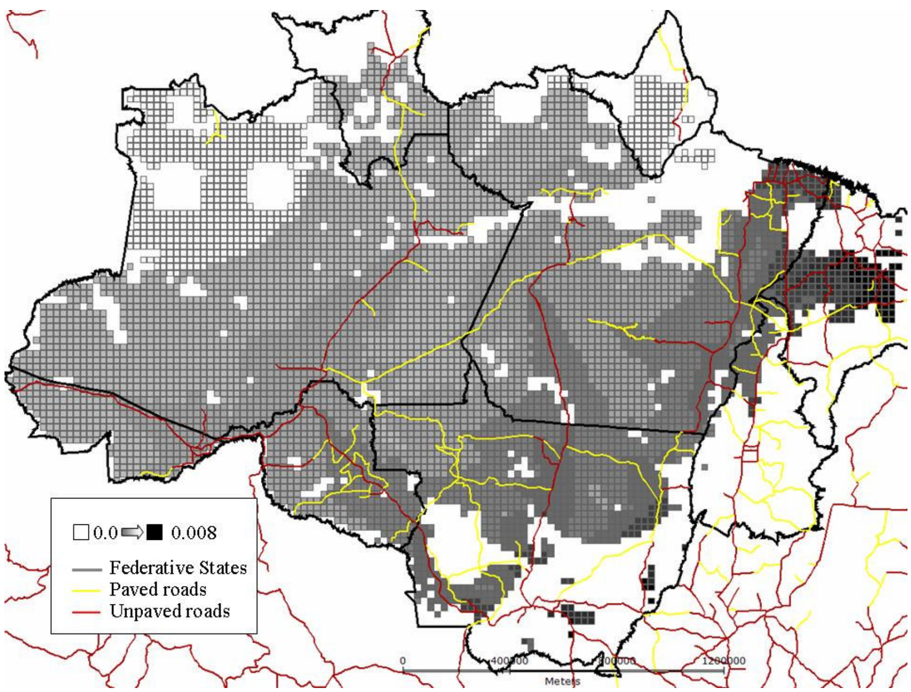


FIGURE 5.5 - – Connection to national markets (São Paulo and Northeast) in 2010.

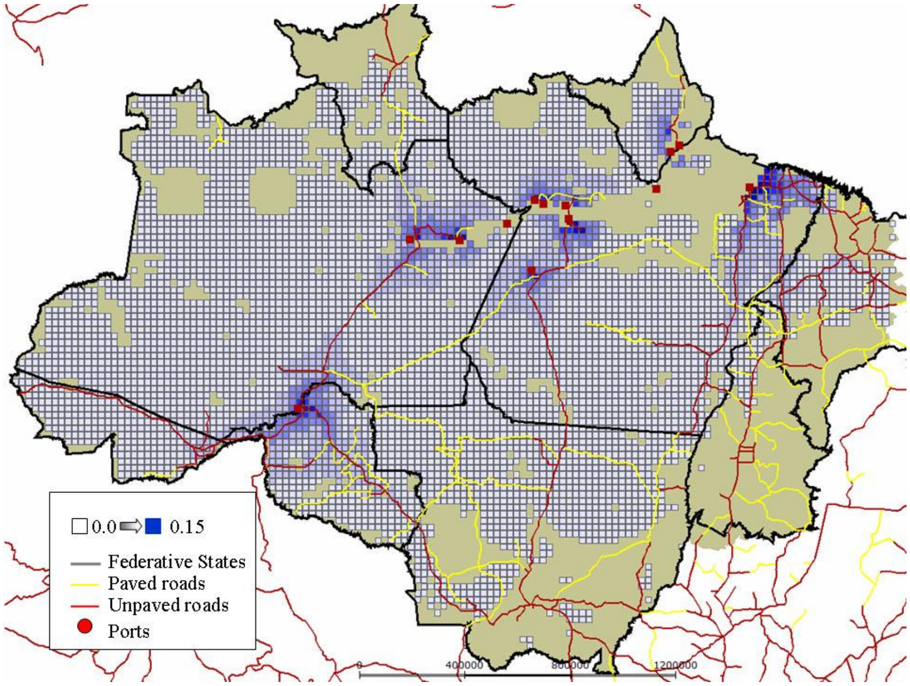


FIGURE 5.6 – Connection to Amazonia ports in 1997.

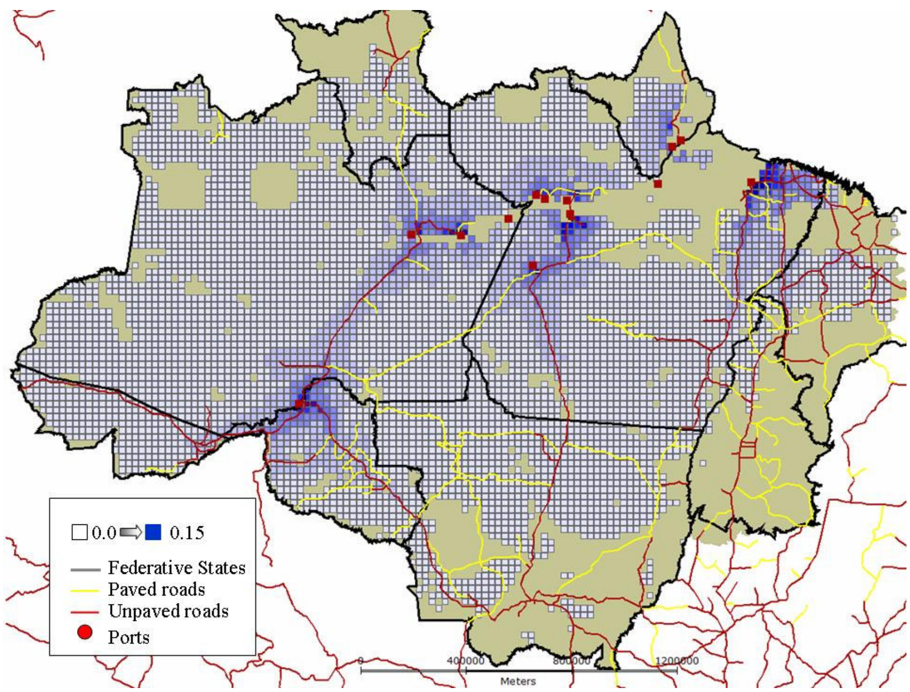


FIGURE 5.7 – Connection to Amazonia ports in 2010.

5.2.5.4 Law enforcement scenarios

Three alternative scenarios are considered, summarized in Table 5.5:

- *No law enforcement*. Private reserves continue to be largely disrespected. Deforestation pace only slows down after 80% of forest cover in each cell has been removed. This is the scenario considered in most explorations: A, B, C, and E.

- *Private reserves enforcement.* An overall increase in the maintenance of private forest reserves is assumed in this scenario. The premise is that after 50% of original forest has been removed in each cell, deforestation pace slows down, due to law enforcement practices. This scenario is analyzed in Exploration D.

- *Local command and control*: In certain high pressure areas, command and control actions take place. In these controlled areas, two premises are adopted: (a) private forest reserves are more respected; (b) illegal land appropriation practices are inhibited, slowing the deforestation process. This scenario can also be seen as the presence of the State, or a "governance" level, non-uniformly distributed across the region. Outside the controlled areas, allocation parameters represent the current low level of law enforcement in the Amazonia, as Table 5.5 this scenario is also analyzed in Exploration D.

TABLE 5.5 – Law enforcement scenario parameters.

	Forest cover threshold (forest_ threshold)	Maximum allowed change (change_max_lim)
No law enforcement	20%	50%
Private Reserve partial enforcement	50%	50%
Local Command and Control:		
Controlled areas	50%	20%
Outside controlled areas	20%	50%

5.3 Results and discussion

This section compares the results of the five explorations using maps of hot spots of change in the forest cover from 1997 to 2020 resulting from the CLUE application. Besides the visual comparison of the hot-spot maps, selected sites are used to assess quantitatively the intra-regional differences in the results. Figure 5.8 illustrates these sites. This quantitative assessment analyzes results inside and outside of protected areas separately. Thirteen sites are used outside protected areas, distributed in the new frontiers and more consolidated areas, as Table 5.6 shows. Table 5.7 describes the sites selected inside protected areas. The two areas in the Central macro-region are only created in 2004 in the paving and protecting allocation scenario.

Outside Protected Areas

Site	Site name
1	Sáo Felix/Iriri
2	BR 163 - South
3	BR 163 - North
4	BR 163/BR 230
5	BR 230 - Ruropólis/Trairão
6	BR 230 - Apuí
7	BR 319 - Humaitá
8	BR 319 - Manicoré
9	BR 319 - Manaus
10	Marabá
11	Cumaru/São Felix
12	Terra Nova do Norte
13	Aripuanã

Inside Protected Areas

Site	Site name
1	Terra do Meio
2	South of Amazonas
3	Xingu IL
4	MT

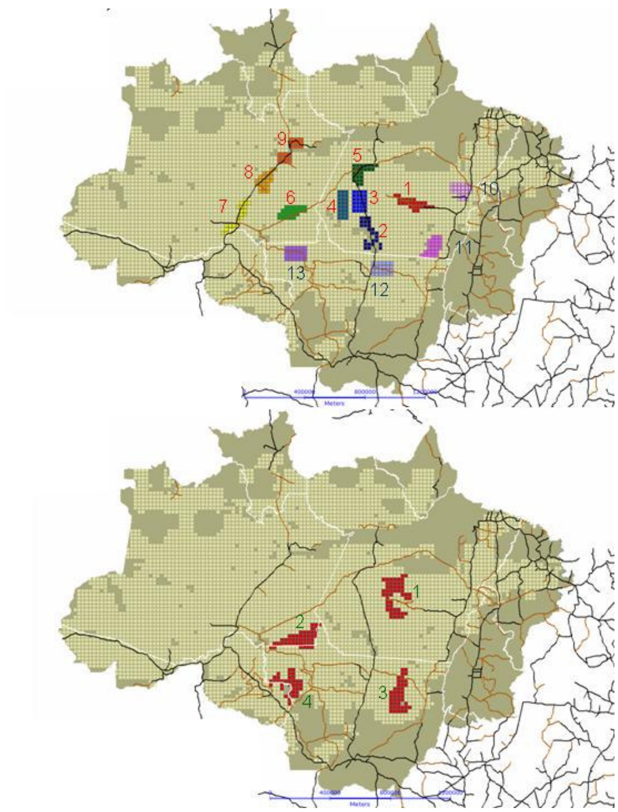


FIGURE 5.8 – Sites for quantitative comparison of results.

TABLE 5.6 – Sites for quantitative assessments of intra-regional differences outside protected areas.

Site number	Site name	Description/Location	Macro-region	State
1	São Felix/Iriri	New frontier - São Felix/Iriri	Central	Pará
2	BR 163 - South	New frontier – Cuiaba-Santarém (South of Novo Progresso)	Central	Pará
3	BR 163 - North	New frontier - Cuiaba-Santarém (North of Novo Progresso)	Central	Pará
4	BR 163/BR 230	New frontier - Cuiaba-Santarém	Central	Pará
5	BR 230 - Ruropólis/Trairão	Traditional occupation area	Central	Pará
6	BR 230 - Apuí	New frontier - South of Amazonas	Central	Amazonas
7	BR 319 - Humaitá	New frontier - South of Amazonas	Central	Amazonas
8	BR 319 - Manicoré	New frontier - South of Amazonas	Central	Amazonas
9	BR 319 - Manaus	Traditional occupation area	Central	Amazonas
10	Marabá	Traditional occupation area	Arch	Pará
11	Cumaru/São Felix	Unoccupied area in Southern Pará	Arch	Pará
12	Terra Nova do Norte	Traditional occupation area	Arch	Mato Grosso
13	Aripuanã	Unoccupied area in Northern Mato Grosso	Arch	Mato Grosso

TABLE 5.7 – Sites for quantitative assessments of intra-regional differences inside protected areas.

Site number	Site name	Macro-region	State
1	Terra do Meio	Central	Pará
2	Sul do Amazonas	Central	Amazonas
3	Xingu IL	Arch	Mato Grosso
4	MT	Arch	Mato Grosso

Sites outside protected area have the same size (15.000 km^2, containing 24 cells of 25x25 km ^{2}). The comparison indicator in this case is percentage of the overall change allocated in each test site (change in deforestation from 1997 to 2020 in the test site divided by change in the whole Amazon). Minimum value of the indicator is 0%, and maximum value is 2.5% (in the baseline demand scenario, this maximum value corresponds to a deforestation of 12.500 km inside the test site in the period, i.e., 83% of change). Although absolute values and range of the indicators are small, relative differences among sites are clear. *The goal of the comparison is to use better assess which areas gained preference over others in the allocation procedure in each exploration.* For the test sites inside protected areas, as their sizes vary, the percentage of total area deforested in 2020 is use as the comparison indicator.

5.3.1 Exploration A – Analysis of alternative factors: accessibility

This exploration compares the effects of using alternative regression models to assess the relative importance of different accessibility factors. We employ the *amazon_roads_100* model at coarse resolution, and compare the spatial patterns derived from using different models at the fine scale. The focus is especially in the Central macro-zone, where the new Amazonia frontiers are located (Section 2.3). This exploration compares the use of the *amazon25*, *arch25* and *central25* regression models. Table 5.8 compares the three most significant regression coefficients in each model. Regarding *accessibility factors*, the models differ as follows:

- In the *amazon25* model, only *distance to roads* is one of the three most significant variables. Connection to ports and distance to rivers are also significant in the model. Connection to markets was not included in this model due to the high correlation to distance to roads (see Table 5.2).

- In the *arch25* model, *connection to markets* and distance to roads are considered, and connection to market presents greater importance than distance to roads.

- In the *central25* model, *connection to ports* and *distance to rivers* are more important than connection to markets. Distance to roads is the most significant variable.

This exploration uses the *baseline demand* scenario, the *no change allocation* scenario, and the *no law enforcement* scenario.

TABLE 5.8 - Three most important deforestation determining factors in terms of standardized betas. Variables are listed in order of importance. Plus or minus signal indicate a positive or negative impact on increasing or decreasing deforestation.

Coarse scale models			
amazon_roads100		***amazon_urban100***	
Distance to roads	-	Distance to urban centres	-
Humid climate	-	Number of settled families	+
Fertile soils	+	Humid climate	-

Fine scale models							
amazon25		***arch25***		***central25***		***occidental25***	
Distance to roads: Paved / Unpaved	- / -	Protected areas	-	Distance to roads	-	Distance to urban centers	-
Protected areas	-	Connection to markets	+	Connection to ports	+	Distance to roads	-
Humid climate	-	Distance to roads: Paved / Unpaved	- / -	Distance to rivers	-	Distance to rivers	-

Figures 5.9 to 5.11 show alternative forest change patterns from 1997 to 2020 (hot spots of change) resulting from the three CLUE model runs. Figure 5.9 shows the resulting hot-spots of change of using the *amazon25* in all spatial partitions. Figure 5.9.b shows the results of different models for each spatial partition (*arch25, central25 and occidental25*). Figure 5.9.c shows the outcome of use of the *arch25* model in all spatial partitions. Figure 5.13 presents a quantitative comparison for some of the test sites.

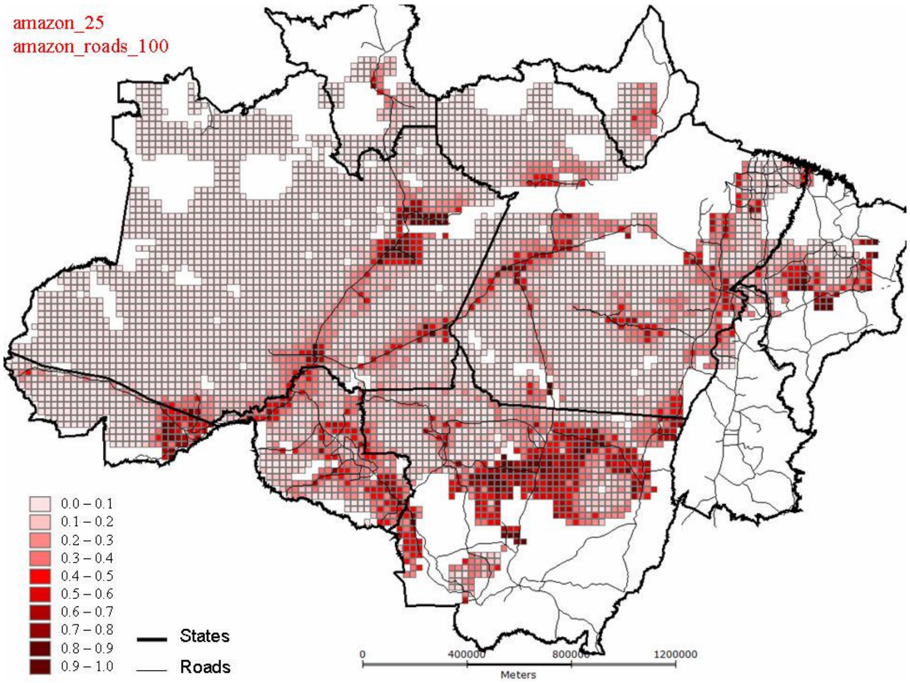


FIGURE 5.9 – Exploration A: *amazon25*.

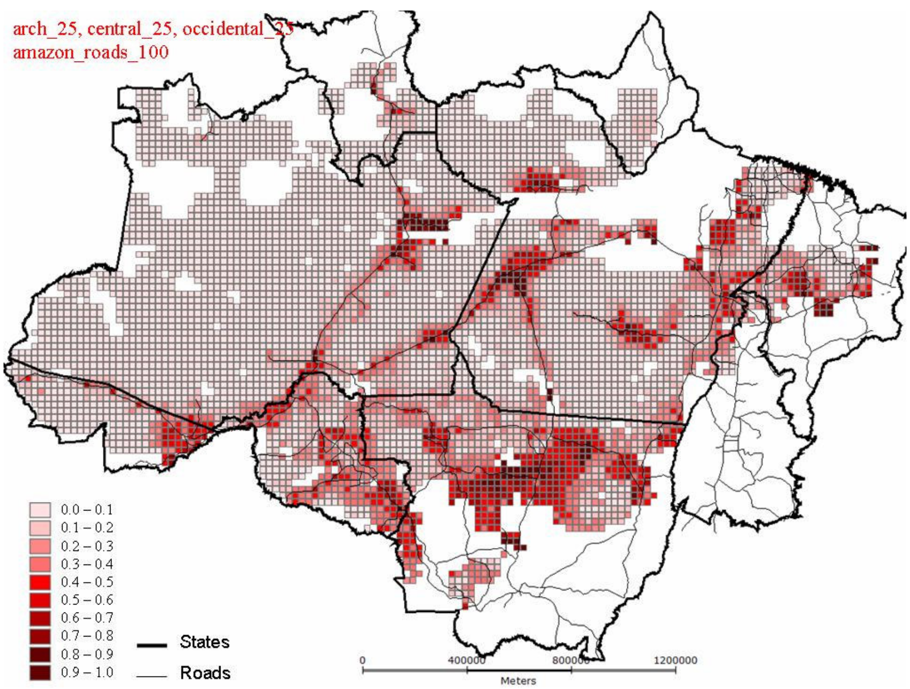


FIGURE 5.10 – Exploration A: *arch25, central25, occidental25*.

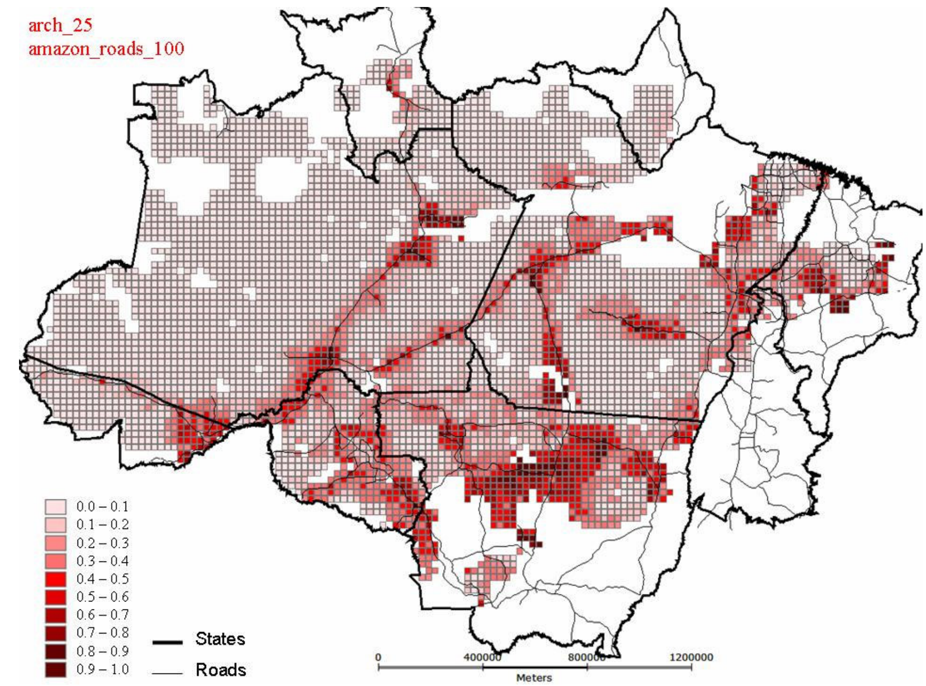


FIGURE 5.11 – Exploration A and B: *arch25, amazon_roads_100*.

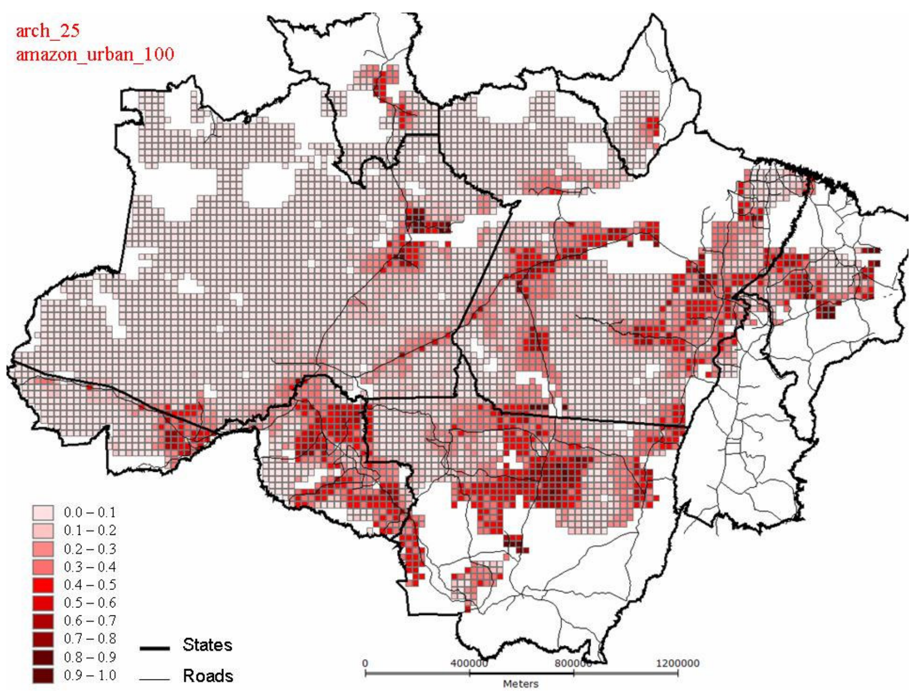
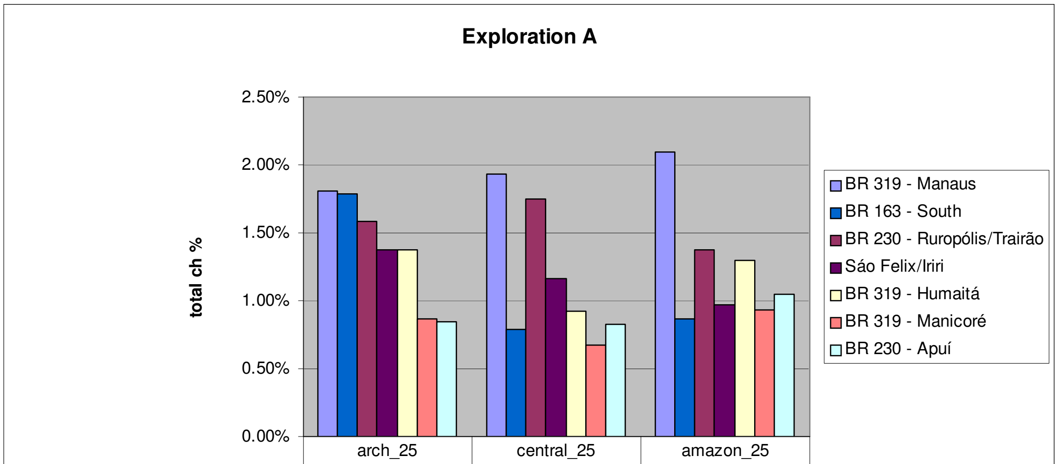


FIGURE 5.12 – Exploration B: *arch25, amazon_urban_100*.



	arch_25	central_25	amazon_25
BR 319 - Manaus	1.81%	1.94%	2.09%
BR 163 - South	1.79%	0.79%	0.86%
BR 230 - Ruropólis/Trairão	1.58%	1.75%	1.37%
Sáo Felix/Iriri	1.38%	1.16%	0.97%
BR 319 - Humaitá	1.37%	0.93%	1.30%
BR 319 - Manicoré	0.87%	0.67%	0.93%
BR 230 - Apuí	0.85%	0.83%	1.05%

FIGURE 5.13 – Exploration A: quantitative comparison among selected test sites.

When the *amazon25* model is used (Figure 5.9), resulting patterns at the Central macro-region tend to concentrate around the Amazon river and ports, and distribute unevenly along existing roads, with a dominance in the Porto Velho-Manaus road (BR 319). When the *central25* models is used in the Central area (Figure 5.10), resulting patterns tend to concentrate even more around the Amazon river and close to ports, due to the importance of connection to ports and distance to rivers in this model. These two models do not capture the dynamics of the Amazonian new frontiers appropriately. Currently active areas, such as the Cuiabá-Santarém show a less marked pattern than the PortoVelho-Manaus, for instance, where the process is starting only now. The pressure in São Felix/Iriri is also not captured in both models.

Using the *arch25* model in all regions (Figure 10.c) captures the different temporal stage of occupation among different new frontiers, with a stronger process both in the Cuiabá-Santarém and São-Felix/Iriri areas (see comparison in Figure 5.13). Resulting patterns reflect the importance of the connectivity to national markets (São Paulo and

Northeast) to explain the higher pressure in these areas. This heterogeneity (in space and time) could not be captured using only measures of distance to roads.

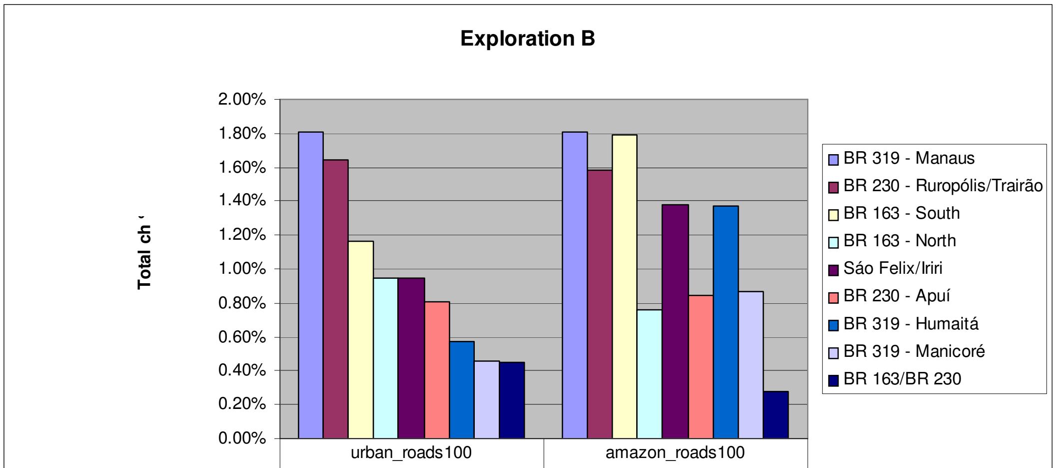
Based on these results, the *arch25* model is used as the fine resolution model for the other explorations presented below. This does not mean an assumption that the process that happened in the Arch is going to be repeated in the other areas. Instead, the assumption is that the *arch25* model better captures the current and possible axes of development presented in Section 2.4, especially due to the inclusion of the connection to markets variable. The *arch25* model presents another advantage for scenario building: protected areas have a higher importance in comparison to the other models, increasing their effectiveness as a deterrent to the deforestation process. The *arch25* model also includes important variables such as distance to timber production areas and percentage of fertile soils.

In the *arch_25* model, climate variables are not used. This may also explain the difference among the *amazon25, central 25, and arch_25* results in the Central macro-region. The *amazon25* and *central25* include climate conditions as important deterrents of occupation, and this may reinforce the concentrated patterns around the Amazon river in both models (see climate condition variables in Figures 3.22 3.23). Connection to markets and climate conditions are highly correlated in the Arch and in the whole Amazonia, and could not be placed in the same regression models. Chapter 4 discusses the importance of such variables in the occupation process of Amazonia, and concludes that the diffusive nature of deforestation, distance to roads and to urban centres, climate and connection to markets, and the *interaction among them*, contributed significantly for the pattern of deforestation in 1996/1997. In the following explorations, connection to markets is used in the fine resolution (*arch25* model). Climate conditions influence is maintained in the large scale, through both coarse resolution models (*amazon_roads100* and *amazon_urban100*), as shown in Table 5.8. In this way, we use the CLUE model multi-scale approach to incorporate the complementary influence of important and correlated variables. The multi-scale approach is also explored in relation to other pair of highly correlated variables, distance to roads and distance to urban centres, as discussed in the next Exploration.

5.3.2 Exploration B – Analysis of alternative factors: local markets

This exploration analyzes the effects of including distance to urban centres in the coarse resolution model. Distance to urban centres is a proxy of the accessibility to local markets. The aim of exploration B is to explore how the local markets contribute to the new frontiers, and to assess the difference between the large-scale influence of the distance to roads and that of the distance to urban centres.

Exploration B uses the *arch25* model in the fine resolution, and compares the use of the distance to roads model (*amazon_roads100*) with the distance to urban centres model (*amazon_urban100*), in the coarse resolution. Table 5.8 compares the three most significant regression coefficients in each model. This exploration uses the *baseline demand* scenario, the *no change allocation* scenario, and the *no law enforcement* scenario. The result of the *amazon_roads100* model is shown in Figure 5.11, and that of the *amazon_urban100* model is shown in Figure 5.12. Figure 5.14 presents a quantitative comparison for some of the test sites.



	urban_roads100	amazon_roads100
BR 319 - Manaus	1.81%	1.81%
BR 230 - Ruropólis/Trairão	1.64%	1.58%
BR 163 - South	1.16%	1.79%
BR 163 - North	0.95%	0.76%
Sáo Felix/Iriri	0.95%	1.38%
BR 230 - Apuí	0.81%	0.85%
BR 319 - Humaitá	0.57%	1.37%
BR 319 - Manicoré	0.46%	0.87%
BR 163/BR 230	0.45%	0.28%

FIGURE 5.14- Exploration B: quantitative comparison among selected test sites.

In the *amazon_urban100* model, that includes distance to urban centres in the coarse resolution, distance to roads loses importance in the overall pattern, and importance of connection to the rest of the country is reinforced. The incorporation of the distance to urban centres reinforces the heterogeneity of projected patterns. The model result concentrates the deforestation in the Cuiabá-Santarém area, especially in the central portion of the road, and creates a connection to the eastern part of the Transamazônica road, as shown in Figure 5.12. The area close to the Porto Velho–Manaus road is kept almost undisturbed, except at its extremes. The Apuí and Nova Aripuanã areas, in the eastern Transamazônica, are identified as occupation hotspots under both explorations.

The differences between model results illustrated in Figures 11, 12 and 14 are a result of the interaction between the two scales in the CLUE allocation module (Section 5.2.1). When the amazon_roads100 model is used at the coarse scale, and arch25 at the fine scale, distance to roads is emphasized at both scales, and led the allocation process. But, when the *amazon_urban100* is used instead, other factors may be indirectly favoured at the fine scale, as the influence from the coarse scale favours other cells. Another interesting aspect in Figure 12 is that distance to urban centres has an influence on resulting patterns, but does not determine them. For instance, the urban centres (see Figure 3.8) in the south of Amazonas (e.g., Humaitá), or along the western part of the Transamazônica (e.g., Apuí), do not influence the resulting patterns as much as the single one in the Cuiabá-Santarém (Novo Progresso), due to the interactions with other factors, especially connection to markets.

Exploration B does not incorporate the hypothesis of paving for any of the existing roads in the Central area. Even so, the Cuiabá-Santarém, Apuí, and SãoFelix areas exhibit strong occupation pressure, under all regression models. The Amazon riverbanks, close to Santarém and Manaus, also exhibit strong deforestation in all models.

5.3.3 Exploration C - Policy analysis: paving and protected areas

This exploration considers the impact of public policies on projected deforestation hotspots. This analysis complements explorations A and B, by assessing the relative importance of different factors when new infra-structure and protected areas are created. Exploration C uses the same regression models as Exploration B: the *arch_25* model in at the fine resolution, and compares the use of the *amazon_roads_100* and *amazon_urban_100* models at the coarse resolution. This exploration also uses the *baseline demand* and the *no law enforcement* scenarios, but the *paving and protection allocation* scenario instead.

Figure 5.15 illustrates the results for the *amazon_roads100* and Figure 5.16 illustrates the results for the *amazon_urban100* models. Results should also be compared to Figures 5.10 and 5.11 respectively, in which the *no change allocation* scenario is employed. Figure 5.17 presents a quantitative comparison for some of the test sites outside protected areas.

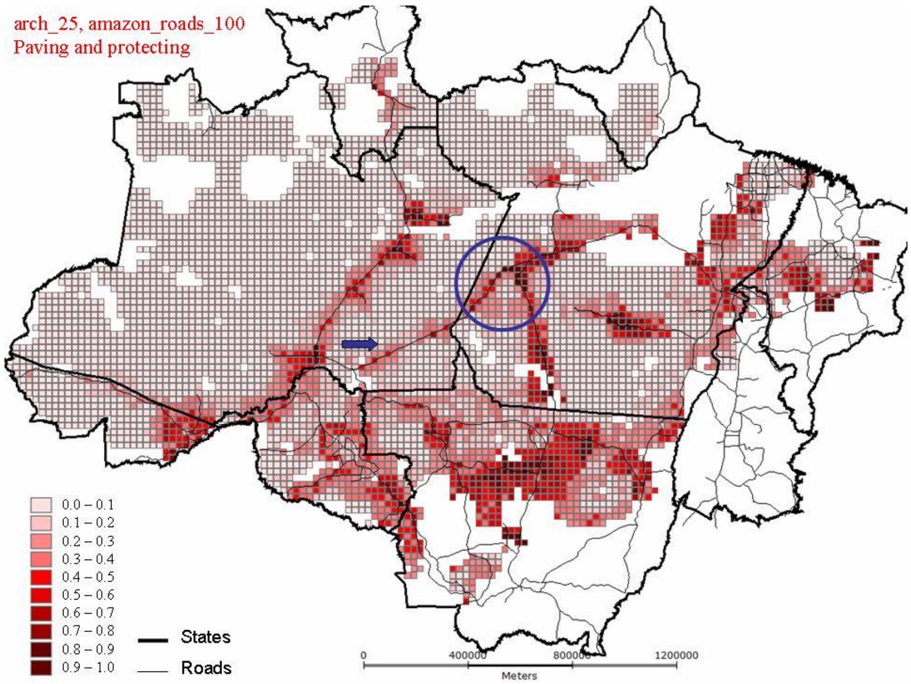


FIGURE 5.15 - Exploration C – Paving and Protecting allocation scenario: *arch25, amazon_roads100*.

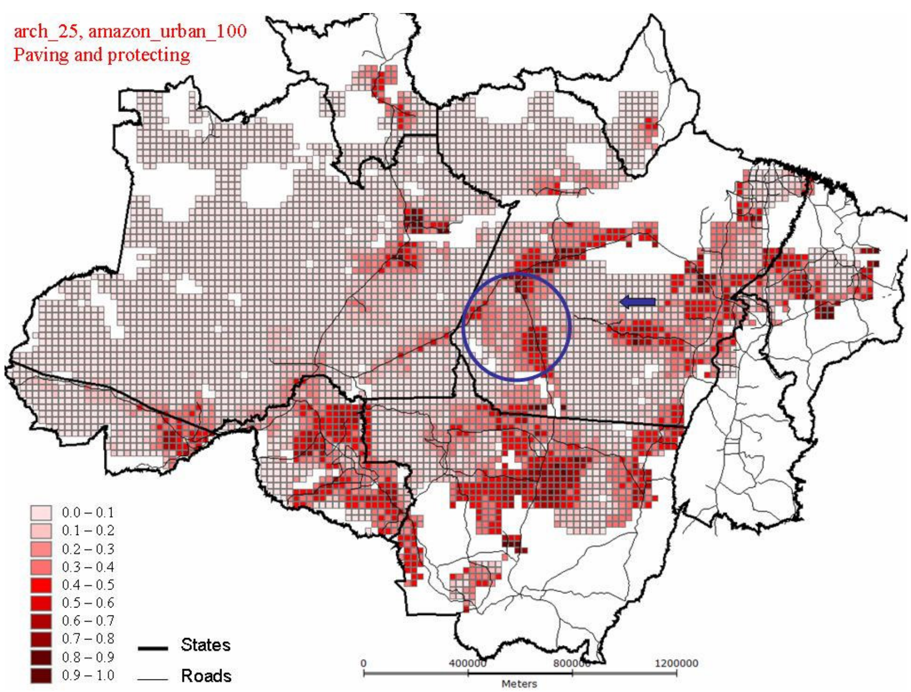
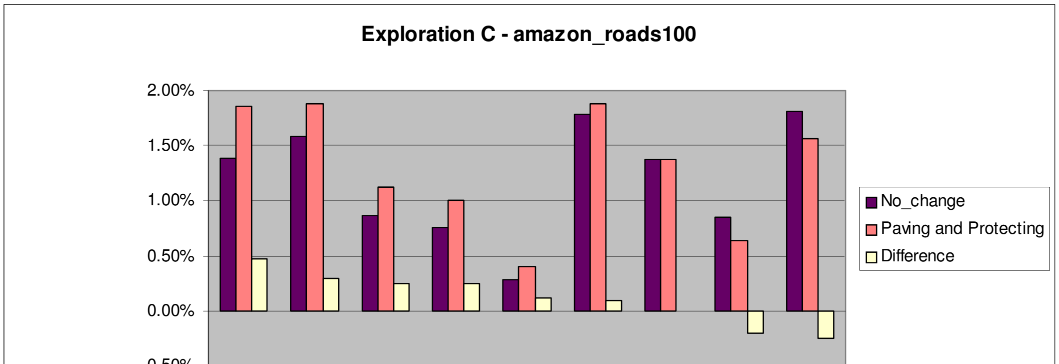
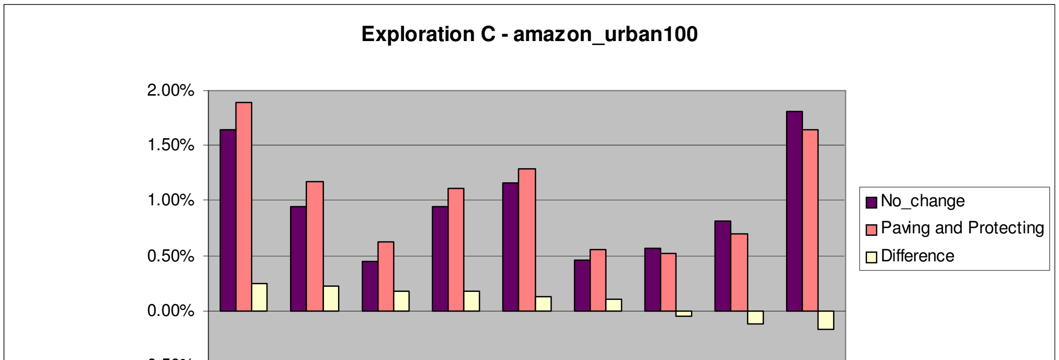


FIGURE 5.16 - Exploration C – Paving and Protecting allocation scenario: *arch25, amazon_urban100*.



	Sáo Felix/Iriri	BR 230 - Ruropólis/Trairão	BR 319 - Manicoré	BR 163 - North	BR 163/BR 230	BR 163 - South	BR 319 - Humaitá	BR 230 - Apuí	BR 319 - Manaus
No_change	1.38%	1.58%	0.87%	0.76%	0.28%	1.79%	1.37%	0.85%	1.81%
Paving and Protecting	1.85%	1.88%	1.12%	1.01%	0.40%	1.88%	1.37%	0.64%	1.56%
Difference	0.47%	0.29%	0.25%	0.25%	0.12%	0.09%	0.00%	-0.21%	-0.25%



	BR 230 - Ruropólis/Trairão	Sáo Felix/Iriri	BR 163/BR 230	BR 163 - North	BR 163 - South	BR 319 - Manicoré	BR 319 - Humaitá	BR 230 - Apuí	BR 319 - Manaus
No_change	1.64%	0.95%	0.45%	0.95%	1.16%	0.46%	0.57%	0.81%	1.81%
Paving and Protecting	1.89%	1.17%	0.63%	1.12%	1.29%	0.56%	0.52%	0.69%	1.64%
Difference	0.25%	0.22%	0.17%	0.17%	0.13%	0.10%	-0.05%	-0.11%	-0.17%

FIGURE 5.17 - Exploration C: quantitative comparison among selected test sites (outside protected areas)

As Figure 5.17 illustrates, results show heterogeneous impacts of these policies in different areas. In both models, road paving has a larger impact in the Cuiabá-Santarém road in comparison to the Porto Velho-Manaus road.

In the Porto Velho-Manaus road, when the *amazon_road100* model is used, the road paving brings a greater overall impact that in the *amazon_urban100*. The latter model tends to concentrate deforestation in the extremes of the Porto Velho-Manaus road. This difference is explained by increased importance of the connection to cities and ports in the *amazon_urban100* model. Besides, as discussed in the last section, when combining different models in different scales, distance to roads loses importance in the overall pattern, and importance of connection to the rest of the country is reinforced. Considering the occupation history of the region, and the fact that the Porto Velho-Manaus road traverses a remote region, without any cities of significant sizes, and the results of the *amazon_urban100* model seems more appropriated than the *amazon_roads100* model for experiment C. However, the *arch25* model used in the fine resolution does not emphasize the connection to ports variable influence in this region. If a modified model were used in the fine resolution giving more importance to connection to ports than in the current *arch_25* model (which reinforces connection to national markets) a stronger deforestation pressure would possibly result in the Porto Velho Manaus. Figure 5.6 and 5.7 show the temporal evolution of the connection to ports variable when the roads are paved. These effects of paving are stronger in the Porto Velho-Manaus area. This indicates that the dynamics in this region differs from the other new frontiers (e.g, SãoFelix, for instance), given its specific connectivity and also biophysical conditions (see Figures 3.20 3.21 3.22 3.23), so uniform projections based on the same factors may be misleading.

The results of Exploration C indicate a migration of the deforestation from one area to another, since the regional demand for land is kept constant. Compared to Exploration B (where roads are not paved), results show that deforestation increases in cells closer to the newly paved roads, and decreases in non-paved roads. For example, deforestation decreases in the Apuí region, in the Eastern part of Transamazônica road, which is not paved in Exploration C. The same holds for protected areas: where new protected areas are created, the occupation process slows down (see also Figure 5.29). But, as demand is kept constant, creation of protected areas induces the migration of deforestation to other areas. For instance, the deforestation in the Terra do Meio decreases due to the creation of protected areas, but it compensated by an increase in other areas, such as the western side of the Cuiabá-Santarém road.

Although the spatial interactions seen in the model results are a direct consequence of our premises regarding demand (demand for land is fixed, so it will be allocated somewhere by the model), they are useful as they clearly illustrate how these interactions may occur. Results illustrate how the local policies effects may be felt in other areas, not necessarily in a beneficial way, according to the actor's perceptions of new constraints and opportunities created by policies. They also facilitate the envisioning of how the productive system that generates such demand can influence the occupation process. The productive system (e.g., the soybean market chain, the beef market chain) act in several spatial and temporal scales; in the medium and long run it may reorganize, and contribute to the occupation of new locations to attend a growing demand for agricultural products. Intensification would be another possible reaction to policy imposed constraints in the access to land (especially in the case of an overall decrease in land availability), and this is not treated in our current model. The results of Exploration C indicate that these intra-regional interactions must be taken into account for public policy making, and that understanding these market chains is essential to the design of effective policies for the Amazonia.

5.3.4 Exploration D - Policy analysis: law enforcement

Exploration D consists of analyzing the results of two law enforcement scenarios presented in Table 5.5: the *Private Reserves Enforcement* and the *Local Command and Control* scenarios. In this exploration, we use the same models as Exploration A (the *amazon_roads100* model at coarse resolution and the *arch25* model at fine resolution), the *baseline demand* scenario and the no change allocation scenario. Figure 5.18 present the results of the "Private Reserves" law enforcement scenario. Figure 5.20 illustrates the controlled areas used "Local Command Control" scenario, on top of Exploration A results (*amazon_roads100, arch_25, No law enforcement scenario*). Figure 5.21 shows the "Local Command Control" scenario results. Figures 5.19 and 5.22 present quantitative assessments of change in selected test sites the two scenarios.

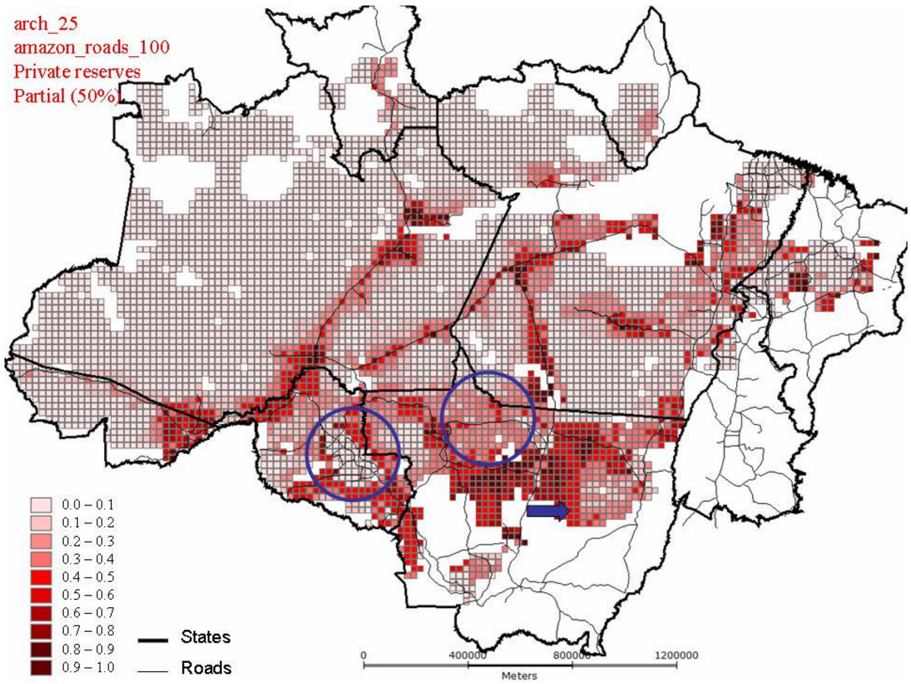


FIGURE 5.18 - Exploration D – *Private Reserve Partial* Law Enforcement scenario: *arch25, amazon_urban100*

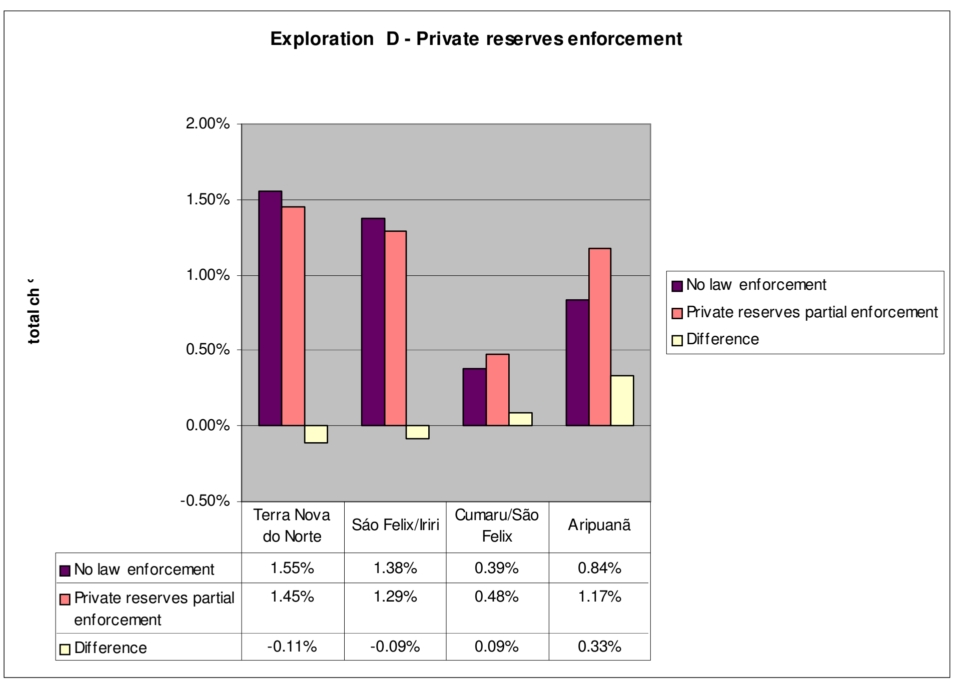


FIGURE 5.19 - Exploration D: quantitative comparison among selected test sites in the *Private Reserves Partial* law enforcement scenario.

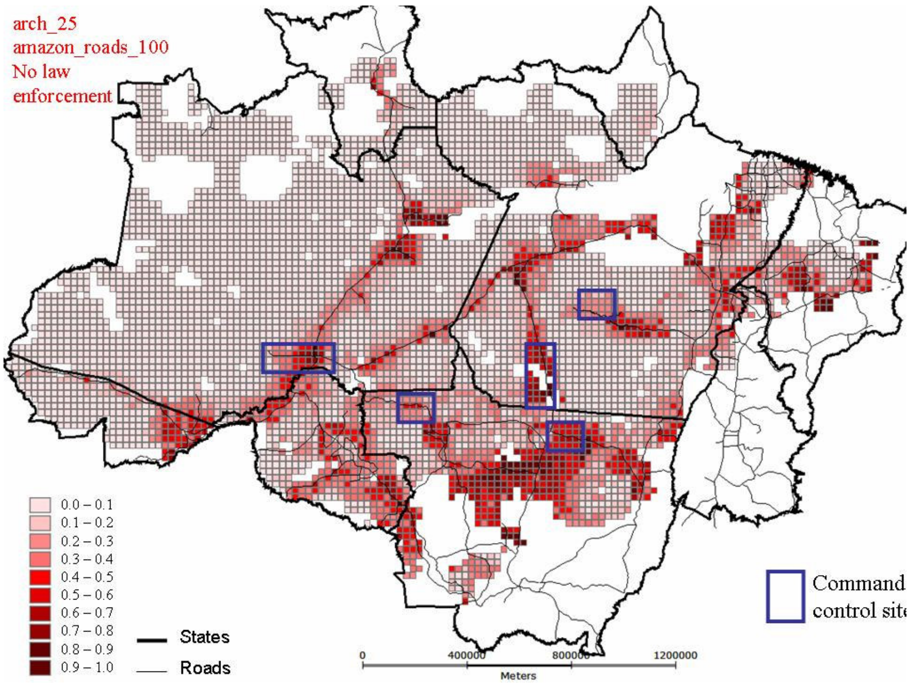


FIGURE 5.20 - Exploration D - *No law enforcement* scenario: *arch25, amazon_urban100*

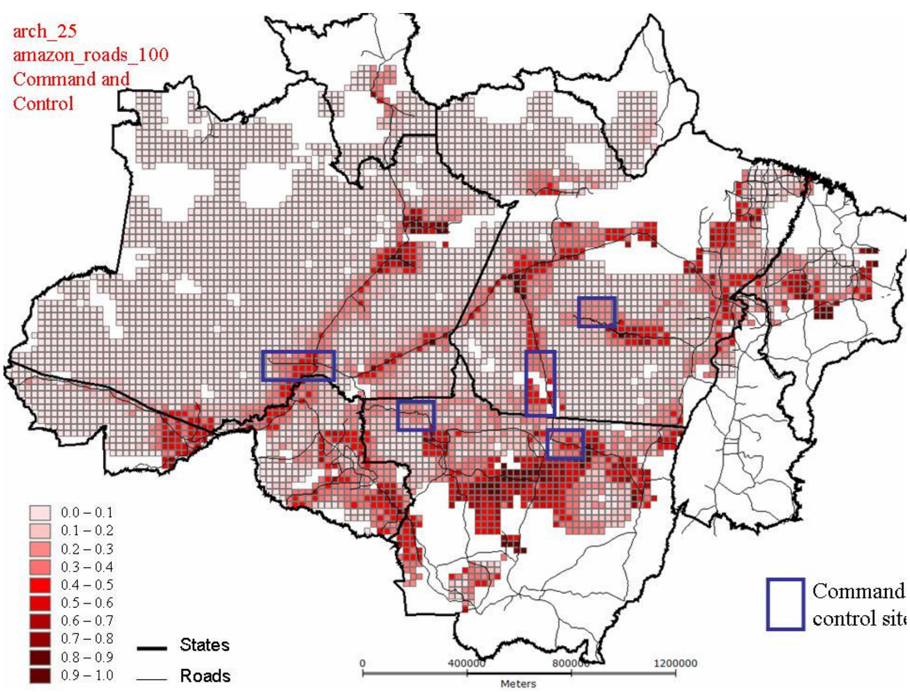
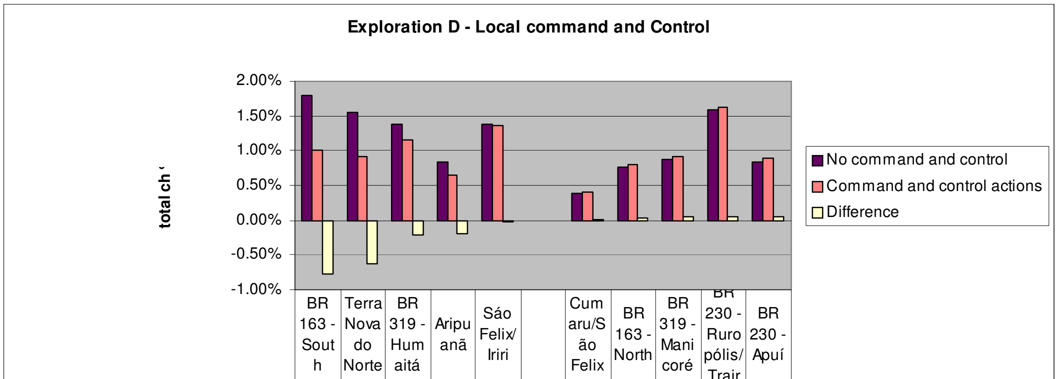


FIGURE 5.21 - Exploration D - *Local Command and Control* scenario: *arch25, amazon_urban100*

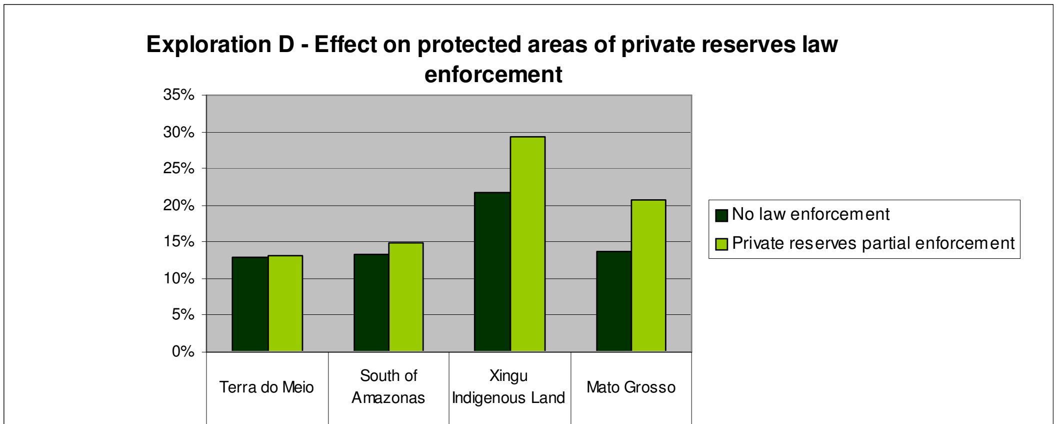


	BR 163 - South	Terra Nova do Norte	BR 319 - Humaitá	Aripuanã	Sáo Felix/ Iriri		Cumaru/São Felix	BR 163 - North	BR 319 - Manicoré	BR 230 - Ruropólis/ Trair	BR 230 - Apuí
No command and control	1.79	1.55	1.37	0.84	1.38		0.39	0.76	0.87	1.58	0.85
Command and control actions	1.01	0.92	1.15	0.64	1.36		0.40	0.79	0.91	1.63	0.89
Difference	-0.78	-0.63	-0.22	-0.20	-0.02		0.02	0.03	0.05	0.05	0.05

FIGURE 5.22 - Exploration D: quantitative comparison among selected test sites in the *Command and Control* law enforcement scenario.

Exploration D shows the same intra-regional interaction patterns as previous results, as demand is kept constant. The enforcement of private forest reserves across the region decreases the change in previously occupied areas, but creates an overall pressure in other areas (Figures 5.18 and 5.19). Compare Rondônia and the north of Mato Grosso, for instance, as marked in Figure 5.18. Local command and control actions results show that localized actions are effective in the areas where they are applied (Figures 3.21 and 3.22), but create a pressure somewhere else. For instance, deforestation increases in the northern part of Cuiabá-Santarém road when actions are concentrated in its southern part. These results can be interpreted as a hypothetical "governance level" heterogeneously distributed in space. They show that localized command and control actions are not sufficient to reduce deforestation, if the demand is not reduced.

This exploration show interesting results about the Arch macro-region. In the *Private Reserves* scenario, there is less saturation (cells 100% deforested), for instance in Rondônia, but occupation spreads over the whole Arch area. In this scenario, higher pressure is also felt in the protected areas, specially the ones in areas with higher connectivity level, as the Xingu Indigenous Land in the Mato Grosso state. Figure 5.29 illustrates these heterogeneous impacts quantitatively.



	Terra do Meio	South of Amazonas	Xingu Indigenous Land	Mato Grosso
No law enforcement	13%	13%	22%	14%
Private reserves partial enforcement	13%	15%	29%	21%

FIGURE 5.23 - Exploration D: quantitative comparison among selected test sites in the *Private Reserves Partial* law enforcement scenario.

Although this is a very improbable scenario (law enforcement in private reserves but not in the protected areas), results should be analyzed under another perspective, as a warning: if demand for land is constant, and private reserves are enforced, occupation *pressure* will increase in other areas, including the protected areas. We ran an alternative simulation, maintaining the same demand level for the Arch, but pushing the forest threshold to 80%, as would be required by current Brazilian legislation. The model failed to allocate the demand. These results indicate that occupation level in the Arch will be reaching a limit in 2020, and reinforce that to preserve the remaining forest areas in the Arch, in public and private lands, effective and generalized command and control measures will be necessary. In next section, this aspect is further discussed, as we present results related to the market constraints on demand for land.

5.3.5 Exploration E: Alternative demand scenarios

Exploration E considers the impact of increasing and decreasing the demand, representing the expansion or retraction of market forces that act on the Amazonia. It uses the paving and protecting allocation scenario. This analysis complements Exploration C, exploring the potential outcomes of the new infra-structure and protected areas in alternative market constraint scenarios. As in Exploration C, it uses the *arch25* model at fine resolution, and compares the results of roads model (*amazon_roads100*) and the distance to urban centres model (*amazon_urban100*) at coarse resolution. Roads are paved according to the schedule shown in Table 5.4 according to the *Paving and Protecting* allocation scenario. The *no law enforcement* scenario is adopted.

The results for *decreasing* demand are shown in Figure 5.24 (*amazon_roads100* model) and Figure 5.25 (*amazon_urban100* model). The results of *increasing* demand are shown in Figure 5.26 (*amazon_roads100* model) and Figure 5.27 (the *amazon_urban100*). It is useful to compare the results with the results of Exploration C.

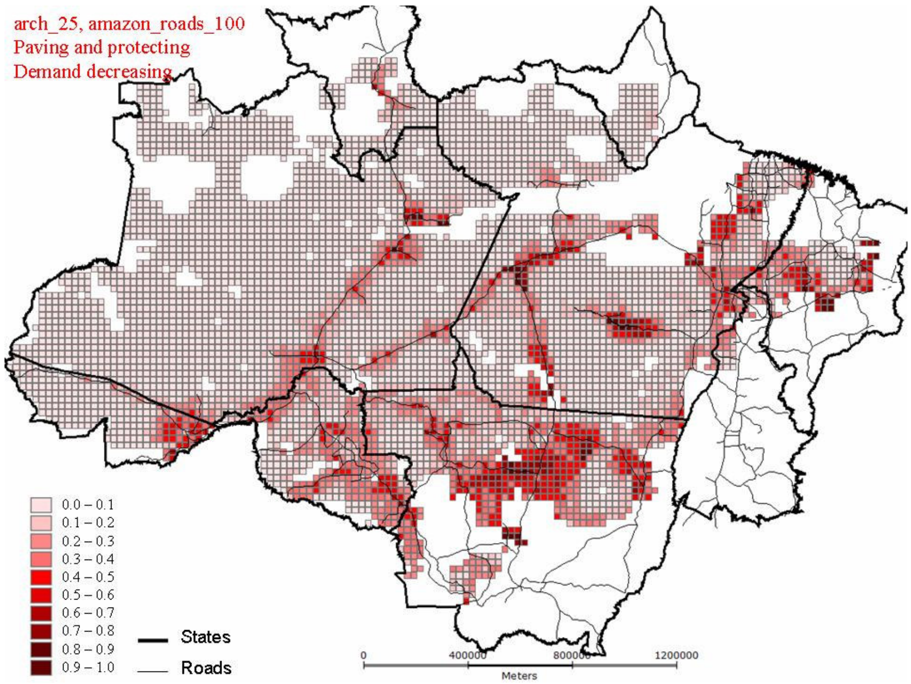


FIGURE 5.24 - Exploration E – *Decreasing* demand: *arch25, amazon_roads100*.

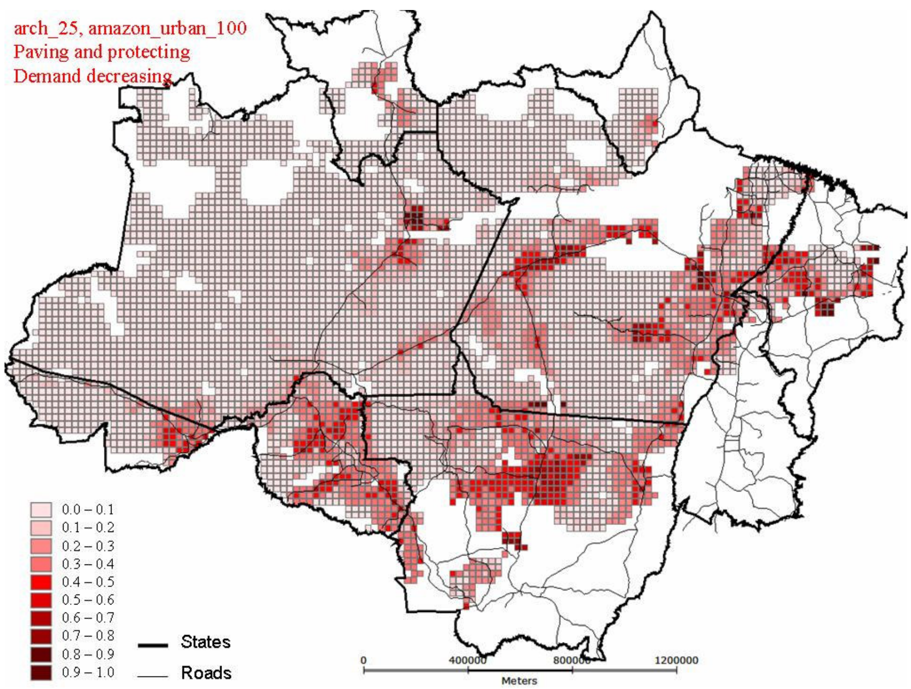


FIGURE 5.25 - Exploration E – *Decreasing* demand: *arch25, amazon_urban100*.

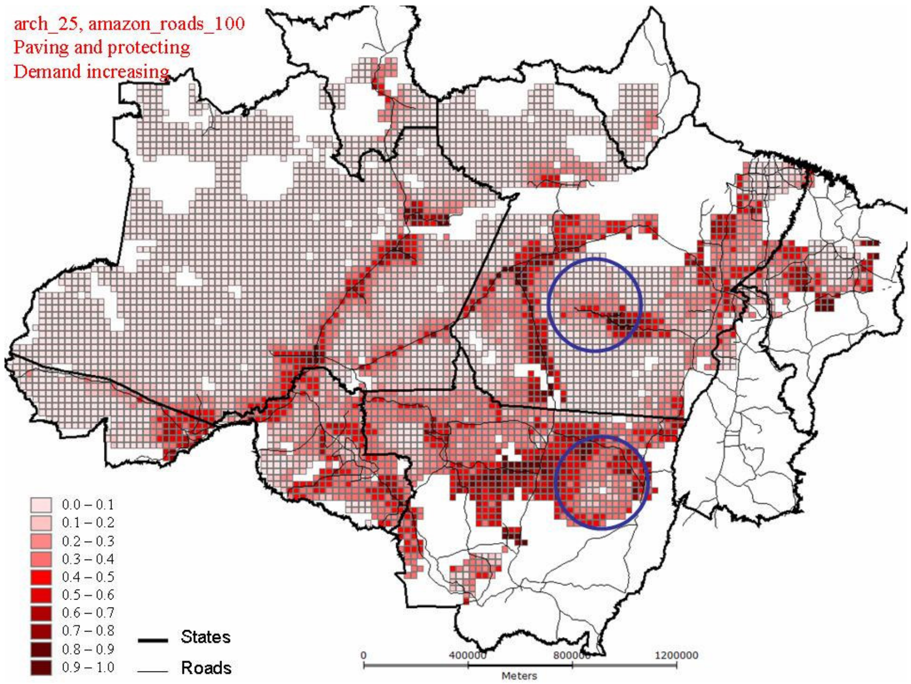


FIGURE 5.26 - Exploration E – *Increasing* demand: *arch25, amazon_roads100*.

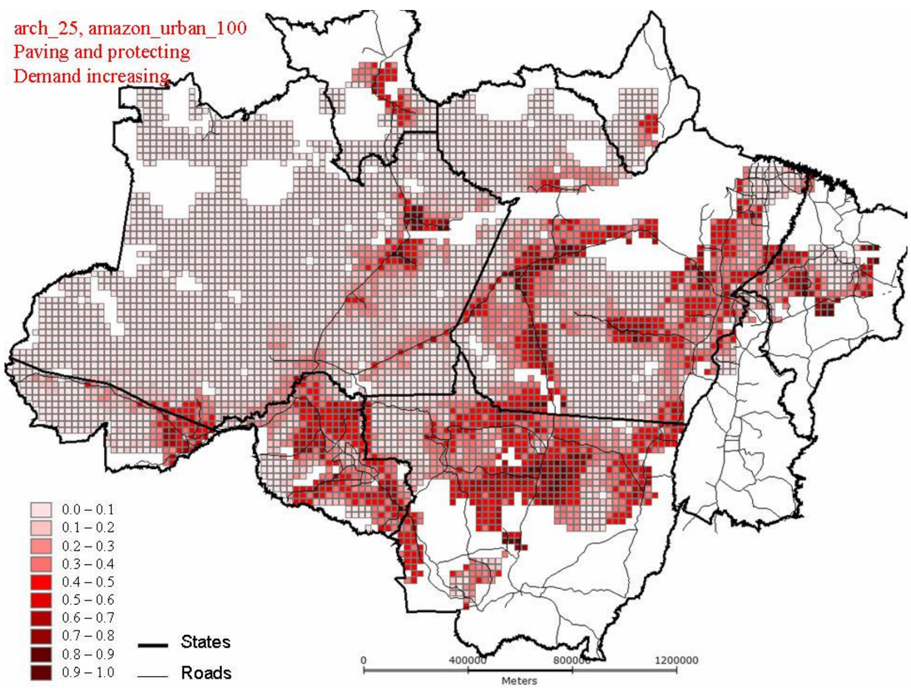


FIGURE 5.27 - Exploration E – *Increasing* demand: *arch25, amazon_urban100*.

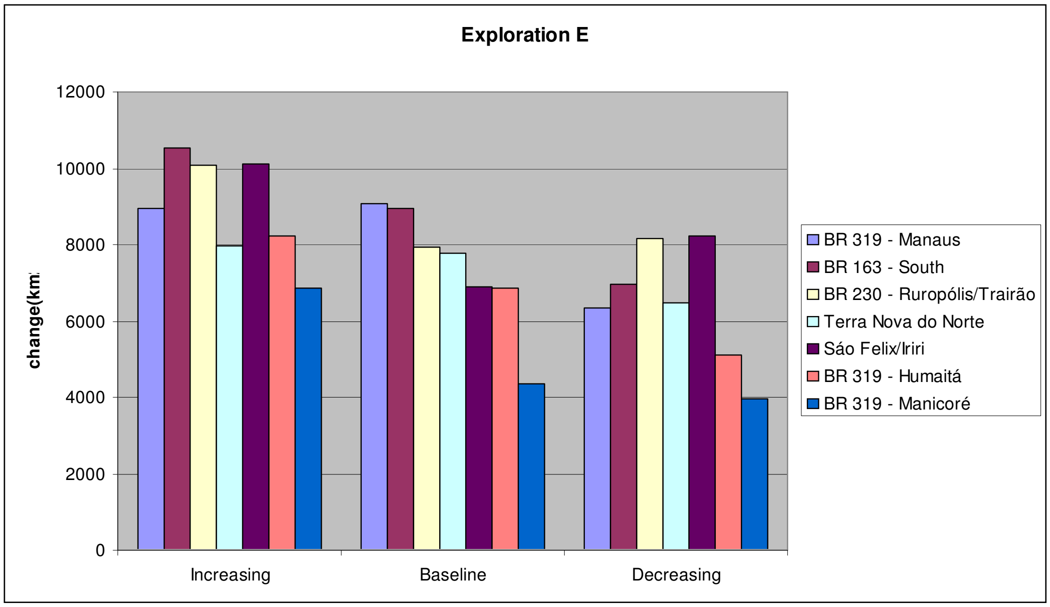
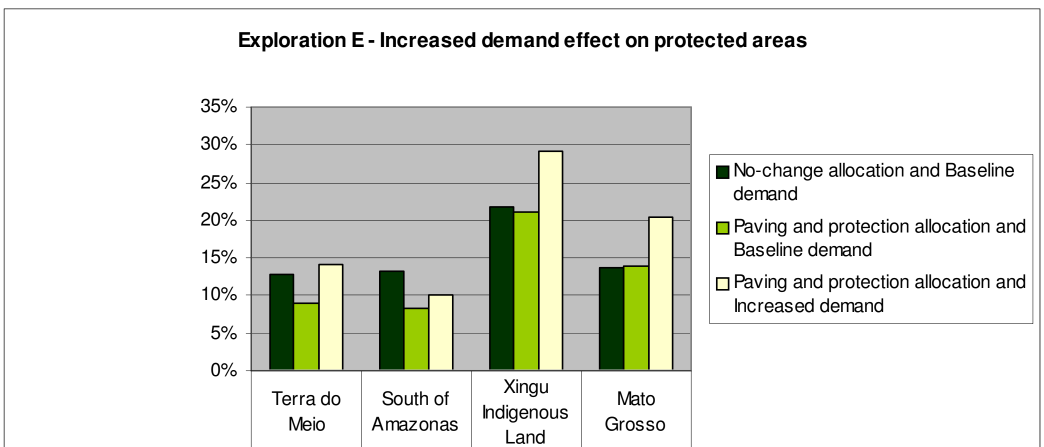


FIGURE 5.28 - Exploration E: quantitative comparison among selected test sites (outside protected areas)



	Terra do Meio	South of Amazonas	Xingu Indigenous Land	Mato Grosso
No-change allocation and Baseline demand	13%	13%	22%	14%
Paving and protection allocation and Baseline demand	9%	8%	21%	14%
Paving and protection allocation and Increased demand	14%	10%	29%	21%

FIGURE 5.29 - Exploration E: quantitative comparison among test sites (inside protected areas).

Compared to Exploration C (constant demand), Exploration E results show similar patterns, both when demand increases and decreases. For increased demand (Figures 5.26 and 5.27), the added quantity of change is not uniformly distributed over the region, especially in the Central area, as illustrated in as Figure 5.28. In the Cuiabá-Santarém and São Felix/Iriri the impact is stronger, due to better connectivity characteristics than other areas. However under any demand scenario (considering the paving and protection scenario), the following test sites presented the largest changes, even if the relative order changed: BR163–South, BR230-Ruropólis/Trairão and São Felix/Iriri in Pará State; BR319–Manaus, BR 319–Humaitá, BR 319–Manicoré in Amazonas State; and Terra Nova do Norte in Mato Grosso State.

Increased demand also causes a higher pressure on protected areas, in a non-uniform way, as pointed out in Figures 5.26 and 5.29. This pressure is stronger in the Arch protected areas (for instance in the Xingu Indigenous Land), but it can also be felt in the more connected areas in Central region, for instance in Terra do Meio. As Figure 5.29 show, the decrease in the deforestation rate in the Terra do Meio area obtained by the creation of the protected areas could be lost if the overall demand for land is increased. Results indicate that the vulnerability of protected areas is non-homogeneous across the region, and command and control actions should take this into consideration.

In the situation where demand decreases, the stronger impact is felt in the hotspots of the Central area of Amazonia. The regions along the Cuiaba-Santarém, Porto Velho-Manaus and western Transamazônica roads show a significant decrease in deforestation rates. This is a significant result, since it is the only scenario where the crucial Central region of Amazonia suffers less impact. It indicates that, unless demand for land use is controlled and reduced in the whole of Amazonia, law enforcement policies and creation of protected area will have limited overall impact on the deforestation process.

CHAPTER 6

CONCLUSIONS

6.1 Spatial statistical analysis conclusions

Chapter 4 presented a spatial regression analysis to explore intra-regional differences in the relative importance of land-use determining factors in the Amazon. The analysis was based on a cellular database including several environmental, socio-economic and political potential factors, presented in Chapter 3. The results confirm the first hypothesis explored in this thesis: the relative importance and significance of land use determining factors greatly vary across the Amazon. The quantitative results obtained using this methodology corroborate with the statement of Becker (2001): "in the Amazon coexist sub-regions with different speed of change, due to the diversity of ecological, socio-economic, political and of accessibility conditions". The use of spatial regression models also corroborated earlier assessments about the diffusive nature of land-use change in the Amazon (Alves, 2002) as showed by the high values of the autocorrelation coefficient in all models. Only in the Occidental region values were slightly lower, indicating a less intense diffusive pattern and speed of change.

The models show the significance of several of the potential determining factors, demonstrating that focusing on single factor analysis can be misleading. *It is the interaction of many factors that can explain the land-use patterns in the Amazon*. And the relative importance of such factors varies from one region to another, and unravels the region heterogeneity in terms of patterns and speed of change. For instance, when only the Arch is analyzed, protected areas becomes the second most important factor, after the deforestation spatial dependence coefficient, preceding distance to roads and to urban centers, indicating how they play an important role in avoiding deforestation in high pressure areas. On the other hand, distance to roads is an important factor in all space partitions. But the multi-factor analysis shows that the heterogeneous occupation patterns of the Amazon can only be explained when combining roads to other factors related to the organization of the productive systems in different regions, such as favourable environmental conditions and access to local and national markets. This provides further evidence that the implantation of roads and development poles in the 70s was a first incentive to deforestation, but it continued more elevated in regions that established productive systems linked to the Center, South and Northeast of Brazil (Alves, 2001; Alves, 2002).

The municipality of São Felix do Xingu, a current deforestation hot-spot, is exemplary of this: it has been the lead in deforestation rates in the last years (INPE, 2005), although it is not served by a paved road. Land market plays an important role there, and also lack of State presence, but it also has a very well organized beef market chain (Escada et al., 2005a). The agrarian structure and specific land-use analysis results reinforce the conclusions in relation to the importance of the productive systems, as they point out the heterogeneity of land use systems adopted by different actors, and the influence of the agrarian structure on land-use pattern distribution across the region. Incorporating this heterogeneity of factors, actors, land-use and productive systems is essential to a sound understanding of the land-use change process in the region, especially to subside policy decisions appropriated for each sub-region in a non-uniform and non-misleading way.

6.2 Dynamic modeling conclusions

Chapter 5 presented the results of a modified version of the CLUE modeling framework to explore scenarios of land use change in the Brazilian Amazonia. The concept of "*scenario exploration*" was introduced. Each exploration emphasized a different aspect of the Amazonia occupation process. Out of many possibilities, this work presented the results of five explorations which analyze the effects of *alternative accessibility factors, policies and market constraints*.

Three main conclusions can be drawn from the results. First, connection to national markets is the most important factor for capturing the spatial patterns and different stage of occupation of the new Amazonian frontiers. Second, it is the interaction between connectivity and other factors, which may act in different scales (such as climate and proximity to local markets) that influence the intra-regional dynamics, and creates differentiated local conditions in the new expansion axes. Such patterns cannot be explained by single factor that focus on the role of roads, for instance. And third, these intra-regional differences led to heterogeneous impact of policies across the region. These three conclusions corroborate with this thesis hypotheses, about the heterogeneity of land use determining factors and the importance of connection to markets in the occupation process.

Results also point out that public policies for the Amazonia must take into consideration the spatial and temporal interaction between localized policies and regional processes. Our models do not incorporate any assumptions regarding how policies affect (positively or negatively) the overall deforestation rates. Instead, we analyzed the patterns emerging from changing three constraints separately: (a) infra-structure; (b) law enforcement and conservation policies; and (c) market forces. *The interaction among these three constraints is not well understood at this moment*. Results illustrate how the local policies effects may be felt in other areas, not necessarily in a beneficial way, according to the actor's perceptions of new constraints and opportunities created by policies. Besides, the productive system acts in several spatial and temporal scales. In the medium and long run, market chains may reorganize, according to the constraints imposed by policy action, and contribute to the occupation of new areas to attend a growing demand for agricultural products Such processes and interactions happen at different hierarchical levels, so multi-scale and multi-localities studies are necessary.

The results also indicate that, in complex regions such as Amazonia, scenario exploration is a powerful tool for comparing the results of land use models. Given the inbuilt uncertainties of LUCC model, controlled scenarios where one key parameter changes at a time are very useful to gain insight over the occupation process.

6.3 Suggestions for future work

Based on the results and conclusions of this thesis, the suggestions of future work about the whole Amazonia occupation process are:

- Intra-regional interactions in the Amazonia need to be better understood. Future work should primarily aim at understanding how *the balance between public policies and market constraints, mediated by heterogeneous local conditions*, can affect the future of the Amazonia occupation process. This requires multi-scale and multi-localities studies, as these processes and interactions happen at different hierarchical levels.

- *Different market chains may influence the occupation process in different ways.* The suggestion is to continue this work by refining the pasture and temporary agriculture studies, focusing on *cattle and soybeans expansion* in the Amazonia. A new IBGE agricultural census is planned for 2006.

- The connectivity measures proposed in this thesis are based on the road network. Future work should refine these measures, and include river and train transport networks, in *compound measures of connectivity considering the whole transport network system.* Other types of network could also be explored, such as the telecommunication and urban networks.

- This thesis explores *the use of empirical derived relationships combined with knowledge about the occupation processes*. This was achieved mainly by comparing the effects of alternative regression models on projected patterns. A step beyond would be to change regression coefficients based on expert knowledge in controlled explorations. For instance, increasing the importance of connection to ports in the *arch25* model to explore its effects.

- In this work, we introduced a mechanism in the CLUE framework to incorporate the heterogeneous presence of the State across the region, tested in the law enforcement scenarios. We used a spatial indicator to refrain or speed up processes of change on top of (and interacting with) the spatial determining factors empirically derived. This concept could further explored as a mean of *incorporating other subjective/qualitative indicators not easily derived from empirical evidence in the modeling framework.* For instance, to explore the effectiveness of the presence of IBAMA or INCRA in different regions; the aspirations of different States towards conservation and development; the level of social organization of small farmers, indigenous peoples, etc.

- The allocation scenarios built in this thesis were based on the temporal evolution of the accessibility and protection factors. *Allocation scenarios related to other factors* could also be explored, for instance: the creation and growth of urban centres; the migration of timber production sites; the changes in the agrarian structure related to the soybeans expansion in the Amazon; the evolution of technological variables in the Arch related to agricultural intensification, etc.

Finally, we conclude that statistical and dynamic models, when used with knowledge about the underlying processes, and based on clear premises, can be useful tools to provide insights about the occupation process of the Amazonia, and properly subside public policies.

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