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SPATIOTEMPORAL TRENDS OF LAND USE CHANGE IN THE BRAZILIAN AMAZON

Giovana Mira de Espindola

Doctorate Thesis at Post Graduation Couse applied in Remote Sensing, advised by Drs. Leila Fonseca, Gilberto Câmara, e Ana Paula Aguiar, approved in March 16, 2012.

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ABSTRACT

The Brazilian Amazon region is undergoing significant changes due to climatic effects and human activities. In recent decades, the region has experienced marked variability in deforestation, and after a long period of increase, the deforestation rates have sharply decreased in more recent years. To better understand the predominant trends and critical factors influencing deforestation across the region, it is necessary to describe land use change dynamics over space and time. In this study, we present enhanced methods to reveal the spatiotemporal determinant factors of land use change by using remote sensing data, socioeconomic data and statistical models. We combined Landsat TM-based deforestation information with agricultural census data to produce maps of the cumulative proportion of deforestation and major agricultural land uses throughout the Brazilian Amazon in 1997 and 2007, on a regular grid with spacing of 25 km x 25 km. All of our analyses were derived from a data set that includes a range of cultural-institutional, socio-demographic, environmental and economic factors. First, this study builds linear and spatial regression models to assess determinant factors of deforestation and those major agricultural land uses for the states of Pará, Rondônia, and Mato Grosso in 1997 and 2007. Second, it uses the annual proportion of deforestation from 2002 to 2009 to build spatial multi-regression models that incorporate autoregressive components in space and time. Finally, this study addresses the subregional trends of forest change by analyzing the spatiotemporal variability of deforestation during the last decade. Our subregional analyses feature human occupation histories and land use change dynamics into each of the six subregions selected in the states of Pará and Mato Grosso.

TENDÊNCIAS ESPAÇO-TEMPORAIS DAS MUDANÇAS DE USO DA TERRA NA AMAZÔNIA BRASILEIRA

RESUMO

A Amazônia brasileira tem passado por transformações significativas devido, principalmente, a alterações climáticas e atividades humanas. Nas últimas décadas, a região registrou variações consideráveis no desflorestamento, e após um longo período de crescente aumento, as taxas de desflorestamento têm diminuído bastante nos últimos anos. Assim, para melhor entender as tendências e os fatores determinantes que influenciaram o desflorestamento, se faz necessário considerar as dinâmicas espaço-temporais das mudanças de uso da terra em toda a região. Neste sentido, este estudo apresenta métodos inéditos que estabelecem tais fatores determinantes pela utilização de dados de sensoriamento remoto, dados socioeconômicos e modelos estatísticos. Para tanto, combinamos informações do desflorestamento derivadas de imagens Landsat TM com dados dos últimos censos agropecuários para produzir mapas do acumulado do desflorestamento e dos principais usos agrícolas para toda a Amazônia em 1997 e 2007, com base em uma grade regular de 25 km x 25 km. Todas as análises foram obtidas a partir de um banco de dados que agrega uma ampla variedade de fatores culturais, institucionais, sócio-demográficos, ambientais e econômicos. Primeiramente, este estudo apresenta modelos de regressão linear e espacial que estabelecem os fatores determinantes do desflorestamento e dos principais usos agrícolas nos estados do Pará, Rondônia e Mato Grosso em 1997 e 2007. Em segundo, este estudo utiliza o incremento anual do desflorestamento entre 2002 e 2009 para construir modelos de regressão espaço-temporais. Por último, o estudo aborda tendências sub-regionais do desflorestamento pela análise de sua variabilidade espaço-temporal na última década. As análises sub-regionais analisam o histórico de ocupação humana e a dinâmica das mudanças de uso da terra em cada uma das seis sub-regiões selecionadas nos estados do Pará e Mato Grosso.

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1. INTRODUCTION

1.1. Motivation

Global change research over the past 30 years has made great contributions to understanding the Earth system, including the role of local processes and their global impacts. Concerns about land change are presented in this research agenda with the realization that land surface processes influence climate (Lambin and Geist 2006). Although understanding and predicting the impacts of land change on climate is required for projections into the future, numerous studies have also focused on modeling and explaining the underlying causes and consequences of land use and land cover changes.

While land use and land cover changes are intimately linked for a wide range of coupled human-environment or social-biophysical systems analyses relevant to a much broader Earth system perspective, the complexity of causes, processes and impacts of land use change were the primary focus of this thesis. This thesis is based on the understanding that the causes and consequences of land use change depend on the geographic, historical and social context of a region, being dominated by multiple institutional arrangements, multiple spatiotemporal scales and complex interactions.

In Brazil, land use change has increased markedly in the last decades both in terms of extent and intensity. In the Brazilian Amazon, land use before and after deforestation is altering and converting the rainforest at unprecedented rates. As a signatory to the United Nations Framework Convention on Climate Change (UNFCCC), Brazil has committed itself to the global effort to stabilize the atmospheric levels of greenhouse gas emissions into the atmosphere. The Brazilian government recently set measurable targets for decreasing deforestation in the Brazilian Amazon, which is considered to be a major step toward the mitigation of Brazilian emissions. Over the last decade (2000-2010), the rate of tropical deforestation in the Brazilian Amazon was amongst the fastest in the world, being responsible for significant negative externalities such as loss of biodiversity, erosion, floods, lowered water tables, and an increased release of carbon into the atmosphere (Shukla, Nobre et al. 1990; Fearnside 1996).

Deforestation in the Brazilian Amazon and in the *Cerrado* savannas was intensified by the contemporary movement of people into the region, which began in the 1970s, along with the agricultural frontier movement. The exploitation and settlement of the Brazilian Amazon in the 1970s was largely induced by government policies and subsidies (Becker 2005). Since those years, deforestation has mainly been related to private investments in agricultural expansion associated with large-scale cattle ranching, small-scale familiar farming and soybean expansion (Angelsen 1997; Machado 1998).

Although deforestation across the region has sharply decreased over the past few years, which is claimed to be the result of enforcement efforts and monitoring initiatives conducted by the government, the main drivers of change in deforestation rates have to be better connected to a broader context that takes into account all the institutional dimensions, social aspects and market forces of the process. There are, in addition, compelling reasons for assessing the main drivers of change in deforestation and considering whether the current trend of decrease can be maintained and how new drivers are replacing old ones. Finally, we should be able to address the climatic, social and economic implications emerging from this situation.

1.2. Defining the Region

The Amazon rainforest is a tropical moist broadleaf forest settled in much of northern South America, mostly in northern Brazil. It occupies an area of more than 8 million sq km and represents about half of the Earth’s remaining rainforests in the world. Being the largest and most species-rich tract of tropical rainforests, the Amazon has a huge live collection of fauna and flora species, which vary due to several geophysical reasons, like moisture, rainfall and latitude. Rivers permeate the region, such as the Amazon River, which crosses the region from west to east. It is estimated that the Amazon River carries out between 34 and 121 million liters of water per second and deposits a daily average of 3 million tons of sediment near its mouth. The annual outflow from the river accounts for one-fifth of all the fresh water that drains into the oceans of the world.

The climate in the Amazon is warm, rainy and humid, and its rainy and dry seasons represent the seasonal cycle. The soils are old, weathered and leached, a result of large areas of tectonically and geomorphologically stable land surfaces. A few types of soils make up most of the total area of the Amazon (Sombroek 1966). The region comprises a complex mosaic of forests, savannahs, flooded lowlands and transition areas, being a largely diverse region, in which subregions with different rates of change coexist, due the diversity of ecological, political and socioeconomic conditions (Becker 2001).

The Legal Brazilian Amazon refers to an area that encompasses the northern region of Brazil plus Mato Grosso and Maranhão (Figure 1.1). The legal region was defined for regional planning purposes, and the Legal Brazilian Amazon is the basis of our study. The region covers an area of approximately 5 million sq km or 58 percent of the national territory of Brazil. Although the Brazilian Amazon in this context is considered as a uniform forest biome, the expansion of the legal borders into areas not technically dominated by rainforest resulted from a political compromise designed to allow the *Cerrado* areas in Mato Grosso and Maranhão to benefit from regional development incentives. In this study, we included all of the Legal Brazilian Amazon, rather than only the northern region of Brazil, for an important reason: our study focuses on the national deforestation rates and the national environmental policies that are applied across the entire Legal Brazilian Amazon.

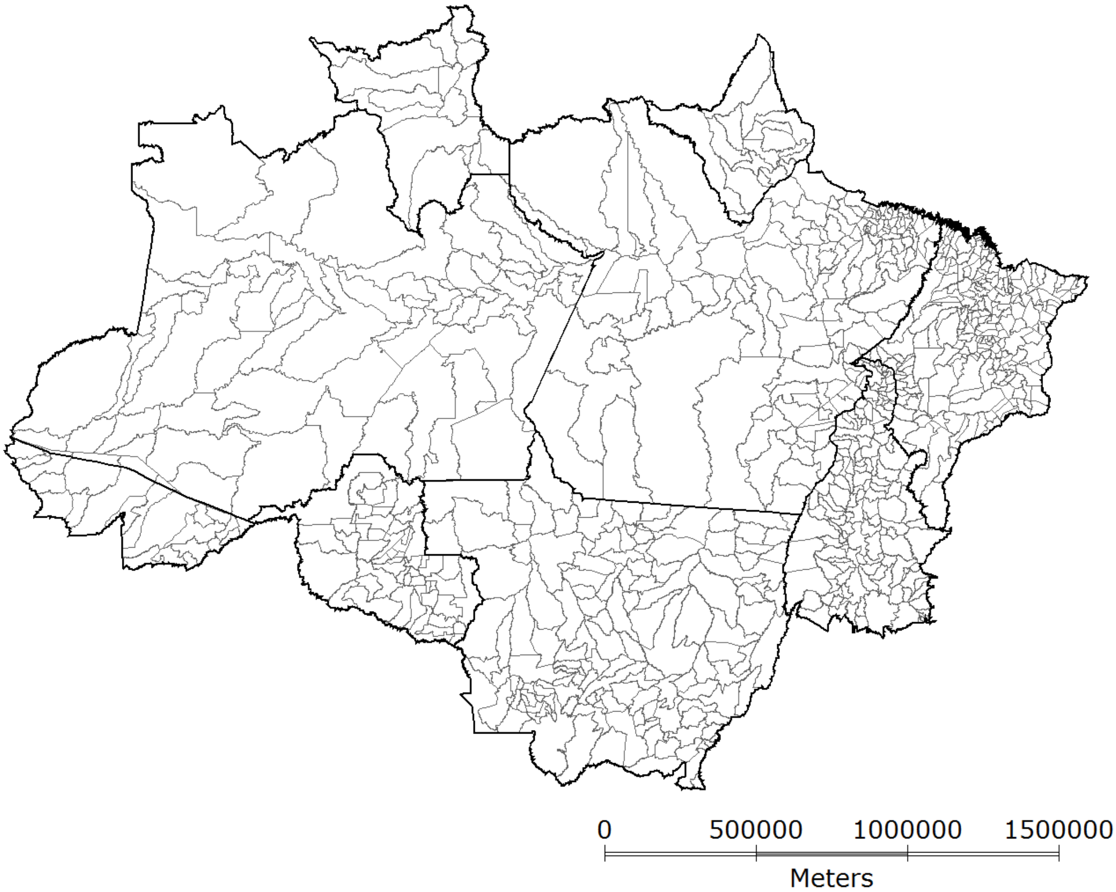


Figure 1.1 – Spatial extent of municipality polygons within the states of the Brazilian Amazon.

1.3. Levels of Analysis

To compile deforestation information from satellite imagery, census data from agricultural surveys, and socioeconomic data from other different sources into a single dataset, all data were aggregated to regular grids of 25 km x 25 km and 5 km x 5 km (see Figures 1.2 and 1.3). The data sources for both granularities were the same, and we attempted to provide the standardization and smoothing needed for the statistical analysis (25 km, Figure 1.2) by keeping a more detailed resolution used on the analysis of local dynamics (5 km, Figure 1.3).

The data from the agricultural surveys and most of the data from the other sources were available at municipal levels, being the smallest spatial unit of aggregation. Considering the huge differences in size of the municipal boundaries in the Brazilian Amazon, it is important to highlight the impacts of such differences on the analysis and on the results that were obtained. In municipalities such as Altamira and São Félix do Xingu, the largest in Pará state, the information from dynamic urbanized areas, smaller villages and communities are aggregated into a single unit. In the best possible case, there would be a perfect correspondence between the spatial resolution of the regular grids and the information available used in the analysis. Moreover, the municipal boundaries change over time, and a homogenization was made to compare data from different years.

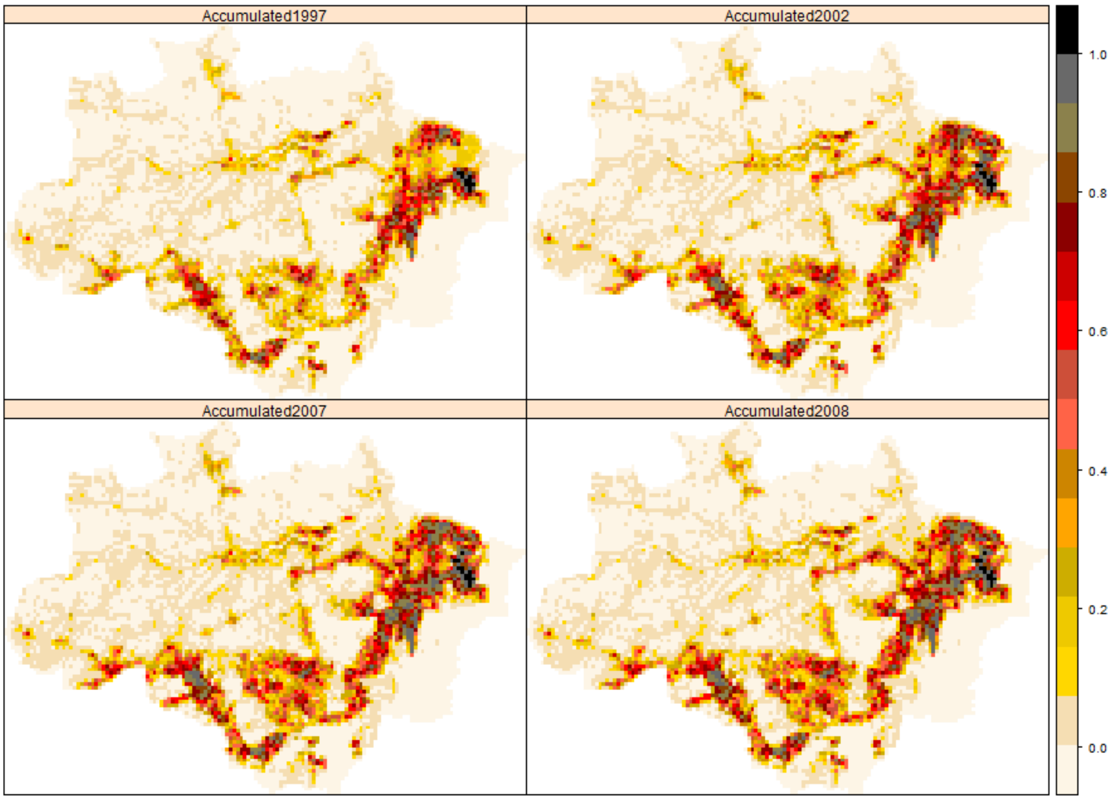


Figure 1.2 – Proportion of cumulative deforestation for each cell of 25 km x 25 km in 1997, 2002, 2007 and 2008.

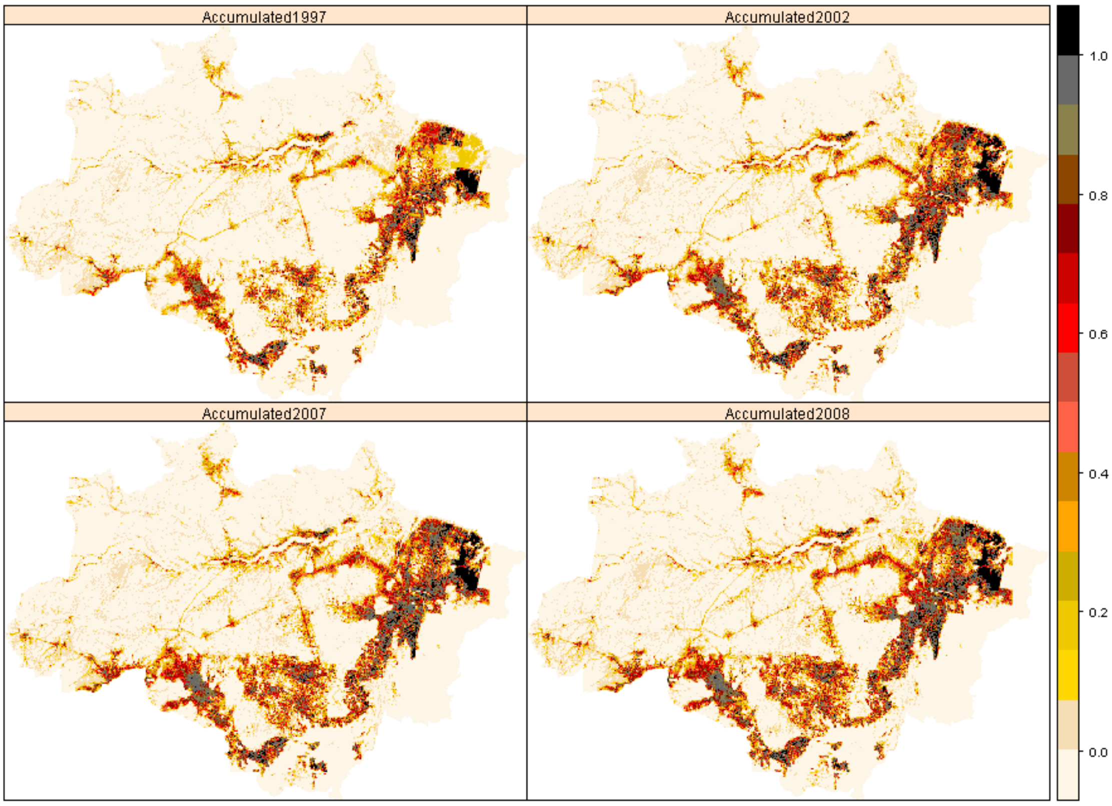


Figure 1.3 – Proportion of cumulative deforestation for each cell of 5 km x 5 km in 1997, 2002, 2007 and 2008.

1.4. Variables and Data Sources

The data used in this study were aggregated from different sources. The aggregation was made by using a range of strategies available into the *TerraView* application or into the *aRT* R package (aRT-Team 2010; TerraView 2010). The most important and relevant derived variables are described below, and a more detailed overview is given in Appendix 1A.

Deforestation: Derived from maps of cumulative deforestation in 1997 and in 2002 and maps of annual deforestation from 2002 until 2009 (Figures 1.2 and 1.3). The proportion of cumulative deforestation and yearly (annual increments) deforestation were computed from 2002 to 2009 in both grid resolutions (INPE 2011).

Agricultural land uses: Deforested areas were decomposed into primary agricultural uses (pasture, temporary agriculture and permanent agriculture) while combining the information of deforestation with information from the 1996 and 2006 agricultural censuses (IBGE 2008) (see Appendix A).

Agrarian structure: Land distribution indicators, such as the proportion (in terms of the number of properties and the 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 and 2006 agricultural censuses.

Land tenure and planning: Including the conservation units and establishment of settlements while considering the specific rules of territory use.

Public policies: Governmental laws and plans and command and control programs that define local arrangements of territory use.

Commodities prices: Agricultural commodities will be analyzed while considering the information of prices, demand from internal and external markets, and production to the main market chains in the region, i.e., beef and soybeans (IPEA 2008).

Accessibility to markets: Distance to roads, rives and urban centers, connection to national markets and ports (IBGE 2008), according to different market chains. These measures were refined for different market chains related to the main commodities in the Brazilian Amazon, using the same approach suggested by AGUIAR (2006).

1.5. Analyzing and Sharing the Data

The analyses of this study were performed using R, a language and environment for statistical computing and graphics (R-Team 2005). The scripts created during this study are partially available on the Internet, and most of the results obtained in this study can be easily reproduced. For example, the methodological approach used to decompose deforested areas into primary agricultural uses is described in Appendix A.

In addition, the concept of Linked Science was used to produce part of the data and the scripts available for R-users (see http://linkedscience.org/data/linked-brazilian-amazon-rainforest/). This approach allows for the combination of all of the linked data to be used as a source for the statistical analysis of deforestation. These data can be accessed in a Linked Data fashion via a SPARQL-endpoint and via URLs. Linked Data solves the access component, and the SPARQL package in R allows for querying a subset of the data. Tutorials for using the SPARQL package in R to handle Spatially Linked Data and for calculating deforestation per state, for example, are also freely available on the same URL.

1.6. Objectives, Thesis Structure and Content

The central objective of this thesis is to study the deforestation trends in the Brazilian Amazon over the last decade with quantitative and qualitative methods to investigate such trends. We focused on deforestation trends to achieve the following aims:

- Quantify the determinant factors of deforestation over the last decade, considering the Brazilian Amazon and subregions.

- Explore how changes in national environmental policies and market forces can influence deforestation trends.

- Understand how deforestation trends varied according to distinct historical, institutional and socioeconomic contexts.

To accomplish these aims, the analyses presented in this thesis consider the following assumption: *the hotspots of deforestation in the Brazilian Amazon contributed differently to deforestation rate variations in response to policy and market conditions according to their specific historical, institutional and socioeconomic contexts*.

This thesis was written as a collection of papers related to a core theme. While each paper investigates a specific scientific question, the papers are connected by the necessity of gaining a better understanding of the predominant trends and critical factors influencing deforestation across the Brazilian Amazon.

Chapter 2: The objective of this chapter is to integrate satellite and census data in order to quantify the distribution and proportions of major agricultural land uses in the Brazilian Amazon. We developed linear and spatial regressions of determinant factors associated with land use change for the states of Pará, Rondônia and Mato Grosso, to reveal how variations in these factors relate to census data. We quantitatively compared the distribution and deforestation factors in 1996/1997 and 2006/2007, as well as the main land uses (pasture, temporary and permanent agricultures).

Chapter 3: Following Chapter 2, this chapter aims to analyze the variability over space and time of yearly deforestation (annual increments of deforestation) across the Brazilian Amazon region from 2002 to 2009. Our ultimate goal is to analyze the effects of national environmental policies applied by the Brazilian government compared to the influence of the market. We developed linear and spatial multiple regression models for a set of potential determining factors driving deforestation. This was accomplished by considering the yearly proportion of deforestation computed for each cell of a regular grid of 25 km x 25 km and a set of human-induced predictors, including the national environmental policies conducted by the Brazilian government and market price variations for soybean and meat, amongst other predictors. We analyzed the deforestation trends for the entire period of time (2002-2009) and separately for the time period when the deforestation rates were increasing (2002-2004) or decreasing (2005-2009).

Chapter 4: The goal of this chapter is to provide an integrated quantitative and qualitative analysis of land use change at a subregional level. We selected six hotspots of land use change in the states of Pará and Mato Grosso, each of one with distinct historical and socioeconomic contexts. For each subregion we analyzed the spatiotemporal variability of agricultural production, socioeconomic indicators and deforestation rates. We aligned such variability under a time line of major national deforestation control policies and macroeconomic contexts after 2000. The assumption is that deforestation rates are not decreasing homogenously and that the maintenance of this decreasing depends on recognizing and understanding such variability across different contexts.

Appendix A: In this Appendix we present a methodology to combine satellite remote sensing and census data to quantify the distribution and fraction of major agricultural land uses – pasture, temporary and permanent agriculture – in the Brazilian Amazon. This work comparatively quantifies the distribution of the main land uses in 1996/1997 and 2006/2007 periods.

2. AGRICULTURAL LAND USE DYNAMICS IN THE BRAZILIAN AMAZON BASED ON REMOTE SENSING AND CENSUS DATA[1]

Abstract

The potential impact of deforestation in the Brazilian Amazon on greenhouse gas emissions to the atmosphere calls for policies that take account of changes in forest cover. Although much research has focused on the location and effects of deforestation, little is known about the distribution and reasons for the agricultural uses that replace forest cover. We used Landsat TM-based deforestation and agricultural census data to generate maps of the distribution and proportion of four major agricultural land uses throughout the Brazilian Amazon in 1997 and 2007. We built linear and spatial regression models to assess the determinant factors of deforestation and those major agricultural land uses – pasture, temporary agriculture and permanent agriculture – for the states of Pará, Rondônia, and Mato Grosso. The data include 30 determinant factors that were grouped into two years (1996 and 2006) and in four categories: accessibility to markets, public policies, agrarian structure, and environment. We found an overall expansion of the total agricultural area between 1997 and 2007, and notable differences between the states of Pará, Rondônia, and Mato Grosso in land use changes during this period. Regression models for deforestation and pasture indicated that determinant factors such as *distance to roads* were more influential in 1997 than in 2007. The *number of settled families* played an important role in the deforestation and pasture, the effect was stronger in 2007 than 1997. *Indigenous lands* were significant in preventing deforestation in high-pressure areas in 2007. For temporary and permanent agricultures, our results show that in 1997 the effect of small farms was stronger than in 2007. The mapped land use time series and the models explain empirically the effects of land use changes across the region over one decade.

[1]This chapter is the exact version of the paper: de Espindola, G.M., de Aguiar, A.P.D., Pebesma, E., Câmara, G., Fonseca, L. (2012) Agricultural land use dynamics in the Brazilian Amazon based on remote sensing and census data. Applied Geography 32, 240-252.

2.1. Introduction

Deforestation is considered to be one of the largest sources of greenhouse gas emissions into the atmosphere. Using the estimated emissions from land use change deforestation and other land use data it has been calculated that carbon dioxide (CO_2) from land use change contributed to 12% (in terms of CO_2 equivalents) of the total anthropogenic greenhouse gas emissions in 2008 (Quéré, Raupach et al. 2009). From 2000-2009 the rate of tropical deforestation in the Brazilian Amazon was amongst the fastest in the world, averaging 17,486 sq km per year (INPE 2011). Significant negative externalities have been created as a result, such as loss of biodiversity, erosion, floods, lowered water tables, as well as increased release of carbon into the atmosphere (Shukla, Nobre et al. 1990; Fearnside 1996). All these effects make the Brazilian Amazon region one of the hotspots of global environmental change (Achard, Eva et al. 2002; Laurance, Albernaz et al. 2004; IPCC 2007; IPCC 2007).

Critical problems, such as tropical deforestation, are relatively well understood at regional level. At this level, considerable research has focused on estimating rates of forest conversion (mainly by using satellite remote sensing) and on evaluating the factors that influence these rates (Fearnside 1990; Fearnside, Tardin et al. 1990; Skole and Tucker 1993; Alves 2002; Margulis 2004; Chambers, Asner et al. 2007). The most frequently mentioned determinant factors of deforestation include regional variants of driver combinations in which economic factors, institutions and national policies are prominent (Lambin 1994; Geist and Lambin 2001; Margulis 2004; Geist, McConnell et al. 2006). It is clear that multiple processes influence the spatial and temporal dynamics of deforestation, and that there are significant gaps in knowledge to be filled (Gibson, McKean et al. 2000; Dietz, Ostrom et al. 2003).

Assessments of factors associated with land use change in the Brazilian Amazon have so far mostly used econometric models and grid-based models. Using a non-spatial and region-wide level econometric analysis, Reis & Guzmán (1992) found that the most important factors of change in the region were *population density*, *road network density* and *extension of cultivated areas*. Andersen & Reis (1997) also used an econometric model. They found that 11 factors were responsible for the land use change in the Brazilian Amazon from 1975 to 1995, among them *distance to the federal capital*, *earlier deforestation in area*, *rural population density*, *land prices* and *size of cattle herd*. Pfaff (1996) focused on the period from 1978 to 1988 and analyzed the relevance of biophysical variables (*soil quality* and *vegetation type*), transport-related variables (*road network*, *density in the area* and *its neighbors*) and government-related variables (*development policies*). Margulis (2004), however, presented an econometric model for analyzing the occupation of the Brazilian Amazon, quantifying the spatial and temporal relationships of the main agricultural activities (*timber extraction*, *pasture* and *crops*). Based on grid models, Perz & Skole (2003) developed a spatial regression model for secondary vegetation in the Amazon Basin and showed that determinant factors have significant spatial variation among different regions. Laurance, et al. (2002) performed statistical analysis to assess the relative importance of determinant factors. They found the three most important factors were *population density*, *distance to roads*, and *dry season duration*. The results reported by Soares-Filho, et al. (2006) indicate that the most important factors for predicting deforestation location in the Amazon Basin are *proximity to roads*, *indigenous reserves* and *proximity to urban centers*. More recently, Soares-Filho, et al. (2010) showed that *indigenous lands*, *strictly protected areas* and *areas of sustainable use* inhibited deforestation between 1997 and 2008.

Although the rates of forest loss have been examined across the Brazilian Amazon, little is known about the transition from mature forest to agricultural uses. Most information about agricultural land use in the Brazilian Amazon comes from agricultural censuses (IBGE 1996; IBGE 2006). These censuses form the most complete survey of land management and provide data on areas under different land use categories (pasture and crops, for example), levels of mechanization and agricultural inputs, allowing for detailed analyses of social, economic, and environmental aspects of agriculture across the region (Cardille and Foley 2003).

The most compelling reason to monitor land use change is the strong effect of the land use trajectory[2] on the state of changed areas. Concepts of land use trajectories have been used to identify some dominant pathways leading to specific land use outcomes, and have been presented as typical sequences of causes of tropical deforestation[3] (Alves, Morton et al. 2009). The potential transition pathway from forest to other land uses depends on the state of the human occupation and on site conditions, such as: proximity to roads (Alves 2002); presence of settlements and land tenure (Moran, Brondízio et al. 2005); the soils, environment and climate (Nobre, Sebestyen et al. 1997); and market conditions. The techniques now available to integrate satellite and census data could improve the corresponding spatial details needed to monitor different suites of possible transitions (Alves, Morton et al. 2009; Morton, DeFries et al. 2009).

In the 1960s and 1970s, the migration into the Brazilian Amazon region was stimulated by government policies and subsidies (Becker 2005), in a bid to populate the region and integrate it into the rest of the country. After the 1990s, migration continued apace, as did the deforestation, largely because of private investments in agricultural expansion, associated with large-scale cattle ranching, soybean cultivation, and small-scale subsistence farming. Since then, land use practices have been affected by market arrangements, including legal and illegal market chains, and by the requirement to certify timber, beef, and soybean products that has been imposed by market chain consumers. In addition, initiatives to value the forest, such as alternative technologies and market chains based on biodiversity products, and payment for ecosystem services have also impacted land change dynamics.

A review from the 1985-2006 period shows that the significant amount of deforestation from 1985 to 1995 forced the Brazilian government to take actions to protect endangered areas. From the mid to late 1990s, major initiatives emerged and are still influencing the rates of deforestation. One of the initiatives was the adoption of a

[2]The same land use trajectory can result from different suites of transitions, depending on the type of initial forest disturbance. For example, a forest to pasture trajectory can occur directly, if mature forest is clear-cut to sow grass, or indirectly, if pasture is created after logging or crop cultivation.
[3]In this study, we use the term “deforestation” to describe the situations of complete removal of tree cover.

systematic and consistent approach to areas designated as national parks (Rylands and Brandon 2005). As a result, Brazil has expanded the network of Amazon protected areas from 1.26 to 1.82 million sq km since 2005. As well as the growth in the protected areas, the indigenous lands have also expanded: they currently cover about 20% of the Brazilian Amazon, and some play a very significant role in protecting the forest from ongoing development. In the ten years from 1996 to 2006, various other initiatives were taken to reduce deforestation in the Amazon region (Nepstad, Soares-Filho et al. 2009), and these have produced significant land use changes. These measures have succeeded in slowing down deforestation. Since 2004, when the area deforested was 27,772 sq km in 2004 (the highest annual total for 10 years), the annual area deforested has declined steadily: to only 6,451 sq km in 2010 (INPE 2011). These lowest deforestation rates since 2005 reflect lower commodity prices in the international market, and also the stricter control exercised by the Brazilian government. Despite this, between 1996 to 2006 the area under agricultural land uses in the Brazilian Amazon, including permanent and temporary crops, and natural and sown pasture, increased from 568,949 sq km to 663,177 sq km (IBGE 1996; IBGE 2006).

Against this background, the present study aims to integrate satellite and census data in order to quantify the distribution and proportions of major agricultural land uses in the Brazilian Amazon. We developed linear and spatial regressions of determinant factors associated with land use change for the states of Pará, Rondônia and Mato Grosso, to reveal how variations in these factors relate to census data. We quantitatively compared the distribution and deforestation factors in 1996/1997 and 2006/2007, as well as the main land uses (pasture, temporary and permanent agricultures). Our analysis was based on a subset of 30 potential explanatory variables selected on the basis of Aguiar, et al.(2007).

The chapter is organized as follows. Section 2 presents the data and methods used. Section 3 presents the results. We conclude with a discussion in which we consider the land use dynamics in the region and summarize the main findings.

2.2. Material and Methods

2.2.1 Study area and spatial resolution

The study area was the Brazilian Amazon region, which covers an area of more than 5 million sq km. We generated land use maps for the entire Brazilian Amazon, but for our statistical analysis we focused solely on the states of Pará, Rondônia, and Mato Grosso. These three states cover an area of more than 2 million sq km, representing around 46% of the area of the total region. Over the past three decades, these states have had the highest rates of deforestation in the region, and have accounted for 82% of the region's deforestation (INPE 2011). For our analyses, all variables representing deforestation, land uses (pasture, temporary and permanent agricultures) and potential determinant factors were aggregated to grid cells of 25 km x 25 km (Figure 2.1).

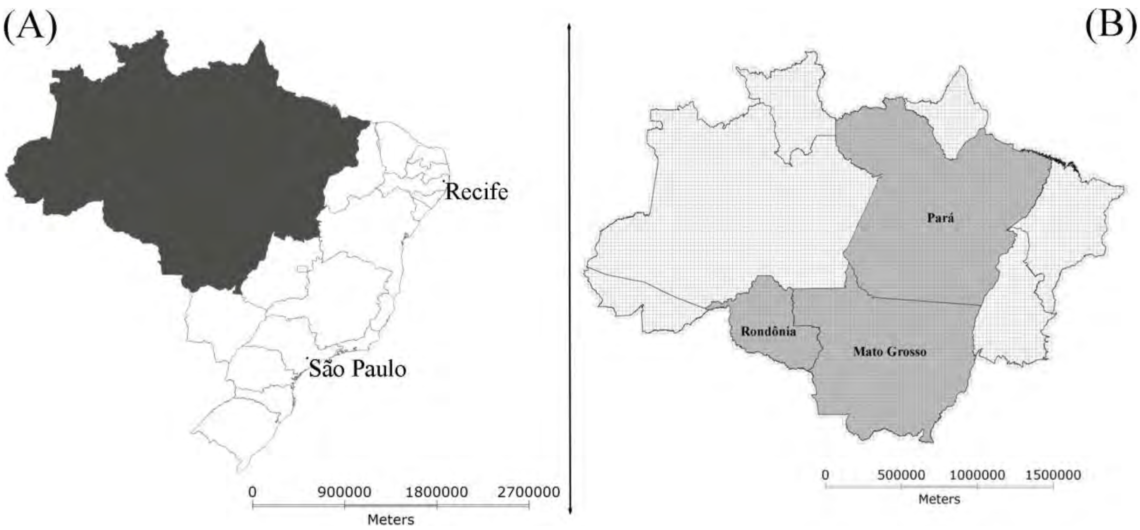


Figure 2.1 – (A) Map of Brazil showing the location of the Brazilian Amazon region (all in darker gray), and the location of São Paulo and Recife cities. (B) Regular grid of 25 km x 25 km over the Brazilian Amazon region; the states of Pará, Rondônia and Mato Grosso are shown in gray.

2.2.2 Deforestation and land uses

We used Landsat TM-based 1997-2007 deforestation maps produced under the Amazon monitoring program of the Brazilian National Institute for Space Research (INPE 2011). The percentages of cumulative deforestation in 1997 and 2007 were computed for each cell. Cells with large proportion (>20%) of cloud cover, non-forest vegetation, or cells outside the Brazilian Amazon were omitted from our statistical analyses. The cells omitted due to cloud cover accounted for less than 5% of the number of cells covering the study area. We were left with 2,232 cells in total for the states of Pará, Rondônia, and Mato Grosso (Appendix 2A). Figure 2.2 shows that from 1997 to 2007 deforestation increased and tended to occur close to previously deforested areas, producing a distinctive pattern (Alves, Morton et al. 2009).

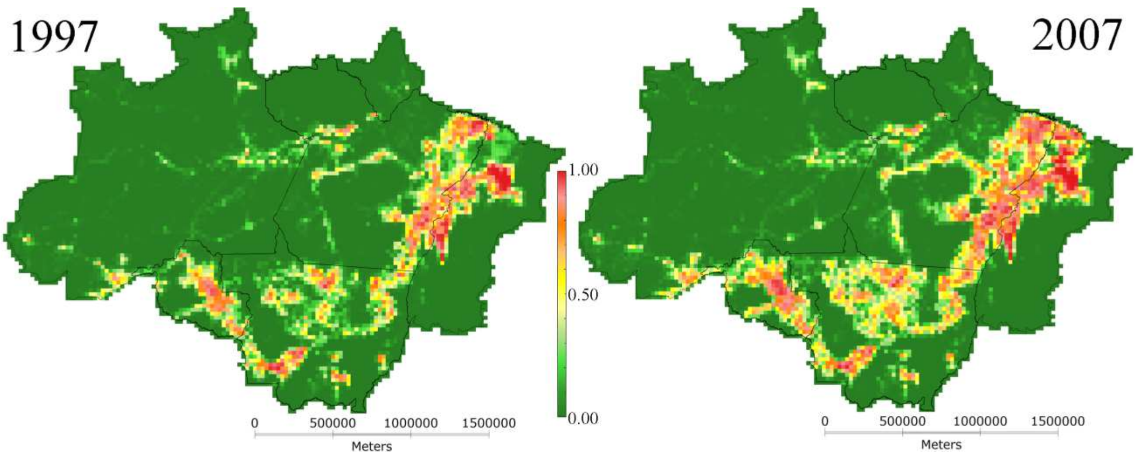


Figure 2.2 – Proportion of cumulative deforestation for each cell in 1997 (left) and 2007 (right).

The cumulative deforestation in 1997 and 2007 was decomposed into the main agricultural uses – pasture, temporary and permanent agricultures – by combining the TM-based 1997-2007 deforestation maps from INPE (2011), and census information from the agricultural censuses in 1996 and 2006 (IBGE 1996; IBGE 2006). Municipality-based census data (Figure 2.3) was converted from polygon-based information to grid cells of 25 km x 25 km. The total agricultural area for each municipality was taken from the deforestation maps; the proportion of each agricultural use was taken from the census data. This computation assumed that the proportion of land use types was uniformly distributed over the deforested areas of each municipality.

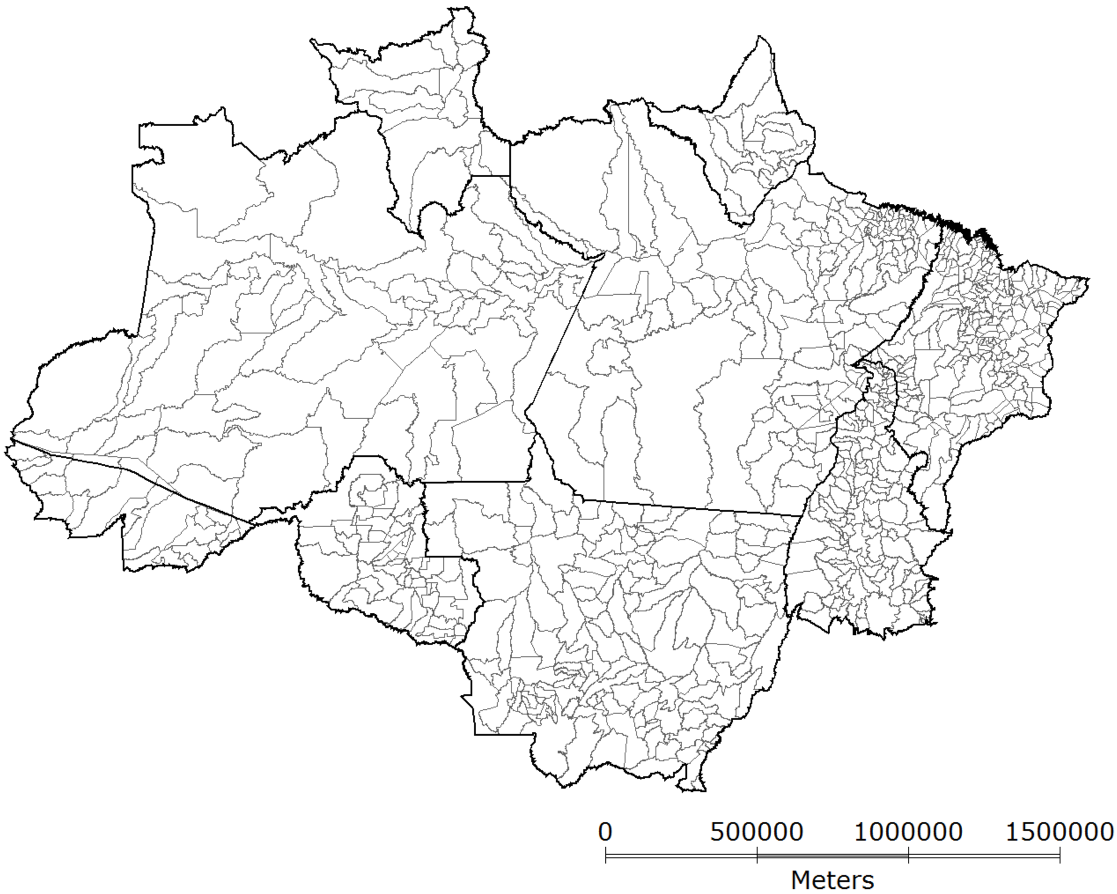


Figure 2.3 – Spatial extent of municipality polygons within the states of the Brazilian Amazon.

2.2.3 Potential determinant factors

For each of the two years 1996/1997 and 2006/2007, the data included 30 variables that were grouped into four main categories: accessibility to markets, public policies, agrarian structure, and environment. According to Aguiar, et al. (2007), these variables could potentially explain differences in land use in 1997. As pointed out in the Introduction, so far, most studies in the Brazilian Amazon have been restricted to deforestation, though Aguiar, et al. (2007) also decomposed deforestation into the main agricultural land uses. In addition, Aguiar, et al. (2007) included the socioeconomic and biophysical factors adopted in previous work, added measures of connectivity to ports and to markets, and introduced agrarian structure indicators that had not been used before. Summarizing, Table 2.1 shows our subset of potential explanatory variables in 1996/1997 and 2006/2007. All the variables were aggregated to the grid cells of 25 km x 25 km. Appendix 2A contains maps of the main determinant factors used in our statistical analyses.

The accessibility to markets initially included Euclidean *distance to roads*, *distance to urban centers*, *distance to wood extraction* (or timber extraction) and *distance to mineral deposits* in 1996 and 2006. Euclidean *distance to rivers* was considered invariant over time. The *Distance to Roads 1996* variable, for example, measures the Euclidean distance from each cell to the nearest paved or non-paved road in 1996. Euclidean *distance to roads* and *distance to urban centers* were considered as a proxy for accessibility to local markets and basic services. Following IBGE (2011), *urban centers* were defined as places with a cluster of permanent residents. Appendix 2A shows that the density of roads and urban centers in the north of Mato Grosso was higher in 2006 than in 1996. Euclidean *distance to wood extraction* and *distance to mineral deposits* were measured in the same way, and showed no large differences between 1996 and 2006. Other measures of accessibility to markets included the *connection to ports* and markets in 1996 and 2006. For our analyses we computed connectivity indicators for each cell, measuring the minimum path distance through the road network from each cell to ports and markets. As described by Aguiar (2006), we distinguished paved from non-paved roads using the *generalized proximity matrix* (GPM). In the group of markets, we recognized *connection to São Paulo* and *connection to national markets* (São Paulo and Recife, see Figure 2.1).

The public policies variables are all related to government actions, such as the creation of planned settlements, protected areas and indigenous lands. The *number of settled families* was computed taking the average of this value in each municipality weighted by the area intersection between the municipality and the grid cell. The *protected areas* and *indigenous lands* variables reflect the percentage of each cell that is covered by (or intersects with) the polygons of these areas. The agrarian structure variables were based on municipality-level information, indicating the proportion in terms of area inside the municipality of small (< 200 ha), medium (200 to 1000 ha) and large (> 1000 ha) farms. The environment variables were related to land conditions such as soil fertility and climate. Fertility data was derived from IBGE natural resource maps, integrating soil type, morphology, texture, and drainage information. Climate data was derived from CPTEC/INPE, where the *seasonal index* was used to represent the soil moisture seasonality, and the *humidity index* was used to distinguish between wet and dry climates (Salazar, Nobre et al. 2007; Piribauer 2010).

2.2.4 Exploratory analyses and selection of variables

In the statistical models we describe in this chapter, dependent variables are those associated with land uses (the proportions of deforestation, pasture, temporary agriculture and permanent agricultures in each cell), and the independent variables (or potential explanatory variables) are those grouped into four main categories: accessibility to markets, public policies, agrarian structure and environment. An initial exploratory analysis showed that some of the relationships between dependent and independent variables were not linear. We applied a logarithmic transformation to all dependent variables and to some independent variables. Table 2.1 shows these variables annotated with 'log10'. This transformation shows that the independent variables are related to the initial choice of forest areas to be cut.

We also found a high degree of correlation among pairs of independent variables. This high correlation was used to exclude variables like *seasonal index* which is highly correlated with *humidity index*. The set of independent variables selected for the regression analysis (Table 2.2) were chosen on the basis of model selection by exhaustive searching, considering separate best models of all sizes. As the model search does not actually fit each model, the results do not contain coefficients or standard errors. Thus, the statistical analyses were done with two subsets of independent variables, covering the broadest possible range of categories while minimizing correlation problems.

Table 2.1 – Explanatory variables in 1996/1997 and 2006/2007.

Subset of Potential Explanatory Variables						
Category	Variable 1996/1997	Description 1996/1997	Variable 2006/2007	Description 2006/2007	Unit	Source
Land Use	Deforestation 1997	Deforestation until 1997 (log10)	Deforestation 2007	Deforestation until 2007 (log10)	% Area	INPE
	Pasture 1997	Pasture in 1997 (log10)	Pasture 2007	Pasture in 2007 (log10)	% Area	INPE
	Temporary 1997	Temporary agriculture in 1997 (log10)	Temporary 2007	Temporary agriculture in 2007 (log10)	% Area	INPE
	Permanent 1997	Permanent agriculture in 1997 (log10)	Permanent 2007	Permanent agriculture in 2007 (log10)	% Area	INPE
Accessibility to Markets	Distance to Roads 1996	Euclidean distance to roads in 1996 (log10)	Distance to Roads 2006	Euclidean distance to roads in 2006 (log10)	Km	IBGE
	Distance to Urban Centers 1996	Euclidean distance to urban centers in 1996 (log10)	Distance to Urban Centers 2006	Euclidean distance to urban centers in 2006 (log10)	Km	IBGE
	Distance to Wood Extraction 1996	Euclidean distance to wood extraction in 1996 (log10)	Distance to Wood Extraction 2006	Euclidean distance to wood extraction in 2006 (log10)	Km	IBGE
	Distance to Rivers	Euclidean distance to large rivers (log10)	Distance to Rivers	Euclidean distance to large rivers (log10)	Km	IBGE
	Distance to Mineral Deposits 1996	Euclidean distance to mineral deposits in 1996 (log10)	Distance to Mineral Deposits 2006	Euclidean distance to mineral deposits in 2006 (log10)	Km	IBGE
	Connection to Ports 1996	Indicator of strength of connection to ports through roads network in 1996	Connection to Ports 2006	Indicator of strength of connection to ports through roads network in 2006	-	IBGE
	Connection to São Paulo 1996	Indicator of strength of connection to São Paulo through roads network in 1996	Connection to São Paulo 2006	Indicator of strength of connection to São Paulo through roads network in 2006	-	IBGE
	Connection to National Markets 1996	Indicator of strength of connection to national markets (São Paulo and Recife) through roads network in 1997	Connection to National Markets 2006	Indicator of strength of connection to national markets (São Paulo and Recife) through roads network in 2006	-	IBGE
Public Policies	Number of Settled Families 1996	Number of settled families until 1996 (log10)	Number of Settled Families 2006	Number of settled families until 2006 (log10)	Number of families	MMA

	Protected Areas 1996	Protected areas in 1996	Protected Area 2006	Protected areas in 2006	% Area	MMA
	Indigenous Lands 1996	Indigenous lands in 1996	Indigenous Lands 2006	Indigenous lands in 2006	% Area	MMA
Agrarian Structure	Small Properties 1996	Area of small properties in 1996	Small Properties 2006	Area of small properties in 2006	% Area	IBGE
	Medium Properties 1996	Area of medium properties in 1996	Medium Properties 2006	Area of medium properties in 2006	% Area	IBGE
	Large Properties 1996	Area of large properties in 1996	Large Properties 2006	Area of large properties in 2006	% Area	IBGE
Environment	High Fertility	High fertility soils	High Fertility	High fertility soils	% Area	IBGE
	Seasonal Index	Seasonal index	Index Seasonal	Seasonal index	-	INPE
	Humidity Index	Humidity index	Humidity Index	Humidity index	-	INPE

Table 2.2 – Subset of statistical models: *roads and settlements* and *urban centers and agrarian structure.*

Subset of Statistical Models		
Models	**01 - Roads and Settlements**	**02 - Urban Centers and Agrarian Structure**
Dependent Variables	Deforestation Pasture Temporary Agriculture Permanent Agriculture	
Independent Variables	Distance to Roads Number of Settled Families Distance to Wood Extraction Distance to Rivers Connection to National Markets Protected Areas Indigenous Lands High Fertility Humidity Index	Distance to Urban Centers Small Properties Distance to Wood Extraction Distance to Rivers Connection to National Markets Protected Areas Indigenous Lands High Fertility Humidity Index

2.2.5 Regression modeling

The statistical analyses were done using R, a language and environment for statistical computing and graphics (R-Team 2005). We used ordinary linear and spatial lag regression models to establish the relative importance of the determinant factors for different land uses. The linear regression analyses were done to model the relationship between the dependent and independent variables, and the spatial regression analyses were to model the autocorrelation of the dependent variables. For land use data, the assumption underlying ordinary linear regression that observations are independent does not hold, because neighboring land use observations are typically spatially correlated. We applied a spatial lag regression model to assess the spatial dependence of the variables using maximum likelihood estimation (Bivand, Pebesma et al. 2008). Our models are shown in Table 2.2, which summarizes our two explanatory variable subsets: *roads and settlements* and *urban centers and agrarian structure*.

Differences among variables in groups of models were found to be significant in some of the models but non-significant in others. In order to compare the performance of different models, the R-squared value (coefficient of determination) is used. To compare the relative importance of each determinant factor in each model we will present the standardized regression coefficients (*Beta*) and the corresponding standard error for each variable.

2.3. Results

This section summarizes the main findings and compares the results obtained from land use time series, and by regression modeling for 1996/1997 and 2006/2007. The comparison shows how the deforestation was impacted by land use changes, and also shows how the importance of determinant factors changed over time.

2.3.1 Models of deforestation

The regression models for deforestation in 1997 and 2007 revealed some important changes in the patterns of human occupation in the Brazilian Amazon. They are summarized in Figure 2.4, Figure 2.5 and Table 2.3. Figures 2.4 and 2.5 show error bars of approximate 95% confidence intervals (estimate +/- 2 standard errors). The confidence intervals were used to infer which determinant factors changed from 1996/1997 to 2006/2007: when the confidence intervals did not overlap for a particular factor, we assumed this indicated a significant difference (change) in this factor's influence on the dependent variable. When 95% confidence intervals are used and they do not overlap, the indication of significant difference in that factor is conservative (Payton, Greenstone et al. 2003).

Figure 2.4 shows the *Beta* values in *roads and settlements* models, and compares the determinant factors in 1997 and 2007. The R-squared values performed better in 2007 (0.71) than that in 1997 (0.63), however, the difference was smaller for the spatial lag models (0.88 for 2007 and 0.85 for 1997: see Table 2.3). The variables *distance to wood extraction*, *distance to rivers*, *protected areas* and *humidity index* did not change their influence from 1997 and 2007, although some of them affect the linear models. All the other variables changed their influence, most notably *distance to roads*, *number of settled families* and *indigenous lands*. *Connection to national markets* and *high fertility* changed very little between these two years. *Distance to roads* was more influential in 1997 than in 2007, indicating that the tendency to deforest along the roads decreased. Previous studies tended to emphasize the distance to roads as the main factor determining deforestation (Laurance, Albernaz et al. 2004), but our results indicate that even in 1997 other variables were also important, and in 2007 the distance to roads was not so relevant. *Number of settled families* was also important in the deforestation process, having a higher positive impact in 2007 than it did in 1997, mostly because during this period the number of settlements increased. Finally, *indigenous lands* variables were crucial in preventing deforestation in areas of high population pressure.

Figure 2.5 shows the *Beta* values for the *urban centers and agrarian structure* models of 1997 and 2007. For these models, the R-squared values also performed better in 2007 (0.68) than in 1997 (0.57), and the spatial lag models had values similar to those of the *roads and settlements* models (0.87 for 2007 and 0.85 for 1997: see Table 2.3). Figure 2.5 also indicates that the effects of the variables *distance to urban centers* and *small* *properties* did not change over time. However, when both variables are considered, the *distance to wood extraction* and *distance to rivers* variables showed a change from 1997 to 2007. In addition, in 1997 the *distance to rivers* variable had an opposite response for the *urban centers and agrarian structure* model in 1997, indicating that at this date the deforestation tended to occur along the main rivers. The variables *connection to national markets, protected areas* and *humidity index* did not reveal a change in their influence from 1997 to 2007, and still seem to be key factors in explaining the deforestation process in the Brazilian Amazon. *High fertility* did not change much either during the period considered, but *indigenous lands* variables were crucial in 2007.

The results are similar for the spatial lag regression models. They included one additional variable (*W Deforestation*), which indicates the degree to which the dependent variable is spatially autocorrelated. The R-squared values of the spatial lag models are significant and in all the models of deforestation they are higher than 0.84 (see Table 2.3). This is the quantitative evidence that corroborates earlier assessments that indicated that the regional pattern of deforestation is a diffusive process, and tends to occur close to previously cleared areas. As expected, when the spatial lag regression models are used, all betas decrease, but not uniformly.

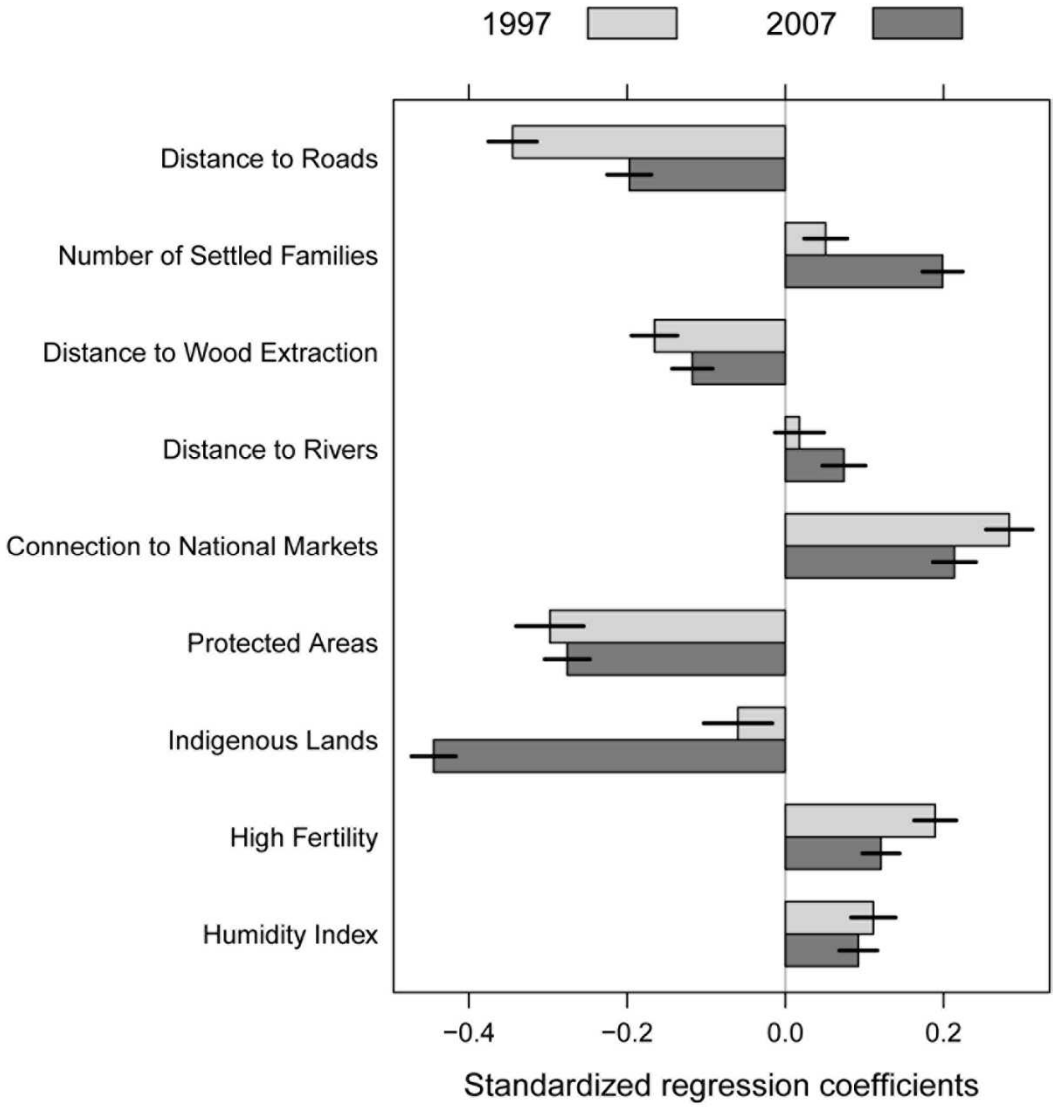


Figure 2.4 – Standardized regression coefficients for deforestation, and for the *roads and settlements* models of 1996/1997 and 2006/2007, approximate 95% confidence intervals were computed by +/- 2 standard errors.

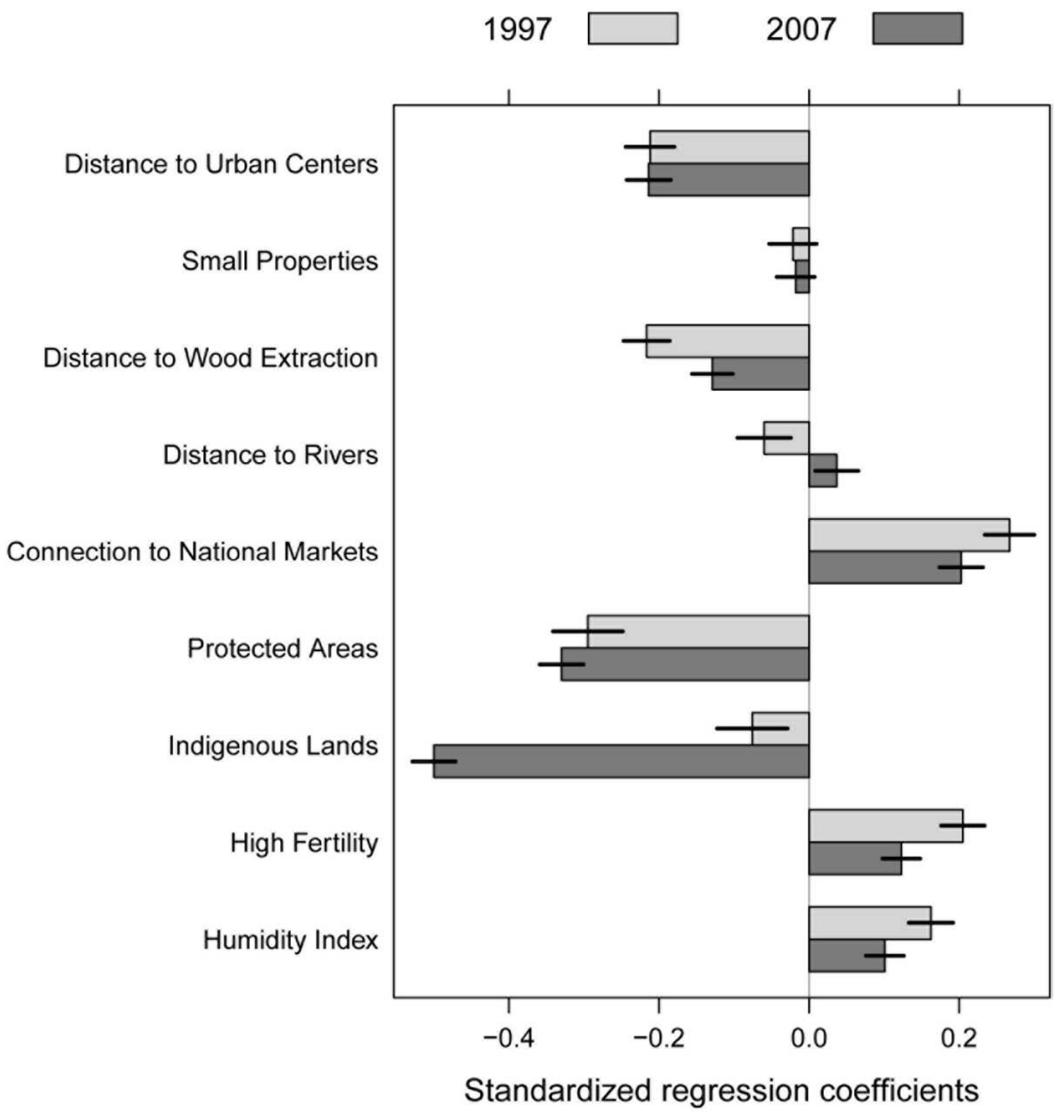


Figure 2.5 – Standardized regression coefficients for deforestation, and for the *urban centers and agrarian structure* models of 1996/1997 and 2006/2007, approximate 95% confidence intervals were computed by +/- 2 standard errors.

Table 2.3 – Spatial lag regression models for log transformed deforestation determinant factors.

Lag Regression					
Roads and Settlements			**Urban Centers and Agrarian Structure**		
1996/1997					
Variable	***Beta***	**Std. Error**	**Variable**	***Beta***	**Std. Error**
R-squared:	**0.848**		**R-squared:**	**0.843**	
W Deforestation 1997	0.777	0.014	W Deforestation 1997	0.819	0.013
Distance to Roads	-0.121	0.011	Distance to Urban Centers	-0.031	0.010
Number of Settled Families	0.005	0.009	Small Properties	0.003	0.010
Distance to Wood Extraction	-0.033	0.010	Distance to Wood Extraction	-0.052	0.010
Distance to Rivers	0.012	0.010	Distance to Rivers	-0.008	0.011
Connection to National Markets	0.058	0.010	Connection to National Markets	0.048	0.010
Protected Areas	-0.111	0.014	Protected Areas	-0.107	0.014
Indigenous Lands	-0.028	0.014	Indigenous Lands	-0.033	0.014
High Fertility	0.037	0.009	High Fertility	0.038	0.009
Humidity Index	0.035	0.009	Humidity Index	0.043	0.009
2006/2007					
Variable	***Beta***	**Std. Error**	**Variable**	***Beta***	**Std. Error**
R-squared:	**0.879**		**R-squared:**	**0.876**	
W Deforestation 2007	0.743	0.014	W Deforestation 2007	0.751	0.013
Distance to Roads	-0.040	0.009	Distance to Urban Centers	-0.084	0.011
Number of Settled Families	0.080	0.008	Small Properties	-0.010	0.008
Distance to Wood Extraction	-0.015	0.009	Distance to Wood Extraction	0.005	0.009
Distance to Rivers	0.024	0.009	Distance to Rivers	0.015	0.009
Connection to National Markets	0.037	0.009	Connection to National Markets	0.026	0.009

Protected Areas	-0.128	0.010	Protected Areas	-0.139	0.010
Indigenous Lands	-0.201	0.011	Indigenous Lands	-0.215	0.011
High Fertility	0.024	0.008	High Fertility	0.017	0.008
Humidity Index	0.030	0.008	Humidity Index	0.036	0.008

2.3.2 Maps and models of land uses

This section presents the maps representing 1996/1997 and 2006/2007 agricultural distribution and density for the entire Brazilian Amazon. At the end, we present the results for the best model (*roads and settlements* versus *urban centers and agrarian structure*) for the states of Pará, Rondônia, and Mato Grosso when the dependent variables are pasture, temporary agriculture and permanent agriculture. Our analyses in this section are based on those discussed in section 2.3.1.

Figures 2.6, 2.7 and 2.8 show, respectively, the resulting pasture, temporary agriculture and permanent agriculture patterns in 1996/1997 and 2006/2007. Pasture occurred throughout the deforested areas and was the major land use in both years (1996/1997 and 2006/2007). It increased concomitantly with the increase in deforestation (Figure 2.6). In 1997, pasture covered approximately 84% of the total deforested area of the states of Pará, Rondônia and Mato Grosso, and by 2007 had increased to 92% of the total deforested area. Temporary agriculture (Figure 2.7) represented about 8% of the total deforested area in 1997 and 17% of the total deforested area in 2007. It is important to notice the high concentration of temporary agriculture in the central region of Mato Grosso in 2007, where it is directly associated with commercial soybean production on large farms. Finally, permanent agriculture (Figure 2.8) covered around 1% and 5% of the total deforested area in 1997 and 2007. Regarding permanent agriculture, it should be noticed that between 1997 and 2007 its concentration decreased in the central region of Rondônia; the reason is that land change trajectories in Rondônia are strongly connected to policies for land reform and the change from small-scale subsistence farming to cattle-raising (Soler and Verburg 2010). Table 2.4 shows the trends in the four land uses over the states of Pará, Rondônia and Mato Grosso, expressed as number of grid cells in which the area under the given land use changed by more than 10%.

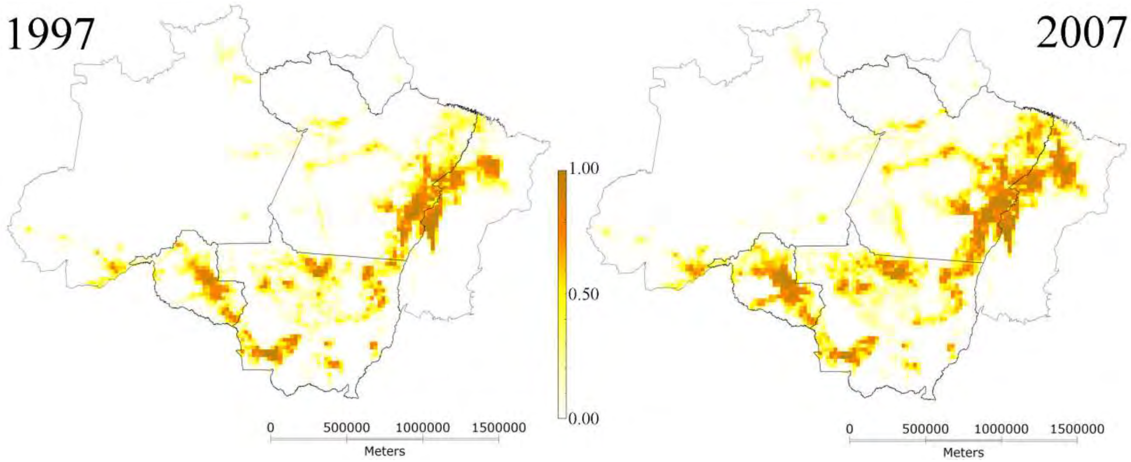


Figure 2.6 – Proportion of pasture in 1997/1996 (left) and 2007/2006 (right).

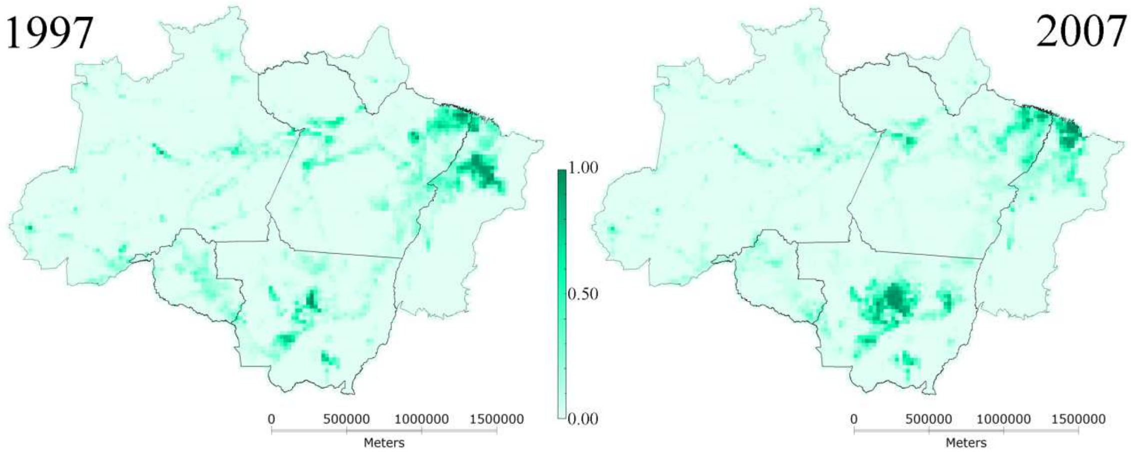


Figure 2.7 – Proportion of temporary agriculture in 1997/1996 (left) and 2007/2006 (right).

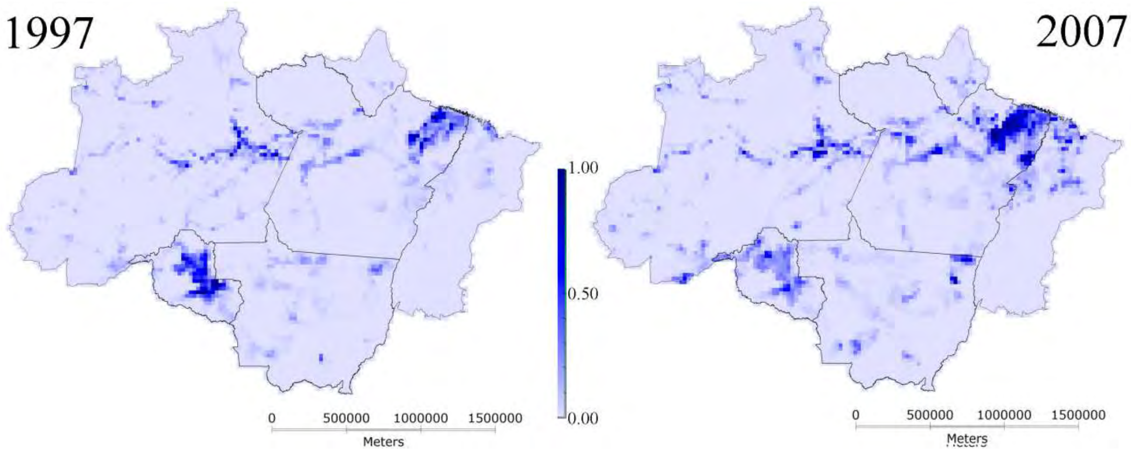


Figure 2.8 – Proportion of permanent agriculture for 1997/1996 (left) and 2007/2006 (right).

Table 2.4 – Land use trends in the four land uses over the states of Pará, Rondônia and Mato Grosso: numbers express the cells under the given land use changed by more than 10%.

Quantitative Land Use Trends		
	1996/1997	**2006/2007**
Number of valid cells	2232	2232
Number of cells with more than 10% deforestation	986	1300
Number of cells with more than 10% pasture	832	1196
Number of cells with more than 10% temporary agriculture	84	221
Number of cells with more than 10% permanent agriculture	11	68

The regression models also revealed that pasture was spread throughout the region; its determinant factors are very similar to deforestation ones (Figure 2.9 and Table 2.5). This is not surprising, given the large deforested area converted into pasture. For these models, the R-squared values for the linear regressions were 0.58 in 1997 and 0.65 in 2007; the corresponding values yielded by the spatial lag models were 0.85 in 1997 and 0.86 in 2007. Temporary and permanent agricultures presented differentiated and concentrated patterns (Figures 2.10 and 2.11, and Table 2.5). The R-squared values for these models were 0.52 and 0.45 for temporary agriculture in 1997 and 2007, compared with 0.82 and 0.81 for the spatial lag models. For permanent agriculture they were 0.39 in 1997 and 0.45 in 2007 (compared with 0.84 and 0.84 for the spatial lag models). The variables *distance to urban centers* and *protected areas* had the same trend as the deforestation models, and their values did not differ significantly between 1997 and 2007. Our results also indicate a tendency for temporary and permanent agriculture to occupy areas associated with small farms in 1997. This trend was stronger in 1997 than it was in 2007, which was caused by the fact that in certain locations small farms had been aggregated to form medium and large farms. The *distance to wood extraction* variables showed a change from 1997 to 2007 that was similar to that yielded by the deforestation models. The *distance to rivers* variable did not change for temporary agriculture but did change for permanent agriculture. *Connection to national markets* played a role in both models, but had more influence on temporary agriculture, because this kind of agriculture is highly correlated with the expansion of the soybean area in Mato Grosso. Contrary to the deforestation models, here *indigenous lands* variables followed an opposite trend in 1997, having a positive effect on temporary and permanent agricultures. In 2007, the *humidity index* variables also showed a trend opposite to those of the deforestation models.

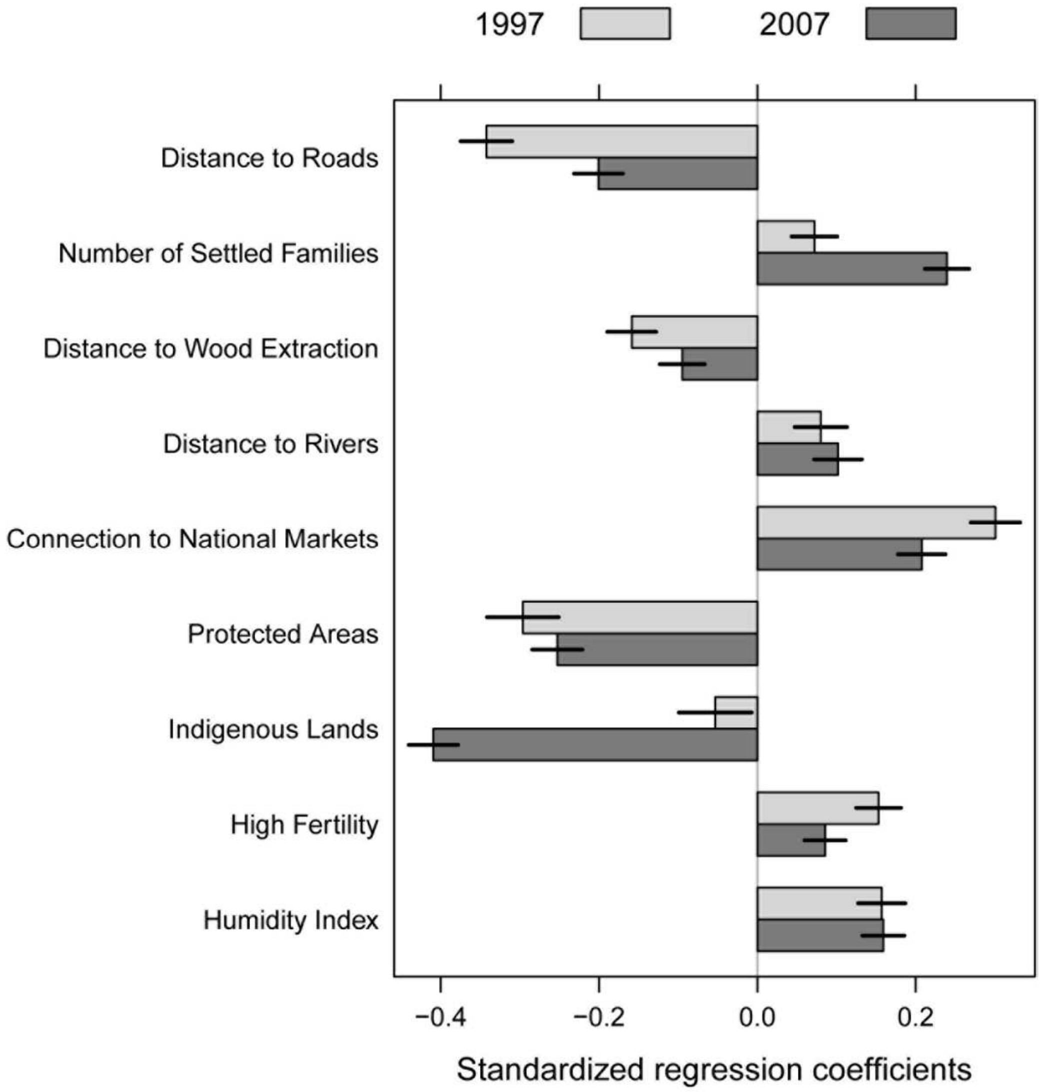


Figure 2.9 – Standardized regression coefficients for pasture, and for the *roads and settlements* models of 1996/1997 and 2006/2007, approximate 95% confidence intervals are computed by +/- 2 standard errors.

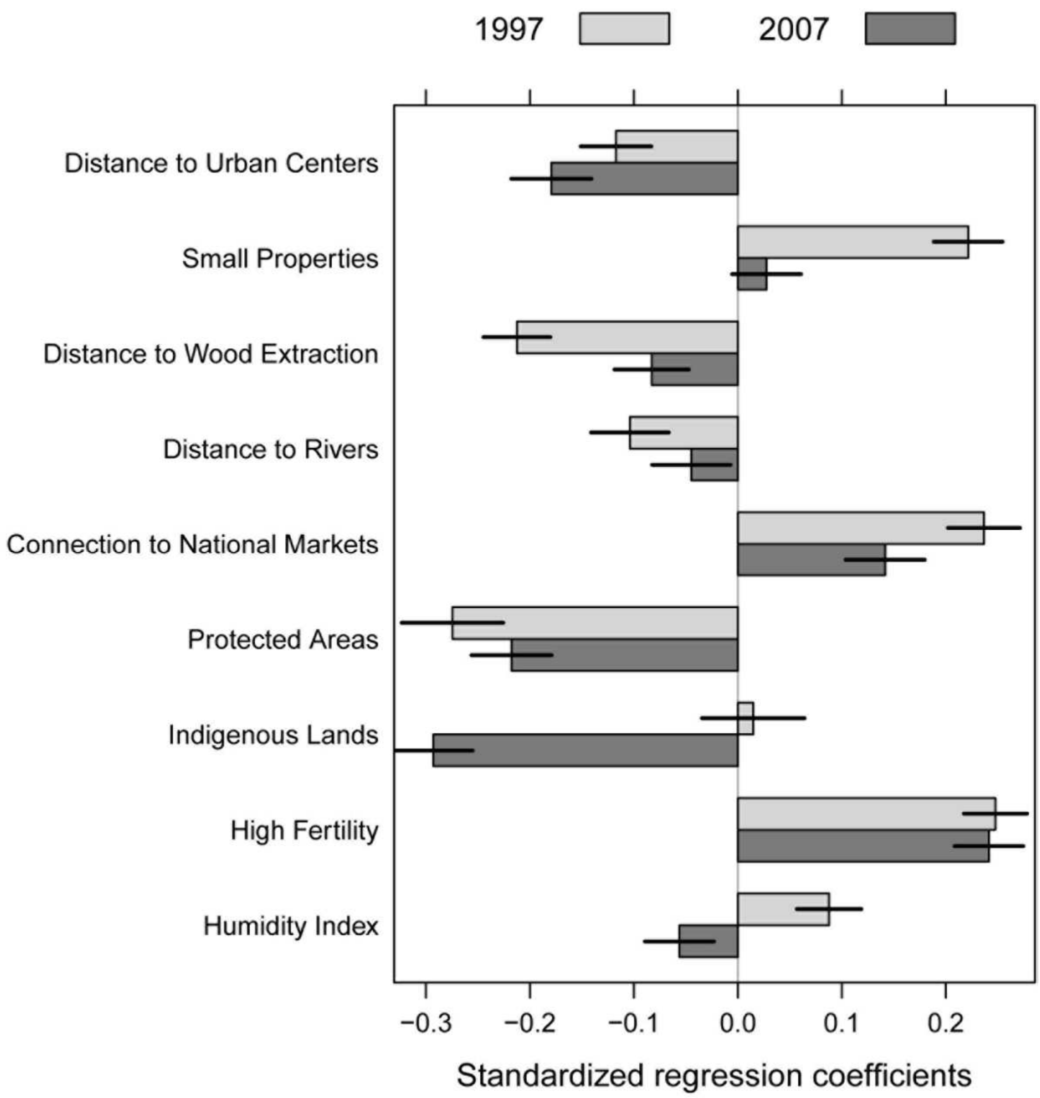


Figure 2.10 – Standardized regression coefficients for temporary agriculture, and for the *urban centers and agrarian structure* models of 1996/1997 and 2006/2007, approximate 95% confidence intervals are computed by +/- 2 standard errors.

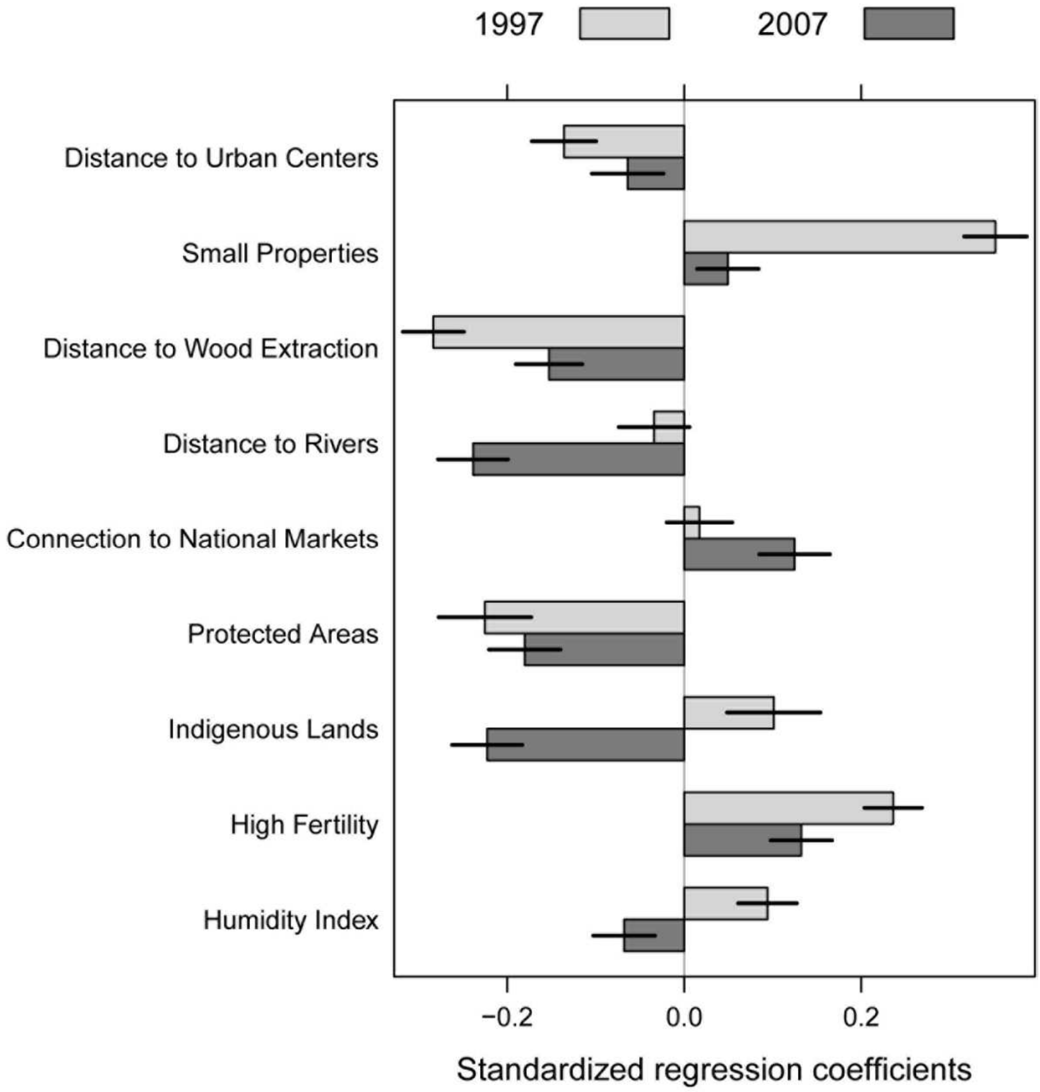


Figure 2.11 – Standardized regression coefficients for permanent agriculture, and for the *urban centers and agrarian structure* models of 1996/1997 and 2006/2007, approximate 95% confidence intervals are computed by +/- 2 standard errors.

Table 2.5 – Spatial lag regression models for log-transformed land uses determinant factors.

Lag Regression					
1996/1997			**2006/2007**		
Pasture - Roads and Settlements					
Variable	***Beta***	**Std. Error**	**Variable**	***Beta***	**Std. Error**
R-squared:	**0.854**		**R-squared:**	**0.857**	
W Pasture 1997	0.807	0.012	W Pasture 2007	0.770	0.014
Distance to Roads	-0.111	0.010	Distance to Roads	-0.073	0.010
Number of Settled Families	0.008	0.009	Number of Settled Families	0.058	0.009
Distance to Wood Extraction	-0.029	0.009	Distance to Wood Extraction	-0.017	0.009
Distance to Rivers	0.025	0.010	Distance to Rivers	0.012	0.010
Connection to National Markets	0.054	0.010	Connection to National Markets	0.037	0.010
Protected Areas	-0.104	0.014	Protected Areas	-0.107	0.011
Indigenous Lands	-0.024	0.014	Indigenous Lands	-0.136	0.011
High Fertility	0.022	0.009	High Fertility	0.018	0.008
Humidity Index	0.046	0.009	Humidity Index	0.062	0.009
Temporary Agriculture - Urban Centers and Agrarian Structure					
Variable	***Beta***	**Std. Error**	**Variable**	***Beta***	**Std. Error**
R-squared:	**0.814**		**R-squared:**	**0.816**	
W Temporary Agriculture 1997	0.831	0.013	W Temporary Agriculture 2007	0.813	0.013
Distance to Urban Centers	-0.020	0.011	Distance to Urban Centers	-0.090	0.013
Small Properties	0.071	0.011	Small Properties	0.026	0.010
Distance to Wood Extraction	-0.054	0.011	Distance to Wood Extraction	0.003	0.011
Distance to Rivers	-0.005	0.012	Distance to Rivers	-0.029	0.011
Connection to National Markets	0.042	0.011	Connection to National Markets	0.009	0.011

Protected Areas	-0.100	0.016	Protected Areas	-0.080	0.012
Indigenous Lands	0.004	0.015	Indigenous Lands	-0.092	0.011
High Fertility	0.043	0.010	High Fertility	0.029	0.010
Humidity Index	0.026	0.010	Humidity Index	0.023	0.010
Permanent Agriculture - Urban Centers and Agrarian Structure					
Variable	***Beta***	**Std. Error**	**Variable**	***Beta***	**Std. Error**
R-squared:	**0.838**		**R-squared:**	**0.839**	
W Permanent Agriculture 1997	0.871	0.011	W Permanent Agriculture 2007	0.886	0.010
Distance to Urban Centers	-0.026	0.010	Distance to Urban Centers	-0.068	0.012
Small Properties	0.079	0.010	Small Properties	0.020	0.009
Distance to Wood Extraction	-0.051	0.010	Distance to Wood Extraction	-0.005	0.011
Distance to Rivers	0.013	0.011	Distance to Rivers	-0.009	0.010
Connection to National Markets	0.005	0.010	Connection to National Markets	-0.024	0.010
Protected Areas	-0.083	0.014	Protected Areas	-0.056	0.011
Indigenous Lands	0.024	0.014	Indigenous Lands	-0.053	0.010
High Fertility	0.026	0.009	High Fertility	0.013	0.009
Humidity Index	0.024	0.009	Humidity Index	0.018	0.009

2.4. Discussion and Conclusions

Although the maps in Figures 2.6, 2.7 and 2.8 show an overall increase in agricultural area, some areas with agricultural activity expanded rapidly over the 1997-2007 period, while others showed little or no growth in agricultural activity. Pasture intensified and spread across eastern Pará, central Rondônia, and the north of Mato Grosso. The influence of temporary agriculture decreased in those regions, and increased in central Mato Grosso. Permanent agriculture remained unchanged, but decreased in Rondônia. Eastern Pará and central Rondônia experienced a large increase in pasture and a decrease in the area of land under crops. The results are consistent with observations that in areas of pioneer occupation much cropland is converted into pasture, and in areas of recent frontier much forest is converted into pasture (Leite, Costa et al. 2010).

The census data revealed that pasture was the most common land use in the Brazilian Amazon, and that the conversion of newly deforested areas to pasture increased from 70% in 1997 to 80% in 2007. Of the three states investigated, Pará had the greatest intensification of pasture, increasing from 58,249 sq km in 1996 to 90,433 sq km in 2006 (IBGE 1996; IBGE 2006). Some factors help to explain the continued predominance of pasture in land use changes in the Brazilian Amazon. For example, the expansion of the cattle herd shows that extensive cattle ranching is profitable in parts of the Brazilian Amazon (Margulis 2004). Also, higher stocking rates are more common found in most deforested areas, which suggests an intensification of pasture use (Alves, Morton et al. 2009).

In Mato Grosso the area under temporary agriculture increased from 27,824 sq km in 1996 to 57,344 sq km in 2006 (IBGE 1996; IBGE 2006). The forest conversion to cropland in Mato Grosso is of particular interest because of the state's specific socio-demographic, economic, and bioclimatic conditions, which increase the probability that a different land use system will be established. Such growth in croplands is due to massive investments by commercial soybean farmers as well as to the success of farming systems and crop breeding research. Despite that, the main driver of forest loss in that state is large-scale cattle farming, even though the direct conversion of forest to cropland contributed substantially to the number of large deforested areas. The deforestation in Mato Grosso is much more mechanized than in the other two states. This mechanization makes it more likely that forest will be cleared and accelerates the deforestation.

With regard to the spatial dependence of our determinant variables, we know that land use tends to be spatially correlated, i.e. that land use change in one area tends to be correlated with that in adjacent or nearby areas. In this chapter, we interpreted the differences between standardized regression coefficients for 1996/1997 and 2006/2007 as temporal changes in the influence of factors on deforestation and agricultural uses. A more detailed study should be done to find out to what extent this change can be attributed to temporal changes in dependent or independent variables, or both. In our study we made a number of simplifying assumptions, including: (i) a linear response between dependent (log cells proportion of deforestation or agricultural land uses) and the independent (partly log-transformed) factors; (ii) absence of interactions between the factors and dependent variable; (iii) absence of temporal correlation between the dependent variables for 1997 and 2007; and (iv) independent and identically distributed regression residuals. As our data were not derived from a controlled experiment, the results –notably the linear regression coefficients and their confidence intervals – should be interpreted with care, and be seen as an approximation. Using spatial lag regression modeling as an extension to linear regression is a first step towards exploring spatiotemporal data more thoroughly by regression modeling.

In this chapter we integrated information from agriculture censuses with satellite data to provide additional information. This combination enabled us to analyze the spatial patterns of deforestation and agricultural uses within the Brazilian Amazon. We have shown that the extent and the rates of land use changes among the three states studied are largely driven by a set of conditions. Our mapped land uses time series and regression models show the distribution and proportion of major agricultural land uses, and also how these are influenced by several potential determinant factors.

3. SPATIOTEMPORAL VARIABILITY OF DEFORESTATION IN THE BRAZILIAN AMAZON: WHICH FACTORS ARE RESPONSIBLE FOR DECREASING THE RATES?[4]

Abstract

Deforestation in the Brazilian Amazon has sharply decreased over the past years. Although the Brazilian government claims that the decrease is a result of enforcement efforts and monitoring initiatives, the influence of such initiatives over a long period of time has not been analyzed in depth. To better determine the predominant trends and critical factors of deforestation across the region, it is essential to have an understanding of the history of national environmental policies and market pressures which would favor or restrict deforestation. Thus, the present study addresses those trends by analyzing the spatiotemporal variability of deforestation using Landsat TM-based maps for 2002-2009. Our ultimate goal is to analyze the effects of national environmental policies applied by the Brazilian government compared to the influence of the market. A number of potential determinant factors driving deforestation were examined using spatial multiple regression models that incorporate autocorrelation components in space and time. The yearly proportion of deforestation computed for each cell of a regular grid of 25 km x 25 km and a set of human-induced predictors, some of which were related to national environmental policies, were considered. We analyzed the deforestation trends for the entire period of time (2002-2009) and separately for the time period when the deforestation rates were increasing (2002-2004) or decreasing (2005-2009). Our analysis empirically demonstrates that the variability of deforestation was influenced by both policy and market factors. Additionally, we show that these influences have been changing over the years.

[4]This chapter is the updated version of the paper co-authored with Pebesma, E., Câmara, G., de Aguiar, A.P.D., Fonseca, L., in preparation to be submitted to the journal Global Environmental Change.

3.1. Introduction

The Brazilian Amazon region appears to be an environment that is undergoing major changes due to climate change and human activities. In recent decades, the region has undergone marked variability in deforestation[5], and after a long period of increase, the deforestation rates have sharply decreased over the past years (INPE 2011). Shortly after the announcement that global carbon dioxide emissions from deforestation and other land use change were 0.9±0.7 PgC in 2010, leading to total emissions (including fossil fuel and land use change) of 10.0±0.9 PgC (Peters, Marland et al. 2012), the Brazilian government announced that the deforestation rates in the Brazilian Amazon fell by 38.2 percent compared to 2010 and 67.1 percent compared to 2009 rates (INPE 2011). In 2010, the deforestation rates in the Brazilian Amazon reached the lowest rates ever recorded for the second consecutive year, totaling 7,000 sq km of forest removed, which represents a record-breaking decrease in rates since the monitoring began in 1988. Although the Brazilian government claims that this recent decrease is the result of enforcement efforts and monitoring initiatives, the influence of such initiatives over a long period of time has not been analyzed in depth.

The growing debate regarding the extent to which deforestation is a result of cultural-institutional, socio-demographic, environmental and economic factors, has garnered considerable research focused on modeling and explaining the underlying causes and consequences of deforestation across the region (Achard, Eva et al. 2002; Alves 2002; Cardille and Foley 2003; Laurance, Albernaz et al. 2004; Câmara, Aguiar et al. 2005; Aguiar 2006; Soares-Filho, Nepstad et al. 2006; Alves 2007; Chambers, Asner et al. 2007; Alves, Morton et al. 2009; Nepstad, Soares-Filho et al. 2009). In summary, deforestation in the Brazilian Amazon has expanded since the government began to promote the occupation of the region in the late 1960s, and since the late 1970s, Brazil has enacted national environmental policies against deforestation. Recently, in 2008, the Brazilian government adopted the National Plan on Climate Change – NPCC (Brazil 2008), which defined the goal of an 80% reduction in the deforestation rates by the year 2020. In 2004, prior to the NPCC, the government launched an action plan called

[5]In this study, we use the term "deforestation" to describe the situations of complete removal of tree cover (clear cut).

PPCDAM (acronym in Portuguese) (Brazil 2004) that focused on the prevention and control of deforestation by considering three thematic areas: land and territorial organization; monitoring and control; and incentives for sustainable productive activities. Since then, Brazil has expanded the network of protected areas in the Amazon from 1.26 to 1.82 million sq km, in response to the land and territorial organization thematic area. In addition, the observed results were also obtained by monitoring and control, namely by the implementation of the Brazilian satellite monitoring programs, aimed at quantifying deforestation and providing the basis for combating and preventing illegal deforestation. For example, the combat and prevention of deforestation by applying environmental fines enhanced the presence of the Brazilian Environmental Police – IBAMA (acronym in Portuguese) in high pressure areas, which has also been effective in reducing deforestation. Still, in 2008, municipalities responsible for half of the deforestation in the 2004-2007 period were the focus of another national action to register properties, advertise illegal holdings, cancel lines of credit for illegal landholders, and pressure buyers of Amazonian products (Nepstad, Soares-Filho et al. 2009; Lambin and Meyfroidt 2011).

From another perspective, the most recent analyses suggest that economic globalization and increasing global food demand also accelerate forest conversion in high potential areas (Lambin and Meyfroidt 2011). In the Brazilian Amazon, there is evidence that deforestation is driven by market arrangements that include legal and illegal market chains, and even more recently, by the requirement to certify timber (although timber is still a limited export commodity in Brazil), beef, and soybean products that have been imposed by market chain consumers (Malingreau, Eva et al. 2011; Rudorff, Adami et al. 2011). Moreover, the international demand for agricultural products appears to influence the rates of deforestation once investments in infrastructure related to the national markets have integrated into the region. For example, from 1995 to 2008, meat exports from Brazil grew from 7.2% to 25% of the national production (IBGE 2006), and the Brazilian Amazon accounted for 84% of the growth of the Brazilian cattle herd during this period. Soybean production also influenced the expansion of deforestation directly and indirectly (Morton, DeFries et al. 2009; Arima, Richards et al. 2011).

Usually, the interplay between the two apparently antagonistic driving factors of land use change, i.e., the actions to reduce deforestation and the growing of market pressure, has not been included in land use change modeling frameworks. In general, assessments of the factors associated with land use change in the Brazilian Amazon have, thus far, mostly used econometric models and grid-based models for a fixed time step baseline. Using a non-spatial and region-wide level econometric analysis, Reis and Guzmán (1992) found that the most important factors of change in the region were *population density*, *road network density* and *extension of cultivated areas*. Andersen and Reis (1997) also used an econometric model. They found that 11 factors were responsible for the land use change in the Brazilian Amazon from 1975 to 1995, including *distance to the federal capital*, *earlier deforestation in area*, *rural population density*, *land prices* and *size of cattle herd*. Pfaff (1996) focused on the period from 1978 to 1988 and analyzed the relevance of biophysical variables (*soil quality* and *vegetation type*), transport-related variables (*road network*, *density in the area* and *its neighbors*) and government-related variables (*development policies*). Margulis (2004), however, presented an econometric model for analyzing the occupation of the Brazilian Amazon, quantifying the spatial and temporal relationships of the main agricultural activities (*timber extraction*, *pasture* and *crops*). Based on grid models, Perz and Skole (2003) developed a spatial regression model for secondary vegetation in the Amazon Basin and showed that determinant factors have significant spatial variation among different regions. Laurance et al. (2002) performed statistical analyses to assess the relative importance of determinant factors. They found that the three most important factors were *population density*, *distance to roads*, and *dry season duration*. The results reported by Soares-Filho et al. (2006) indicate that the most important factors for predicting the location of deforestation in the Amazon Basin are *proximity to roads*, *indigenous reserves* and *proximity to urban centers*. More recently, Soares-Filho et al. (2010) showed that *indigenous lands*, *strictly protected areas* and *areas of sustainable use* inhibited deforestation between 1997 and 2008. Finally, Aguiar et al. (2007) and de Espindola et al. (2012) used spatial regression models for comparing the determinant factors of deforestation and the major agricultural land uses – pasture, temporary agriculture and permanent agriculture – for 25 km x 25 km grid cells covering most of the Brazilian Amazon.

Based on these studies, the present chapter aims to analyze the variability over space and time of yearly deforestation (annual increments of deforestation) across the Brazilian Amazon region from 2002 to 2009. Our ultimate goal is to analyze the effects of national environmental policies applied by the Brazilian government compared to the influence of the market. We developed linear and spatial multiple regression models for a set of potential determining factors driving deforestation. This was accomplished by considering the yearly proportion of deforestation computed for each cell of a regular grid of 25 km x 25 km and a set of human-induced predictors, including the national environmental policies conducted by the Brazilian government and market price variations for soybean and meat, amongst other predictors. We analyzed the deforestation trends for the entire period of time (2002-2009) and separately for the time period when the deforestation rates were increasing (2002-2004) or decreasing (2005-2009).

In this study, we considered the creation of protected areas and the application of environmental fines over space and time as human-induced predictors of our statistical models related to the national environmental policies, and the fluctuation of commodity prices (soybean and meat) and the variability of areas with planted commodities (soybean and sugarcane) as proxies for market pressure related to global food demand aspects and the resulting growing demand for agricultural land, respectively.

This chapter is organized as follows: Section 2 presents the data and methods used, and Section 3 presents the results and discussion. We conclude with a major discussion in which we consider the causes of deforestation trends in the region and summarize the main findings.

3.2. Material and Methods

3.2.1 Study area and spatial resolution

The study area was the Legal Brazilian Amazon region, which covers in total more than 5 million sq km. For our analyses, all variables representing yearly deforestation and potential determinant factors (external predictor variables) were aggregated to grid cells of 25 km x 25 km (Figure 3.1). We used the Landsat TM-based 2002-2009 deforestation maps produced under the Amazon monitoring program of the Brazilian National Institute for Space Research (INPE 2011). The yearly (annual increments) proportion of deforestation from 2002 to 2009 was computed for each grid cell. Cells with a large proportion (>20%) of cloud cover, non-forest vegetation, water, or cells outside the Brazilian Amazon were omitted from our statistical analyses. The cells omitted due to cloud cover accounted for less than 5% of the number of cells covering the study area. We finally selected 4,994 cells for the entire region (Figure 3.2). Figure 3.2 shows that from 2002 to 2009, yearly deforestation was slightly altered in location and intensity across the region.

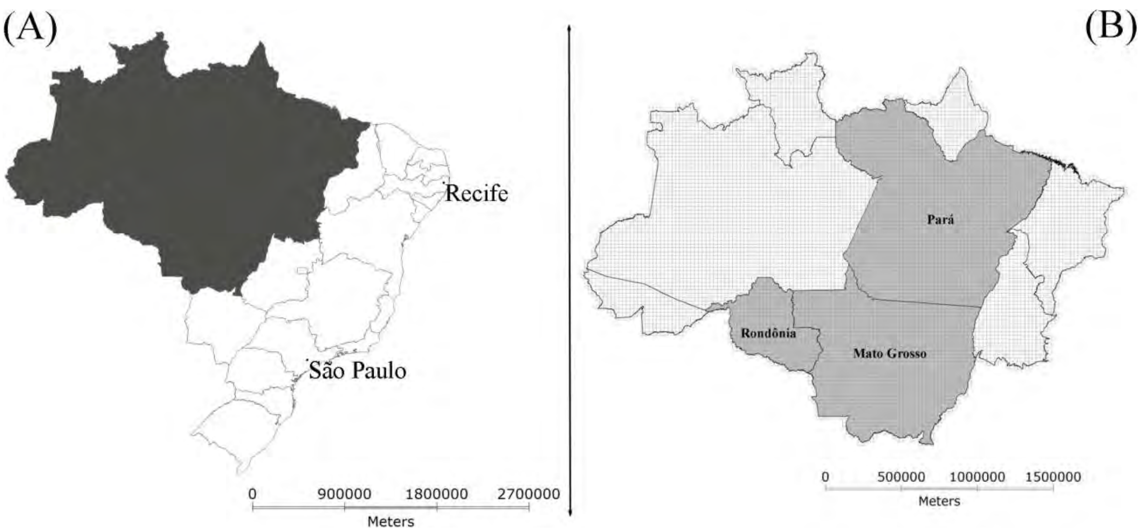


Figure 3.1 – (A) Map of Brazil showing the location of the Brazilian Amazon region (all in darker gray), and the location of São Paulo and Recife cities. (B) Regular grid of 25 km x 25 km over the Brazilian Amazon region; the states of Pará, Rondônia and Mato Grosso are shown in gray.

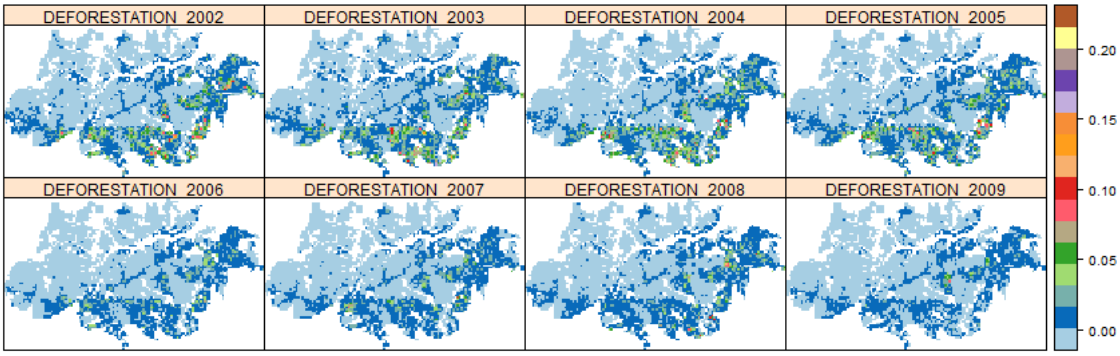


Figure 3.2 – Maps with proportion of deforestation for each year from 2002 to 2009.

3.2.2 Potential determinant factors

The dependent variable was yearly deforestation from 2002 to 2009 for 25 km x 25 km grid cells (Figure 3.2). We analyzed the deforestation for the entire period of time (2002-2009) and separately for the time period when the deforestation rates were increasing (2002-2004) or decreasing (2005-2009). The variability of deforestation during these periods was explained by (i) an autocorrelation effect in space, in time or in space-time and by (ii) external potential determining factors (external predictor variables). For each year from 2002 to 2009, external predictors included 20 variables (Appendix 2A) that were grouped into three main categories: space (S), time (T) and space-time (ST), meaning that some predictor variables varied only over space (S), some varied only over time (T), and some varied over space and time (ST). According to Aguiar, et al. (2007) and de Espindola et al. (2012), these variables could potentially explain the variability of deforestation at a regional level during these periods. Although some of the space and space-time variables were only available at the spatial level of municipality units, all of them were converted from polygon-based information to grid cells of 25 km x 25 km (de Espindola, de Aguiar et al. 2012). Appendix 2A contains maps and figures of the external predictors used in our statistical analyses.

To summarize, Table 2.1 shows the resulting subset of external predictor variables from 2002 to 2009, which were found after running an exploratory analyses to select those predictor variables. We found a degree of correlation among pairs of independent variables that were previously selected, and we made our decision based on the highest correlation between dependent and independent variables. An exploratory analysis also showed that some of the relationships between the dependent and independent variables were not linear. We applied a logarithmic transformation to all of the dependent variables (yearly deforestation over time) and to some independent variables. Table 2.1 shows these variables annotated with '*log10*' (de Espindola, de Aguiar et al. 2012).

Spatial predictors (S) included Euclidean *distance to roads, distance to urban centers* and *distance to rivers,* and all of them were considered invariant over time. The *Distance to Roads* variable, for example, measures the Euclidean distance from each cell to the nearest paved or non-paved road in 2006. Euclidean *distance to roads* and *distance to urban centers* were considered proxies for the accessibility to local markets and basic services. Following IBGE (2011), *urban centers* were defined as places with a cluster of permanent residents. On the other hand, measures of the accessibility to national markets included the *connection to ports* and markets in 2006. We also recognized *connection to São Paulo* and *connection to national markets* (São Paulo and Recife, see Figure 3.1). For our analyses we computed connectivity indicators for each cell, measuring the minimum path distance through the road network from each cell to ports and markets. As described by Aguiar (2006), we distinguished paved from non-paved roads using the *generalized proximity matrix* (GPM).

Temporal predictors (T) included *price of soybean* and *price of meat*. We selected both of these variables due to the prediction that deforestation during the period might be driven, to some extent, by fluctuations in soybean and meat prices (commodity prices). We assumed these variables as a proxy for market pressure related to global food demand aspects and the resulting growing demand for agricultural land. The fluctuations of soybean and meat prices were expressed in Brazilian currency (R$). Soybean prices were obtained from monthly average prices and reflect the amount that farmers received for a 60 kg bag of soybeans, while meat prices were obtained from monthly average prices that ranchers received for 15 kg of cattle (IPEA 2008).

Spatiotemporal predictors (ST) included both the *protected areas* and *change in protected areas* variables. The *protected areas* variable reflected the percentage of each cell that was covered by (or intersects with) the polygons of these areas, while the *change in protected areas* variable reflected the difference in percentage for each cell over each pair of consecutive years. The third variable, related to national control policies, was the *number of environmental fines,* which was computed by taking the average of this value in each municipality and weighted by the area intersection between the municipality and the grid cell. Additionally, the *value of environmental fines* was computed in the same way, and both *change in number of environmental fines* and *change in value of environmental fines* were considered, due to their differences over each pair of consecutive years. The data on municipal environmental fines from IBAMA has not been used thus far in spatial multiple regression models. Some of these data were recently launched and difficult to access, though theoretically, they should be readily available to the public. Spatiotemporal predictors (ST) also included four variables related to market arrangements, including *planted soybean area* and *planted sugarcane area*. Both of these variables were computed from the value in each municipality weighted by the area intersection between the municipality and the grid cell; changes in both variables over each pair of consecutive years were also considered. Finally, we included the municipal *total population* and municipal amount of *total exports* per year from 2002 to 2009.

Table 1 – External predictor variables from 2002 to 2009.

Subset of External Predictor Variables												
Category	**Variable**	**Description**	**Time**								**Unit**	**Source**
			2002	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**		
Land Use	Deforestation	Yearly deforestation (log10)									% Area	INPE
Space (S)	Distance to Roads	Euclidean distance to roads in 2006 (log10)	Invariant								Km	IBGE
	Distance to Urban Centers	Euclidean distance to urban centers in 2006 (log10)	Invariant								Km	IBGE
	Distance to Rivers	Euclidean distance to large rivers (log10)	Invariant								Km	IBGE
	Connection to Ports	Indicator of strength of connection to ports through roads network in 2006	Invariant								-	IBGE
	Connection to São Paulo	Indicator of strength of connection to São Paulo through roads network in 2006	Invariant								-	IBGE
	Connection to National Markets	Indicator of strength of connection to national markets (São Paulo and Recife) through roads network in 2006	Invariant								-	IBGE
Time (T)	Price of Soybean	Yearly fluctuation of national annual soybean price									R$	FGV
	Price of Meat	Yearly fluctuation of national annual meat price									R$	IPEA
Space-Time (ST)	Protected Areas	Protected areas (log10)									% Area	MMA
	Change in Protected Areas	Change in protected areas (log10)									% Area	MMA
	Number of Environmental Fines	Number of environmental fines (log10)									Number	IBAMA
	Change in Number of Environmental Fines	Change in number of environmental fines (log10)									Number	IBAMA
	Value of Environmental Fines	Value of environmental fines (log10)									Value	IBAMA

	Change in Value of Environmental Fines	Change in value of environmental fines (log10)									Value	IBAMA
	Area of Planted Soybean	Area of planted soybean (log10)									% Area	IBGE
	Change in Area of Planted Soybean	Change in area of planted soybean (log10)									% Area	IBGE
	Area of Planted Sugarcane	Area of planted sugarcane (log10)									% Area	IBGE
	Change in Area of Planted Sugarcane	Change in area of planted sugarcane (log10)									% Area	IBGE
	Total Population	Total population (log10)									Average	IBGE
	Total Exports	Total exports (log10)									Average	IBGE

3.2.3 Regression modeling

Regression modeling approximates a dependent variable with n observations $y = (y_1, \ldots, y_n)'$ to a set of p independent variables $x_j = (x_{1j}, \ldots, x_{nj})'$ by the linear function,

$$y = \sum_{j=1}^{p} \beta_j \cdot x_j + e = X\beta + e$$

, where X is the design matrix that has x_{ij} on row i and column j. The regression coefficient vector β is typically estimated by minimizing the residual sum of squares, $e'e$.

Simultaneous autoregression (SAR) models (Cressie and Wikle 2011) define the residual process $y - X\beta$ to follow an autoregressive process, i.e., $Y - X\beta = B(Y - X\beta) + v$

, which can be rewritten as

$$Y = X\beta + (I - B)^{-1} v \quad (1)$$

, where v follows a zero-mean normal distribution with a covariance matrix $\sigma^2 I$ (i.e., is independent), and B defines residuals that are correlated and to what degree they are correlated. Typically, B is sparse, and $B_{ii} = 0$. Non-zero values B_{ij} occur only when Y_i and Y_j are *neighbors*. Additionally, we assume that the non-zero values of B have a single value, which is the parameter that describes the degree of autocorrelation. This value is called λ for any non-zero B_{ij}, cells i and j are neighbors and $B_{ij} = \lambda$. To define spatial neighbors, we used the *queen neighbors*, corresponding to the 8 cells adjacent to each grid cell, or less in the case of boundary cells or missing value (or masked) pixels in the neighborhood.

For a spatiotemporal regression model, we denote $y_{[t]} = (y_{1,t}, \ldots, y_{n,t})$ as the observation in grid cell i and time step $t \in \{1, \ldots, m\}$. As a first step from purely spatial SAR models towards spatiotemporal SAR models, in addition to the spatial autoregressive effect of the residuals, we can incorporate a temporally lagged

observation $y_{[t-1]}$ into the regression, as in
$$y_{[t]} = X\beta + \gamma y_{[t-1]} + (I - B)^{-1}\nu, \qquad t = 2, \dots, m, \quad (2)$$
where B only addresses spatial neighbors. We call this ***Model 2***, given that ***Model 1*** is a simple linear regression model. In the second approach, the SAR model (1) is specified for all time steps, but the B matrix not only addresses spatial neighbors $y_{i,t}$ and $y_{j,t}$ with $i \neq j$ but also the two temporal neighbors of $y_{i,t}$, $y_{i,t-1}$ and $y_{i,t-1}$. A simplifying assumption here is that a simple autocorrelation coefficient describes the correlation both in space and time. We call this ***Model 3***. In the third approach, ***Model 4*** extends ***Model 3*** with spatiotemporal neighbors, i.e., observations $y_{i,t}$ and $y_{i,t-1}$ are correlated when grid cells i and j are neighbors. Again, a single correlation coefficient is fitted to describe correlations between all (spatial, temporal, and spatiotemporal) neighbors. Figure 3.3 shows the different neighbors defined in Models 2, 3 and 4.

The statistical analyses were performed using R, a language and environment for statistical computing and graphics (R-Team 2005). We used ordinary linear and SAR models to establish the relative importance of the determinant factors for yearly deforestation for the entire period of time (2002-2009), and separately for the time period when the deforestation rates were increasing (2002-2004) or decreasing (2005-2009). The linear regression analyses were performed to model the relationship between the dependent and independent variables, and SAR regression analyses were performed to model the autocorrelation of the dependent variables in space and time. For deforestation data, the assumption underlying ordinary linear regression that observations are independent does not hold, because neighboring deforestation observations are typically spatially and temporally correlated. Unlike de Espindola et al. (2012) who used only spatial lag SAR models, we preferred to use both lag and error models. Despite showing only the results of the spatial error SAR models in detail, we will comment the main differences between them. Here, we preferred the error SAR models, especially because the lag models only take into account the endogenous spatially lagged dependent variable.

Regressions were carried out with the R functions *spautolm* and *lagsarlm* from the R package spdep (Bivand, Pebesma et al. 2008). The first function provides a maximum likelihood estimation of β and λ, but does not simultaneously estimate β, λ and γ using maximum likelihood. One solution to this would be to define neighbors in space and time. In order for this to constitute a viable method, this definition must be combined with a weighting factor that defines how neighboring in space compares to neighboring in time, in terms of weights. The solution chosen here was to add the temporal factor to the fixed effects $X\beta$, effectively leading to a more least squares-oriented solution. Although the error models appeared to fit the data somewhat better than the lag models, we also obtained values for the *lagsarlm* and associated impacts with standard errors and p values.

To compare the performance of different error SAR models considering types of neighbors (Figure 3.3) and periods of time (2002-2009, 2002-2004 and 2005-2009), the R-squared value (coefficient of determination), λ (Lambda) and σ^2 (Sigma squared) was used. For Models 2, 3 and 4, the equivalent *Nagelkerke R-squared* was computed. To compare the relative importance of each determinant factor in each model we will present the standardized regression coefficients (*Beta*) and the corresponding standard error for each variable.

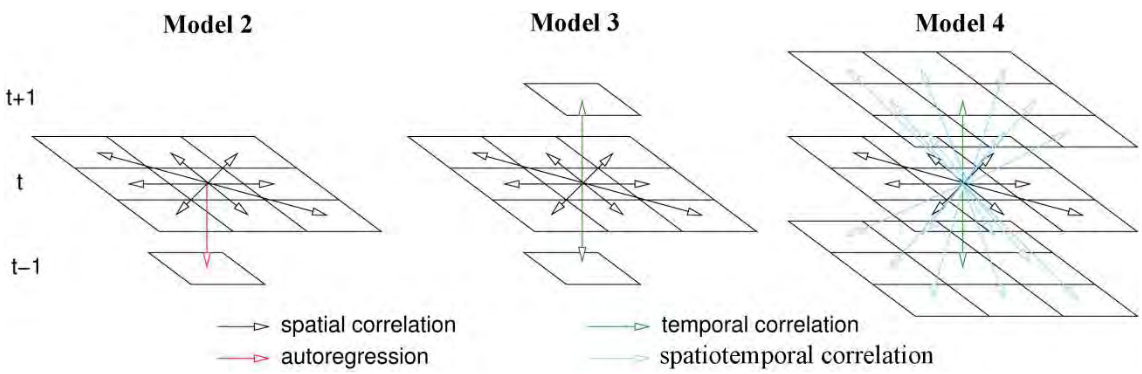


Figure 3.3 – Neighbors addressed for Models 2, 3 and 4.

3. Results and Discussion

This section summarizes the main findings and compares the results obtained from our four regression error SAR models processed for the full period (A) and two sub-periods

(B, C) of analysis: (A) comprises 2002-2009, which represents the entire period of analysis; (B) comprises 2002-2004, which represents the time period when the deforestation rates were increasing; and (C) comprises 2005-2009, which represents the time period when the deforestation rates were decreasing. The comparison showed how yearly deforestation was impacted by external predictors and neighbor cells over space and time. Maps of yearly deforestation for the 2002-2009 period are shown in Figure 3.2. The explanatory variables are addressed for each grid cell and time step t, defined in Section 3.2.2. Each of the regression models (Section 3.2.3) were computed for the full set of predictors. Table 3.2 lists the regression coefficients for those variables that were found to be significant for at least one of the three models at the $\alpha = 0.1$ level for 2002-2009 (A). On the other hand, Table 3.3 and Table 3.4 list the regression coefficients for 2002-2004 (B) and 2005-2009 (C), respectively. From these results it can be seen that a fair number of predictors are significant, and have similar standardized regression coefficient values for each of the three error SAR models, considering different neighbors. It is also clear from the λ values and the autoregression coefficient for *Deforestation (t-1)* that autocorrelation in space and time is different. This was ignored for Model 3 and Model 4, where a single λ value was fitted. For the three periods of analysis, ***Model 1*** (ordinary linear regression model) found significance in most of the variables, and the R-squared values performed better in the 2002-2004 period (0.76) than in 2002-2009 (0.72) and 2005-2009 (0.72). The significance values are based on the assumption of uncorrelated observations, which is highly unrealistic.

Model 2 included one additional variable *Deforestation (t-1)*, which indicates the degree to which the dependent variable is spatially autocorrelated (0.65, 0.63 and 0.67 for periods A, B and C, respectively). The *Nagelkerke R-squared* values of these SAR models were significant, and in the three periods of analysis, they were higher than 0.80 (see Tables 3.2, 3.3 and 3.4). This is the quantitative evidence that corroborates earlier assessments, which indicated that the regional pattern of deforestation is a diffusive process, and tends to occur close to previously cleared areas (Alves 2002). As expected, when the SAR models are used, fewer and different variables were found to be significant. As shown in Figure 3.4, when the entire period (A) is considered, spatial predictors (S), such as *distance to roads*, *connection to ports*, *connection to São Paulo* and *connection to national markets*, were found to be significant and had similar *Beta* values (magnitude and direction) as the ones found by de Espindola et al. (2012), except for the *connection to national markets* variable, which was found to be positive in this early assessment. Similar results were found for the period when the deforestation rates were increasing (B), except for the *connection to national markets* variable that was not found to be significant for this time period. For the period when the deforestation rates were decreasing (C), *connection to ports*, *connection to São Paulo* and *connection to national markets* were found to be significant. Interestingly, purely temporal (temporal predictors) variables were found to be significant for time periods (B) and (C). For the 2002-2004 (B) time period, *price of meat* was negatively correlated with yearly deforestation. For the 2005-2009 (C) time period, *price of soybean* was negatively correlated with yearly deforestation and *price of meat* was positively correlated. Considering spatiotemporal predictors (ST), time period (A) had significant values for *protected areas*, *change in value of environmental fines*, *area of planted sugarcane* and *total exports*. For time period (B), *protected areas*, *change in protected areas* and *change in area of planted soybean* were found to be significant. For time period (C), *protected areas*, *number of environmental fines* and *total population* were significant.

In ***Model 3***, fewer variables were found to be significant for the three analyzed time periods. Despite that, the *Nagelkerke R-squared* values are significant and, in the three periods of analysis, they were higher than 0.73 (see Tables 3.2, 3.3 and 3.4). As shown in Figure 3.5, when period (A) is considered, spatial predictors (S), such as *distance to rivers*, *connection to ports*, *connection to São Paulo* and *connection to national markets*, were found to be significant and had similar *Beta* values (magnitude and direction) as the values obtained by de Espindola et al. (2012), except for the *connection to national markets* variable, which was found to be positive in this early assessment. We obtained similar results for time period (B), except for the *distance to roads* variable, which was found to be significant and positively correlated with yearly deforestation. For time period (C), we obtained similar results as for time period (B), except for the *connection to national markets* variable, which was not found to be significant here. Again, purely temporal variables were found to be significant for time periods (B) and (C). For the 2002-2004 (B) time period, *price of soybeans* was positively correlated with yearly deforestation. For the 2005-2009 (C) time period, *price of soybeans* was negatively correlated with yearly deforestation, and *price of meat* was positively correlated. Considering spatiotemporal predictors (ST), time period (A) had significant variables, namely *protected areas* and *area of planted sugarcane*. For time period (B), *protected areas*, *area of planted soybean* and *change in area of planted sugarcane* were found to be significant. For time period (C), we obtained similar results as for time period (B).

We obtained more significant variables in ***Model 4***, however, the *Nagelkerke R-squared* values in the three time periods of analysis were lower than the ones obtained from Model 3. Despite that, the *Nagelkerke R-squared* values here were higher than 0.68 (see Tables 3.2, 3.3 and 3.4). As shown in Figure 3.6, when period (A) was considered, the spatial predictors (S) that were found to be significant were the same ones (magnitude and direction) obtained in Model 3. For time period (B), *distance to roads*, *distance to urban centers*, *distance to rivers*, *connection to ports*, *connection to São Paulo* and *connection to national markets* were found to be significant. For time period (C), we obtained the same variables, except for *distance to urban centers,* which was not found to be significant in this time period. For the purely temporal variables, we obtained similar results (magnitude and direction) as in Model 3. Finally, considering the spatiotemporal predictors (ST), *protected areas*, *change in value of environmental fines* and *area of planted sugarcane* were the significant variables obtained in time period (A). For time period (B), *protected areas*, *number of environmental fines*, *area of planted soybean* and *change in area of planted soybean* were found to be significant. For time period (C), *protected areas*, *change in protected areas*, *number of environmental fines*, *value of environmental fines*, *area of planted soybean*, *change in area of planted soybean* and *change in area of planted sugarcane* were found to be significant.

According to the results, it seems that there is significant spatial correlation in the residuals because the estimated value of λ is always higher than 0.720, being closer to 1 for Models 3 and 4. In the likelihood ratio test, we compare the model with no spatial autocorrelation (i.e., $\lambda = 0$) to the one that allows for it. Comparing the results obtained from the error models and the lag models, the obtained coefficient values usually differed by a factor of less than 2-5. The significance of most of the values was reasonably comparable. However, the significances of the lag models are apparently not as relevant because of the spill-over effects. Thus, we also obtained the associated impacts for the lag models (LeSage and Pace 2009).

Generally speaking, we obtained the expected values for the spatial predictors (S). For the *connection to national markets* variable, for example, we obtained a negative correlation with yearly deforestation, most likely because the connection to Recife is not as relevant as is the connection to São Paulo. Although the investments in infrastructure had integrated the region with the international markets, our results show that the connection to the markets is much more relevant for explaining the deforestation than the distance to roads or rivers, for example. Previous studies tend to emphasize the distance to roads as the main factor determining deforestation (Laurance, Albernaz et al. 2004), but our results indicate that other variables were even more important. Moreover, the Brazilian government's plan *Avança Brasil*, in the first half of the 2000s to upgrade infrastructure in the Amazon region, was seen by these studies as a major threat to the region, with predictions of additional deforestation of 4,000 to 13,500 sq km per year, which appear not to have occurred so far (Carvalho, Barros et al. 2001; Carvalho, Moutinho et al. 2004; Soares-Filho, Nepstad et al. 2006).

In spite of finding significant correlations between the yearly deforestation and commodity prices (temporal predictors) for periods (B) and (C), we did not find them to be significant for the whole period (A). A rapid increase in soybean and meat process, accompanied by a steep rise in deforestation, was noted during the 2002-2004 period. However, this positive relationship does not hold for the following years. The prices fell back to 2002 prices in 2004, and then they started rising again in 2006 without impacting the decrease in the deforestation rates. Today, Brazil is one of the world's largest exporters of agricultural and food products, and it seems crucial to also understand the role of soybean and pasture expansion in deforestation. The greatest amount of deforestation during the 2002-2009 period occurred in the states of Pará, Rondônia, and Mato Grosso (Figure 3.2). Although de Espindola et al. (2012) had shown an overall increase in agricultural area, some areas with agricultural activity expanded rapidly over the 1997-2007 period, while others showed little or no growth. Pasture intensified and spread across eastern Pará, central Rondônia, and the north of Mato Grosso. The influence of temporary agriculture decreased in those regions and increased in central Mato Grosso. Permanent agriculture remained unchanged but decreased in Rondônia. Eastern Pará and central Rondônia experienced a large increase in pasture and a decrease in the area of land under crops. The results are consistent with the observations that in areas of pioneer occupation, much cropland is converted into pasture, and in areas of recent frontier, much forest is converted into pasture (Barona, Ramankutty et al. 2010; Leite, Costa et al. 2010).

It is interesting to see the impacts of the creation of protected areas (spatiotemporal predictors) as barriers to deforestation. From our results, it was clear that the creation of protected areas is of higher importance in period (C) than in period (B). Thus, land zoning represents an essential component of land use policies aimed at preserving natural forests, while enhancing food production. As a result, 54% of the Brazilian Amazon is now under some form of protection. On the other hand, the results of the environmental fines were not as relevant as expected. We believe that the nature of the data that was aggregated at a municipal level was not ideal for showing the significance of such actions. The application of fines is a local action with some strict national impact, although enforcement was put into place at various levels of administration. Clear cut, forest degradation and fires were closely monitored, and fines were levied for land clearing. Such enforcements and associated fines had an impact on deforestation with a growth of saved areas (avoided deforestation).

Finally, population was also a relevant aspect of deforestation because it has grown rapidly. The Brazilian Amazon is now populated by more than 25 million inhabitants (13% of Brazil's population), and has seen an urban growth rate five times that of the whole country over the last 20 years, with the proportion of the urban population (79%) now approaching the national average (82%) (IBGE 2011). The growth in population does not explain the deforestation by itself, but it is crucial to have a better understanding of the demographic aspects of deforestation given that the traditional forms of rural sustenance were replaced, in terms of economic importance, by the emergence of large peasant farming communities and the creation of pastures for cattle raising and soybean cultivation.

Table 3.2 – Standardized regression model coefficients for models processed for 2002-2009, and their significance (codes: $0 < {***} \leq 0.001 < {**} \leq 0.01 < {*} \leq 0.05 < . \leq 0.1$). *S* indicates purely spatial predictors, *T* purely temporal predictors, and *ST* spatiotemporal varying predictors.

Variable	**Category**	**Model 1**		**Model 2**		**Model 3**		**Model 4**	
Deforestation *(t-1)*	**ST**	**0.776**	***	**0.645**	***				
Distance to Roads	**S**	**-0.035**	***	**-0.010**	*	**0.012**	.	**0.013**	*
Distance to Urban Centers	**S**							**0.010**	.
Distance to Rivers	**S**	**0.011**	**			**-0.039**	***	**-0.040**	***
Connection to Ports	**S**	**0.011**	**	**0.021**	***	**0.071**	***	**0.065**	***
Connection to São Paulo	**S**	**0.022**	***	**0.090**	***	**0.161**	***	**0.135**	**
Connection to National Markets	**S**	**0.029**	***			**-0.129**	**	**-0.148**	**
Price of Soybean	**T**	**0.018**	***			**0.048**	***	**0.053**	***
Price of Meat	**T**	**-0.033**	***	**-0.044**	***				
Protected Areas	**ST**	**-0.016**	***	**-0.022**	***	**-0.041**	***	**-0.039**	***
Change in Protected Areas	**ST**	**-0.011**	***	**0.030**	**				
Number of Environmental Fines	**ST**	**0.082**	***					**0.031**	**
Change in Number of Environmental Fines	**ST**	**0.017**	***						
Value of Environmental Fines	**ST**	**-0.051**	***						
Change in Value of Environmental Fines	**ST**	**0.008**	***						
Area of Planted Soybean	**ST**	**-0.013**	***			**-0.024**	**	**-0.040**	***
Change in Area of Planted Soybean	**ST**	**0.031**	***	**0.010**	.			**0.008**	.
Area of Planted Sugarcane	**ST**	**-0.006**	.						
Change in Area of Planted Sugarcane	**ST**	**0.006**	.			**0.009**	*		
Total Population	**ST**	**-0.008**	.						
Total Exports	**ST**	**0.007**	.						

λ		0.720	0.962	0.969
σ^2		0.172	0.202	0.262
R^2/Nagelkerke R^2	**0.72**	**0.81**	**0.76**	**0.71**

Table 3.3 – Standardized regression model coefficients for models processed for 2002-2004, and their significance (codes: 0 < *** ≤ 0.001 < ** ≤ 0.01 < * ≤ 0.05 < . ≤ 0.1). *S* indicates purely spatial predictors, *T* purely temporal predictors, and *ST* spatiotemporal varying predictors.

Variable	**Category**	**Model 1**		**Model 2**		**Model 3**		**Model 4**	
Deforestation *(t-1)*	**ST**	**0.758**	***	**0.627**	***				
Distance to Roads	**S**	**-0.059**	***	**-0.024**	**				
Distance to Urban Centers	**S**	**-0.012**	.						
Distance to Rivers	**S**					**-0.038**	**	**-0.039**	**
Connection to Ports	**S**			**0.031**	**	**0.120**	***	**0.122**	***
Connection to São Paulo	**S**	**0.111**	***	**0.199**	***	**0.337**	***	**0.328**	***
Connection to National Markets	**S**	**-0.055**	***	**-0.083**	***	**-0.212**	**	**-0.229**	**
Price of Soybean	**T**	**-0.020**	***						
Price of Meat	**T**								
Protected Areas	**ST**			**-0.016**	*	**-0.026**	*	**-0.026**	*
Change in Protected Areas	**ST**								
Number of Environmental Fines	**ST**	**0.031**	*						
Change in Number of Environmental Fines	**ST**								
Value of Environmental Fines	**ST**								
Change in Value of Environmental Fines	**ST**	**0.026**	***	**0.012**	.			**0.018**	**
Area of Planted Soybean	**ST**								
Change in Area of Planted Soybean	**ST**								
Area of Planted Sugarcane	**ST**	**0.021**	***	**0.023**	**	**0.028**	*	**0.035**	**
Change in Area of Planted Sugarcane	**ST**	**0.012**	*						
Total Population	**ST**								

Total Exports	**ST**	**0.040**	*******	**0.022**	**.**		
λ				**0.697**		**0.925**	**0.928**
σ^2				**0.158**		**0.200**	**0.232**
R^2/*Nagelkerke* R^2		**0.76**		**0.83**		**0.76**	**0.74**

Table 3.4 – Standardized regression model coefficients for models processed for 2005-2009, and their significance (codes: $0 < *** \leq 0.001 < ** \leq 0.01 < * \leq 0.05 < . \leq 0.1$). *S* indicates purely spatial predictors, *T* purely temporal predictors, and *ST* spatiotemporal varying predictors.

Variable	Category	Model 1		Model 2		Model 3		Model 4	
Deforestation *(t-1)*	**ST**	**0.788**	***	**0.672**	***				
Distance to Roads	**S**	**-0.024**	***			**0.015**	.	**0.016**	*
Distance to Urban Centers	**S**								
Distance to Rivers	**S**	**0.009**	*			**-0.038**	***	**-0.040**	***
Connection to Ports	**S**	**0.0163**	***	**0.017**	*	**0.042**	**	**0.034**	*
Connection to São Paulo	**S**	**-0.021**	**	**0.031**	*	**0.149**	**	**0.140**	*
Connection to National Markets	**S**	**0.074**	***	**0.066**	***			**-0.111**	.
Price of Soybean	**T**	**-0.173**	***	**-0.180**	***	**-0.114**	***	**-0.088**	***
Price of Meat	**T**	**0.214**	***	**0.204**	***	**0.161**	***	**0.175**	***
Protected Areas	**ST**	**-0.015**	***	**-0.023**	***	**-0.053**	***	**-0.049**	***
Change in Protected Areas	**ST**							**0.012**	**
Number of Environmental Fines	**ST**	**0.070**	***	**0.031**	*			**0.067**	***
Change in Number of Environmental Fines	**ST**	**0.011**	**						
Value of Environmental Fines	**ST**	**-0.048**	***					**-0.072**	***
Change in Value of Environmental Fines	**ST**	**0.006**	.						
Area of Planted Soybean	**ST**	**-0.011**	**			**-0.037**	**	**-0.040**	***
Change in Area of Planted Soybean	**ST**	**0.013**	***					**0.023**	***
Area of Planted Sugarcane	**ST**	**-0.009**	*						
Change in Area of Planted Sugarcane	**ST**					**0.011**	.	**0.011**	.
Total Population	**ST**			**0.019**	*				

Total Exports	**ST**				
λ			**0.688**	**0.953**	**0.964**
σ^2			**0.186**	**0.226**	**0.294**
$R^2/Nagelkerke\ R^2$		**0.72**	**0.80**	**0.73**	**0.68**

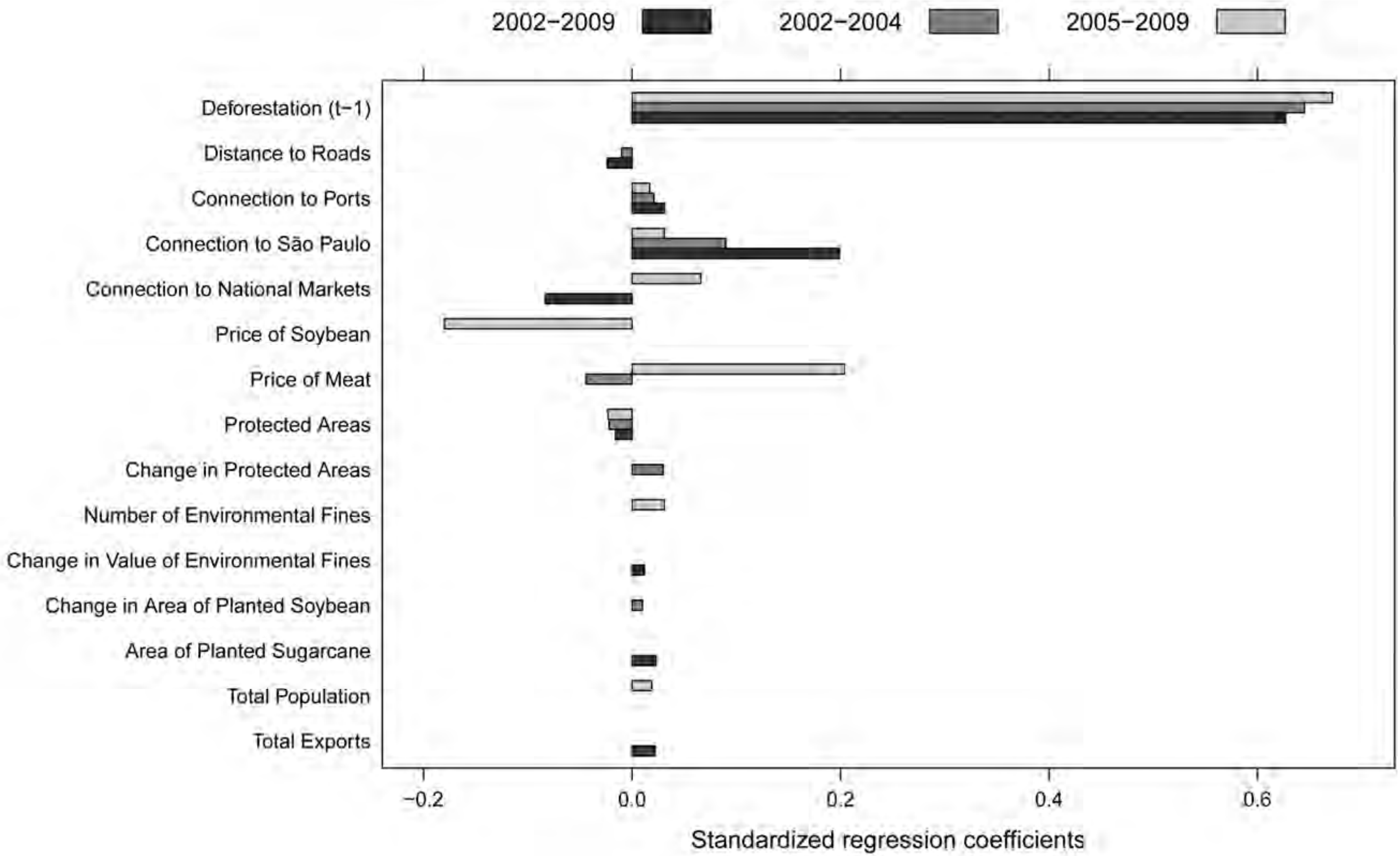


Figure 3.4 – Standardized regression coefficients for Model 2 of periods: (A) 2002-2009, (B) 2002-2004 and (C) 2005-2009.

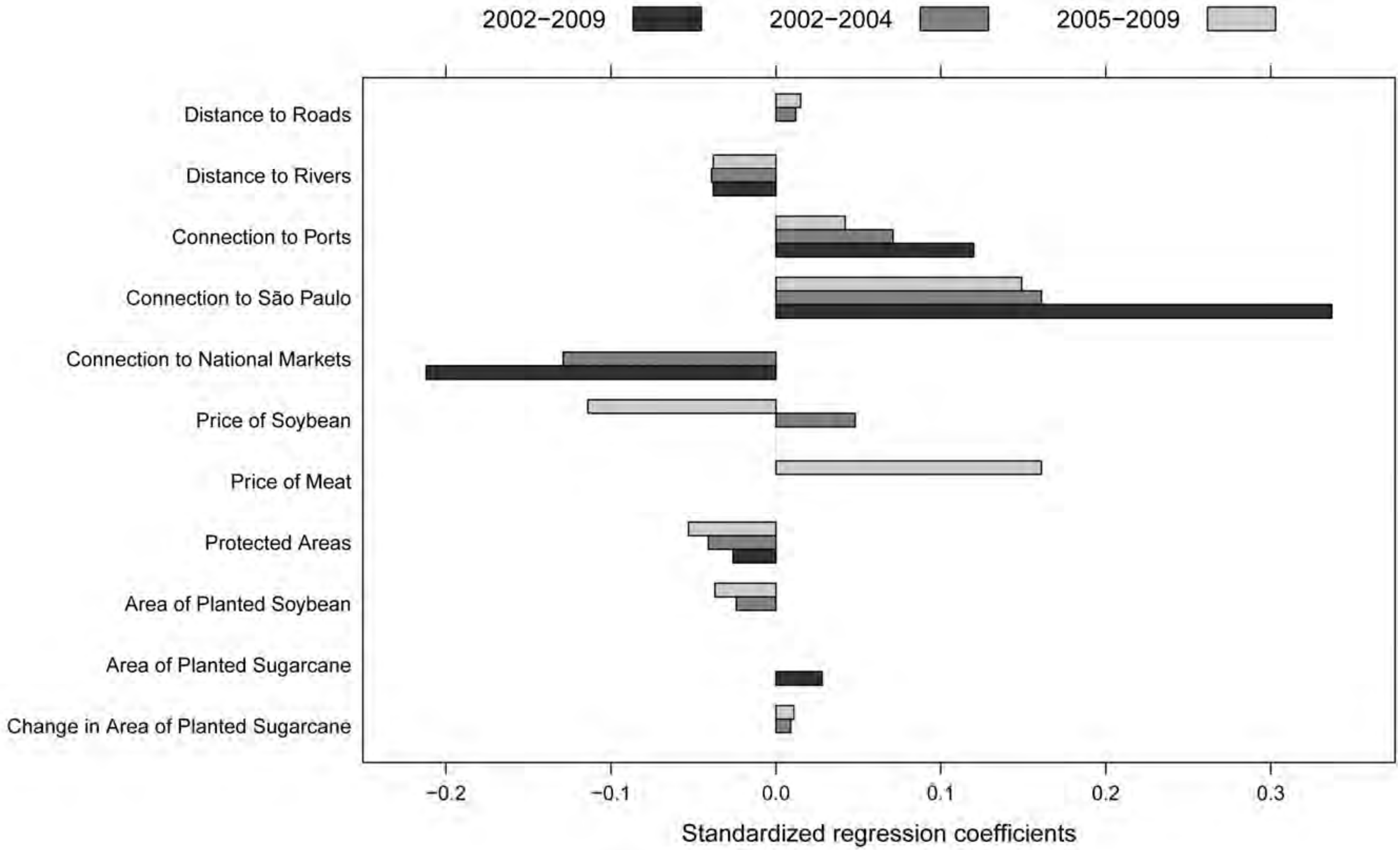


Figure 3.5 – Standardized regression coefficients for Model 3 of periods: (A) 2002-2009, (B) 2002-2004 and (C) 2005-2009.

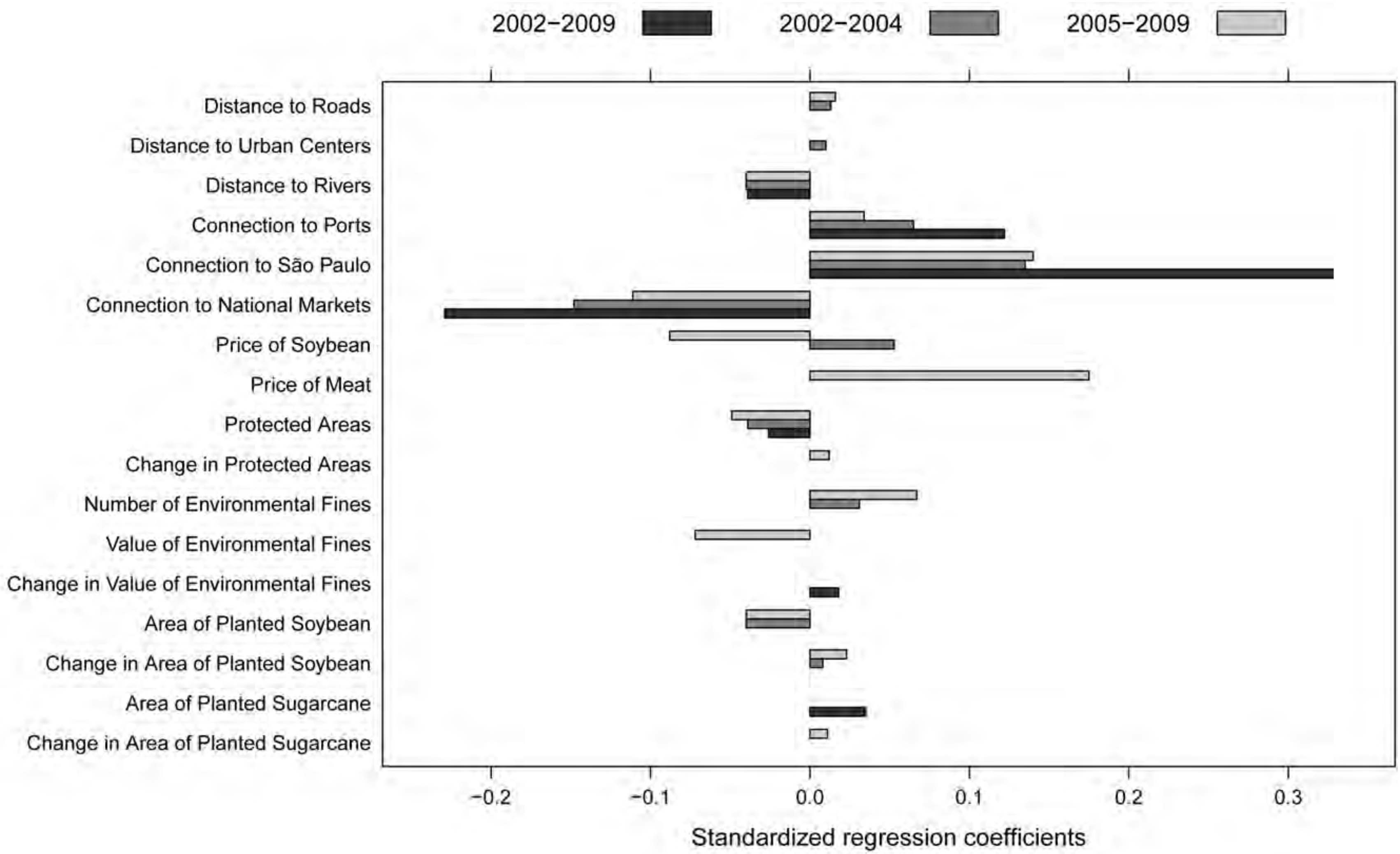


Figure 3.6 – Standardized regression coefficients for Model 4 of periods: (A) 2002-2009, (B) 2002-2004 and (C) 2005-2009.

3.4. Conclusions

Building on the work of Aguiar et al. (2007) who looked at one-time spatial regressions and de Espindola et al. (2012) who compared spatial regression models at two moments in time, this study shows the first step towards directly modeling and explaining spatial and temporal changes in the annual deforestation for 25 km x 25 km grid cells covering the entire Brazilian Amazon during a period (2002 to 2009) when the deforestation underwent marked variability. We did so by including predictors related to national environmental policies and market pressure. The regression models evaluated here considered the yearly deforestation and a set of human-induced predictors ranging across space and time. As far as we know, this study is the first to use this approach. The regression models entertained here were deliberately simple, and a better understanding of the governing processes can be obtained by evaluating a wider range of datasets and regression models. Improvements of these results might be obtained when (i) grid cell sizes other than the current 25 km x 25 km cells are used, (ii) more than one time lagged autoregressive terms are used, (iii) an estimation procedure is used that can model autocorrelation in space and time separately.

The results obtained in this study confirm previous regional-scale findings that related deforestation and commodity prices. In addition, we also showed that the influence of national environmental policies is quite significant and has been increasing over the years. Moreover, for the three periods of analysis, our results show that the influence of most of the driving factors has been changing throughout the years. In other words, the Brazilian Amazon cannot be considered a simple unit that is subject to international aspects, such as global food demand and climate change. On the contrary, the region needs to be recognized considering the ambivalent aspects of national policies and global situations that are likely to determine future trends in deforestation. The implementation of environmental laws, for example, has been effective, and data show that controls can even counter price incentives to open new deforested areas. Finally, the deforestation in the Brazilian Amazon is a dynamic process that needs to be more realistically assessed, considering the interplay between cultural-institutional, socio-demographic, environmental and economic factors at different scales. Further research is needed to complement the answer of our question, and we recommend the use of subregional analysis to increase the understanding of deforestation trends in the Brazilian Amazon.

4. SUBREGIONAL VARIABILITY OF DEFORESTATION IN THE BRAZILIAN AMAZON: HOW ARE THE RATES DECREASING?[6]

Abstract

The Brazilian Amazon region has undergone marked variability in deforestation in recent decades, and after a long period of increase, the deforestation rates have sharply decreased over the past years. During a time of stringent macro-economic conditions, Brazil has been successful in decreasing deforestation by strengthening national environmental policies and by implementing Brazilian satellite monitoring programs, which are aimed at quantifying deforestation and providing the basis for illegal deforestation combat. As a result, the deforestation rates in 2011 reached the lowest rates ever recorded, for the second consecutive year. Although the rates have being decreasing since 2005, the deforestation trends across the region have significantly varied in frequency and magnitude. The states of Pará, Rondônia and Mato Grosso, for example, have the highest recorded rates of deforestation over the last three decades. In 2011, while the rates in Pará decreased by 15.0 percent compared to 2010, the rates in Rondônia increased by 100.0 percent. Using six hotspots of land use change in the states of Pará and Mato Grosso, the present study addresses the subregional trends of deforestation by analyzing its spatiotemporal variability using Landsat TM-based maps from 2002 to 2009. We analyzed human occupation history and land use change dynamics in each of these subregions and linked the impacts of major national environmental policies and market factors. During this period, we found that deforestation trends were not equal in these six regions. There was, however, a negative association between deforestation and local environmental enforcement actions in four of these regions.

[6]This chapter is the updated version of the paper co-authored with de Aguiar, A.P.D., Câmara, G., Fonseca, L., in preparation to be submitted to the journal Land Use Policy.

4.1. Introduction

The Brazilian Amazon region has received much attention from policy and scientific forums, given the dramatic environmental changes facing the rainforest since the 1960s. Recently, the international debate surrounding deforestation has been influenced by the explanation of the causes and consequences of deforestation in a context of specific national environmental policies and macroeconomic conditions (Câmara et al., 2005; Foley et al., 2007; Laurance et al., 2004). As deforestation rates have been decreasing for seven consecutive years (2005-2011), it is essential to better describe the predominant trends and critical factors that have determined land use change dynamics across the region. Moreover, it is crucial to understand the history of national environmental policies, market forces and other factors that may favor or restrict deforestation.

A review of the history of deforestation in the Brazilian Amazon shows it has been influenced by six major activities: mineral and forest exploration, extensive rangeland for cattle, infrastructure projects for hydroelectric power, roads, colonization projects and, more recently, production of agricultural commodities (Araújo and Lená, 2010; Toledo et al., 2011). In the 1970s and 1980s, massive amounts of deforestation resulted from public policies aimed at occupying the region. There was debate questioning the economic rationally of the deforestation process and subsequent land use changes, especially focusing on infrastructure projects and large enterprises of the private sector (Andersen and Reis, 1997; Fearnside, 1996; Lambin, 1994; Skole and Tucker, 1993). In the 1990s, while deforestation was still substantial, an increasing number of case studies began to question the diversification of investment sources and the decentralization of projects and policies by giving value to biodiversity and creating sustainable agricultural systems (Angelsen and Kaimowitz, 1999; Kaimowitz and Angelsen, 1998; Liverman et al., 1998; Machado, 1998; Pfaff, 1999). Finally in the 2000s, after a long period of increase, deforestation has been sharply decreased. Instead of the treatment of the region as a unit, subregional characterization and analyses have been utilized, which include land tenure market, agribusiness and monetary valuation of environmental services (Aguiar, 2006; Alves et al., 2009; Brondizio and Moran, 2011; Nepstad et al., 2009; Soares-Filho et al., 2010).

Since the 1900s, scientists have often applied different approaches to study the determinant factors of deforestation. In the past, many Amazon-wide studies concluded that *population growth* and deforestation were strongly correlated (Fearnside, 1990; Lambin, 1994; Reis and Guzmán, 1992). Pfaff (1996), in turn, focused on the period from 1978 to 1988 and analyzed the relevance of biophysical variables (*soil quality* and *vegetation type*), transport-related variables (*road network*, *density in the area* and *its neighbors*) and government-related variables (*development policies*). Margulis (2004), however, presented an econometric model for analyzing the occupation of the Brazilian Amazon, quantifying the spatial and temporal relationships of the main agricultural activities (*timber extraction*, *pasture* and *crops*). Based on grid models, Perz and Skole (2003) developed a spatial regression model for secondary vegetation in the Amazon Basin and showed that determinant factors have significant spatial variation among different regions. Laurance et al. (2002) performed statistical analysis to assess the relative importance of determinant factors. They found that the three most important factors were *population density*, *distance to roads*, and *dry season duration*. The results reported by Soares-Filho et al. (2006) indicate that the most important factors for predicting deforestation location in the Amazon Basin are *proximity to roads*, *indigenous reserves* and *proximity to urban centers*. More recently, Soares-Filho et al. (2010) showed that *indigenous lands*, *strictly protected areas* and *areas of sustainable use* inhibited deforestation between 1997 and 2008.

Despite the huge progress made since the 1990s, studies based on highly aggregated units of analysis (countries and states) generally offer limited insight into the trends and dynamics of deforestation and land use changes across the region. Region-based analyses are limited, as they obscure subregional processes and interactions, and thus do not fully explore the complexity of the Brazilian Amazon. On the other hand, while regional analyses obtain the sum of the trends, detailed results from local studies (farm-level) are indirectly impacted by global and national policies and market pressures, making generalization difficult. Midway between region-wise and local-based studies is the path to address both the complexity of the region as well as the influence of external factors at different levels. Subregional analyses, in turn, respond to the call of empirical results that are comparable from one hotspot to another and serve as inputs to policies across different regions (Brondizio and Moran, 2011; Toledo et al., 2011).

Against this background, the goal of this chapter is to provide an integrated quantitative and qualitative analysis of land use change at a subregional level. We selected six hotspots of land use change in the states of Pará and Mato Grosso, each of one with distinct historical and socioeconomic contexts. For each subregion we analyzed the spatiotemporal variability of agricultural production, socioeconomic indicators and deforestation rates. We aligned such variability under a time line of major national deforestation control policies and macroeconomic contexts after 2000. The assumption is that deforestation rates are not decreasing homogenously and that the maintenance of this decreasing depends on recognizing and understanding such variability across different contexts.

The chapter is organized as follows: Section 2 presents each subregion and the data used. Section 3 presents the results. Section 4 presents the discussion and conclusions in which we consider the causes of deforestation and land use change dynamics at subregional levels.

4.2. Material and Methods

4.2.1 Study area

The study area is the Brazilian Amazon region (Figure 4.1A) and six of its subregions, selected as hotspots of land use change (Figure 4.1B). The area as a whole covers more than 5 million sq km, and the selected hotspots of land use change cover areas ranging from approximately 52,000 sq km to 326,000 sq km (Appendix 4A). The six subregions were selected in the states of Pará and Mato Grosso where the highest rates of deforestation were observed in the past three decades (INPE, 2011). Appendix 4A shows the municipalities included in each subregion. In addition, these subregions were selected based on the diversity of human occupation histories and deforestation trends.

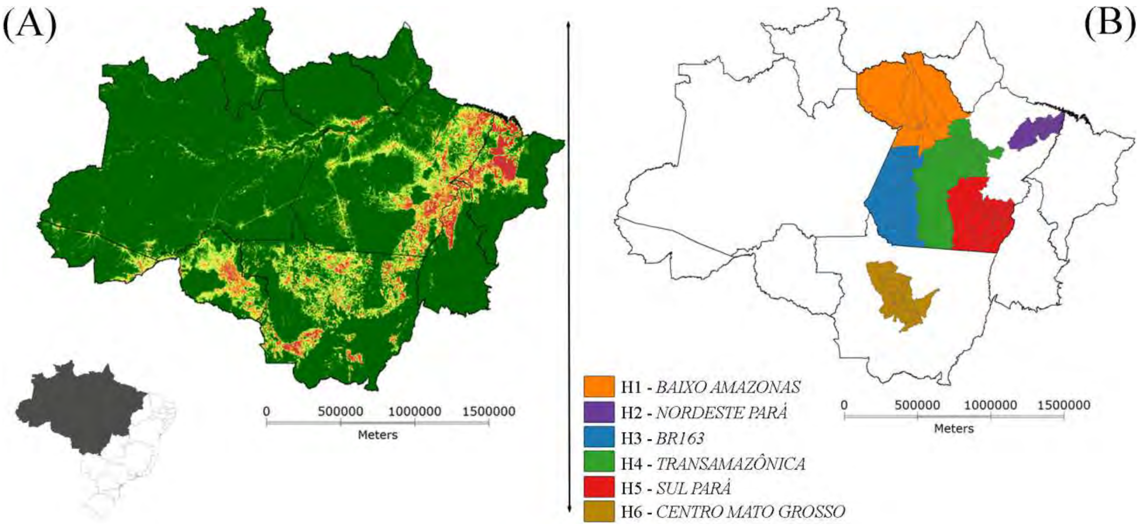


Figure 4.1 – (A) Map of Brazil showing the location of the Brazilian Amazon region (bottom-left, all in darker gray), and the regular grid of 5 km x 5 km over the Brazilian Amazon region showing the proportion of cumulative deforestation for each cell in 2009. (B) Map of the Brazilian Amazon region showing the location and names of the six subregions selected as hotspots of land use change.

2.2 Data source and indicators

To better present the dynamics of deforestation across the region, we used Landsat TM-based 1997-2009 deforestation maps produced under the Amazon monitoring program (PRODES) of the Brazilian National Institute for Space Research (INPE, 2011). As described by de Espindola et al. (2012b), all data representing deforestation and agricultural land uses – pasture, temporary and permanent agricultures – were aggregated to grid cells of 5 km x 5 km. In this study, the proportion of cumulative deforestation in 1997 and 2007 (Figure 4.2) was classified into main agricultural uses by combining the TM-based 1997-2007 deforestation maps from INPE (2011) and census information from the agricultural censuses in 1996 and 2006 (IBGE, 1996, 2006). Municipality-based (Figure 4.3) census data were converted from polygon-based information to grid cells of 5 km x 5 km. The total agricultural area for each municipality was obtained from the deforestation maps. The proportion of each agricultural use was obtained from the census data. The 1996/1997 and 2006/2007 maps representing agricultural distribution and density for the entire Brazilian Amazon were shown in Figures 4.4, 4.5 and 4.6 (Aguiar et al., 2007; de Espindola et al., 2012b).

The yearly (annual increments) proportion of deforestation from 2002 to 2009 was also computed for each grid cell (Figure 4.7). Cells with a large proportion (>20%) of cloud cover, non-forest vegetation, water, or cells outside the Brazilian Amazon were omitted from our analyses. The cells omitted due to cloud cover accounted for less than 5% of the number of cells covering the study area. In this study, we focused on the subregional trends of deforestation, which we defined as the sum of the yearly proportion of deforestation computed for each 5 km x 5 km cell within each of the six subregions.

Although the proportions of cumulative and yearly deforestation were well computed for each cell, the spatiotemporal configuration of forest cleaning, by itself, does not explain the critical factors that determine the variability of deforestation across the region. It is well understood that better assessments of land use change depend critically on the ability to also include the social determinants of deforestation. When the assessment is for a region as large the Brazilian Amazon, census and population data are the best sources of information on the socioeconomic and demographic characteristics of the region. In Brazil, most of the information about socioeconomic characteristics comes from agricultural census data (IBGE, 1996, 2006). Agricultural censuses form the most complete survey of land management, including areas under different land use categories (pasture versus crops, for example), levels of mechanization and agricultural inputs, allowing for a detailed analyses of the social, economic, and environmental aspects of agriculture across the region (Alves et al., 2009; Cardille and Foley, 2003). Moreover, the indicators of economic structure presented in this study were derived from municipality-based agricultural and demographic census data compiled by the IBGE (Brazilian Institute for Geography and Statistics).

For the agrarian structure estimates, we used data from agricultural censuses in 1996 and 2006 (IBGE, 1996, 2006). The agrarian structure data were aggregated for each subregion, indicating the proportion, in terms of number, of small (< 100 ha), medium

(100 to 500 ha) and large (> 500 ha) farms within the municipality (Figure 4.8). In addition to these characteristics, we added additional data, such as total production and number of cattle, for each subregion in 1996 and 2006. Furthermore, we included the total area of land covered by temporary and permanent agriculture from 2002 to 2009 (Table 4.1).

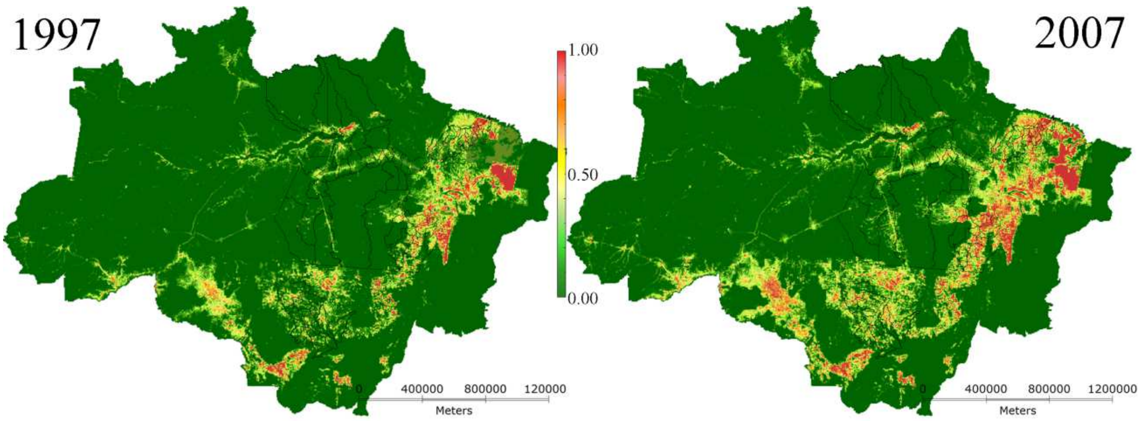


Figure 4.2 – Proportion of cumulative deforestation for each cell in 1997 (left) and 2007 (right).

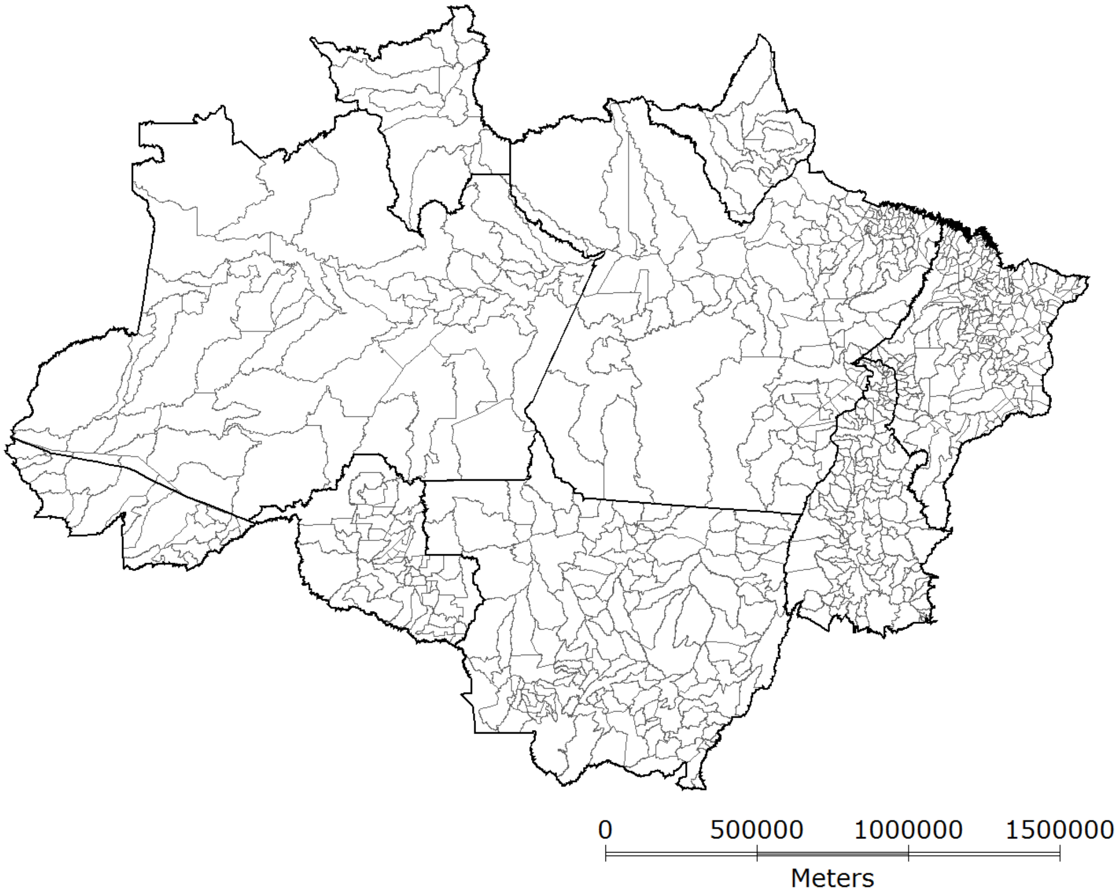


Figure 4.3 – Spatial extent of municipality polygons within the states of the Brazilian Amazon.

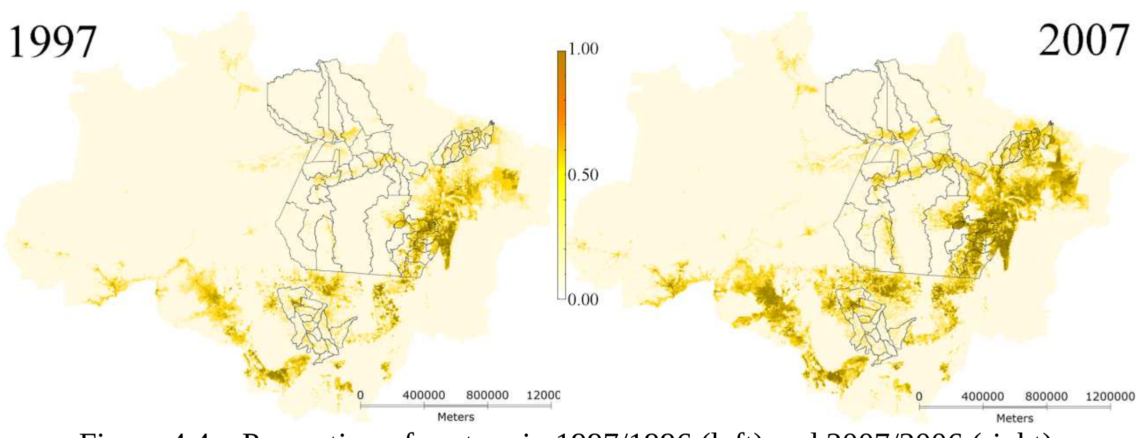


Figure 4.4 – Proportion of pasture in 1997/1996 (left) and 2007/2006 (right).

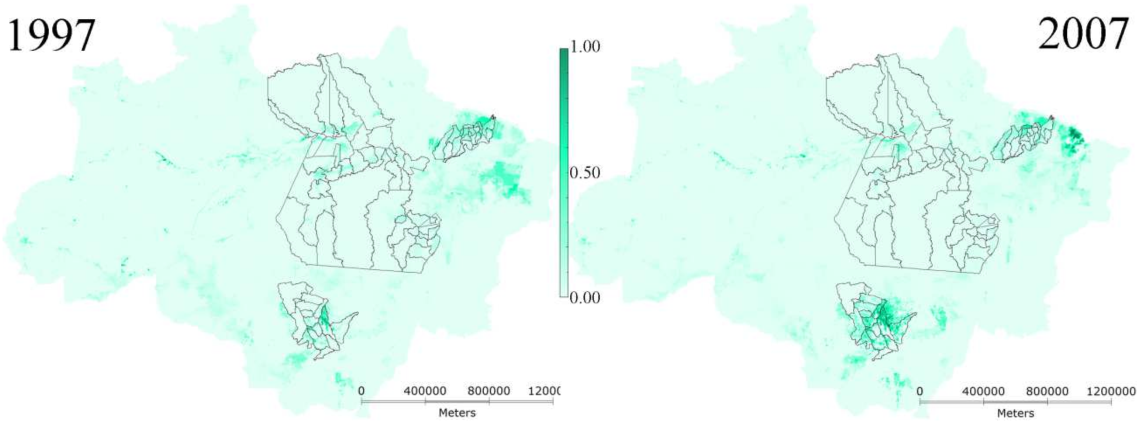


Figure 4.5 – Proportion of temporary agriculture in 1997/1996 (left) and 2007/2006 (right).

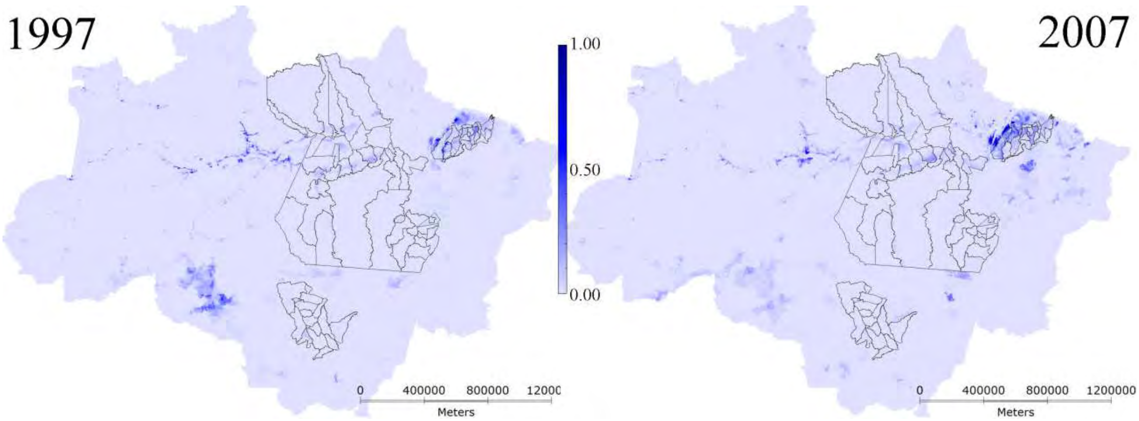


Figure 4.6 – Proportion of permanent agriculture for 1997/1996 (left) and 2007/2006 (right).

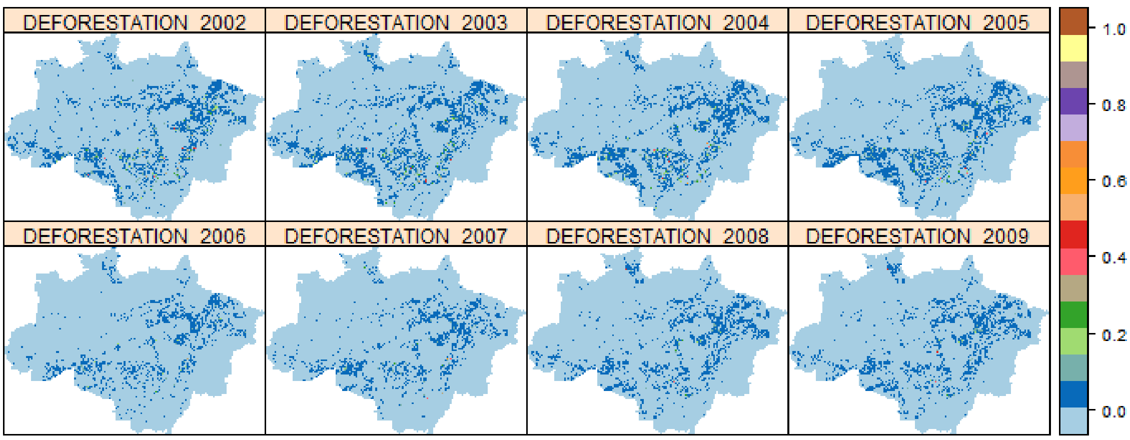


Figure 4.7 – Maps with proportion of deforestation for each year from 2002 to 2009.

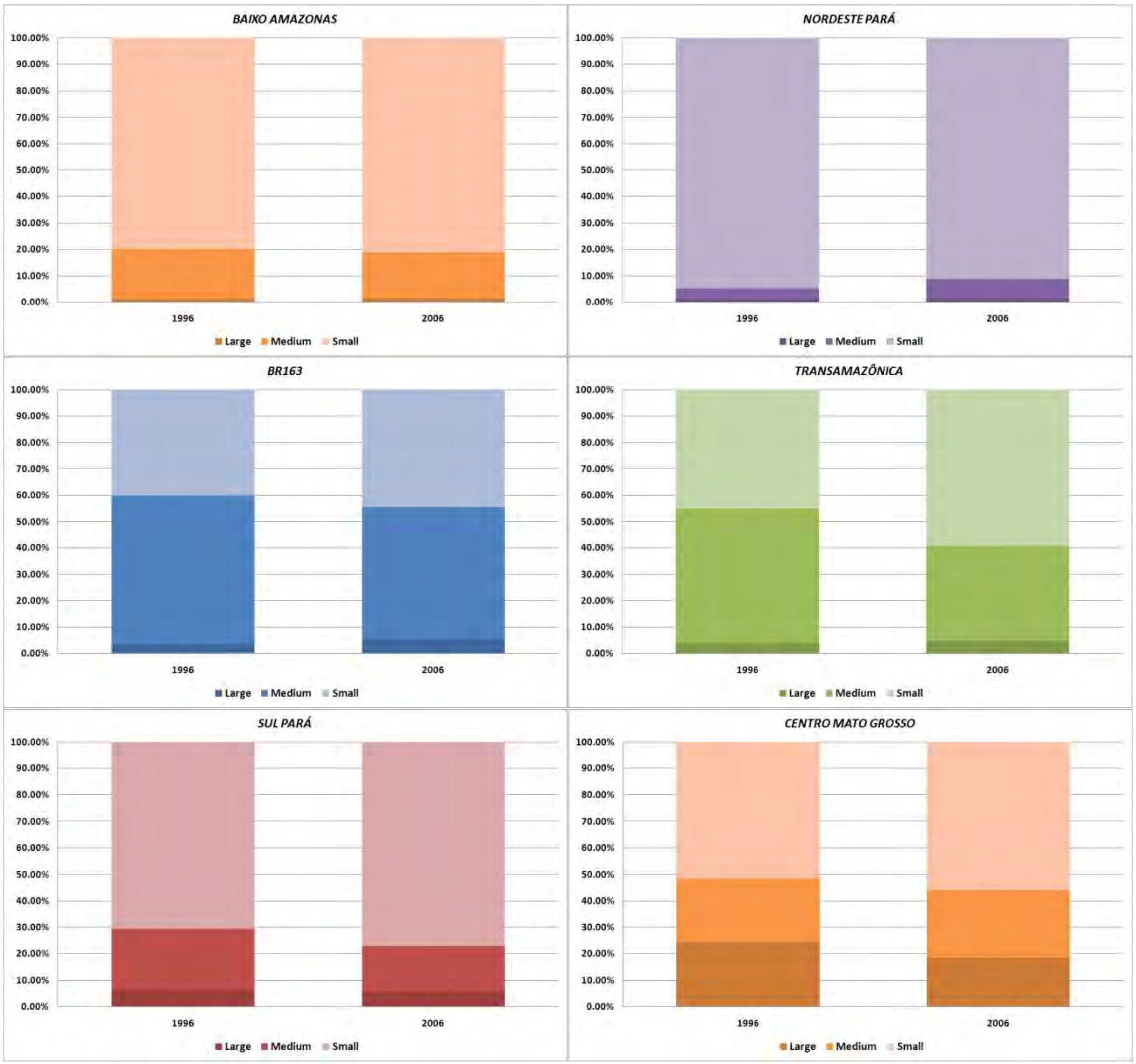


Figure 4.8 – Agrarian structure for each subregion in 1996 and 2006.

Table 4.1 – Total production, cattle and agricultural areas for each subregion.

Production, Cattle and Agricultural Areas for Subregion								
BAIXO AMAZONAS								
	1996	**2006**						
Total Production (R$)	100165906.00	273088000.00						
Total of Cattle (Nº)	539816	618793						
	2002	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**
Temporary Planted Area (Km²)	1472.23	2195.70	2442.63	2410.93	2152.21	1982.84	2047.29	2013.13
Permanent Planted Area (Km²)	89.73	86.62	71.22	74.34	72.04	73.36	71.49	69.02
NORDESTE PARÁ								
	1996	**2006**						
Total Production (R$)	153423494.00	764457000.00						
Total of Cattle (Nº)	420997	695054						
	2002	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**
Temporary Planted Area (Km²)	1335.25	1396.35	1417.71	1682.77	1519.91	1603.81	1424.35	1326.02
Permanent Planted Area (Km²)	619.92	704.79	727.37	777.94	841.12	821.02	813.06	774.62
BR163								
	1996	**2006**						
Total Production (R$)	25687202.00	69843000.00						
Total of Cattle (Nº)	205759	572035						
	2002	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**
Temporary Planted Area (Km²)	453.58	475.44	525.47	543.48	483.89	527.09	518.40	488.83
Permanent Planted Area (Km²)	93.71	90.42	87.27	95.31	90.58	91.16	95.17	93.81
TRANSAMAZÔNICA								
	1996	**2006**						
Total Production (R$)	82354827.00	232868000.00						
Total of Cattle (Nº)	563263	1631903						
	2002	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**
Temporary Planted Area (Km²)	680.48	639.28	619.90	670.98	571.28	539.44	475.19	438.53
Permanent Planted Area (Km²)	603.85	672.14	676.69	684.64	719.42	738.10	736.29	687.61
SUL PARÁ								
	1996	**2006**						
Total Production (R$)	125979683.00	222432000.00						
Total of Cattle (Nº)	1973200	5290481						
	2002	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**
Temporary Planted Area (Km²)	1552.19	1583.14	1470.23	1472.72	1361.01	1321.55	987.76	865.24
Permanent Planted Area (Km²)	202.74	201.59	90.47	69.86	73.84	83.96	79.87	81.65

CENTRO MATO GROSSO								
	1996	**2006**						
Total Production (R$)	262211054.00	2421411000.00						
Total of Cattle (Nº)	1053051	1324416						
	2002	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**
Temporary Planted Area (Km²)	18551.38	21422.84	25342.85	28487.97	27044.73	28499.07	31665.06	29862.75
Permanent Planted Area (Km²)	48.73	55.09	56.67	81.84	47.68	48.57	150.21	156.40

4.3. Results

4.3.1 Review of major national environmental policies in the 2000s

A review of the 1996-2006 period shows that significant amounts of deforestation until 2004 forced the Brazilian government to take actions to protect endangered areas. From the mid to late 1990s, major initiatives emerged and are still influencing the rates of deforestation. In addition to considering national environmental (governmental) actions, in this study, we also consider a review of relevant NGO (Non-Governmental Organization) and private section actions against deforestation (see Table 4.2).

From 2000 to 2010, one initiative was the creation of the National System of Conservation Units of Nature (SNUC) in 2000 and the adoption of a systematic and consistent approach to areas designated as national parks (Rylands and Brandon, 2005). As a result, Brazil has expanded the network of protected areas in the Amazon from 1.26 to 1.82 million sq km since 2005. As well as the growth of protected areas, the indigenous lands have also expanded; currently, they cover approximately 20% of the Brazilian Amazon, and some play a very significant role in protecting the forest from ongoing development. Until 2009, approximately 44% of the Brazilian Amazon territory was under some form of protection in public lands (Shanley et al., 2011). Appendix 4B contains maps of the subregions, which show the mosaic of public lands before 2002 and after 2002.

In 2004, the government launched an action plan called PPCDAM (acronym in Portuguese, see Table 4.2) (Brazil, 2004), which focused on the prevention and control of deforestation, considering three thematic areas: land and territorial organization; monitoring and control; and incentives for sustainable productive activities. This was the first attempt to have a more comprehensive plan to address deforestation. Since then, additional actions were taken to enable territorial planning and land tenure regulation, a result obtained by the land and territorial organization thematic area. In addition, the observed results were also obtained through the monitoring and control of the thematic area by the implementation of the Brazilian satellite monitoring programs, aimed at quantifying deforestation and providing the basis for illegal deforestation combat and prevention actions. For example, the combat and prevention of deforestation by applying environmental fines enhanced the presence of the Brazilian Environmental Police – IBAMA (acronym in Portuguese) in high pressure areas, which has also been shown to be effective in reducing deforestation. Figure 4.9 shows the number of environmental fines applied over each one of the subregions selected in this study.

Recently in 2008, the Brazilian government established the National Plan on Climate Change, NPCC (Brazil, 2008), which defined the goal of an 80% reduction in the deforestation rates by the year 2020. Additionally, the municipalities responsible for half of the deforestation in the 2004-2007 period were the focus of another national action to register properties, advertise illegal holdings, cancel lines of credit for illegal landholders, and pressure buyers of Amazonian products (Lambin and Meyfroidt, 2011; Nepstad et al., 2009).

Table 4.2 – Review of governmental and private actions against deforestation.

Review of Governmental and Private Actions from 2000 to 2010			
Category	**Year**	**Action**	**Description**
Governmental Actions	2000	National System of Conservation Units of Nature (SNUC)	Federal Law 9985/2000. The act established the *National System of Conservation Units of Nature* – SNUC, defining criteria and standards for the creation, deployment and management of conservation units.
	2004	Action Plan for Prevention and Control of the Legal Amazon Deforestation (PPCDAM)	Initially comprised 13 ministries of the federal government, under direct coordination of the President's Chief of Staff. It refers to a governmental effort on the prevention and control of deforestation.
		(a) Land and Territorial Organization	Coordination of territorial planning and land tenure regulation.
		(b) Monitoring and Control	Implementation of the Brazilian satellite monitoring programs.
		(c) Incentives for Sustainable Productive Activities	Coordination for creating sustainable agricultural systems.
	2006	National Strategic Plan on Protected Areas (PNAP)	Included the concept of *Indigenous Lands* and *Quilombola* territories. The goal is to guide the actions for the establishment of a system of ecologically representative and effectively managed protected areas, integrating terrestrial and marine areas by 2015.
	2006	Public Forest Law	Federal Law 11284/2006. The law sets out the approach to be taken in the allocation of timber concessions in public forests for sustainable production involving the private sector, communities and other potential stakeholders.
	2008	National Plan on Climate Change	The plan aims to achieve a 40% reduction in average annual deforestation in 2006-09 in comparison with 1996-2005, followed by two further reductions of 30% in the periods 2010-13 and 2014-17.
	2008	Sustainable Amazon Plan (PAS)	Aim to define guidelines for sustainable development in the Brazilian Amazon, proposing strategies and lines of action that aim for the social, economic and environmental development of the region.
	2009	Prevention of the Use of Illegal Timber in the Building Industry Act	Asks for proof of the legal origin of timber from building companies.
	2009	Legal Land Program (*TerraLegal*)	Federal Law 11952/2009. Aim at expediting land regularization of up to 300,000 informal occupations in public land on the Legal Amazon.

Private Section Actions	2006	Soy Moratorium	Implementation of the soybean moratorium in the Brazilian Amazon on the purchase of soybeans grown on lands cleared after July 26, 2006.
	2009	Beef Industry Moratorium	Brazil's biggest domestic beef buyers announced they would suspend contracts with suppliers found to be involved in the Brazilian Amazon deforestation.

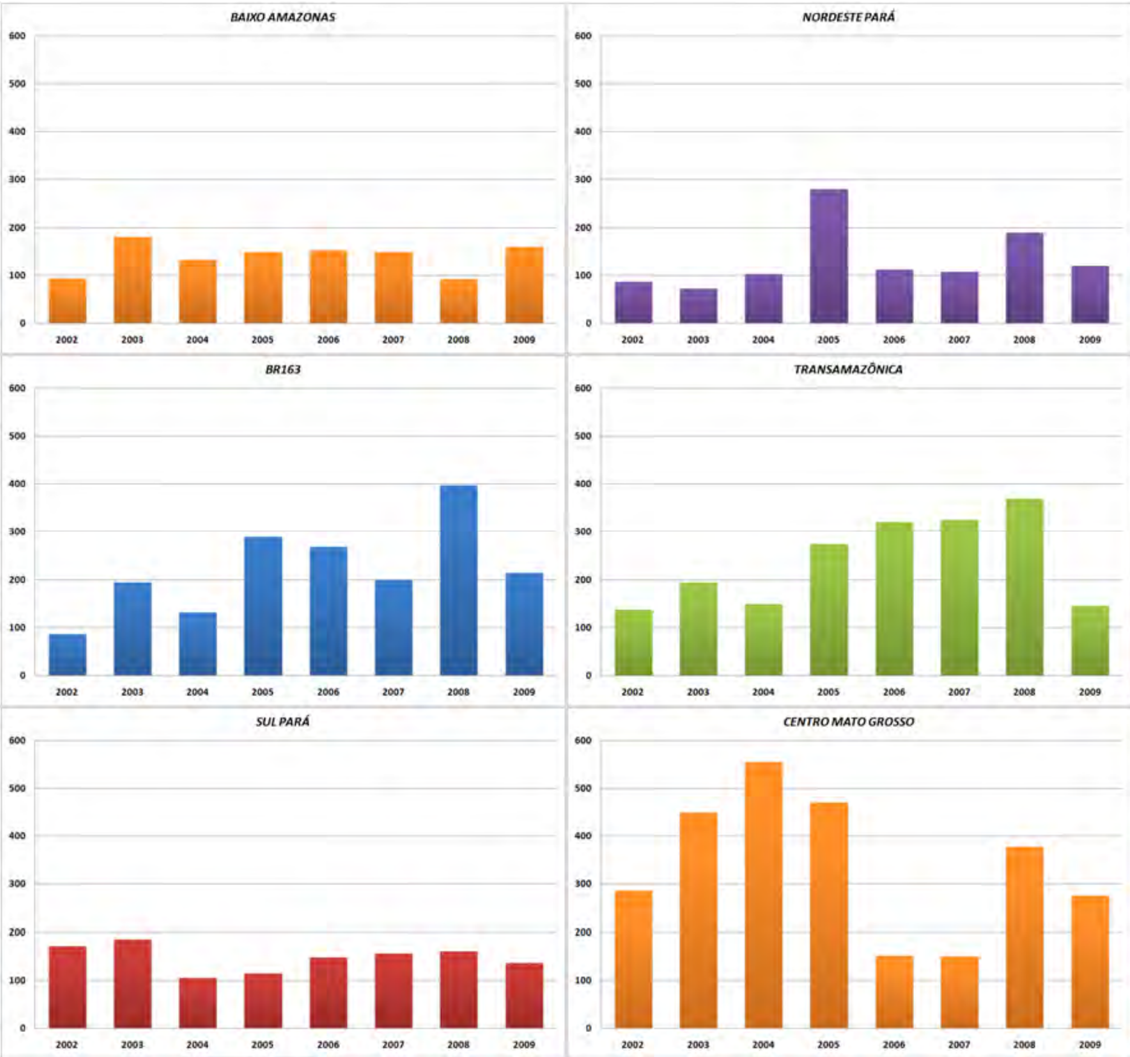


Figure 4.9 – Environmental fines applied in each subregion from 2002 to 2009.

4.3.2 Deforestation and hotspots of land use change

Deforestation across the entire region increased over these 10 years (1997-2007) (Figure 4.2) and tended to occur close to previously deforested areas, showing a strong spatial structure as noted by other authors (Alves, 2002; Alves et al., 2009). Figure 4.4 shows that pasture spread over the whole deforested area, was the major land use in both periods (1997 and 2007), and has increased following the deforestation patterns. Pasture was also established mainly across eastern Pará, central Rondônia, and north of Mato Grosso. As shown in Figure 4.5, with regards to temporary agriculture, two states deserve attention. In Maranhão, temporary agriculture moved from the center of the state to the north. In Mato Grosso, the area increased by more than 100% from 1996 to

2006 (IBGE, 1996, 2006). The forest conversion to cropland in Mato Grosso represents a case of particular interest due to the massive investments made by commercial soybean farmers as well as the success of farming systems and crop breeding research. However, permanent agriculture is the smallest agricultural land use category in the entire study area. Over ten years, it was replaced by pasture in Rondônia but increased in some areas of northeast Pará, as shown in Figure 4.6. During both periods, overall agricultural activities were concentrated in the southeast region of the Brazilian Amazon, especially across eastern Pará, central Rondônia, and north of Mato Grosso. From these areas and isolated patches, agricultural activity rapidly spread over the 1996/1997 and 2006/2007 periods (de Espindola et al., 2012a).

Based on that and on the notable differences regarding socioeconomic conditions and the resulting spatial patterns of land use change across the entire region, six hotspots of land use change were selected in the states of Pará and Mato Grosso (see Figure 4.1).

BAIXO AMAZONAS

The *Baixo Amazonas* region is crossed by the Amazon River at its confluence with the Tapajós River. The region covers 12 municipalities in Pará, including Santarém, and encompasses a total area of approximately 317,274 sq km (Appendix 4A). The total population was 678,936 in 2010, with 271,161 (39%) living in rural areas. The region has 23,659 family agriculture farms and 36,787 settlement families and is covered by a network of public lands, including protected areas of integral protection, protected areas of sustainable use and indigenous lands (Appendix 4B). During 2002-2009, new protected areas were created, which extended to almost the entire region. The region has been dominated by small farms, representing 79.89% and 81.16% of the total number of properties in 1996 and 2006, respectively (Figure 4.8).

Important activities in the region's economy include: wood, latex and nut extraction; jute, cassava, rice and soybean crops; cattle, swine and poultry farming; and fishing and the natural fibers industries. During the 1996-2006 period, the total production grew from around R$ 100,000 M in 1996 to more than R$ 270,000 M in 2006. In addition, the number of cattle ranged from 540,000 in 1996 to 619,000 in 2006. Temporary and permanent agriculture remained more or less constant during this period. The region featured approximately 2,000 sq km of temporary agriculture and 69 sq km of permanent agriculture in 2009 (Table 4.1). The main increase in temporary agriculture happened from 2002 to 2003, when the total area changed from 1,400 sq km to 2,100 sq km. This increase was associated with the expansion of soybean crops in the Santarém region. Since 2006, soybean producers in the Santarém and Belterra municipalities are under a soy moratorium (Rudorff et al., 2011), which is an agreement between major soybean companies to not trade soybean that is produced in areas that were deforested after July 2006 (Table 4.2).

NORDESTE PARÁ

The *Nordeste Pará* region is characterized by the consolidation of family agriculture based on production systems that mainly include permanent crops and cattle farming. The region covers 18 municipalities in Pará, and encompasses a total area of 57,250 sq km (Appendix 4A). The total population was 734,545 in 2010, with 353,352 (48%) living in rural areas. The region has 23,542 family agriculture farms and 16,204 settlement families and is sparsely covered by indigenous lands. No protected areas (integral protection nor sustainable use) are found in the region (Appendix 4B). This region has also been dominated by small farms, representing 94.79% and 91.22% of the total number properties in 1996 and 2006, respectively (Figure 4.8).

Important activities in the region's economy include: grain crops (soybean and corn); dendê palm cultivation and black pepper production; and mining, fishing and cattle. During the 1996-2006 period, the total production grew from approximately R$ 153,000 M in 1996 to more than R$ 764,000 M in 2006. In addition, the number of cattle ranged from 421,000 in 1996 to 695,000 in 2006. Temporary and permanent agriculture remained more or less constant during this period. The region featured approximately1,326 sq km of temporary agriculture and 775 sq km of permanent agriculture in 2009 (Table 4.1). The *Nordeste Pará* region is one of the most representative regions in the state of Pará in terms of gross production value of the state, and the several production systems represent competitive forms of use for the land. Such competition creates tensions that generally extend to property and social relationships and is projected in the environmental unbalances that increase the risk of deforestation.

BR163

The *BR163* region is crossed by the Cuiabá – Santarém (*BR163*) highway, which is slated to be paved as an export corridor for soybean via the Amazon River. The highway would primarily be used to transport soybean from rapidly expanding areas of this crop in the central part of Mato Grosso. The paving of the *BR163* highway could result in deforestation and illegal logging, mainly because the region has historically had problems with lawlessness and the prevalence of impunity, and matters related to environmental and land tenure have especially gone unregulated.

The *BR163* highway influence region covers 6 municipalities in Pará, and encompasses a total area of 190,427 sq km (Appendix 4A). The total population was 209,209 in 2010, with 91,825 (44%) living in rural areas. The region has 7,409 family agriculture farms and 12,428 settlement families and is covered by a network of public lands, including protected areas of integral protection, protected areas of sustainable use and indigenous lands (Appendix 4B). During 2002-2009, new protected areas were created, extending almost the entire region. The region has been dominated by medium farms, representing 56.23% and 50.08% of the total number properties in 1996 and 2006, respectively. However, the presence of small farms is also substantial, representing 40.22% and 44.58% of the total number properties in 1996and 2006, respectively (Figure 4.8).

Important activities in the region's economy include: mineral extraction; grain (rice, beans, soybean and corn) and permanent crops (coffee, cacao, black pepper); and fishing and cattle. During 1996-2006, total production grew from around R$ 26,000 M in 1996 to R$ 70,000 M in 2006. In addition, the number of cattle ranged from 206,000 in 1996 to 572,000 in 2006. Temporary agriculture decreased from 707 sq km in 1996 to 543 in 1997, and after that, it remained more or less constant. Permanent agriculture remained constant during the entire period, consisting of 94 sq km in 2009 (Table 4.1).

TRANSAMAZÔNICA

The *Transamazônica* region covers 10 municipalities in the state of Pará, encompassing a total area of 251,839 sq km, and is crossed by the *Transamazônica* highway (Appendix 4A). The total population was 340,056 in 2010, with 154,179 (45%) living in rural areas. The region has 17,411 family agriculture farms and 26,542 settlement families and is covered by a network of public lands, including protected areas of integral protection, protected areas of sustainable use and indigenous lands (Appendix 4B). During 2002-2009, new protected areas were created, extending almost the entire region. The region has been dominated by small and medium farms. Small farms represented 45.22% of the number of total properties in 1996 and 59.34% in 2006. Medium properties represented 50.95% of the number of total properties in 1996 and 35.87% in 2006 (Figure 4.8).

Important activities in the region's economy include: cattle farming activities focusing on beef, leather and dairy production; grain crops (rice, beans, soybean and corn); and permanent crops and ore extraction (nickel). During 1996-2006, total production grew from around R$ 82,000 M in 1996 to more than R$ 233,000 M in 2006. In addition, the number of cattle ranged from 563,000 in 1996 to 1,632,000 in 2006. During this period, temporary agriculture decreased, while permanent agriculture increased. The region featured approximately 439 sq km of temporary agriculture and approximately 688 sq km of permanent agriculture in 2009 (Table 4.1).

SUL PARÁ

The *Sul Pará* region covers 15 municipalities in the state of Pará, including São Félix do Xingu, and encompasses a total area of 181,250 sq km (Appendix 4A). The region is characterized by land speculation, cattle expansion, and massive rates of deforestation. Road construction, investments in electrical energy, financial credit for cattle, and land tenure policies have all fueled regional occupation, making the area one of the most dynamic agricultural frontiers in the Brazilian Amazon (Mertens et al., 2002). The total population was 473,042 in 2010, with 173,040 (37%) living in rural areas. The region has 19,824 family agriculture farms and 26,237 settlement families and is covered by a network of public lands, including protected areas of integral protection, protected areas of sustainable use and indigenous lands (Appendix 4B). The region has been dominated by small farms, representing 70.66% and 77.11% of the total number of properties in 1996 and 2006, respectively (Figure 4.8).

Important activities in the region's economy include: cattle farming activities focusing on beef, leather and dairy production; grain crops (rice, beans, soybean and corn); and permanent crops and ore extraction (nickel). Compared to all other activities, livestock farming is especially significant in this region. During 1996-2006, total production grew from around R$ 126,000 M in 1996 to more than R$ 222,000 M in 2006. In addition, the number of cattle ranged from 1,973,000 in 1996 to 5,290,000 in 2006. The region was the most impacted by the beef industry moratorium (Table 4.2). During this period, temporary agriculture decreased, while permanent agriculture remained constant. The region featured approximately 865 sq km of temporary agriculture and 82 sq km of permanent agriculture in 2009 (Table 4.1).

CENTRO MATO GROSSO

The *Centro Mato Grosso* region covers 15 municipalities in the state of Mato Grosso and encompasses a total area of 117,150 sq km (Appendix 4A). The region is covered by a few settlements, indigenous lands and protected areas (Appendix 4B). This area has been dominated by small farms (in number), however, the amount of medium and large properties are significant. Large properties (properties ranging from 500ha to more than 500ha) represented 24.23% and 18.44% of the total number of properties in 1996 and 2006, respectively (Figure 4.8). Important activities in the region's economy include cattle farming activities and soybean production. During this period, *Centro Mato Grosso* accounted for most of the increase in cropland area from new deforestation. Soybean is driven by global market forces, which is different from many of the land use changes that have dominated the scene across the Brazilian Amazon.

During 1996-2006, total production grew from approximately R$ 262,000 M in 1996 to more than R$ 2,421,000 M in 2006. The number of cattle ranged from 1,053,051 in 1996 to 1,324,416 in 2006. The temporary agriculture reached 31,665 sq km in 2008, and the highest level of permanent agriculture was 156 sq km in 2009 (Table 4.1). The agro-business sector in the region has become more competitive and has intensified soybean production by increasing mechanization and improving farm productivity. The expansion of soybean cropland into areas that were previously covered by forest was one of the main causes of deforestation in the state of Mato Grosso, contributing to 17% of the total forest loss during 2000-2004 (Morton et al., 2008). After 2006, the region was mostly impacted by the soy moratorium monitoring program (Table 4.2) (Rudorff et al., 2011).

4.4. Discussion and Conclusions

To investigate the deforestation trends in each subregion during 2002-2009, the yearly proportion of deforestation was compared. Figure 4.10 shows the national deforestation rates and trends in each subregion. During this period, we found unequal trends in deforestation over these six regions. The data show that large gaps in frequency and magnitude existed across these regions. Although it is possible to see a common pattern of decreased deforestation among the regions, the changes differ significantly for each subregion. It is also apparent that the fluctuations at the national level (annual deforestation and rates) are not a direct reproduction of the trends at the subregional level. Although we used deforestation data from PRODES to analyze the trends at both the national and subregional levels, it is important to clarify that PRODES provides detailed spatial information each year about new deforestation areas (increments) identified from satellite images (Figure 4.7), and this information is used to compute the annual rates (sq km per year). The annual deforestation rates are non-spatial information that are computed using the date of August 1st as a reference, according to the methodological approach described by PRODES (INPE, 2011). The annual rates are computed using a formula that considers the image acquisition dates and missing data. Depending on the year, this may cause differences when the simple sum of the increments is compared to the annual rates (see Figure 4.10).

We also analyzed the association between the number of environmental fines applied in each subregion (Figure 4.9) and the resulting deforestation trends (Figure 4.10). We found that there is a negative association between enforcement actions and deforestation in four of the six regions (*Baixo Amazonas*, *BR163*, *Transamazônica*, and *Sul Pará*). Such actions were coordinated by another Amazon monitoring program (DETER), which detects deforestation on a monthly basis. In 2007, for example, when DETER showed that deforestation had doubled in November compared to the same period in the previous year, the government prioritized field inspections in critical municipalities. In 2008, such field operations also resulted in fines and confiscation of equipment and goods related to the environmental crimes.

Figure 4.10 shows that the *Baixo Amazonas* region, for example, maintained a constant rate of deforestation during 2002-2009, accounting for less than 500 sq km of deforested area per year. Although the changes across the region as a whole appear to be blocked by the creation of protected areas, the Santarém area faced major changes during this period, mostly related to soybean production. In the past, the deforestation around the Santarém area was mainly impacted by human occupation, which occurred in waves of economic cycles and immigration. Most migrants in the region took up subsistence farming, and because the area is covered by dry and light soil well suited for mechanized agriculture, the soybean was introduced. Producers from Mato Grosso were encouraged to acquire land in Santarém and Belterra, and they were supported by EMBRAPA (Brazilian Enterprise for Agricultural Research), who developed soybean varieties that were adapted to the region. In 2007-2008, the Santarém area reached 28,000 hectares of soybean production, which represented approximately 3% of the movements through Cargill’s port in Santarém. The most important reasons for this controlled development are the pressure of the soy moratorium after 2006 and the lack of formal land tenure hindering access to financial credit (Lima et al., 2011). On the other hand, the *Nordeste Pará* region, which also maintained a constant amount of deforestation during 2002-2009, had also less than 500 sq km deforested in 2009. In this region, the agrarian structure is dominated by small farmers, and the cattle are widely distributed across the area, contrary to the common view of cattle on large ranches.

There, cattle appear nearly as productive as crops, although cattle are mainly preferred as a means of financing because it is the best option for large and flexible cash reserves.

Both the *BR163* and *Transamazônica* regions faced major forest changes along the same period, and currently, they are mostly covered by protected areas and indigenous lands. In the *BR163* region, the trend of deforestation started to decrease in the 1980s, due to the waning support for settlements and the decaying of the road system (Brondizio and Moran, 2011). The agrarian structure of the region was driven by international market demands for soybeans and new export infrastructure facilities that also intensified land conflicts and illegal land appropriation. There, the most significant decrease in deforestation occurred in 2004, and after that, the amount of deforestation continued at below 10,000 sq km per year. On the other hand, the *Transamazônica* region maintained a minor decrease in deforestation per year, varying from less than 2,000 sq km in 2002 to less than 1,000 sq km in 2009. This region is an example of government-induced colonization centered in small farms, which benefited from better soils and water availably. On average, land tenure is more secure in this region than in other parts of Pará (Walker et al., 2000).

Finally, the most significant changes in forest clearing were observed in *Sul Pará* and *Centro Mato Grosso* regions. The *Sul Pará* region is an area recognized by land speculation, cattle expansion and large amounts of deforestation since the 1990s. Road construction, investments in electrical energy, financial credit for cattle, and land reform policies have all fueled the region, turning it into one of the most dynamic agricultural frontiers in the Brazilian Amazon. The region is also famous for violent land struggle. In 2005, deforestation in the region reached almost 3,500 sq km, but was reduced to less than 1,500 sq km in 2006. Since 2009, the region has also been impacted by the beef industry moratorium, in which four of the world’s largest cattle producers and traders have agreed to a moratorium on buying cattle from newly deforested areas. Finally, the *Centro Mato Grosso* region has also faced major changes in altering the trend of deforestation, reaching almost 3,000 sq km in 2004, but less than only 500 sq km in 2009. During 2002-2009, the deforestation trend across the region was closely associated with temporary agriculture trends. In this area, the presence of roads and the price of agricultural products are the major factors that influence the conversion of forest to agricultural land. Moreover, in a scenario when soybean prices are very attractive, recently deforested land appears to be intensively mechanized for land clearing and soybean production. In this region, the landscape consists of large, highly mechanized soybean farms, many covering thousands of hectares.

The overall discussion about the factors that were responsible for reducing deforestation during these seven consecutive years (2005-2011) is quite limited when analysis is conducted at a national level. At this level, either national environmental policies or market pressures appear to be enough to explain the large decrease in the national deforestation rates. In a moment of stringent economic conditions and harsh environmental debates, the selection of one simple main factor seems imprudent, mainly because declining deforestation has coincided with the implementation of policy measures to reduce deforestation and a collapse of commodity markets. Moreover, although the data show that the decrease is a common pattern across the entire region, the trends of reduction differ significantly among the subregions.

Hence, focusing the analysis of deforestation on a subregional level allows us to: (i) better understand the major factors affecting deforestation in each subregion; (ii) analyze the complexity of the social dimensions of deforestation; (iii) determine the spatiotemporal variability of deforestation; and (iv) support the formulation of more effective public policies for local actions. The impacts of major factors also differ between each region, given their human occupation histories and agrarian structure. When the entire Brazilian Amazon is considered, deforestation is often explained by infrastructure, colonization network and the mosaic of public lands. At certain subregions, other factors, such as the application of environmental fines, are even more relevant.

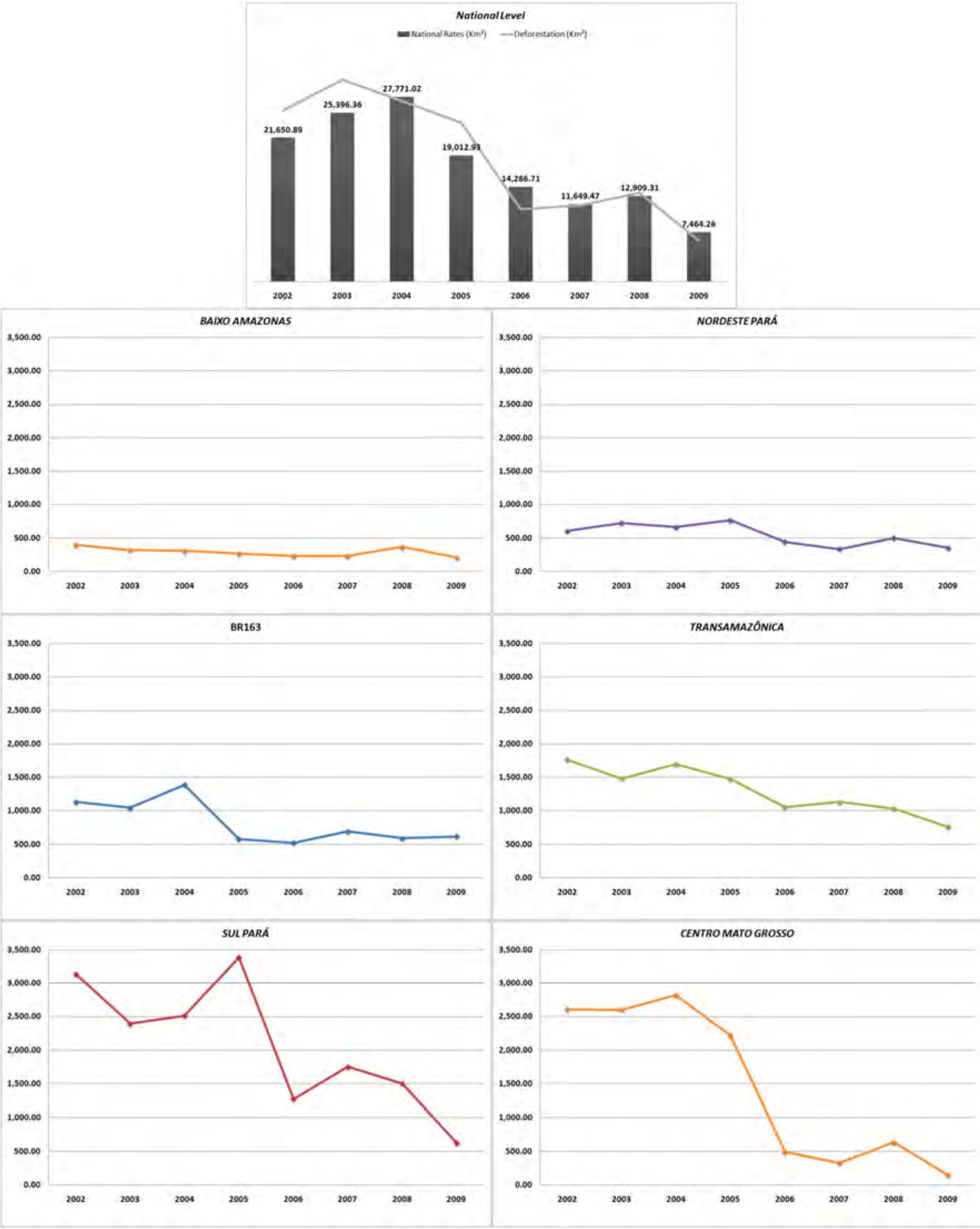


Figure 4.10 – Trends of deforestation in each subregion from 2002 to 2009

5. FINAL REMARKS

This thesis presented a couple of advances related to the development and exploration of quantitative and qualitative methods to investigate deforestation trends in the Brazilian Amazon over the last decade. Its main contributions were:

- A database of spatiotemporal variables related to deforestation in the Brazilian Amazon, available at two spatial resolutions and which allows for national and subregional level analyses.

- An implementation of an open methodological approach for a spatially explicit time series of agricultural land use data which allows the analysis of the spatiotemporal patterns of deforestation and agricultural uses within the Brazilian Amazon.

- An interpretation of the differences between standardized regression coefficients for 1996/1997 and 2006/2007 as temporal changes in the influence of determinant factors on deforestation and agricultural uses over the states of Pará, Rondônia and Mato Grosso.

- An implementation of statistical analysis for spatiotemporal data which directly model and explain spatiotemporal changes in the annual deforestation for 25 km x 25 km grid cells covering the entire Brazilian Amazon during 2002 to 2009, when the deforestation underwent marked variability. The results obtained in this thesis confirm previous regional-scale findings that related deforestation and commodity prices. In addition, we also showed that the influence of national environmental policies is quite significant and has been increasing over the years.

- A subregional quantitative and qualitative analysis showing the decrease in deforestation as a common pattern across the entire Brazilian Amazon, and showing that such trend of decrease differ significantly among subregions.

Additionally, this thesis recognized that land use changes observed at any spatiotemporal scale involves complex synergy with changes observed at other scales. Regarding the statistical analysis for spatiotemporal data, we believe that we have only begun to realize the potential of modeling complex spatiotemporal analyses.

Finally, we believe the Brazilian Amazon is facing a new paradigm of economic growth, social equality and environmental sustainability. In that sense, we argue that a sustainable development could be better achieved by an integrated policy framework which improves coherence at the subregional, national and international levels, considering the changes in the political dynamics and in the global and national economy.

REFERENCES

Achard, F., H. D. Eva, et al. (2002). "Determination of deforestation rates of the world's humid tropical forests." Science **297**(5583): 999 - 1002.

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

Aguiar, A. P. D., G. Câmara, et al. (2007). "Spatial statistical analysis of land-use determinants in the Brazilian Amazonia: exploring intra-regional heterogeneity." Ecological Modelling **Volume 209**(Issues 2-4): Pages 169-188

Alves, D. S. (2002). "Space-time dynamics of deforestation in Brazilian Amazonia." International Journal of Remote Sensing **23**(14): 2903-2908.

Alves, D. S. (2007). Cenários de cobertura e uso da terra e dimensões humanas no LBA. Dimensões humanas da biosfera-atmosfera na Amazônia. B. K. Becker, D. S. Alves and W. d. Costa. São Paulo, EDUSP**:** 39-63.

Alves, D. S., D. C. Morton, et al. (2009). The changing rates and patterns of deforestation and land use in Brazilian Amazonia. Amazonia and Global Change, Geophysical Monograpf Series 186.

Alves, D. S., D. C. Morton, et al. (2009). The changing rates and patterns of deforestation and land use in Brazilian Amazonia. Amazonia and Global Change, Geophysical Monograph Series 186.

Andersen, L. E. and E. J. Reis (1997). Deforestation, development, and government policy in the Brazilian Amazo: an econometric analysis. Brasília, Brazil, IPEA.

Andrade, P. R., P. J. Ribeiro, et al. (2005). Integration of statistics and geographic information systems: the R/TerraLib case. VII Brazilian Symposium on Geoinformatics, Campos do Jordão, Brazil.

Angelsen, A. (1997). "Deforestation: population or market driven?" Development Studies and Human Rights **Working Paper**: 42.

Arima, E. Y., P. Richards, et al. (2011). "Statistical confirmation of indirect land use change in the Brazilian Amazon." Environmental Research Letters **6**(2).

aRT-Team (2010). aRT - R package that provides the integration to the GIS library TerraLib. São José dos Campos, UFPR.

Barona, E., N. Ramankutty, et al. (2010). "The role of pasture and soybean in deforestation of the Brazilian Amazon." Environ. Res. Lett. **5**: 024002.

Becker, B. (2005). "Geopolítica da Amazônia." Journal of the Institute of Advanced Studies of the University of Sao Paulo **19**: 71-86.

Becker, B. K. (2001). "Revisão das políticas de ocupação da Amazônia: é possível identificar modelos para projetar cenários?" Parcerias Estrategicas **12**: 135-159.

Bivand, R. S., E. J. Pebesma, et al. (2008). Applied Spatial Data Analysis with R Use R

Brazil, G. o. (2004). Plano de Ação para a Prevenção e Controle do Desmatamento na Amazônia Legal. G. p. d. t. i. p. a. r. d. í. d. d. d. A. Legal. Brasília.

Brazil, G. o. (2008). National Plan on Climate Change. I. C. o. C. Change. Brasília.

Britannica (2008). Britannica Online Encyclopedia. Available online at: http://www.britannica.com/.

Câmara, G., A. P. D. Aguiar, et al. (2005). "Amazonian deforestation models." Science **307**(5712): 1043 - 1044.

Cardille, J. A. and J. A. Foley (2003). "Agricultural land-use change in Brazilian Amazônia between 1980 and 1995: Evidence from integrated satellite and census data." Remote Sensing of Environment **87**(4): 551-562.

Carvalho, G., A. C. Barros, et al. (2001). "Sensitive development could protect Amazonia instead of destroying it." Nature **409**(6817): 131.

Carvalho, G., P. Moutinho, et al. (2004). "AN Amazon Perspective on the Forest-Climate Connection: Opportunity for Climate Mitigation, Conservation and Development?" Environment, Development and Sustainability **6**(1): 163-174.

Chambers, J. Q., G. P. Asner, et al. (2007). "Regional ecosystem structure and function: ecological insights from remote sensing of tropical forests." Trends in Ecology & Evolution **22**(8): 414-423.

Cressie, N. and C. K. Wikle (2011). Statistics for spatio-temporal data. New York, Wiley.

de Espindola, G. M., A. P. D. de Aguiar, et al. (2012). "Agricultural land use dynamics in the Brazilian Amazon based on remote sensing and census data." Applied Geography **32**(2): 240-252.

Dietz, T., E. Ostrom, et al. (2003). "The Struggle to Govern the Commons " Science **Vol. 302**(no. 5652): pp. 1907 - 1912.

Fearnside, P. M. (1990). "The rate and extent of deforestation in Brazilian Amazonia." Environmental Conservation **17**: 213-226.

Fearnside, P. M. (1996). "Amazonian deforestation and global warming: carbon stocks in vegetation replacing Brazil's Amazon forest." Forest Ecology and Management **80**: 21-34.

Fearnside, P. M., A. T. Tardin, et al. (1990). Deforestation rate in Brazilian Amazonia. São José dos Campos, Brazil, Instituto Nacional de Pesquisas Espaciais.

Geist, H. J. and E. F. Lambin (2001). What drives tropical deforestation?, LUCC Report Series No. 4. **37:** 136p.

Geist, H. J., W. McConnell, et al. (2006). Causes and trajectories of land-use/cover change. Land-use and land-cover change, local process and global impacts. E. F. Lambin and H. Geist, Springer Berlin Heidelberg.

Gibson, C., M. A. McKean, et al. (2000). People and Forests. Communities, Institutions and Governance. Cambridge and London.

IBGE (1996). Censo Agropecuário 1996, Insituto Brasileiro de Geografia e Estatística.

IBGE (2006). Censo Agropecuário 2006, Insituto Brasileiro de Geografia e Estatística.

IBGE (2008). Population Count 2007, Rio de Janeiro, IBGE. Available on-line at http://www.ibge.gov.br/home/estatistica/populacao/contagem2007/.

IBGE (2011). Population Count 2007, Rio de Janeiro, IBGE. Available on-line at http://www.ibge.gov.br/home/estatistica/populacao/contagem2007/.

INPE (2011). PRODES - Amazon deforestation database, São Jose dos Campos, INPE. Available online at: www.obt.inpe.br/prodes.

IPCC (2007). Climate change 2007: synthesis report. An Assessment of the Intergovernmental Panel on Climate Change, Intergovernmental Panel on Climate Change.

IPCC (2007). Summary for Policymakers. Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, United Kingdom and New York, NY, USA., Cambridge University Press.

IPEA (2008). Instituto de Pesquisa Econômica Aplicada.

Lambin, E. F. (1994). Modelling deforestation processes: a review. Research Report 1. Brussels, European Commission.

Lambin, E. F. and H. Geist, Eds. (2006). Land-use and land-cover change: local processes and global impacts. Berlim.

Lambin, E. F., H. Geist, et al. (2006). Introduction: local processes with global impacts Land-use and land-cover change, local process and global impacts. E. F. Lambin and H. Geist, Springer Berlin Heidelberg.

Lambin, E. F. and P. Meyfroidt (2011). "Global land use change, economic globalization, and the looming land scarcity." Proceedings of the National Academy of Sciences **108**(9): 3465-3472.

Laurance, W. F., A. K. M. Albernaz, et al. (2004). "Deforestation in Amazonia." Science **304**(5674): 1109 - 1111.

Laurance, W. F., A. K. M. Albernaz, et al. (2002). "Predictors of deforestation in the Brazilian Amazon." Journal of Biogeography **29**: 737–748.

Leite, C. C., M. H. Costa, et al. (2010). "Historical reconstruction of land use in the Brazilian Amazon (1940-1995)." Journal of Land Use Science **1-20**.

LeSage, J. P. and R. K. Pace (2009). Introduction to spatial econometrics, CRC Press.

Machado, L. O. (1998). A fronteira agrícola na Amazônia brasileira. Geografia e meio ambiente no Brasil. A. Christofoletti, B. K. Becker, F. R. Davidovich and P. P. Geiger. São Paulo, Companhia das Letras**:** 181-217.

Malingreau, J., H. Eva, et al. (2011). "Brazilian Amazon: A Significant Five Year Drop in Deforestation Rates but Figures are on the Rise Again." AMBIO: A Journal of the Human Environment: 1-6.

Margulis, S. (2004). Causes of deforestation of the Brazilian Amazon. W. B. w. paper, World Bank working paper, no.22.

Moran, E. F., E. S. Brondízio, et al. (2005). Population and Environment in Amazônia: Landscape and Household Dynamics. Population, Land Use, and Environment. N. R. Council.

Morton, D. C., R. DeFries, et al., Eds. (2009). Cropland expansion in cerrado and transition forest ecosystems: quantifying habitat loss from satellite-based vegetation phenology. Cerrado Land-Use and Conservation: Assessing Trade-off's Between Human and Ecological Needs. Washington D. C.

Nepstad, D., B. S. Soares-Filho, et al. (2009). "The End of Deforestation in the Brazilian Amazon." Science **326**(5958): 1350-1351.

Nobre, A. C., G. N. Sebestyen, et al. (1997). "Functional localization of the system for visuospatial attention using positron emission tomography." Brain **120**(3): 515-533.

Payton, M. E., M. H. Greenstone, et al. (2003). "Overlapping confidence intervals or standard error intervals: What do they mean in terms of statistical significance?" Journal of Insect Science **3**(34).

Perz, S. G. and D. L. Skole (2003). "Social determinants of secondary forests in the Brazilian Amazon." Social Science Research **32**(1): 25-60.

Peters, G. P., G. Marland, et al. (2012). "Rapid growth in CO2 emissions after the 2008–2009 global financial crisis." Nature Climate Change **2**(2–4).

Pfaff, A. S. P. (1996). What drives deforestation in the Brazilian Amazon? Evidence from satellite and socioeconomic data. New York, The World Bank, Policy Research Department.

Piribauer, T. (2010). Land-use change modeling in the Brazilian Amazon - Exploring the impact of environmental factors. Diplomarbeit, Vienna University of Technology.

Quéré, C. L., M. R. Raupach, et al. (2009). "Trends in the sources and sinks of carbon dioxide." Nature Geoscience **Vol 2.**

R-Team, R. D. C. (2005). R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing.

Ramankutty, N. and J. A. Foley (1999). "Estimating historical changes in global land cover: Croplands from 1700 to 1992." Global Biogeochemical Cycles **13**(4): 997-1027.

Reis, E. J. and R. M. Guzmán (1992). An Econometric Model of Amazon Deforestation. Brasília, Brazil, IPEA.

Rudorff, B. F. T., M. Adami, et al. (2011). "The Soy Moratorium in the Amazon Biome Monitored by Remote Sensing Images." Remote Sensing **3**(1): 185-202.

Rylands, A. B. and K. Brandon (2005). "Brazilian Protected Areas." Conservation Biology **Volume 19**(3): 612–618.

Salazar, L. F., C. A. Nobre, et al. (2007). "Climate change consequences on the biome distribution in tropical South America." Geophysical Research Letters **Vol. 43**: 6.

Shimabukuro, Y., V. Duarte, et al. (2007). "Near real time detection of deforestation in the Brazilian Amazon using MODIS imagery." Ambiente & Água- An Interdisciplinary Journal of Applied Science.

Shukla, J., C. A. Nobre, et al. (1990). "Amazon deforestation and climate change." Science **247**(4948): 1322 - 1325.

Skole, D. and C. Tucker (1993). "Tropical Deforestation and Habitat Fragmentation in the Amazon: Satellite Data from 1978 to 1988." Science **260**(5116): 1905-1910.

Soares-Filho, B., P. Moutinho, et al. (2010). "Role of Brazilian Amazon protected areas in climate change mitigation." Proceedings of the National Academy of Sciences **107**(24): 10821-10826.

Soares-Filho, B., D. Nepstad, et al. (2006). "Modelling conservation in the Amazon basin." Nature **440**(7083): 520-523.

Soler, L. d. S. and P. H. Verburg (2010). "Combining remote sensing and household level data for regional scale analysis of land cover change in the Brazilian Amazon." Regional Environmental Change **DOI: 10.1007/s10113-009-0107-7**.

Sombroek, W. G. (1966). Amazon soils. A reconnaissance of the soils of the Brazilian Amazon region. Wageningen, NL, Centreÿfor Agricultural Publishing and Documentation (PUDOC).

TerraView (2010). TerraView - a GIS application built using the TerraLib GIS library. São José dos Campos, INPE.

Valeriano, D. M., E. M. K. Mello, et al. (2004). Monitoring tropical forest from space: the PRODES digital project. ISPRS, Istanbul.

Verburg, P. H., K. Kok, et al. (2006). Modelling land-use and land-cover change. Land-use and land-cover change, local process and global impacts. E. F. Lambin and H. Geist, Springer Berlin Heidelberg.

APPENDIX A – COMBINING SATELLITE REMOTE SENSING AND CENSUS DATA TO QUANTIFY AGRICULTURAL LAND USE CHANGE IN THE BRAZILIAN AMAZON[7]

Abstract

As pasture and cropland have replaced forest cover in the Brazilian Amazon, the creation of spatial explicit time series of land use is an important concern in modeling land change. Despite much progress in mapping deforestation using satellite remotely sensed data, little is known about the distribution of agricultural land uses that replace forest cover in the Brazilian Amazon. In this appendix we present a methodology to integrate satellite remote sensing and census data over 1996/1997 and 2006/2007 periods. Our resulting land use maps show the distribution and proportion of pasture as well as, temporary and permanent agriculture across the region. More than show an overall expansion of the total agricultural area between 1997 and 2007, our mapped land use time series aim to describe the effects of land use changes across the region over one decade.

Resumo

Considerando que pastagens e plantações têm substituído a cobertura de floresta na Amazônia Brasileira, a criação de séries temporais espacialmente explícitas de usos agrícolas é uma preocupação importante na modelagem das mudanças de uso da terra. Apesar dos avanços no monitoramento do desflorestamento pelo uso de dados de sensoriamento remoto, pouco se sabe ainda sobre a distribuição dos usos agrícolas que substituem a cobertura de floresta na Amazônia Brasileira. Neste apêndice nós apresentamos uma metodologia para a integração dos dados de sensoriamento remoto e censos agropecuários nos períodos de 1996/1997 e 2006/2007. Nossos mapas resultantes mostram a distribuição e a proporção de pastagem e de agriculturas temporárias e permanentes na região. Mais do que mostrar uma expansão da área

[7]This appendix is the exact version of the paper: de Espindola, G.M., de Aguiar, A.P.D., Andrade, P.R.d. (2012) Combining satellite remote sensing and census data to quatify agricultural land use change in the Brazilian Amazon. Revista Brasileira de Cartografia no prelo.

agrícola total entre 1997 e 2007, nossas séries temporais de usos agrícolas objetivam descrever os efeitos dessas mudanças na região durante uma década.

A1. Introduction

Investigating change in land cover and land use has been considered a key theme linked to deforestation in the Brazilian Amazon (Angelsen 1997; Machado 1998; Verburg, Kok *et al*. 2006). Data on forest loss have relied mostly on satellite remote sensing, measuring the extent of tropical deforestation. In the last three decades, the advent of remote sensing satellites has led to the development of instruments to systematically monitor land cover from space.

With 30m spatial resolution multispectral data, Landsat has become the workhorse of land cover change studies. These studies begin with data interpretation for the Brazilian Amazon, quantifying the location and amount of deforestation, which is a precursor of agricultural activity in many areas (Alves 2002; Cardille and Foley 2003; Lambin, Geist *et al*. 2006).

Few countries have projects to monitor change in forest cover that have been in place for several decades, most notably Brazil (Shimabukuro, Duarte et al. 2007; INPE 2011). INPE has four operating systems for monitoring deforestation in the Brazilian Amazon: PRODES, DETER, QUEIMADAS and DEGRAD. These systems aim to analyze the full land cover dynamics in the region.

Although the rates of forest loss have been examined across the Brazilian Amazon, little is known about the transition from mature forest to agricultural land uses. In this area, distribution, abundance and types of land use, distinctly from land cover, still need to be better understood.

The significant knowledge gaps related to the dynamics of human occupation across the region illustrate the need for a spatially explicit time series of agricultural land use data. Such time series could provide land change model inputs like land use history and condition of an area, while facilitating stronger projections of future scenarios (Cardille and Foley 2003; Aguiar 2006; Lambin, Geist *et al*. 2006; Alves, Morton *et al*. 2009).

Most information about agricultural land use in the Brazilian Amazon comes from agricultural census data (IBGE 1996; IBGE 2006). Agricultural censuses form the most complete survey of land management, including areas under different land use categories (pasture versus crops, for example), levels of mechanization and agricultural inputs, and allowing for detailed analyses of social, economic, and environmental aspects of agriculture across the region (Cardille and Foley 2003; Alves, Morton *et al*. 2009).

Historically, agricultural areas in the Brazilian Amazon have increased by bringing more land into production. However, cropland expansion and agricultural intensification have varied across the region. Pará, for example, was characterized by the greatest expansion of pasture, increasing the area under production from 58,249 sq km in 1996 to 90,433 sq km in 2006 (IBGE 1996; IBGE 2006). On the other hand, in Mato Grosso, the area of temporary agriculture increased from 27,824 sq km in 1996 to 57,344 sq km in 2006, showing a high level of mechanization (IBGE 1996; IBGE 2006).

While it does not seem to be possible to create land use data using only satellite images, such information is crucial (Lambin, Geist *et al*. 2006). In this appendix we present a methodology to combine satellite remote sensing and census data to quantify the distribution and fraction of major agricultural land uses – pasture, temporary and permanent agriculture – in the Brazilian Amazon. This work comparatively quantifies the distribution of the main land uses in 1996/1997 and 2006/2007 periods.

The appendix is organized as follows. Section A2 presents a review of previous work. Section A3 presents the study area and spatial resolution. Section A4 presents the methodology used to combine satellite remote sensing and census data over 1996/1997 and 2006/2007 periods. Section A5 presents and discusses the resulting land use maps.

A2. Related work

Methodological advances in providing spatial explicit time series of agricultural land use have captured the corresponding spatial detail needed for studies of land change and future landscape scenarios (Ramankutty and Foley 1999; Cardille and Foley 2003; Leite, Costa *et al*. 2010).

Ramankutty and Foley (1999), for example, presented an approach to derive geographically explicit changes in global croplands from 1700 to 1992. To reconstruct historical croplands, they basically used a remotely sensed land cover classification data set against cropland inventory data. From their 1992 cropland data within a land cover change model, they reconstructed global 5 minute resolution data on permanent cropland areas from 1992 back to 1700.

Another example comes from Cardille and Foley (2003). They used census and satellite records to develop maps of the distribution and abundance of agricultural land uses across the Amazon in 1980 and 1995. In that work, the census-derived information in 1995/1996 was used to estimate agricultural activities in 1980, and from that time they generated a regression tree that statistically linked census and land cover classification data.

Finally, Leite and Costa *et al*. (2010) reconstructed and validated spatial explicit time series of land use in the Brazilian Amazon for the period 1940-1995, through a fusion of historical census data and contemporary land use classification. There, they fitted a linear regression model for land use change over time for each municipality, and the regression equation was used to replace any excluded data.

Although previous studies analyzed the reconstruction of historical agricultural land uses fusing remote sensing and census data, such reconstruction has not been carried out in Brazil since 2006 Agricultural Census was launched. In fact, no methodological approach was presented in a way which could be easily updated.

A3. Study area and spatial resolution

The study area is the Brazilian Amazon rainforest, which covers an area of more than 5 million sq km. In our database, all attributes representing deforestation and land uses – pasture, temporary and permanent agriculture – were aggregated to grid cells of 25 km x 25 km, counting a total of 8580 cells (Figure A1). Our grid cells were created into the *TerraView* application, meaning that the resulting database respected the GIS library *TerraLib* standards (TerraView 2010).

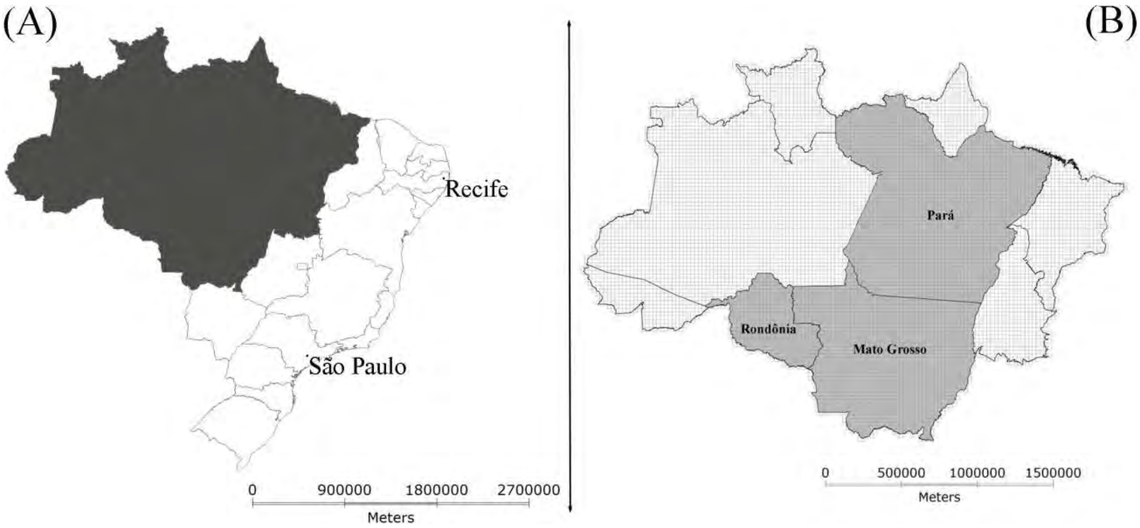


Figure A1 – (A) Map of Brazil showing the location of the Brazilian Amazon region (all in darker gray), and the location of São Paulo and Recife cities. (B) Regular grid of 25 km x 25 km over the Brazilian Amazon region; the states of Pará, Rondônia and Mato Grosso are shown in gray.

A4. Combining satellite remote sensing and census data

In this section we summarize the methodology used to combine satellite remote sensing and census data over 1996/1997 and 2006/2007 periods. Our methodology was processed using *aRT*, an *R* package that provides an integration between the statistical software *R* and *TerraLib* (Andrade, Ribeiro *et al*. 2005).

The *aRT* package was useful to easily integrate our *TerraLib* database (*"db_25k"*) to the statistical functionalities available in *R*. In addition, *R* environmental allows a good reproduction of the presented results by use of scripts.

A4.1. Deforestation maps

A4.1.1 PRODES methodology

We started from the Landsat TM-based deforestation maps produced under the Amazon-monitoring program (PRODES) of INPE (INPE 2011). The first digital version of these deforestation maps was created in 1997, and since 2000 they have been produced annually. PRODES uses an automatic procedure to analyze TM images based on techniques of *linear spectral mixture model*, *image segmentation* and *classification by regions* (Valeriano, Mello *et al*. 2004).

To estimate the extension of deforested areas for 1997 TM images, a shade fraction image was used by INPE, which enhances the difference between forest and deforested areas. To estimate the increment of deforested areas from 2000, soil fraction images were used, mainly because they enhance the difference between forest and recent clear cut areas (Valeriano, Mello et al. 2004; INPE 2011).

A4.1.2 Our methodology

From PRODES 2008 deforestation map, we selected the PRODES class labels needed to create the cumulated deforestation (extension of deforestation) maps for 1997 and 2007. All classes of deforestation occurring until 1997 and 2007 were computed, respectively (Appendix AA). Figure A2 presents the deforestation map with its classes covered by our grid of cells.

Appendix AB shows how we computed the proportion of cumulated deforestation for each cell of our grid of 25 km x 25 km in 1997 and 2007. We present the *aRT* script used to compute the values into each cell. Beginning with the DBMS connection to the MySQL database (*"db_25k"*), we selected our layers of deforestation map (*"PRODES_1997_2008"*) and cells (*"AMZ_CELULAR_25000"*). Afterwards, we selected the labeled pixels inside each cell.

The proportion of each class label was defined based on the PRODES methodology, meaning that the class labels were quantified considering the cloud cover over time. For example, polygons in the PRODES 2008 deforestation map labeled with *"D1997_0"* represent deforested areas detected in 1997 (*"D1997"*), counting 0 years of previous cloud cover over these polygons (*"_0"*). In the same way, polygons labeled with *"D2000_3"* represent deforested areas detected in 2000 (*"D2000"*), counting 3 years of previous cloud cover over these polygons (*"_3"*), and so on and so forth. For 1997, we show Equation A1 as one example:

$$\begin{aligned} \mathit{acumul1997}=(&\mathit{length}(\mathit{which}(\mathit{pixels}==42)) \\ &+0.25*\mathit{length}(\mathit{which}(\mathit{pixels}==45)) \\ &+0.2*\mathit{length}(\mathit{which}(\mathit{pixels}==48)) \\ &+0.17*\mathit{length}(\mathit{which}(\mathit{pixels}==5)) \\ &+0.14*\mathit{length}(\mathit{which}(\mathit{pixels}==10)) \\ &+0.13*\mathit{length}(\mathit{which}(\mathit{pixels}==16)) \\ &+0.11*\mathit{length}(\mathit{which}(\mathit{pixels}==23))) \end{aligned} \qquad \text{(A1)}$$

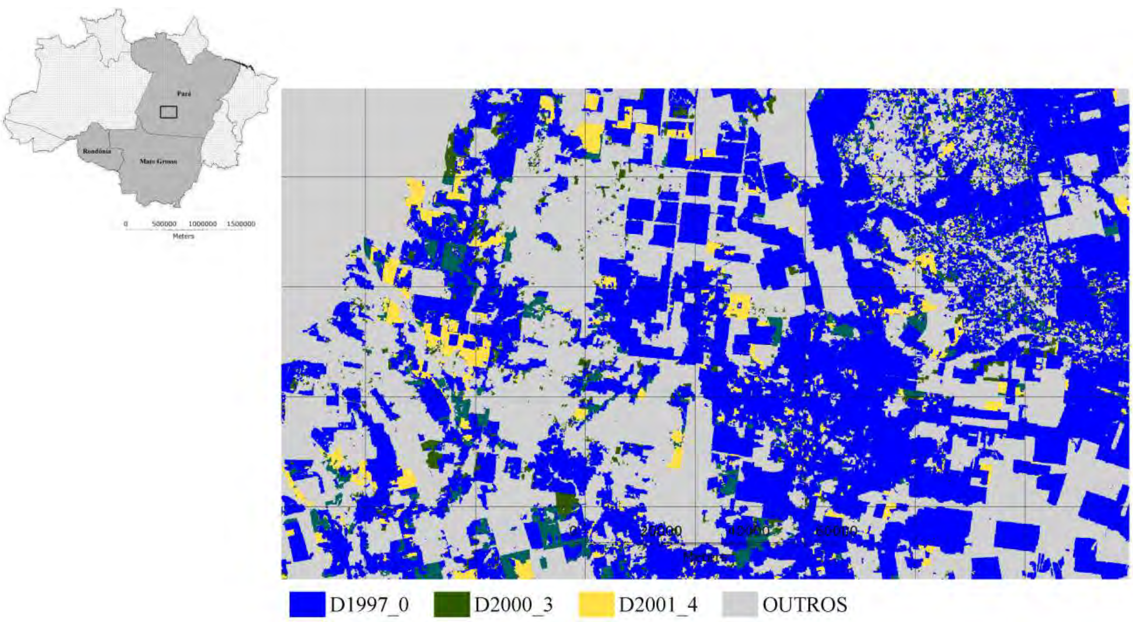


Figure A1 – Regular grid of 25 km x 25 km over PRODES deforestation map.

Finally, we divided the number of labeled pixels by the total number of pixels inside the cell, and wrote the results into the database (*"ACUM_1997"*).

A4.2. Land use maps

The cumulated deforestation in 1997 and 2007 was decomposed into the following main agricultural uses – pasture, temporary and permanent agriculture – combining the PRODES deforestation map in 1997 and 2007 and census information from municipality-based Agricultural Census in 1996 and 2006, respectively (IBGE 1996; IBGE 2006).

Census data were converted from polygon-based information to grid cells of 25 km x 25 km. The location of agricultural areas for each municipality was taken from the deforestation map (computed previously – Section A4.1.2). On the other hand, the proportion of each agricultural use within each cell was taken from the census data (Appendix AC).

The proportion of each agricultural use was computed for each municipality considering the total area of each land use (pasture, for example) divided by the area of this municipality. In our methodology we assumed that the proportion of land use types was uniformly distributed over the deforested areas of each municipality (Aguiar 2006; Aguiar, Câmara *et al*. 2007).

In Appendix AC, we present the *aRT* script used, and the description of the steps are similar to the ones described in section A4.1.2. The difference here is that we also selected the layer related to census data (*"CENSO_1996_625"*), which gives us the proportion of each agricultural use for each municipality.

In that *aRT* script, we first selected the intersections between each cell with each municipality (*getClip*). For each intersection, we computed the number of total labeled pixels multiplied by the proportion of the land use (pasture, in this example). This result is computed for each intersection inside one cell, and then added and multiplied by the resolution of the pixel (100m), and divided by the area of the cell (25 km x 25 km).

A5. Results and discussion

This section summarizes the main findings and compares the results obtained by land use time series in 1996/1997 and 2006/2007 periods. Table A1 shows the trends in the four land uses across the Brazilian Amazon, expressed as number of grid cells in which the proportion under the given land use is more than 10%. Additional results are shown by Espindola and Aguiar *et al*. (2012).

Figure A3 shows that deforestation increased over these 10 years (1997-2007), and also that it tends to occur close to previously deforested areas, showing a strong spatial structure, as pointed out by other authors (Alves, Morton *et al*. 2009). Figure A4 shows that pasture spread over the whole deforested areas, being the major land use in both periods (1997 and 2007), and has increased following the deforestation patterns. Pasture was also established mainly across eastern Pará, central Rondônia, and north of Mato Grosso.

For temporary agriculture, as shown in Figure A5, two states deserve attention. In Maranhão, temporary agriculture moved from the center to the north of the state. In Mato Grosso, the area increased more than 100% from 1996 to 2006 (IBGE 1996; IBGE 2006). The forest conversion to cropland in Mato Grosso represents a case of particular interest due to massive investments made by commercial soybean farmers, as well as to the success of farming systems and crop breeding research. On the other hand, permanent agriculture is the smallest agricultural land use category in the study area. Over ten years, it was replaced by pasture in Rondônia, but increased in some areas of the northeast of Pará, as shown in Figure A6.

In both periods, overall agricultural activities were concentrated in the southeast region of the study area, especially across eastern Pará, central Rondônia, and north of Mato Grosso. From these areas and isolated patches, agricultural activity rapidly spread over 1996/1997 and 2006/2007 periods.

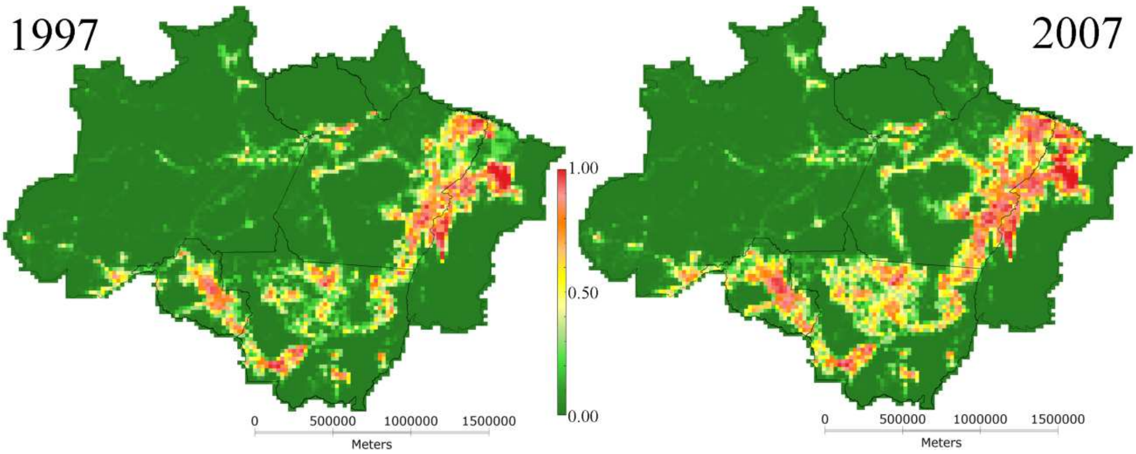


Figure A3 – Proportion of cumulative deforestation for each cell in 1997 (left) and 2007 (right).

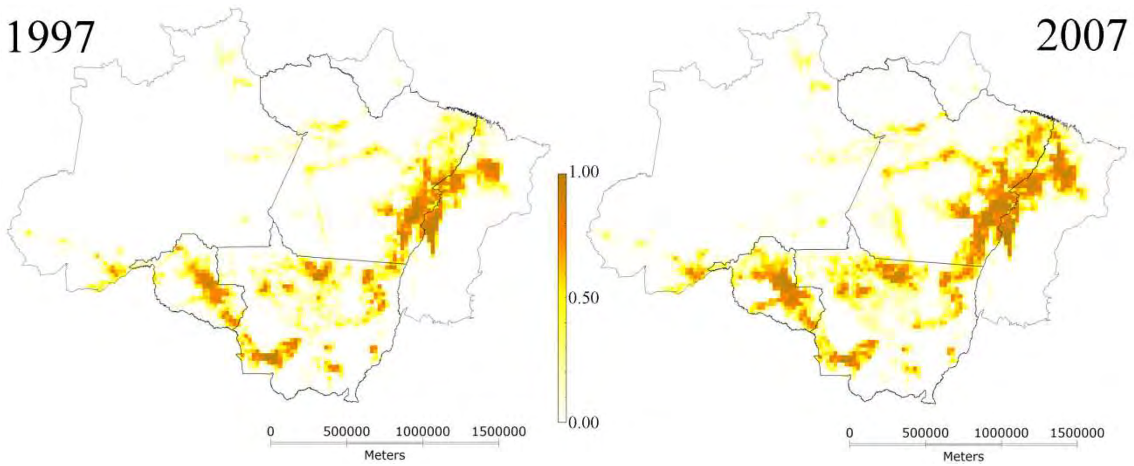


Figure A4 – Proportion of pasture in 1997/1996 (left) and 2007/2006 (right).

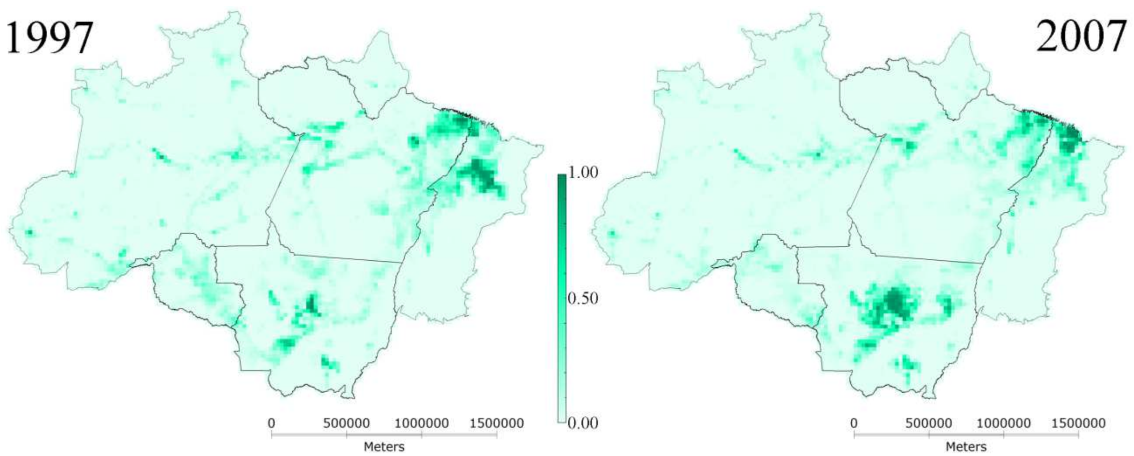


Figure A5 – Proportion of temporary agriculture in 1997/1996 (left) and 2007/2006 (right).

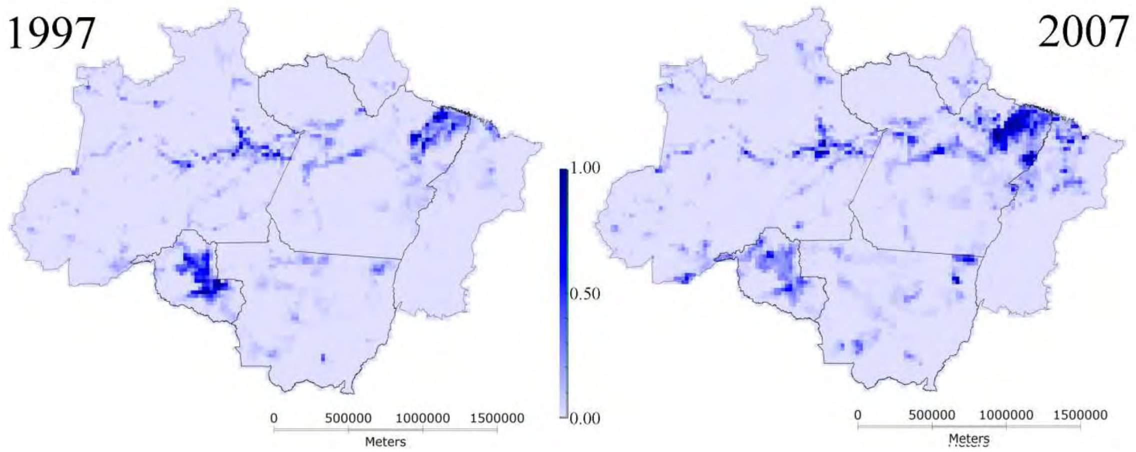


Figure A6 – Proportion of permanent agriculture for 1997/1996 (left) and 2007/2006 (right).

Table A1 – Land use trends in the four land uses over the states of Pará, Rondônia and Mato Grosso: numbers express the cells under the given land use changed by more than 10%.

Quantitative Land Use Trends		
	1996/1997	**2006/2007**
Number of valid cells	2232	2232
Number of cells with more than 10% deforestation	986	1300
Number of cells with more than 10% pasture	832	1196
Number of cells with more than 10% temporary agriculture	84	221
Number of cells with more than 10% permanent agriculture	11	68

A6. Conclusions

Information from agriculture censuses can be integrated with satellite remote sensing data to provide additional information that would otherwise not be available. This combination allows analysis of the spatially explicit patterns of deforestation and agricultural uses within the Brazilian Amazon.

Since deforestation precedes the establishment of much of the new agriculture in the Brazilian Amazon, in this appendix we estimated the distribution and the proportion of pasture as well as, temporary and permanent agriculture across the region. The mapped land use time series aim to explain the effects of land use changes across the region over one decade.

The results shown here require further validation in order to verify the quantification of those land use changes. Suggestion for future research is the use of data samples collected in the field to compute statistical analyzes of the results. However, our maps may be used in land change models, which are capable of simulating the major socioeconomic and biophysical driving forces of land use and cover change.

APPENDIX 1A – LIST OF VARIABLES

DESCRIPTION (FOR EACH CELL)	TYPE	SOURCE	AGGREGATION	UNIT
ID	Other	-	-	-
Column number	Other	-	-	-
Row number	Other	-	-	-
Percentage of new deforestation in 2002	Land Use	INPE	Pixel	%
Percentage of new deforestation in 2003	Land Use	INPE	Pixel	%
Percentage of new deforestation in 2004	Land Use	INPE	Pixel	%
Percentage of new deforestation in 2005	Land Use	INPE	Pixel	%
Percentage of new deforestation in 2006	Land Use	INPE	Pixel	%
Percentage of new deforestation in 2007	Land Use	INPE	Pixel	%
Percentage of new deforestation in 2008	Land Use	INPE	Pixel	%
Percentage of accumulated deforestation until 1997	Land Use	INPE	Pixel	%
Percentage of accumulated deforestation until 2002	Land Use	INPE	Pixel	%
Percentage of accumulated deforestation until 2007	Land Use	INPE	Pixel	%
Percentage of accumulated deforestation until 2008	Land Use	INPE	Pixel	%
Percentage of difference of deforestation in 2003-2002	Land Use	INPE	Pixel	%
Percentage of difference of deforestation in 2004-2003	Land Use	INPE	Pixel	%
Percentage of difference of deforestation in 2005-2004	Land Use	INPE	Pixel	%
Percentage of difference of deforestation in 2006-2005	Land Use	INPE	Pixel	%
Percentage of difference of deforestation in 2007-2006	Land Use	INPE	Pixel	%
Percentage of difference of deforestation in 2008-2007	Land Use	INPE	Pixel	%
Percentage of pasture in 1996	Land Use	INPE	Pixel	%
Percentage of temporary agriculture in 1996	Land Use	INPE	Pixel	%
Percentage of permanent agriculture in 1996	Land Use	INPE	Pixel	%
Percentage of planted forest in 1996	Land Use	INPE	Pixel	%
Percentage of non-used areas in 1996	Land Use	INPE	Pixel	%
Percentage of pasture in 2006	Land Use	INPE	Pixel	%
Percentage of temporary agriculture in 2006	Land Use	INPE	Pixel	%
Percentage of permanent agriculture in 2006	Land Use	INPE	Pixel	%
Percentage of planted forest in 2006	Land Use	INPE	Pixel	%

Percentage of forest in 2007	Land Use	INPE	Pixel	%
Clusters classes	Land Use	-	-	-
Euclidean distance to the nearest municipality centroid in 2006	Accessibility to Markets	IBGE	Municipality	Meters
Euclidean distance to the nearest capital in the Legal Amazon in 2006	Accessibility to Markets	IBGE	Municipality	Meters
Euclidean distance to São Paulo in 2006	Accessibility to Markets	IBGE	Municipality	Meters
Euclidean distance to the nearest port in 2006	Accessibility to Markets	IBGE	Municipality	Meters
Euclidean distance to the nearest large river in 2006	Accessibility to Markets	IBGE	Municipality	Meters
Euclidean distance to the nearest paved road in 2006	Accessibility to Markets	IBGE	Municipality	Meters
Euclidean distance to the nearest non-paved road in 2006	Accessibility to Markets	IBGE	Municipality	Meters
Euclidean distance to the nearest mineral deposity in 2006	Accessibility to Markets	IBGE	Municipality	Meters
Euclidean distance to the nearest road in 2006	Accessibility to Markets	IBGE	Municipality	Meters
Euclidean distance to the nearest municipality seat in 2006	Accessibility to Markets	IBGE	Municipality	Meters
Total population in 2002	Demography	IBGE	Municipality	-
Total population in 2004	Demography	IBGE	Municipality	-
Total population in 2006	Demography	IBGE	Municipality	-
Total population in 2008	Demography	IBGE	Municipality	-
Number of tractors in 2006	Technology	IBGE	Municipality	-
Number of people employed in agriculture in 2006	Technology	IBGE	Municipality	-
Euclidean distance to the nearest timber industry in 2006	Accessibility to Markets	IBGE	Municipality	Meters
Altitude	Environment	SRTM	Classes	Meters
Slop	Environment	SRTM	Classes	Degree
Percentage of indigenous land areas in 2006	Public Policy	MMA	Polygons	%
Price of wood land in 2002	Market Pressure	FNP	Region	R$/h
Price of clean land in 2002	Market Pressure	FNP	Region	R$/h
Price of wood land in 2003	Market Pressure	FNP	Region	R$/h
Price of clean land in 2003	Market Pressure	FNP	Region	R$/h
Price of wood land in 2007	Market Pressure	FNP	Region	R$/h
Price of clean land in 2007	Market Pressure	FNP	Region	R$/h
Price of wood land in 2008	Market Pressure	FNP	Region	R$/h
Price of clean land in 2008	Market Pressure	FNP	Region	R$/h
Percentage of integral protection conservation units in 2006	Public Policy	MMA	Polygons	%
Total number of cattles in 2002	Market Pressure	IPEA	Municipality	-
Total number of cattles in 2003	Market Pressure	IPEA	Municipality	-
Total number of cattles in 2004	Market Pressure	IPEA	Municipality	-

Total number of cattles in 2005	Market Pressure	IPEA	Municipality	-
Total number of cattles in 2006	Market Pressure	IPEA	Municipality	-
Total number of cattles in 2007	Market Pressure	IPEA	Municipality	-
Total area of soybeans in 2002	Market Pressure	IPEA	Municipality	h
Total area of soybeans in 2003	Market Pressure	IPEA	Municipality	h
Total area of soybeans in 2004	Market Pressure	IPEA	Municipality	h
Total area of soybeans in 2005	Market Pressure	IPEA	Municipality	h
Total area of soybeans in 2006	Market Pressure	IPEA	Municipality	h
Total area of soybeans in 2007	Market Pressure	IPEA	Municipality	h
Total area of sugarcane in 2002	Market Pressure	IPEA	Municipality	h
Total area of sugarcane in 2003	Market Pressure	IPEA	Municipality	h
Total area of sugarcane in 2004	Market Pressure	IPEA	Municipality	h
Total area of sugarcane in 2005	Market Pressure	IPEA	Municipality	h
Total area of sugarcane in 2006	Market Pressure	IPEA	Municipality	h
Total area of sugarcane in 2007	Market Pressure	IPEA	Municipality	h
Total of exports in 2003	Market Pressure	IPEA	Municipality	U$
Total of exports in 2004	Market Pressure	IPEA	Municipality	U$
Total of exports in 2005	Market Pressure	IPEA	Municipality	U$
Total of exports in 2006	Market Pressure	IPEA	Municipality	U$
Total of exports in 2007	Market Pressure	IPEA	Municipality	U$
GNP in 2002	Market Pressure	IPEA	Municipality	-
GNP in 2003	Market Pressure	IPEA	Municipality	-
GNP in 2004	Market Pressure	IPEA	Municipality	-
GNP in 2005	Market Pressure	IPEA	Municipality	-
GNP in 2006	Market Pressure	IPEA	Municipality	-
Percentage of integral protection conservation units in 2002	Public Policy	MMA	Polygons	%
Percentage of integral protection conservation units in 2003	Public Policy	MMA	Polygons	%
Percentage of integral protection conservation units in 2004	Public Policy	MMA	Polygons	%
Percentage of integral protection conservation units in 2005	Public Policy	MMA	Polygons	%
Percentage of integral protection conservation units in 2007	Public Policy	MMA	Polygons	%
Percentage of integral protection conservation units in 2008	Public Policy	MMA	Polygons	%
Percentage of degraded forest in 2007	Land Use	INPE	Polygons	%
Average of winter precipitation	Environment	IPEA	Municipality	mm
Average of autumn precipitation	Environment	IPEA	Municipality	mm

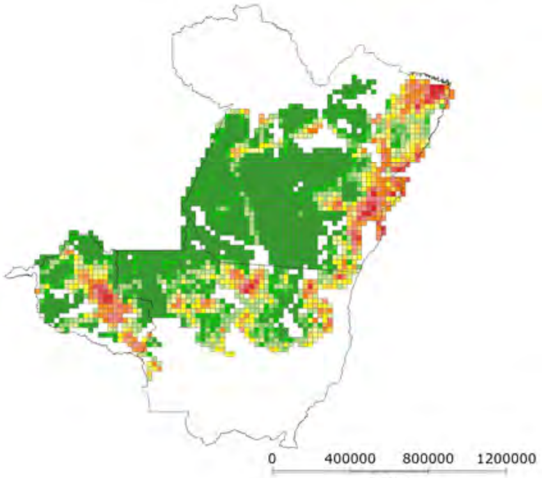
Average of spring precipitation	Environment	IPEA	Municipality	mm
Average of summer precipitation	Environment	IPEA	Municipality	mm
Average of winter temperature	Environment	IPEA	Municipality	°C
Average of autumn temperature	Environment	IPEA	Municipality	°C
Average of spring temperature	Environment	IPEA	Municipality	°C
Average of summer temperature	Environment	IPEA	Municipality	°C
Value of rural credit in 2006	Market Pressure	IPEA	Municipality	U$
Percentage of sustainable use conservation units in 2002	Public Policy	MMA	Polygons	%
Percentage of sustainable use conservation units in 2003	Public Policy	MMA	Polygons	%
Percentage of sustainable use conservation units in 2004	Public Policy	MMA	Polygons	%
Percentage of sustainable use conservation units in 2005	Public Policy	MMA	Polygons	%
Percentage of sustainable use conservation units in 2007	Public Policy	MMA	Polygons	%
Percentage of sustainable use conservation units in 2008	Public Policy	MMA	Polygons	%
Percentage of conservation units in 2002	Public Policy	MMA	Polygons	%
Percentage of conservation units in 2003	Public Policy	MMA	Polygons	%
Percentage of conservation units in 2004	Public Policy	MMA	Polygons	%
Percentage of conservation units in 2005	Public Policy	MMA	Polygons	%
Percentage of conservation units in 2007	Public Policy	MMA	Polygons	%
Percentage of conservation units in 2008	Public Policy	MMA	Polygons	%
Weighted price of cattle in 2002	Market Pressure	IPEA	Municipality	U$
Weighted price of cattle in 2003	Market Pressure	IPEA	Municipality	U$
Weighted price of cattle in 2004	Market Pressure	IPEA	Municipality	U$
Weighted price of cattle in 2005	Market Pressure	IPEA	Municipality	U$
Weighted price of cattle in 2006	Market Pressure	IPEA	Municipality	U$
Weighted price of cattle in 2007	Market Pressure	IPEA	Municipality	U$
Weighted price of soybeans in 2002	Market Pressure	IPEA	Municipality	U$
Weighted price of soybeans in 2003	Market Pressure	IPEA	Municipality	U$
Weighted price of soybeans in 2004	Market Pressure	IPEA	Municipality	U$
Weighted price of soybeans in 2005	Market Pressure	IPEA	Municipality	U$
Weighted price of soybeans in 2006	Market Pressure	IPEA	Municipality	U$
Weighted price of soybeans in 2007	Market Pressure	IPEA	Municipality	U$
Weighted price of alcohol in 2002	Market Pressure	IPEA	Municipality	U$
Weighted price of alcohol in 2003	Market Pressure	IPEA	Municipality	U$
Weighted price of alcohol in 2004	Market Pressure	IPEA	Municipality	U$

Weighted price of alcohol in 2005	Market Pressure	IPEA	Municipality	U$
Weighted price of alcohol in 2006	Market Pressure	IPEA	Municipality	U$
Weighted price of alcohol in 2007	Market Pressure	IPEA	Municipality	U$
Percentage of sustainable use conservation units in 2006	Public Policy	MMA	Polygons	%
Percentage of conservation units in 2006	Public Policy	MMA	Polygons	%
Difference of constant price of meat in 2003-2002	Market Pressure	IPEA	Country	U$
Difference of constant price of meat in 2004-2003	Market Pressure	IPEA	Country	U$
Difference of constant price of meat in 2005-2004	Market Pressure	IPEA	Country	U$
Difference of constant price of meat in 2006-2005	Market Pressure	IPEA	Country	U$
Difference of constant price of meat in 2007-2006	Market Pressure	IPEA	Country	U$
Priority municipalities in control of deforestation in 2007	Public Policy	MMA	Polygons	-
Percentage of new deforestation in 2009	Land Use	INPE	Pixel	%
Percentage of total area of settlements in 2006	Public Policy	INCRA	Polygons	%
Number of settled families in 2006	Public Policy	INCRA	Polygons	-
Euclidean distance to the nearest road in 1996	Accessibility to Markets	IBGE	Municipality	Meters
Euclidean distance to the nearest paved road in 1996	Accessibility to Markets	IBGE	Municipality	Meters
Euclidean distance to the nearest non-paved road in 1996	Accessibility to Markets	IBGE	Municipality	Meters
Euclidean distance to the nearest municipality centroid in 1996	Accessibility to Markets	IBGE	Municipality	Meters
Euclidean distance to the nearest timber industry in 1996	Accessibility to Markets	IBGE	Municipality	Meters
Density of population in 1996	Demography	IBGE	Municipality	-
Percentage of high fertility soils	Environment	IBGE	Municipality	%
Percentage of low fertility soils	Environment	IBGE	Municipality	%
Percentage of very low fertility soils	Environment	IBGE	Municipality	%
Percentage of conservation units in 2009	Public Policy	MMA	Polygons	%
Strength of connection to ports through roads network in 2006	Accessibility to Markets	IBGE	Municipality	-
Strength of connection to São Paulo through roads network in 2006	Accessibility to Markets	IBGE	Municipality	-
Strength of connection to Rio de Janeiro through roads network in 2006	Accessibility to Markets	IBGE	Municipality	-
Strength of connection to São Paulo and Rio de Janeiro through roads network in 2006	Accessibility to Markets	IBGE	Municipality	-
Strength of connection to the nearest capital in the Legal Amazon through roads network in 2006	Accessibility to Markets	IBGE	Municipality	-
Strength of connection to São Paulo and Recife through roads network in 2006	Accessibility to Markets	IBGE	Municipality	-
Average of temperature for the three driest months	Environment	IBGE	Municipality	-
Average of precipitation for the three driest months	Environment	IBGE	Municipality	-
Percentage of classical settlements in 2006	Public Policy	MMA	Polygons	%
Percentage of sustainable settlements in 2006	Public Policy	MMA	Polygons	%

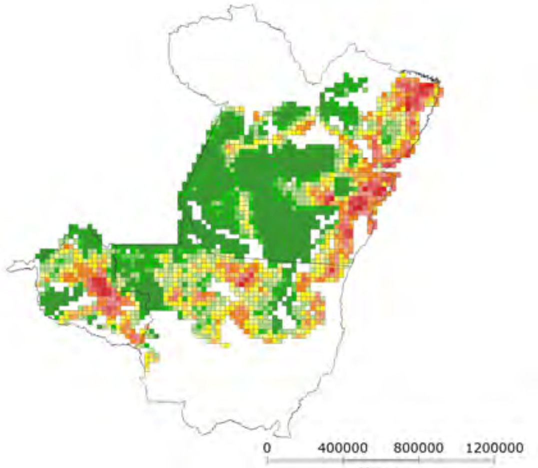
Strength of connection to the nearest city in the Legal Amazon through roads network in 2006	Accessibility to Markets	IBGE	Municipality	-
Minimum temperature	Environment	IBGE	Municipality	-
PVM GDD0 Index	Environment	IBGE	Municipality	-
PVM GDD5 Index	Environment	IBGE	Municipality	-
Percentage of conservation units in 1996	Accessibility to Markets	IBGE	Municipality	%
Number of settled families in 1996	Public Policy	INCRA	Polygons	-
Percentage of total area of settlements in 1996	Public Policy	INCRA	Polygons	%
Total urban population in 1996	Demography	IBGE	Municipality	-
Total rural population in 1996	Demography	IBGE	Municipality	-
Total urban population in 2006	Demography	IBGE	Municipality	-
Total rural population in 2006	Demography	IBGE	Municipality	-
Percentage of small properties in 1996	Agrarian Structure	IBGE	Municipality	%
Percentage of medium properties in 1996	Agrarian Structure	IBGE	Municipality	%
Seasonal index	Environment	INPE	Classes	-
Humidity index	Environment	INPE	Classes	-
Percentage of large properties in 1996	Agrarian Structure	IBGE	Municipality	%
Number of small properties in 1996	Agrarian Structure	IBGE	Municipality	-
Number of medium properties in 1996	Agrarian Structure	IBGE	Municipality	-
Number of large properties in 1996	Agrarian Structure	IBGE	Municipality	-
Strength of connection to ports through roads network in 1996	Accessibility to Markets	IBGE	Municipality	-
Strength of connection to São Paulo through roads network in 1996	Accessibility to Markets	IBGE	Municipality	-
Strength of connection to São Paulo and Recife through roads network in 1996	Accessibility to Markets	IBGE	Municipality	-
Percentage of indigenous land areas in 1996	Public Policy	MMA	Polygons	%
Number of small properties in 2006	Agrarian Structure	IBGE	Municipality	-
Number of medium properties in 2006	Agrarian Structure	IBGE	Municipality	-
Number of large properties in 2006	Agrarian Structure	IBGE	Municipality	-
Percentage of small properties in 2006	Agrarian Structure	IBGE	Municipality	%
Percentage of medium properties in 2006	Agrarian Structure	IBGE	Municipality	%
Percentage of large properties in 12006	Agrarian Structure	IBGE	Municipality	%
Percentage of other uses in 2007	Land Use	INPE	Pixel	%

APPENDIX 2A – MAPS OF DEFORESTATION, LAND USES AND MAIN DETERMINANT FACTORS

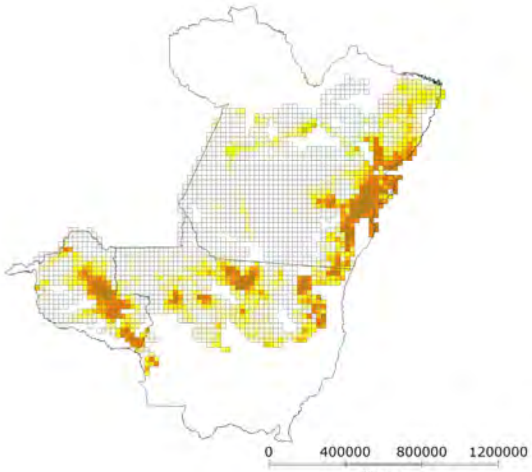
Dependent Variables



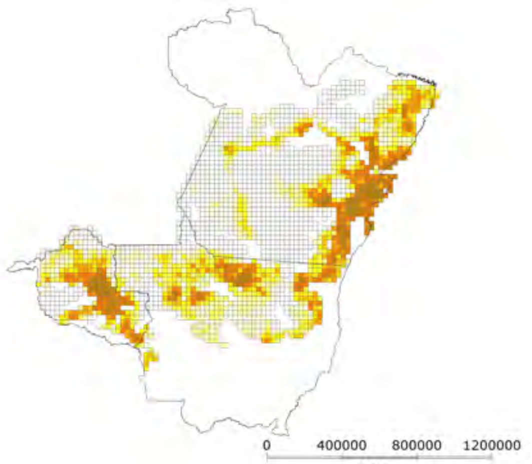
Deforestation in 1997



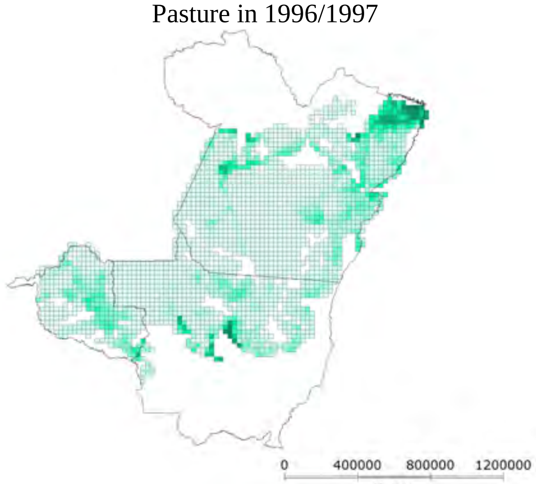
Deforestation in 2007



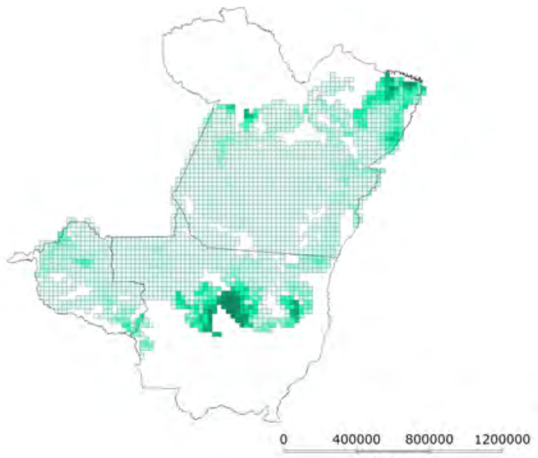
Pasture in 1996/1997



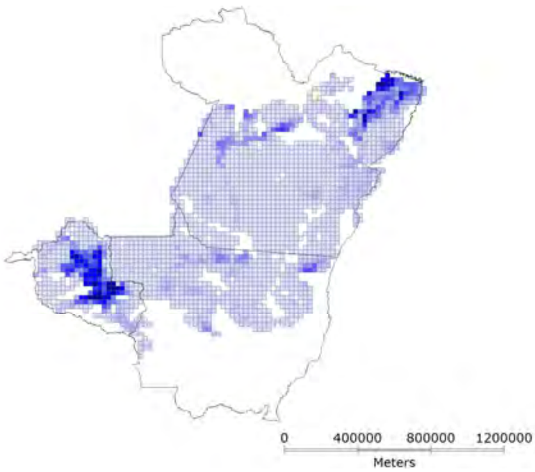
Pasture in 2006/2007



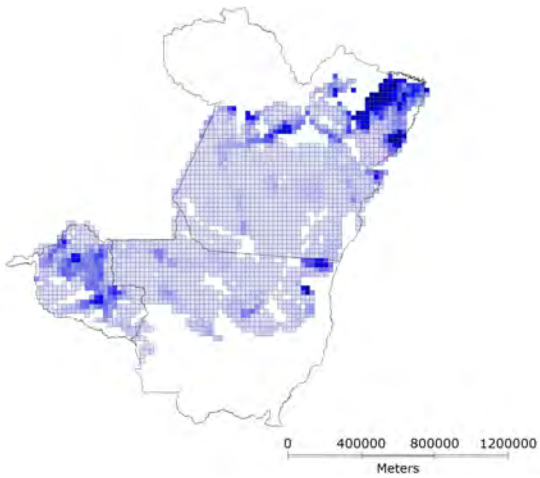
Temporary Agriculture in 1996/1997



Temporary Agriculture in 2006/2007

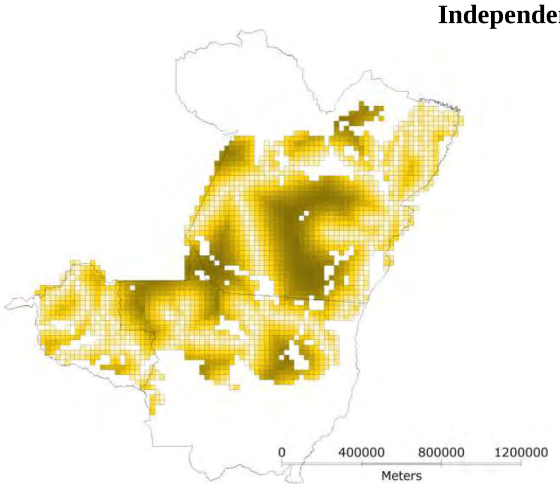


Permanent Agriculture in 1996/1997

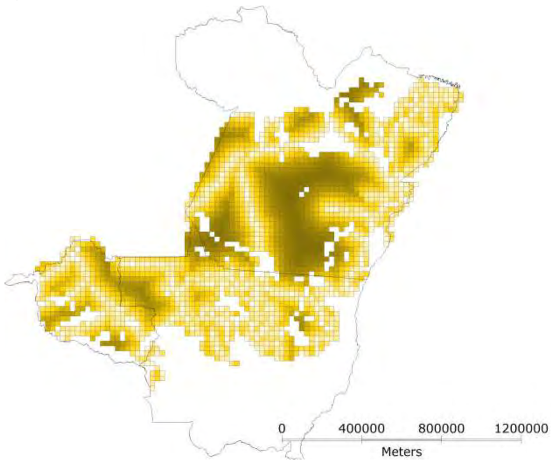


Permanent Agriculture in 2006/2007

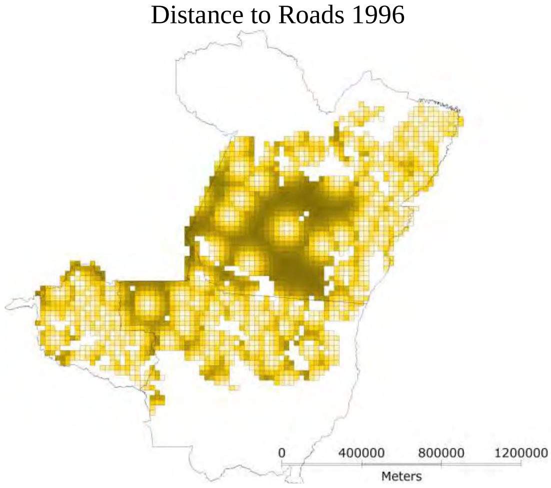
Independent Variables



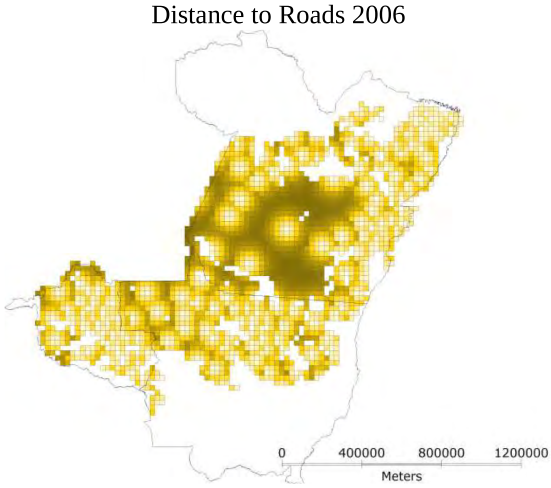
Distance to Roads 1996



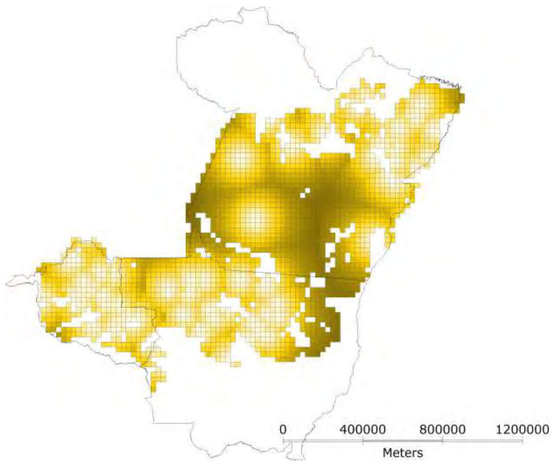
Distance to Roads 2006



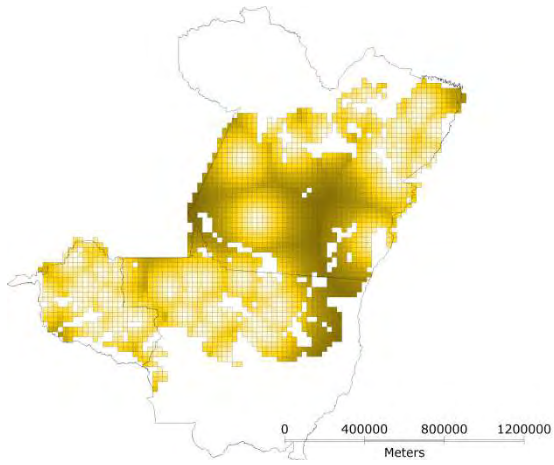
Distance to Urban Centers 1996



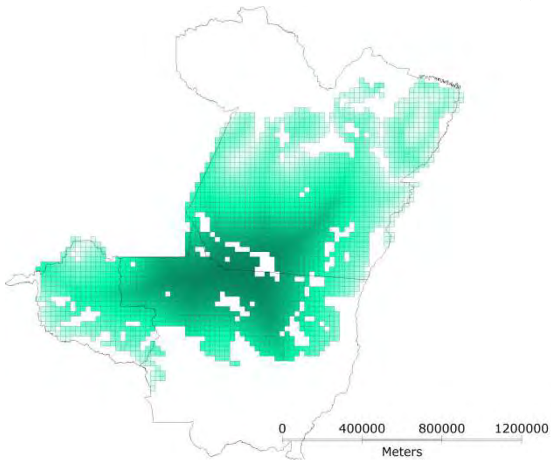
Distance to Urban Centers 2006



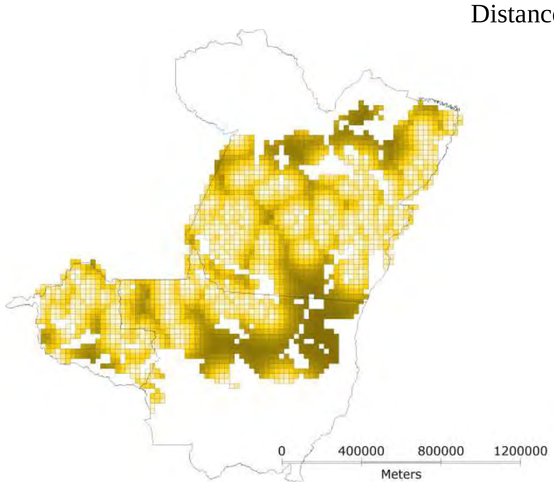
Distance to Wood Extraction 1996



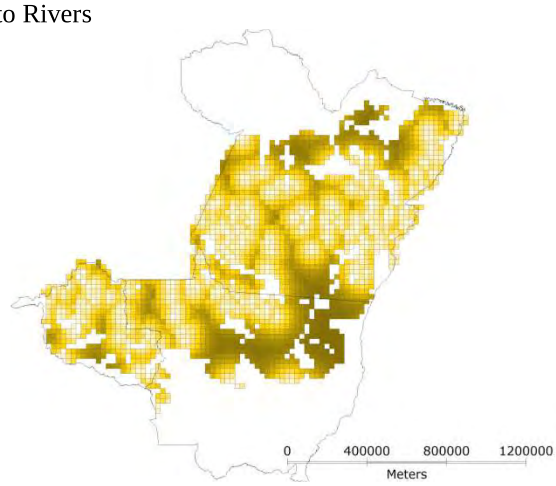
Distance to Wood Extraction 2006



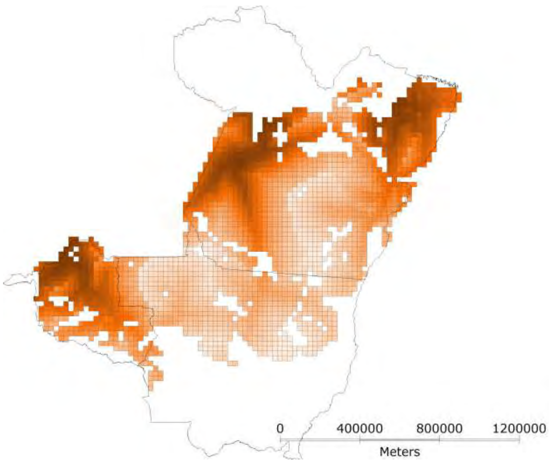
Distance to Rivers



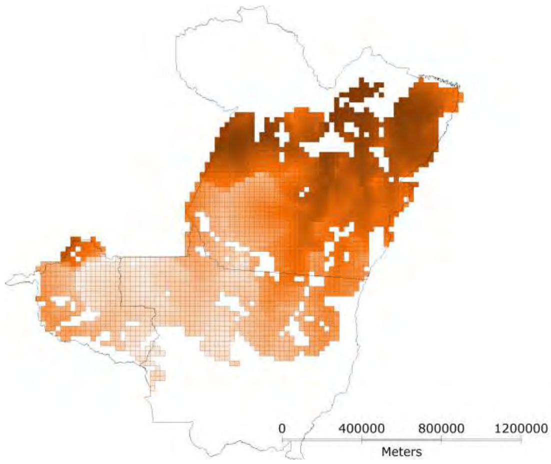
Distance to Mineral Deposits 1996



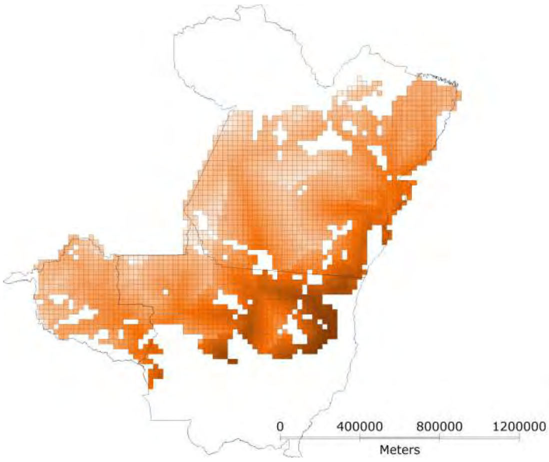
Distance to Mineral Deposits 2006



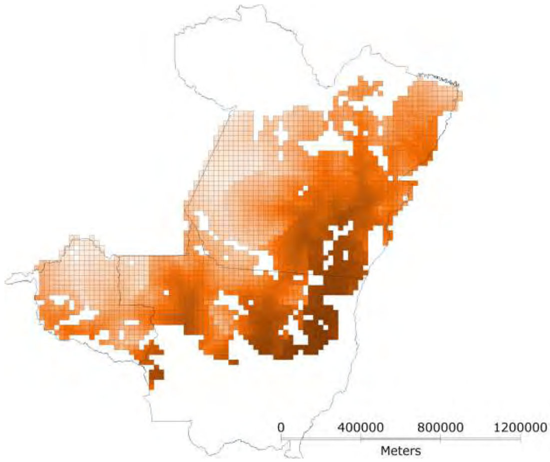
Connection to Ports 1996



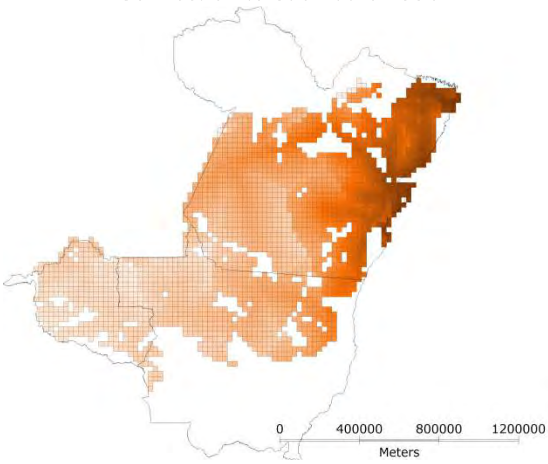
Connection to Ports 2006



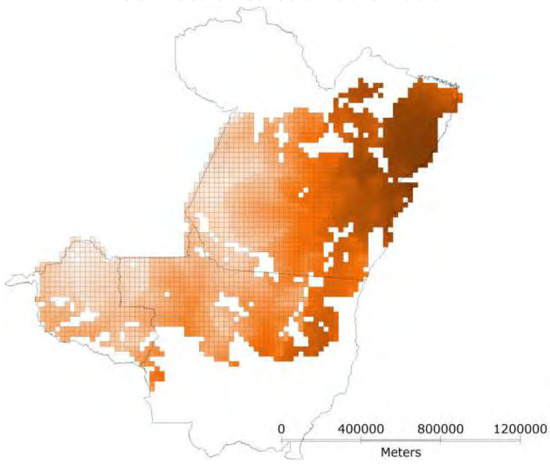
Connection to São Paulo 1996



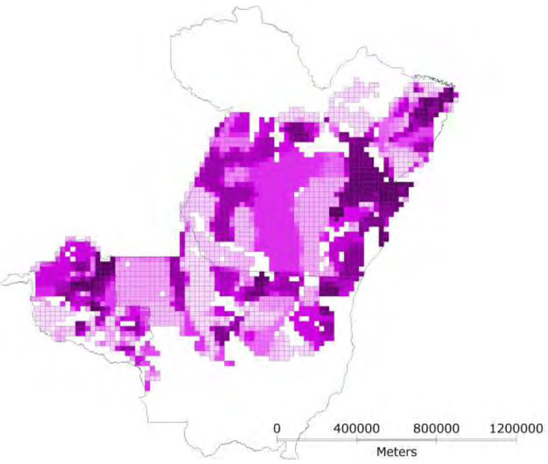
Connection to São Paulo 2006



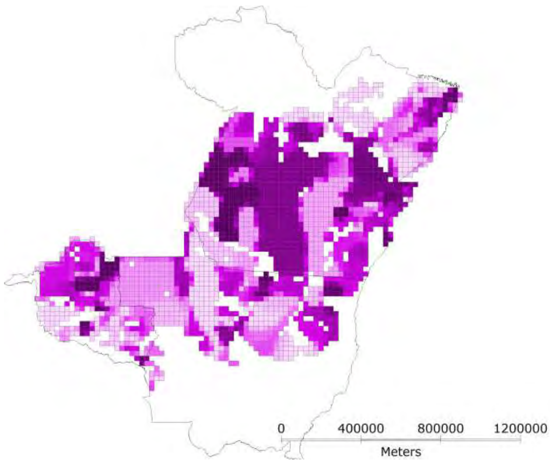
Connection to National Markets 1996



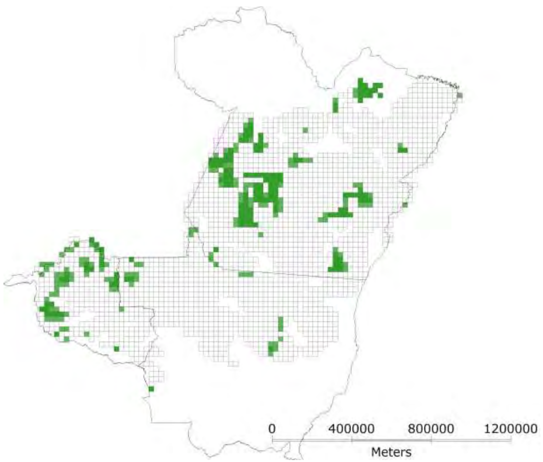
Connection to National Markets 2006



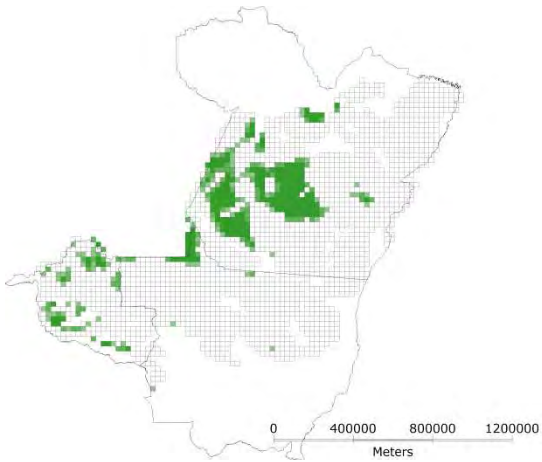
Number of Settled Families 1996



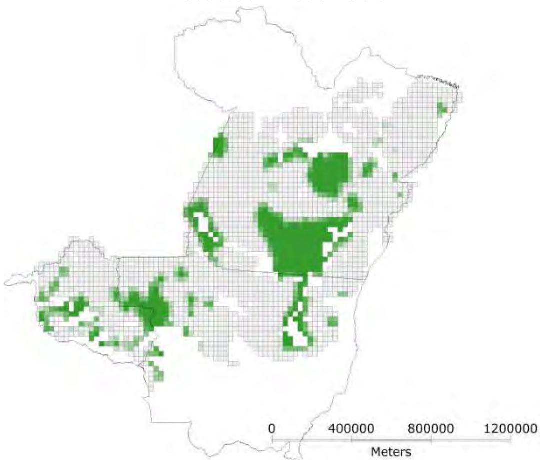
Number of Settled Families 2006



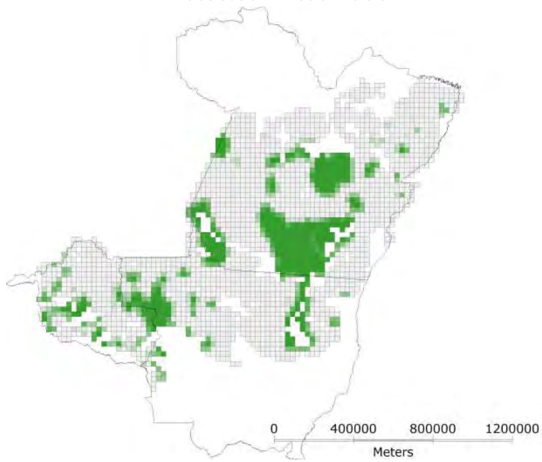
Protected Areas 1996



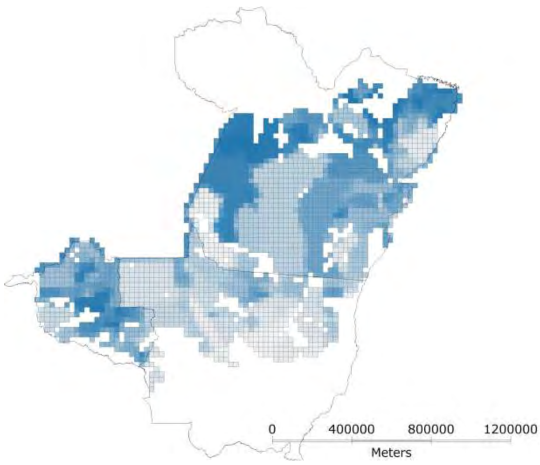
Protected Areas 2006



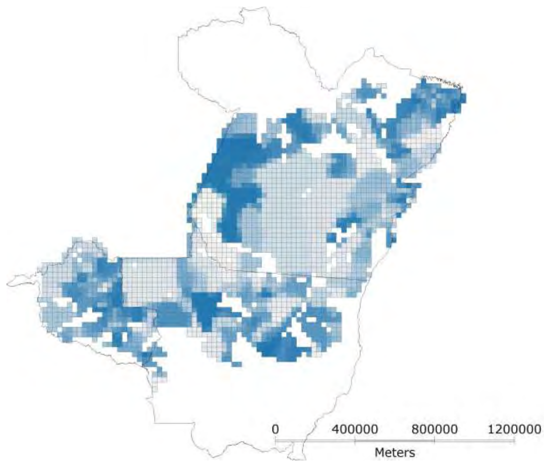
Indigenous Lands 1996



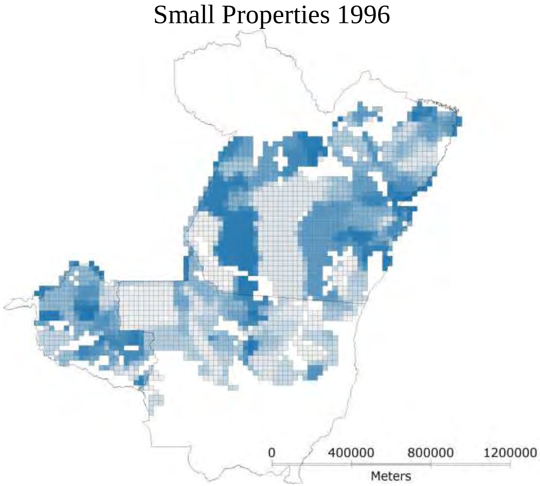
Indigenous Lands 2006



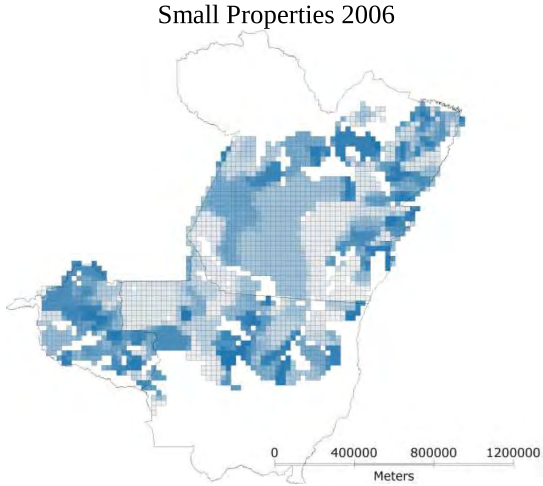
Small Properties 1996



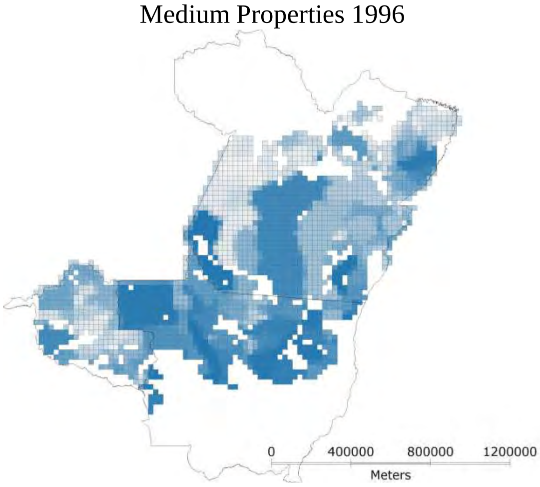
Small Properties 2006



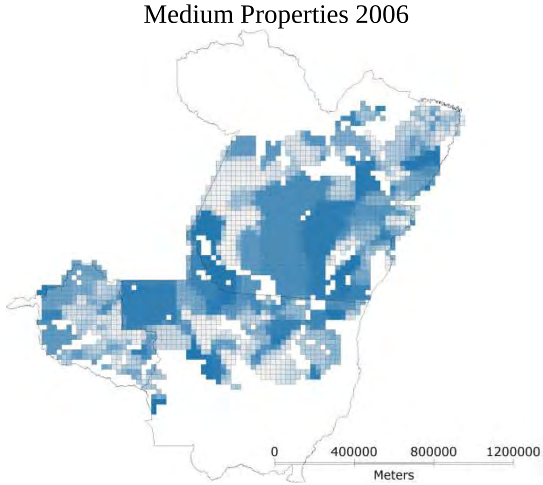
Medium Properties 1996



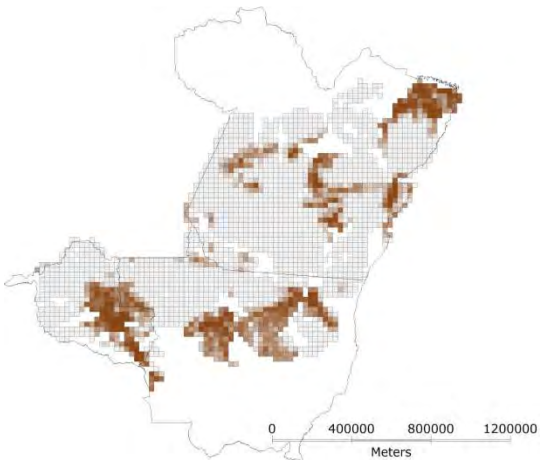
Medium Properties 2006



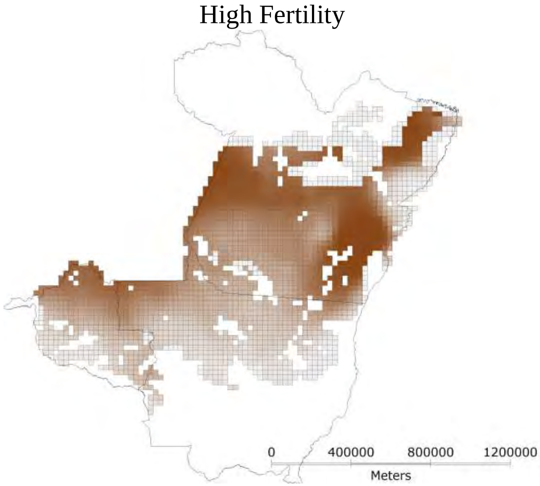
Large Properties 1996



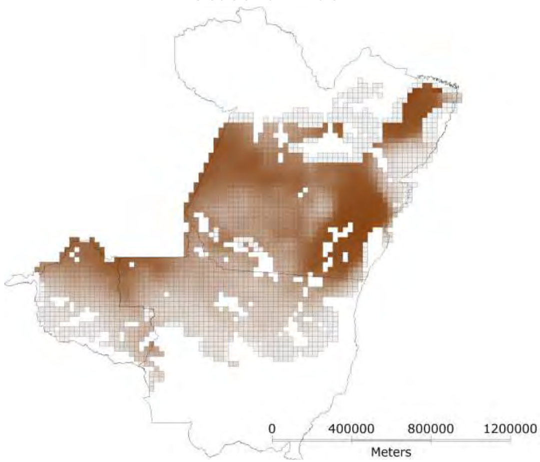
Large Properties 2006



High Fertility



Seasonal Index

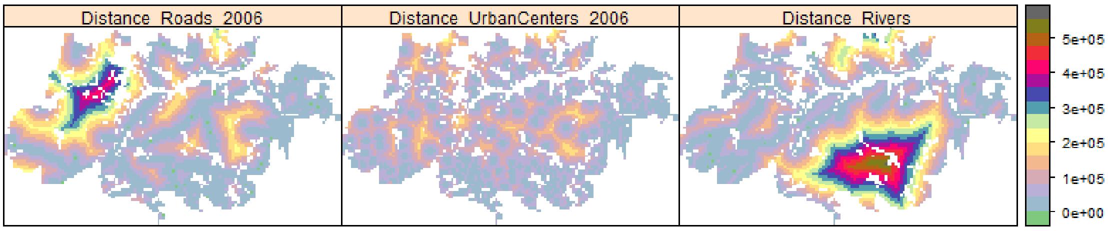


Humidity Index

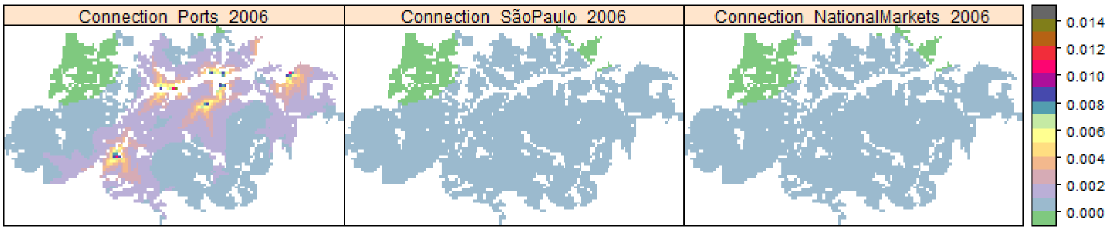
APPENDIX 3A – EXTERNAL PREDICTOR VARIABLES

Space (S)

Euclidean Distances

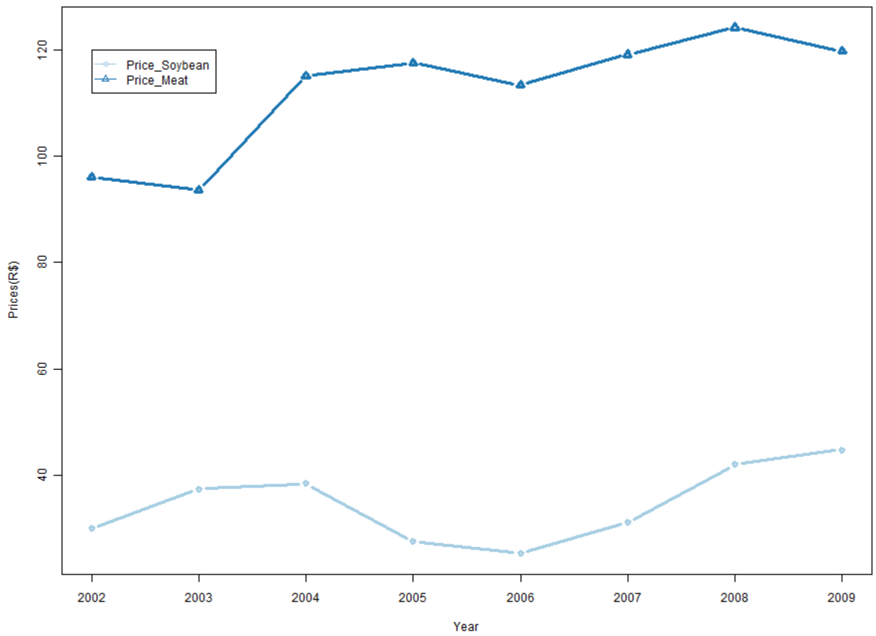


GPM Distances



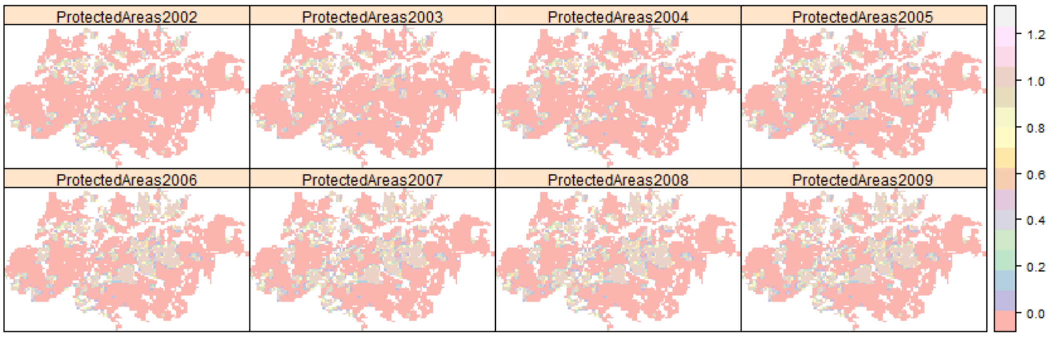
Time (T)

Prices

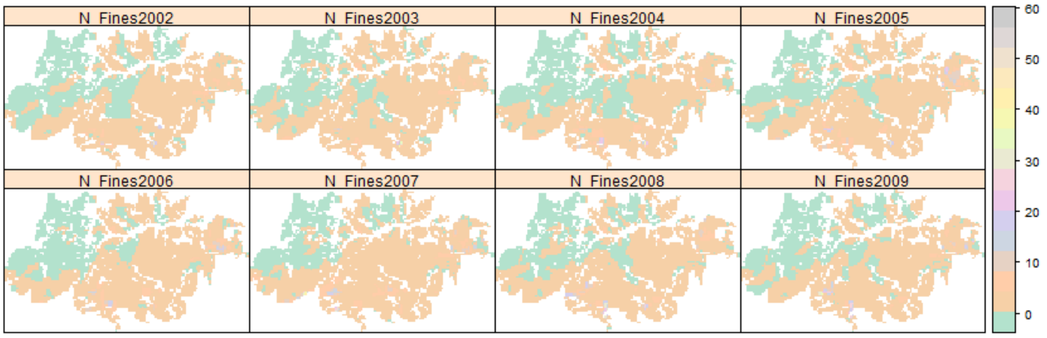


Space-Time (ST)

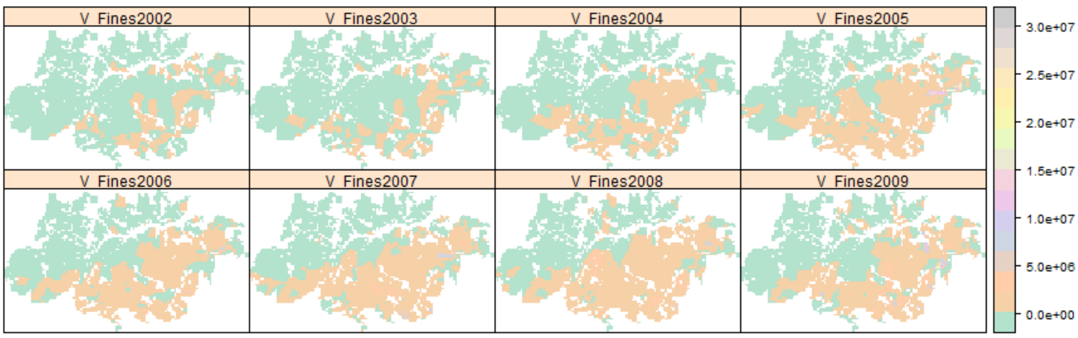
Protected Areas



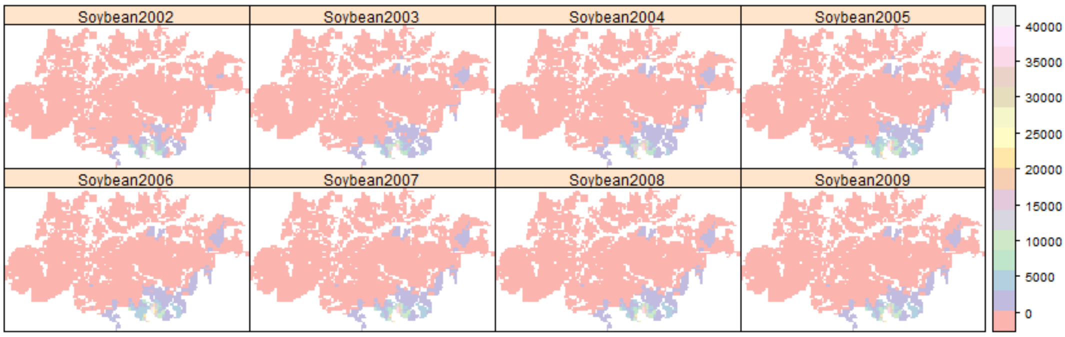
Number of Environmental Fines



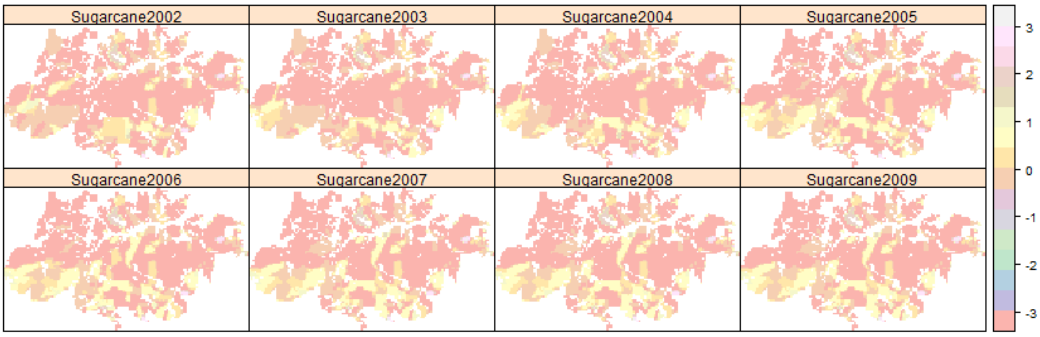
Value of Environmental Fines



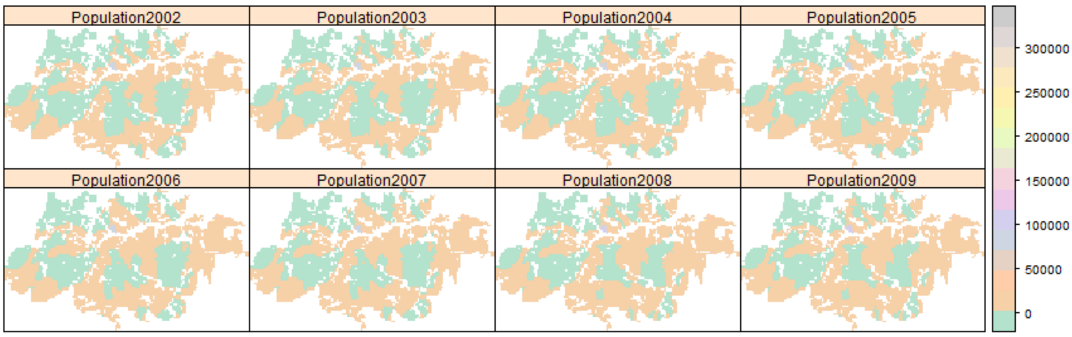
Planted Soybean Area



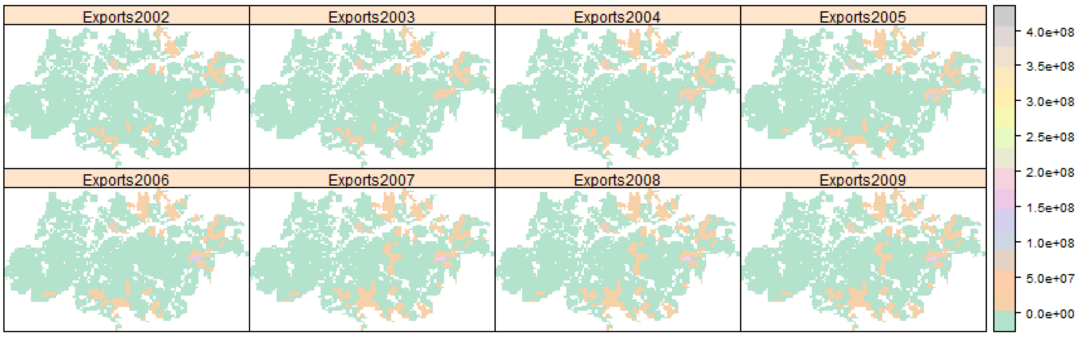
Planted Sugarcane Area



Total Population



Total Exports



APPENDIX 4A – MUNICIPALITIES IN EACH SUBREGION

Municipalities in Each Subregion	
BAIXO AMAZONAS Area (Km²) 325,925.00	Alenquer Almeirim Belterra Curuá Faro Juruti Monte Alegre Óbidos Oriximiná Prainha Santarém Terra Santa
NORDESTE PARÁ Area (Km²) 57,250.00	Acará Aurora do Pará Cachoeira do Piriá Capitão Poço Concórdia do Pará Garrafão do Norte Ipixuna do Pará Irituia Mãe do Rio Moju Nova Esperança do Piriá Ourém Santa Luiza do Pará São Domingos do Capim São Miguel do Guamá Tailândia Tomé-Açu Viseu
BR163 Area (Km²) 197,475.00	Aveiro Itaituba Jacareacanga Novo Progresso Rurópolis Trairão
TRANSAMAZÔNICA Area (Km²) 262,650.00	Altamira Anapu Brasil Novo

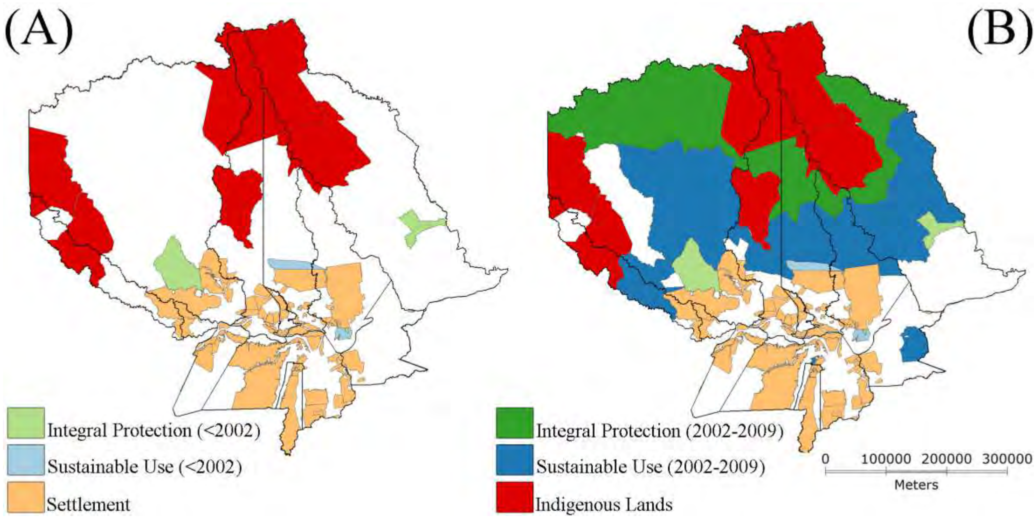
	Medicilândia
	Pacajá
	Placas
	Porto de Moz
	Senador José Porfírio
	Uruará
	Vitória do Xingu
SUL PARÁ Area (Km²) 181,250.00	Água Azul do Norte
	Bannach
	Conceição do Araguaia
	Cumaru do Norte
	Floresta do Araguaia
	Ourilândia do Norte
	Pau D'Arco
	Redenção
	Rio Maria
	Santa Maria das Barreiras
	Santana do Araguaia
	São Félix do Xingu
	Sapucaia
	Tucumã
	Xinguara
CENTRO MATO GROSSO Area (Km²) 117,150.00	Ipiranga do Norte
	Itanhangá
	Juara
	Lucas do Rio Verde
	Nobres
	Nova Maringá
	Nova Mutum
	Nova Ubiratã
	Novo Horizonte do Norte
	Porto dos Gaúchos
	Santa Rita do Trivelato
	São José do Rio Claro
	Sorriso
	Tabaporã
	Tapurah

APPENDIX 4B – NETWORK OF PUBLIC LANDS IN EACH SUBREGION

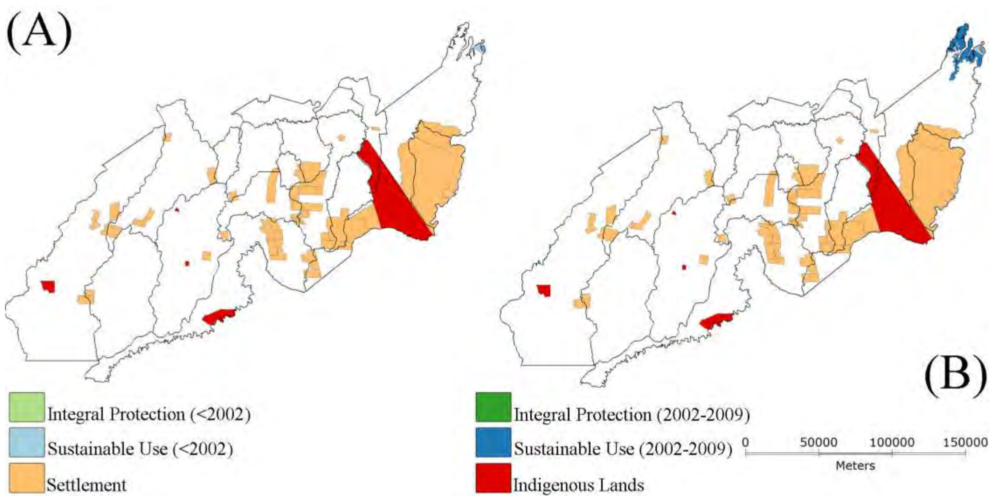
(A) Areas of integral protection and sustainable use created before 2002.

(B) Areas of integral protection and sustainable use created from 2002 to 2009.

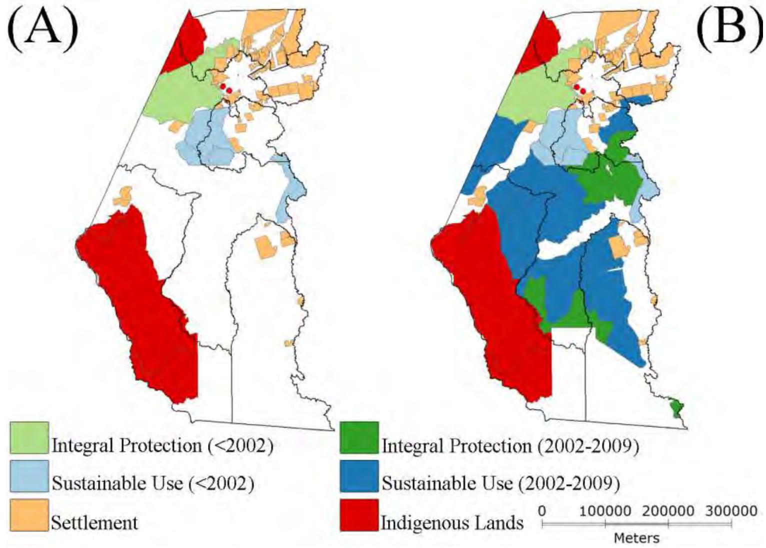
BAIXO AMAZONAS



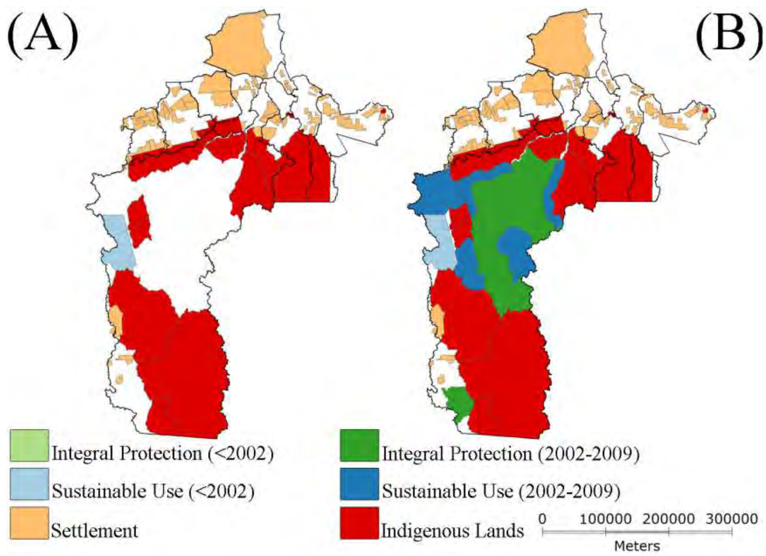
NORDESTE PARÁ



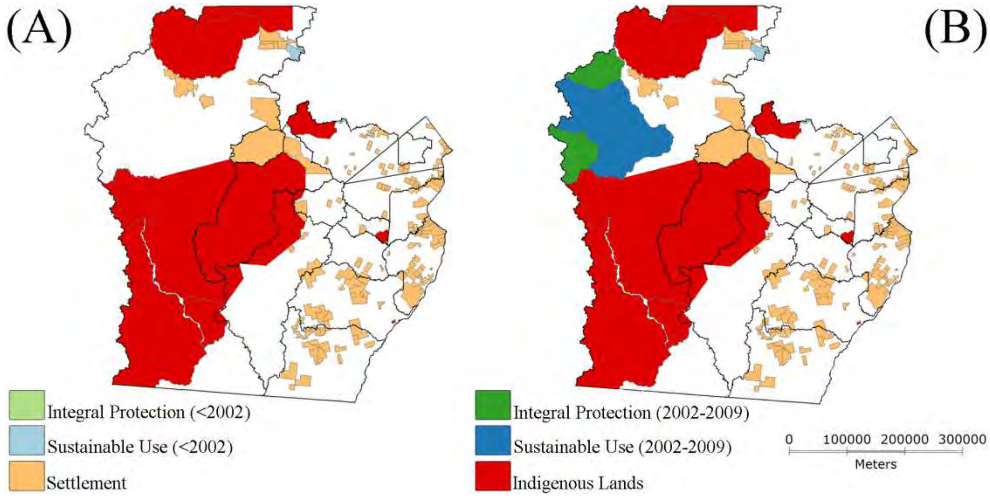
BR163



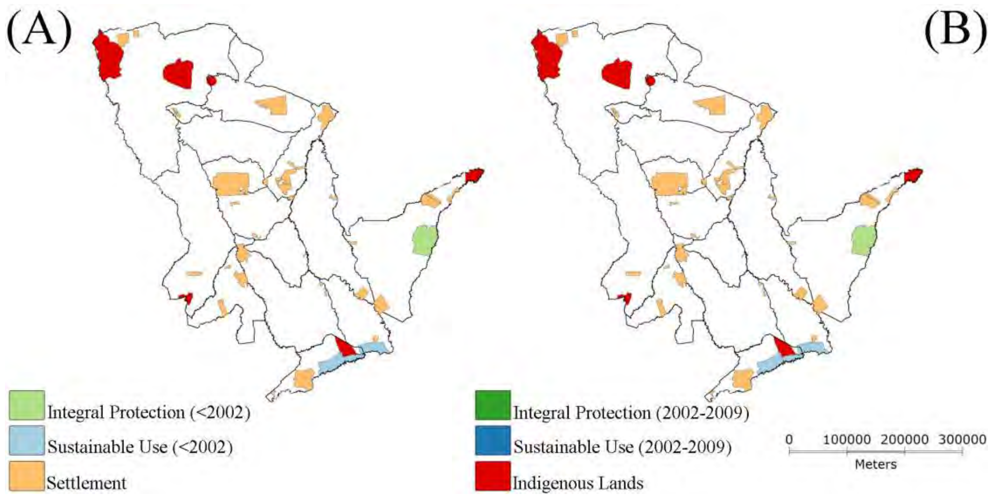
TRANSAMAZÔNICA



SUL PARÁ



CENTRO MATO GROSSO



APPENDIX AA – PRODES CLASSES

Label	Class	Accumulated Deforestation in 1997	Accumulated Deforestation in 2007
1	OUTROS	no	no
2	D2002_0	no	YES
3	D2002_1	no	YES
4	D2002_4	no	YES
5	D2002_5	YES	YES
6	D2003_0	no	YES
7	D2003_1	no	YES
8	D2003_2	no	YES
9	D2003_5	no	YES
10	D2003_6	YES	YES
11	D2004_0	no	YES
12	D2004_1	no	YES
13	D2004_2	no	YES
14	D2004_3	no	YES
15	D2004_6	no	YES
16	D2004_7	YES	YES
17	D2005_0	no	YES
18	D2005_1	no	YES
19	D2005_2	no	YES
20	D2005_3	no	YES
21	D2005_4	no	YES
22	D2005_7	no	YES
23	D2005_8	YES	YES
24	D2006_0	no	YES
25	D2006_1	no	YES
26	D2006_2	no	YES
27	D2006_3	no	YES
28	D2006_4	no	YES
29	D2006_5	no	YES
30	D2006_6	no	YES
31	D2006_OUT	no	YES
32	D2007_0	no	YES
33	D2007_1	no	YES
34	D2007_2	no	YES
35	D2007_3	no	YES
36	D2007_4	no	YES
37	D2007_5	no	YES
38	D2007_6	no	YES
39	D2007_7	no	YES
40	D2007_OUT	no	YES
41	D2008_0	no	no
42	D1997_0	YES	YES
43	D2000_0	no	YES
44	D2000_2	no	YES
45	D2000_3	YES	YES
46	D2001_0	no	YES
47	D2001_3	no	YES
48	D2001_4	YES	YES

APPENDIX AB – aRT SCRIPT USED TO COMPUTE THE PROPORTION OF CUMULATIVE DEFORESTATION FOR EACH CELL IN 1997

```
require(aRT)
conn=openConn("root", "", 3306)
db=openDb(conn, "db_25k")
showLayers(db)

#CELLS
lcells=openLayer(db, "AMZ_CELULAR_25000")
tcells=openTable(lcells)

#PRODES
lraster=openLayer(db, "PRODES_1997_2008")
rraster=getRaster(lraster, as.sp=FALSE)

#OPERATOR
q=openQuerier(lcells, geom="cells")
quant=summary(q)$elements
print(quant)
result=vector("numeric", quant)
ids=vector("character", quant)

for(i in 1:quant)
{
        next_cell=getData(q, quantity=1)
        nc=as.aRTgeometry(next_cell)
        pixels=getPixels(rraster, as.aRTgeometry(next_cell))
        total=length(pixels)

        acumul1997=(length(which(pixels==42))+0.25*length(which(pixels==45))
        +0.2*length(which(pixels==48))+0.17*length(which(pixels==5))
        +0.14*length(which(pixels==10))+0.13*length(which(pixels==16))
        +0.11*length(which(pixels==23)))

        porc=acumul1997/total
        print(i)
        result[i]=porc
        ids[i]=getID(next_cell)
}

df=data.frame(object_id_=ids, ACUM_1997=result, stringsAsFactors=FALSE)
createColumn(tcells, "ACUM_1997", type="n")
updateColumns(tcells, df)
```

APPENDIX AC – aRT SCRIPT USED TO COMPUTE THE PROPORTION OF PASTURE FOR EACH CELL IN 1997

```
require(aRT)
conn=openConn("root", "", 3306)
db=openDb(conn, "db_25k")
showLayers(db)

#CENSUS
lcenso=openLayer(db, "CENSO_1996_625")
censo_pols=getPolygons(lcenso, as.sp=FALSE)
censo_table=openTable(lcenso)
censo_data=getData(censo_table)
colnames(censo_data)

#PRODES
lprodes=openLayer(db, "PRODES_1997_2008")
prodes_raster=getRaster(lprodes, as.sp=FALSE)
resol_raster=(100/1000)*(100/1000)
print(resol_raster)

#CELLS
lcells=openLayer(db, "AMZ_CELULAR_25000")
tcells=openTable(lcells)
resol_cells = (25)*(25)
print(resol_cells)
const=(resol_raster)/(resol_cells)
print(const)

#OPERATOR
q=openQuerier(lcells, geom = "cells")
quant=summary(q)$elements
print(quant)
result=vector("numeric", quant)
ids=vector("character", quant)

for(i in 1:quant)
{
	next_cell=getData(q, quantity=1)
	nc=as.aRTgeometry(next_cell)
	pols=getClip(censo_pols, nc)
	print(i)
	if(is.null(pols))
	{
		result[i] = 0.0
	}
	else
	{
	result[i]=sum(sapply(getID(pols), function(id)
	{
	ss=subset(pols, getID(pols)==id)
	pixels=getPixels(prodes_raster, as.aRTgeometry(ss))
	const*(length(which(pixels==42))+0.25*length(which(pixels==45))+0.2*length(which(pixels=
=48))
```

```
	+0.17*length(which(pixels==5))+0.14*length(which(pixels==10))+0.13*length(which(pixels=
=16))
	+0.11*length(which(pixels==23)))*(censo_data[which(censo_data[,44]==id),38])
	}))
	}
	ids[i] = getID(next_cell)
}

df=data.frame(object_id_=ids, CENSO96_PASTAGEM=result, stringsAsFactors=FALSE)
createColumn(tcells, "CENSO96_PASTAGEM", type="n")
updateColumns(tcells, df)
```