Identifying the Role of Crop Production in Land Cover Change in Brazil, 1990-2006

by:

Elizabeth Barona A.

Department of Geography

McGill University, Montreal

January 2009

A thesis submitted to McGill University in partial fulfillment of the requirements to the Degree of Master of Science

ABSTRACT

Crop production in Brazil has changed significantly over the last decade. New crops are being cultivated to satisfy the world's growing demand for Brazilian export products —a demand that has caused substantial changes in land use and cover, mainly characterized by the increase in large-scale mechanization of agriculture, deforestation, and intensification of agricultural land use.

Brazil currently provides crop production information at the municipality level. This information was analyzed using *Geographic Information Systems* (GIS) to examine changes in the spatial distribution of the production of various crops and livestock in Brazil for 1990-2006. In addition, to better understand the relationship between agricultural expansion and deforestation, spatial data on agricultural expansion and deforestation over the Legal Amazon were statistically analyzed for 2000-2006.

The results indicate that changes in the spatial patterns of crops have indeed taken place in central and northeastern Brazil as well as in the southern Amazon region. The areas to crops such as soybean and sugarcane expanded, surpassing the total area planted to domestic food crops, which, in turn, recorded a significant decrease in area. This crop expansion has exerted pressure on other crops and livestock, pushing them further into the Amazon forest region during 1990-2006.

In the same period, pasture was the predominant land use in the Legal Amazon; however, results indicate that the area planted to soybean increased whereas the area under pasture decreased. Statistical analyses revealed that, in those areas with over 50% forest, deforestation was strongly related to agricultural expansion. Deforestation was related to pasture expansion in the states of Mato Grosso and Rondônia, but not to

soybean expansion. On the other hand, soybean expansion in Mato Grosso seems to be correlated to a decrease in pasture. An increase in pasture was also observed in the states of Para, Acre, and Rondônia, leading to the hypothesis that soybean expansion in Mato Grosso displaced pasture to other states, thereby indirectly causing deforestation elsewhere. The quality of the data precludes more conclusive evidence, and therefore the results should be interpreted with care. However, further work using ground-based and high-resolution remote sensing observation could help elucidate causal relationships.

Résumé

La production agricole du Brésil a changé significativement durant la dernière décennie. De nouvelles cultures ont été adoptées afin de répondre à la croissance de la demande mondiale pour des produits d'exportation brésiliens – une demande qui a occasionné des changements substantiels au niveau de l'utilisation et de la couverture du sol, principalement caractérisés par l'accroissement à large échelle de la mécanisation de l'agriculture, de la déforestation et de l'intensification de l'agriculture.

Le Brésil met à disposition de l'information concernant la production agricole au niveau municipal. Cette information a été analysée par le biais d'un *Système d'Information Géographique* (SIG) afin d'étudier les changements dans la distribution spatiale de la production de différentes cultures et d'élevage au Brésil de 1990 à 2006. De plus, afin de mieux comprendre la relation entre l'expansion agricole et la déforestation, des données spatiales ont été analysée statistiquement pour l'Amazone Légale pour une période allant de 2000 à 2006.

Les résultats indiquent que des changements dans les patrons spatiaux ont en effet pris place au centre et au nord-est du Brésil ainsi qu'au sud de la région amazonienne. Les zones prévues pour cultiver le soja et la canne-à-sucre ont augmenté, surpassant même les surfaces semées pour des cultures vivrières qui ont par ailleurs enregistrées une diminution significative. L'extension de ces cultures a exercé une pression sur les autres cultures et sur les élevages bovins, les poussant à l'intérieur de la forêt amazonienne durant la période 1990-2006.

Au cours de la même période, alors que les pâturages ont prédominé en Amazonie Légale, les résultats indiquent que les surfaces occupées par le soja ont augmentés alors que les surfaces sous pâturage ont diminués. Les analyses statistiques révèlent que dans les zones avec plus de 50% de couvert forestier, la déforestation s'est fait au profit de l'expansion agricole. La déforestation dans les états de Mato Grosso et de Rondônia a été reliée à l'expansion des pâturages plutôt qu'à l'expansion du soja. D'un autre côté, l'expansion du soja à Mato Grosso semble être corrélée à une diminution en pâturage. Une augmentation en pâturage a aussi été observée dans les états de Para, Acre et Rondônia, menant à l'hypothèse que l'expansion du soja à Mato Grosso a provoqué le déplacement des pâturages vers d'autres états, causant ainsi indirectement la déforestation. Par ailleurs, les résultats devraient être interprétés avec précaution puisque la qualité des données a empêché l'obtention d'évidences plus concluantes. Ainsi, d'autres études basées sur l'observation via la télédétection et des mesures de terrain pourront aider à expliquer les relations causales qui ont été identifiées par cette étude.

Acknowledgements

This research project could not have been successfully completed without the invaluable help of several people. First of all, I want to express my gratitude to my advisor, Dr. Navin Ramankutty, for his expert guidance throughout my graduate studies, for the time he always set aside to discuss any research problems that arose, and for helping me keep a clear focus of the job ahead and for encouraging me when times got rough. His support made this research possible.

My sincere thanks also goes to the other members of my thesis supervisory committee, Dr. Oliver Coomes and Dr. Raja Sengupta, for their valuable contributions, comments, and advice.

I am truly grateful to all the staff of the "World Land and Water Lab", especially Bernhard, Navin, Eby, Delphine, Amy, and Greg, who readily shared their know-how and expertise and were a continuous source of support, debate, and guidance in our lab meetings.

I would like to acknowledge the International Center for Tropical Agriculture (CIAT) in Cali, Colombia, for granting me the time to complete my graduate studies. I am very grateful to Dr. Glenn Hyman, my mentor at CIAT, whose vision was the basis for this study. His timely advice and never-ending enthusiasm about my research were essential to its culmination. Thank you, Glenn, for working closely with me throughout this project.

My sincere thanks are also for the McGill-STRI Neotropical Environment Option (NEO) for granting me the Leviston Fellowship. Special thanks to Dr. Catherine Potvin and Dr. Andrew Hendry for their contributions and support during my classes in Panama. In particular, I would like to thank all my classmates—and now great friends—for making the summer courses an amazing experience in many ways, both professional and human.

I'm grateful to my friend Mary Anne, who so kindly offered me a place in her apartment during the last weeks of my stay and who has made this time in Montreal much more enjoyable. Special thanks also goes to Lynn Menendez for editing my thesis and for being more than an editor—a special friend.

Last but not least, I have a deep sense of gratitude for my family and friends in Colombia, who are so important to me. It was not always easy being so far away from home. I would like to thank Jose Luis Claroz for always being there for me.

But it is my loving mother Otilia Adarve and my uncle Jesus Alberto Adarve to whom I dedicate this thesis. Their support and love during these two years have been unconditional.

Table of Contents

List of Figures

List of Tables

CHAPTER 1

Introduction

Land use changes associated with agricultural activities have been the major driving force behind land cover transformation in Latin American countries. Economic development in the region has led to the transformation of natural ecosystems into cropland and the intensification of land use (Barbier 2004). Global and free market arrangements, international market demands, and government policies also play a key role in land cover changes in most Latin American countries (Nepstad et al. 2006; Heyck et al. 2002).

Brazil, in particular, has witnessed rapid land cover change; this country has gradually expanded its agricultural frontier over the last decades. The expansion of cropland into land previously covered by forest has become one of the main causes of deforestation in the Amazon region (Morton et al. 2006). The Brazilian agro-business sector has applied new technologies to improve farm productivity and become more competitive (Mueller 2003; Kaimowitz and Smith 2001). Large-scale mechanized agriculture has led to soil erosion, especially in areas that are not under long-term crop rotations (Fearnside 2001; Dros et al. 2003). The Amazon region is becoming more susceptible to intense market pressure to increase agricultural expansion (Nepstad et al. 2006).

Although a number of studies have addressed the issue of how agriculture activity has affected land cover change in Brazil, there are few comprehensive large-scale studies using available data on agriculture and deforestation. This thesis examines how agricultural production in Brazil has changed from 1990 to 2006, and how this relates to Amazon deforestation during 2000-2006. This chapter first briefly reviews the literature on land-use and land-cover change, and then presents the study objectives and thesis outline.

1.1 Literature Review

Land use and land cover change has become a major component of environmental change and natural resources management at local, regional, and global scales (Turner et al. 1993). The Earth's surface has been irreversibly altered directly and indirectly by humans, mainly to satisfy their needs and aspirations (Vitousek et al. 1997). Ramankutty and Foley (1999) and Klein Goldewijk (2001) documented global land cover changes due to land use over the past 3 centuries. A recent review suggested that such changes in land use and land cover can have a significant environment impact, expressed in terms of loss of biodiversity, soil erosion or degradation, changes in water resources, climate change, and the spread of infectious diseases (Foley et al. 2005).

The term of 'land use' is defined by Turner and Meyer (1994) as the way in which people employ the land and its resources, for example, agriculture, urban development, logging, mining, or grazing. Land cover is the biophysical or natural state of the land surface, such as vegetation (e.g. forest, natural savannas, deserts), developed surfaces (e.g. settlements, paved land) and wet areas (e.g. wetlands). Therefore, land use change is the alteration of one type of land use into another or the intensification of a previous land use. Land cover change involves the conversion from one land cover type to another, or modification or change of the condition of the land cover type, for example, when a forest is converted to pasture or cropland (Meyer and Turner 1994; Turner et al. 1993). In this context there is an ongoing relationship between land use and land cover with conversion, modification, or alteration.

To understand land cover change, it is necessary to consider environmental, socio-economic, technological, cultural, demographic, and political factors that are both directly and indirectly related to the transformation of the Earth's surface (Geist and Lambin 2002; Lambin et al. 2001; Roberts 1996). Different research studies worldwide have addressed the driving forces behind land use changes, interrelationships, the impacts of different land use, the role played by decision makers, and how these decisions affect land cover at different scales (Burgi et al. 2004; Geist and Lambin 2002). More studies are now being conducted primarily as a result of global concerns about the transformation or alteration of natural ecosystems, which in principle could be beneficial but has now proven to trigger an accelerated degradation of ecological resources (Lambin and Geist 2006; Lambin et al. 2003).

In a recent study, Lepers et al. (2005) examined global land cover changes from 1980 to 2000, in an attempt to identify the regions of the world undergoing the most rapid land cover changes. They found that a large proportion of that change, especially in terms of deforestation and forest degradation, has taken place in Southeast Asia and the Amazon region, where the agriculture frontier has advanced more dynamically.

Over the last decades, Latin American countries have experienced large-scale forest conversion and colonization for cattle ranching and increased food production due to the intensification and expansion of agriculture. Deforestation has occurred mainly in the Brazilian Amazon, extending toward the east of the Andes and running along the road that goes from Manaus up to Venezuela (Lambin et al. 2003; Houghton 1991). Recently Rudel (2005) argued that the loss of significant amounts of forest in the Amazon can be mainly attributed to forest transitions due to logging, agricultural expansion for cattle ranching, and extensive forest fires. Rudel also identified the main causes of forest transitions as economic development and forest scarcity (in other words, the loss of forest areas increases the price of forest products).

Many studies on land use change emphasize that the trend of deforestation in the Amazon is driven by the demand for new crop and pasture lands, rather than demand for timber, as occurred in Asia or parts of Africa (Ewers and Laurance 2006; Brown et al. 2005; Rudel 2005; Deadman et al. 2004; Geist and Lambin 2001; Walker et al. 2000). However, the dynamics of deforestation in the Brazilian Amazon is complex and remains a topic of international debate.

1.1.1 Major driving forces of agricultural expansion in Brazil

Brazil is one of the world's largest exporters of agricultural and food products and is also considered a major supplier of these products to international markets. According to the country's Ministry of Agriculture, total land area in Brazil is over 850 million hectares, of which only 60.4 million hectares are dedicated to agriculture. Therefore there is still enormous potential for widespread agricultural expansion.

Brazil's agricultural industry has benefited from agro-food exports, which are becoming increasingly important for the national agricultural sector (Pereira et al. 2002; USDA 2001). In the 1990s, market liberalization triggered the increase of overall agricultural production. Expanding world markets, improved access to local credit, and government incentives, such as tax exemptions, funding of agricultural research, and improved marketing channels and infrastructure, rapidly encouraged the expansion of export crops (Valdes 2006; Brown et al. 2004; Barbier 2004; Caporale 2004).

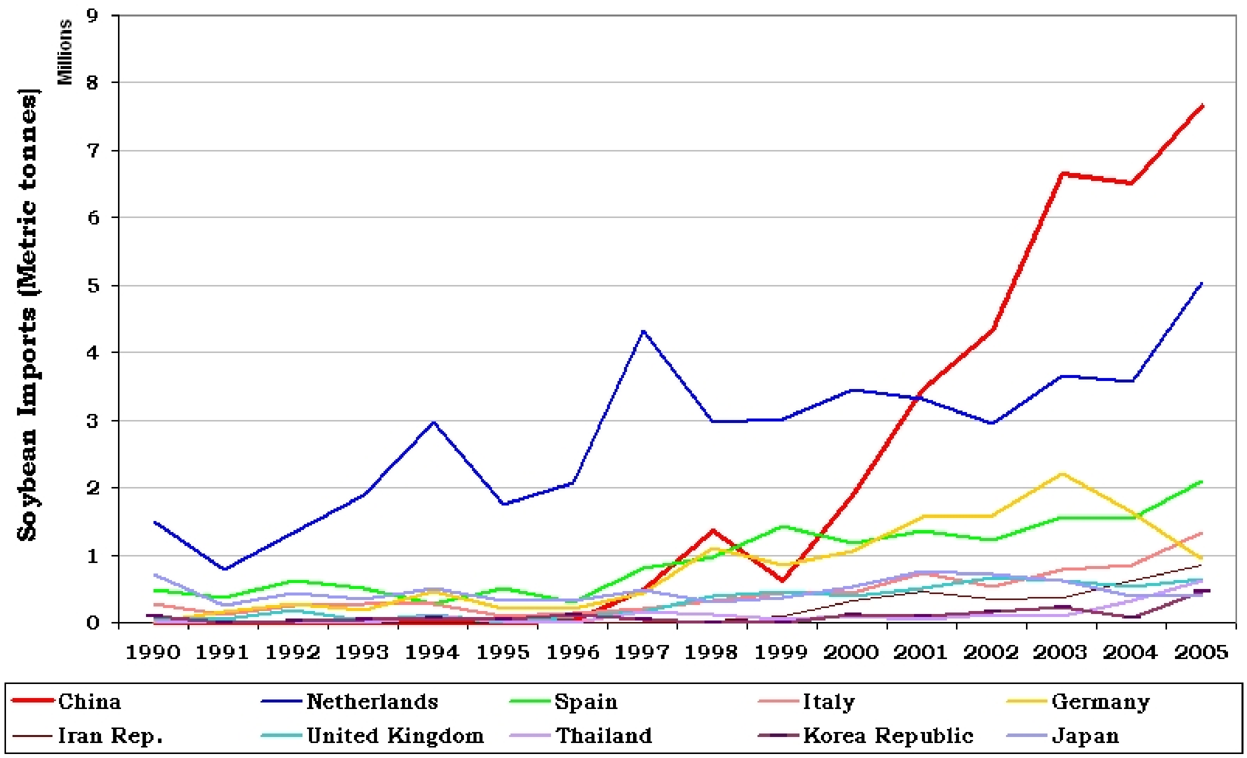
The global demand for soybean oil and soybean meal, which are mainly used in high-protein animal feed and as refined cooking oil, has increased the demand for Brazilian soybean (USDA 2000). According to FAOSTAT[1], China is the world's largest importer of soybean from Brazil, followed by European Union countries (Netherlands, Germany, Spain, and United Kingdom), Iran, Thailand, Korea, and Japan (Figure 1-1). The combination of the growing demand for refined cooking oil in China and tax reductions for food product imports maintains a strong demand for Brazil's soybean. Moreover, the liberalization of soybean trade production and trade policies as well as the agreement with the World Trade Organization (WTO)[2] have contributed to increased soybean imports from Brazil since 1996 (USDA 2004).

According to the Brazilian Institute of Geography and Statistics (IBGE, its Portuguese acronym), soybean cultivation has increased significantly over the past few years, making this crop the most important in terms of harvested area since the 1990s. Sugarcane ranks second in importance in terms of production (3rd in area) and has attracted new investments over the past few years. Half of Brazil's sugarcane production is used to satisfy the increased domestic demand for bio-ethanol and the other half to satisfy domestic consumption and

[1] Food and Agricultural Statistics in Support of Development (FAOSTAT) is a global database of agricultural land use. Its website provides data from 1986 to 2005. (http://faostat.fao.org/).

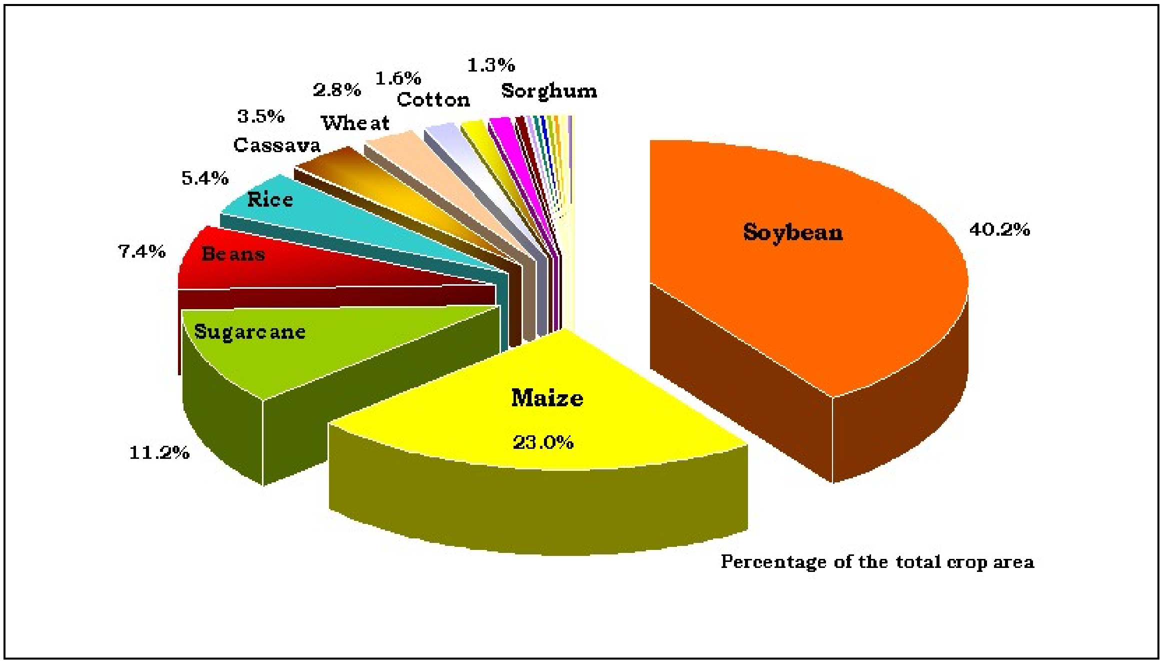
[2] The agreement includes elimination of all no tariff trade barriers, sanitary inspection, and domestic taxes according to WTO rules (USDA Outlook Report 2004).

sugar exports (IBGE 2006; UNICA 2006). Maize is considered the third most important crop because of its use in poultry and swine feed. Beans and rice are subsistence crops and considered the most important staples in Brazil (IBGE 2006) (Figure 1-2).



Source: FAOSTAT 2006.

Figure 1-1. Main countries importing soybean products from Brazil between 1990 and 2005.



Source: IBGE (2006).

Figure 1-2. Crops presenting the largest area under cultivation in Brazil in 2006.

The gradual expansion of Brazil's agricultural frontier can be mainly attributed to the production of export crops (Dross 2004; USDA 2003). However, the need to increase crop exports has also intensified the use of natural resources. Several studies, focusing mainly on the Amazon region, have recently pointed out that, during the last few years, the land dedicated to agricultural production and pasture has increased at the expense of forest areas (Morton et al. 2006), and others suggest that environmental impact is related to the execution of infrastructure projects driven by the agricultural sector (Kirby et al. 2006; Fearnside 2005; Dros et al. 2003; Carvalho et al. 2002; Peres 2001).

Nowadays, agriculture activities in Brazil pose two major concerns: (1) that the increased demand for export crops may trigger competition for existing agricultural land, causing a loss of crop diversity and displacing the small farmer; and (2) that this demand could directly or indirectly push the agricultural frontier into the Amazon region, the Cerrados, or other important ecosystems.

1.2 Purpose of the Study

Knowledge of the geographic distribution of crops is becoming increasingly necessary not only to help local decision makers but also for agricultural and environmental assessment and regional and global change research. Crop distribution maps are vital for commodity studies, agro-ecological models, and numerous environmental applications. Crop distribution mapping can support environmental and land-use change analyses and help determine the relationship between crops and the environmental constraints they face.

This thesis examines the role played by different crops in land cover change in Brazil since 1990. The following questions are addressed:

a. How have the geographic patterns of crops changed in Brazil since 1990?

b. What is the relationship between the spatial patterns of agricultural expansion and deforestation in the Amazon Region during 2000-2006?

To address these questions, the following tasks will be carried out:

1. Development of a consistent database of administrative boundaries over time to integrate and analyze land cover changes since 1990.
2. Analysis of the changing spatial distribution of crops in Brazil from 1990 to 2006.
3. Analysis of the relationship between agricultural expansion and deforestation in the Amazon Region from 2000 to 2006.

1.3 Thesis Outline

The thesis is organized using a distinct research approach, which is described in detail in five separate chapters. Chapters 3 and 4 were written in journal article format to facilitate their subsequent submission for publication.

Chapter 1, *Introduction*, provides a literature review of land use and land cover change globally and in Brazil, as well as an overview of the research problem and study objectives.

Chapter 2, *Developing Consistent Administrative Boundaries for Brazil for the Period 1990-2006*, describes a major technical advance, using geographic information systems (GIS) to create consistent administrative map units over time. The different census statistics used in this project were carefully integrated into the new administrative boundaries for time-series analysis and mapping.

Chapter 3, *The Changing Spatial Distribution of Crops and Livestock in Brazil since 1990*, presents a descriptive analysis of the changes in crop and livestock production at the municipality level in Brazil from 1990 to 2006.

Chapter 4, *The Relationship between Agricultural Expansion and Deforestation in the Amazon Region between 2000-2006*, presents a statistical analysis of the relationship between deforestation in the Amazon and agricultural expansion during the period 2000-2006.

Finally, Chapter 5 summarizes the main results of this study.

Chapter 2

Developing Consistent Administrative Boundaries for Brazil for the Period 1990-2006

2.1 Introduction

Brazil is a Federative Republic, with 5,564 municipalities that form 26 states and a Federal District, and five geographical regions (north, northeast, south, southeast, and central west). The number of municipalities in Brazil has changed significantly over the years. Approximately 1000 new municipalities rose up between 1990 and 2006, as a consequence of economic development and increased population (IBGE 2006). However the number of new municipalities varied depending on the region (Table 2-1). For example, between 1990 and 1994, the number of new municipalities created was highest in the states of Rio Grande do Sul, São Paulo, Santa Catarina, and Parana, where agricultural land was already completely developed and transportation to population centers and export facilities could be readily achieved (Ferreira Filho and Horridge 2004).

On the other hand, between 1994 and 1997, the increase in new municipalities was highest in several northeastern states (Maranhao, Piaui, and Paraiba), and in the southeastern region (mainly Minas Gerais and Sao Paulo) where population density is highest (Sartoris and Igliori

2007). Between 2001 and 2005, new municipalities, although much fewer in number, were mostly created in the market-oriented states such as Mato Grosso and Rio Grande do Sul (Mossi et al. 2003).

Table 2-1. Total number of new municipalities established over 1991-2005.

ID	State	UF code	Number of new municipalities 1991-1994	Number of new municipalities 1994-1997	Number of new municipalities 1997-2001	Number of new municipalities 2001-2005
1	Acre	AC	10			
2	Alagoas	AL	4	1	1	
3	Amapa	AP	6	1		
4	Amazonas	AM				
5	Bahia	BA			2	
6	Ceara	CE	6	3	1	
7	Espiritu Santo	ES	4	6	1	
8	Goias	GO	21	10	4	
9	Maranhao	MA		81		
10	Minas Gerais	MG	33	97		
11	Mato Grosso	MT	22	9	13	2
12	Mato Grosso do Sul	MS	5			1
13	Para	PA	23	15		
14	Paraiba	PB		52		
15	Pernambuco	PE	9	8		
16	Piaui	PI	30	73	1	1
17	Parana	PR	48	28		
18	Rio do Janeiro	RJ	11	10	1	
19	Rio Grande do Nte	RN		14	1	
20	Rondonia	RO	16	12		
21	Roraima	RR		7		
22	Rio Grande do Sul	RS	94	40	30	
23	Santa Catarina	SC	43	33		
24	Sergipe	SE	1			
25	Sao Paulo	SP	53	20		
26	Tocantins	TO	44	16		
	Total new municipalities		**483**	**536**	**55**	**4**

The increasing number of administrative units poses a problem when using these data for the spatial analysis of land use change. Changes over time, reported by municipalities, cannot be analyzed when there are inconsistencies in the new administrative boundaries between the two time periods over which the change is being measured. When a municipality is divided into two, one of the parts often keeps the same name and geocode (geocode is a unique-code associated with each administrative unit). This can be very confusing because one might assume that nothing has changed. Therefore, the administrative areas and shapes must be examined within a geographic information systems (GIS), which is a useful tool for managing large spatial databases. A simple examination of a list of names and geocodes is insufficient.

This problem is not new. Although previous studies (e.g. Sartoris and Iglori 2007) have experienced the same problem, it has often been ignored, assuming that the newly created municipalities (often small) will not affect the final conclusions. However, as showed in Table 2-2, changes in municipality areas can be quite substantial in some regions, affecting up to 50% of the area in some states. The table also shows changes in municipality areas even when administrative boundaries did not change, attributable to the inconsistency between the various IBGE's shapefiles. Ignoring such changes will result in inaccurate analysis and in some cases analysis is even not possible when geocodes are not consistent between different years. To overcome this problem, the 2005 shapefile was used for the final analysis. The shapefiles for the previous years (1991 to 2001) were used solely to identify yearly changes in administrative boundaries.

Table 2-2. Total area of municipalities influenced by change in administrative boundaries over 1991-2005.

ID	State	UF code	Total area	Area influenced by change				% change			
				1991-1994	1994-1997	2000-2001	2001-2005	(1991-94)	(1994-97)	(1997-01)	(2001-05)
1	Acre	AC	16,483,763	10,227,479	0	0	0	62	0	0	0
2	Alagoas	AL	2,788,223	159,996	17,538	65,839	0	6	1	2	0
3	Amapa	AP	14,345,327	4,536,368	3,360,335	0	0	32	23	0	0
4	Bahia	BA	56,687,000	0	0	1,279,766	0	0	0	2	0
5	Ceara	CE	14,948,182	1,140,816	0	0	0	8	0	0	0
6	Espiritu Santo	ES	4,621,964	615,914	900,184	209,471	0	13	19	5	0
7	Goias	GO	34,124,327	6,186,210	2,888,459	695,924	0	18	8	2	0
8	Maranhao	MA	33,334,068	0	20,183,120	0	0	0	61	0	0
9	Minas Gerais	MG	58,837,215	7,709,709	16,793,541	0	0	13	29	0	0
10	Mato Grosso	MT	35,814,579	31,404,693	22,489,388	25,676,782	1,164,520	88	63	72	3
11	Mato Grosso do Sul	MS	90,680,252	3,501,950	0	0	1,079,594	4	0	0	1
12	Para	PA	125,322,445	55,367,620	21,677,467	0	0	44	17	0	0
13	Paraiba	PB	5,668,863	0	2,397,588	0	0	0	42	0	0
14	Pernambuco	PE	9,872,927	1,797,462	1,413,815	0	0	18	14	0	0
15	Piaui	PI	25,259,954	8,538,588	14,828,767	190,180	297,082	34	59	1	1
16	Parana	PR	19,975,417	4,780,793	4,203,725	0	0	24	21	0	0
17	Rio do Janeiro	RJ	4,382,512	945,697	785,601	80,031	0	22	18	2	0
18	Rio Grande do Nte	RN	5,302,866	0	941,878	12,342	0	0	18	0	0
19	Rondonia	RO	23,854,162	13,825,626	15,605,149	0	0	58	65	0	0
20	Roraima	RR	22,530,001	0	14,731,119	0	0	0	65	0	0
21	Rio Grande do Sul	RS	26,912,033	7,686,194	5,552,979	4,703,249	0	29	21	17	0
22	Santa Catarina	SC	9,552,796	2,588,890	2,260,509	0	0	27	24	0	0
23	Sergipe	SE	2,199,725	29,413	0	0	0	1	0	0	0
24	Sao Paulo	SP	24,884,407	4,467,755	1,374,962	0	0	18	6	0	0
25	Tocantins	TO	27,874,827	17,268,647	9,572,826	0	0	62	34	0	0

This table includes all municipality areas (not only the new ones) that belonged to polygons influenced by change. Therefore the areas may be over-estimated.

This chapter describes the development of consistent administrative boundaries using GIS and database techniques so that agriculture and deforestation datasets from Brazil during different time periods can be consistently integrated and analyzed.

2.2 Data Source

The IBGE provided geographic data on administrative boundaries for five years (1991, 1994, 1997, 2001, and 2005) in shapefile[3] format (IBGE 2007). These shapefiles were used as the main source of information on administrative boundaries.

Figure 2-1 shows the changes in municipalities through the different years. In 1991, Brazil was divided into 4491 municipalities and, by 1994, the number had increased to 4974 and then jumped to 5510 in 1997. In 2001, a total of 55 new municipalities were added and, in 2005, the number of municipalities reached 5564.

[3] A shapefile is a spatial vector data format that stores geographic information to be used in GIS software.

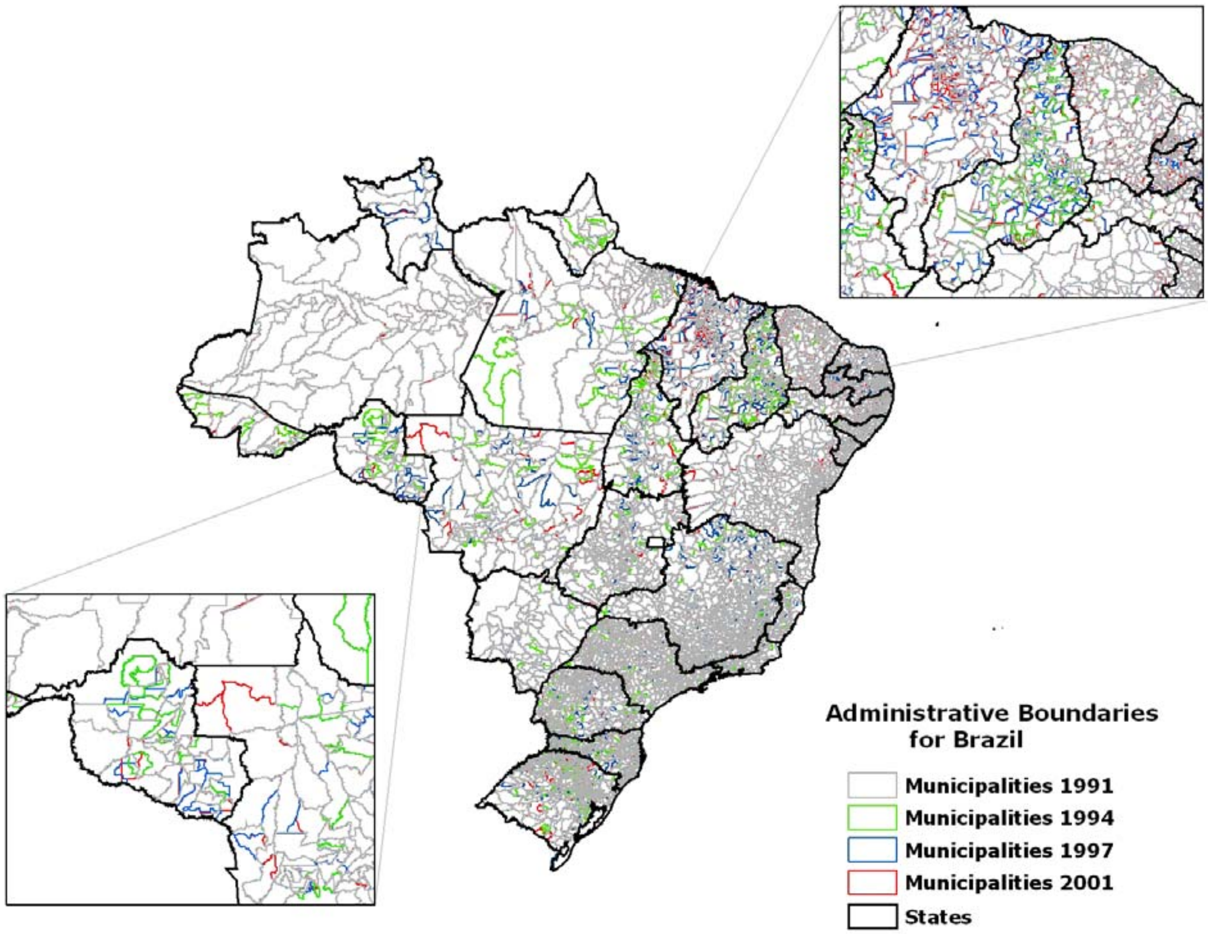


Figure 2-1. Brazilian administrative boundaries, illustrating the change in municipalities for the years 1991, 1994, 1997, and 2001. Data for 2005 is not shown because the change was minimal.

2.3 Methods

2.3.1 Developing consistent administrative boundaries

The different shapefiles were used to (1) identify the new municipalities in each year (1994, 1997, 2001, and 2005), and (2) create a database that contained the historical changes when they occurred. The 2005 digital version (IBGE 2006) contained the most complete information on administrative boundaries for Brazil (5564 administrative units) and was therefore used as basis to create new map units.

The new municipalities established each year were identified using the following GIS techniques: overlay of different shapefiles, multiple queries, and selection. The overall objective was to find the largest administrative unit (or sometimes groups of administrative units) that could be consistently mapped over time. Then, the geographic areas that could be consistently analyzed over time were defined using the following rules:

1. If an administrative unit was split at any given time into smaller units, the larger unit from the previous time period was chosen to represent the data. The tabular data from the smaller units in later time periods were aggregated and assigned to the administrative boundary of the larger unit (Figures 2-2a and 2-2b).

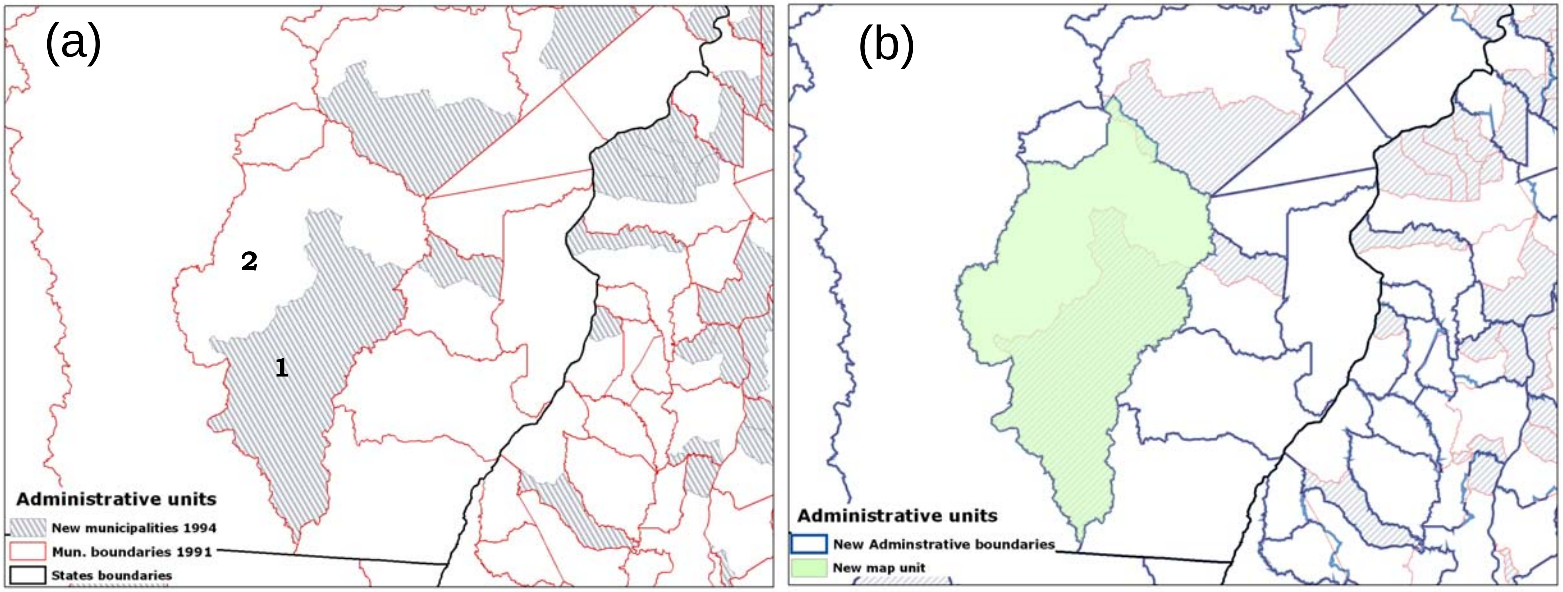


Figure 2-2. New administrative units created for Brazil to represent census statistics from 1990 to 2006 (example 1).

(a) The municipality Cumaru do Norte (1) in the state of Para was created in 1994 by dividing Ourilandia do Norte (2).

(b) The new map unit was created by merging the municipality (1)with Ourilandia do Norte.

The database includes the changes that occur over time. For example, in 1994 the municipality of Ourilandia do Norte in Para was divided to create the new municipality of Cumaru do Norte and then divided again in 1997 to create the municipality of Bannach (Table 2-3a). In this case, the keycode assigned to each of these three municipalities was the previous IBGE code (Geocodigo) from Ourilandia do Norte, but the letter “M” was added (to indicate ‘Merged’). In another example, a larger municipality, Pimenta Bueno in Rondônia, was split into three new municipalities in 1997: Parecis, Primavera de Rondônia, and Sao Felipe D’Oeste. In this case the keycode assigned was that of the larger unit in the previous year (Table 2-3b).

1. Sometimes new municipalities were created by combining several areas of different municipalities where the new municipality boundary cut across old boundaries. In this case, both the tabular data and the shapefiles were aggregated to create a larger pseudo-administrative unit that was consistent over time (Figures 2-3a, 2-3b). For example, the new municipality Tio Hugo in the state of Rio Grande do Sul was created in 2001 by combining portions of the municipalities of Ernestina, Ibirapuita, and Victor Graeff. In this case, all four municipalities were combined into a new pseudo-unit to

represent the data, and a new keycode with the letter “N” (to indicate ‘new’) was assigned to each municipality related with this new area (Table 2-3c).

A keycode was assigned to each municipality as a standard procedure for both the administrative map units and the tabular database. A keycode value not only allows the historical changes that occurred in specific municipalities over time to be determined, but also the tabular statistical data to be linked to new map units. The letter “M” was added to identify when a municipality had been divided and/or modified, and the letter “N” when it had been necessary to create a new map unit.

Table 2-3. Examples of changes in several municipalities of Brazil between 1991 and 2005.

(a)

1991	Mun_Name	UF	1994	Mun Name_94	1997	Mun Name97	2001	Mun Name01	2005	Mun Name05	keycode[1]	Geocodigo[2]
1505437	Ourilandia do Norte	PA	1505437	Ourilandia do Norte	1505437	Ourilandia do Norte	1505437	Ourilandia do Norte	1505437	Ourilandia do Norte	M1505437	1505437
					1501253	Bannach	1501253	Bannach	1501253	Bannach	M1505437	1501253
			1502764	Cumaru do Norte	1502764	Cumaru do Norte	1502764	Cumaru do Norte	1502764	Cumaru do Norte	M1505437	1502764

(b)

1991	Mun_Name	UF	1994	Mun Name_94	1997	Mun Name97	2001	Mun Name01	2005	Mun Name05	keycode	Geocodigo
1100189	Pimenta Bueno	RO	1100189	Pimenta Bueno	1100189	Pimenta Bueno	1100189	Pimenta Bueno	1100189	Pimenta Bueno	M1100189	1100189
					1101450	Parecis	1101450	Parecis	1101450	Parecis	M1100189	1101450
					1101476	Primavera de Rondonia	1101476	Primavera de Rondonia	1101476	Primavera de Rondonia	M1100189	1101476
					1101484	Sao Felipe D'Oeste	1101484	Sao Felipe D'Oeste	1101484	Sao Felipe D'Oeste	M1100189	1101484

(c)

1991	Mun_Name	UF	1994	Mun Name_94	1997	Mun Name97	2001	Mun Name01	2005	Mun Name05	keycode	Geocodigo
4307054	Ernestina	RS	4307054	Ernestina	4307054	Ernestina	4307054	Ernestina	4307054	Ernestina	N4320205	4307054
4309951	Ibirapuita	RS	4309951	Ibirapuita	4309951	Ibirapuita	4309951	Ibirapuita	4309951	Ibirapuita	N4320205	4309951
							4321469	Tio Hugo	4321469	Tio Hugo	N4320205	4321469
4323200	Victor Graeff	RS	4323200	Victor Graeff	4323200	Victor Graeff	4323200	Victor Graeff	4323200	Victor Graeff	N4320205	4323200

[1] The keycode is the variable used to assign a consistent value for each municipality with changes over time.
[2] The 'Geocodigo' is the variable generated by IBGE to identify each municipality with a unique code.

(a) Municipalities divided into two new municipalities in different years (1994 and 1997).
(b) Municipalities divided into small municipalities in the same year (1997).
(c) Municipality created in 2001 from adjacent parts of other municipalities.

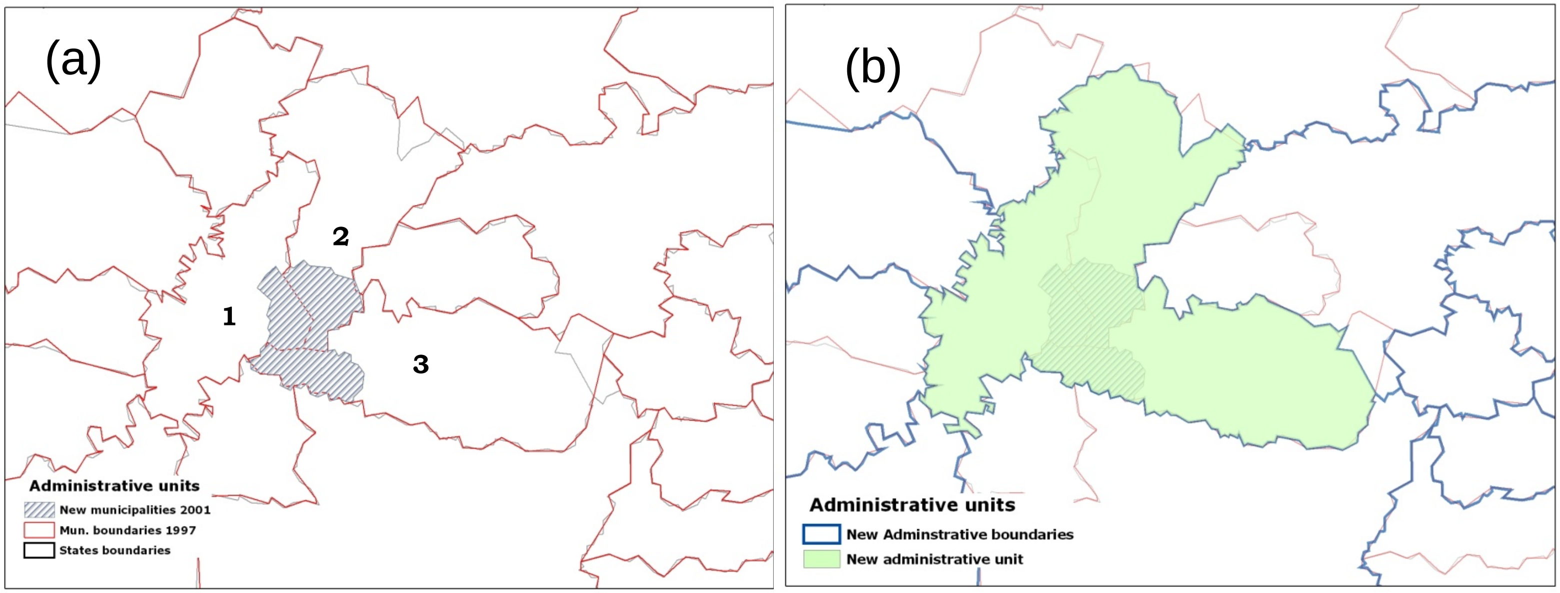


Figure 2-3. New administrative units created to represent census statistics from 1990 to 2006 (Example 2).

(a) The municipality of Tio Hugo in Rio Grande do Sul (shaded area) was created in 2001 by joining adjacent parts of the municipalities of Victor Graeff (1), Ernestina (2), and Ibirapuita (3).

(b) The new map unit combined the four municipalities.

2.3.2 Integrating the dataset of census statistics

The tabular data used in this study come from two sources. Annual crop and livestock statistics for the period 1990-2006 for all of Brazil's municipalities were obtained from the IBGE. Annual information on deforested areas at the municipality level for Legal Amazon, for the period 2000-2006, was obtained from the Brazilian National Institute of Space Research (INPE, its Portuguese acronym).

The different datasets (crops, livestock, and deforested areas) were integrated into the new spatial representation of administrative units for all of Brazil in the case of crops and livestock, and for the Legal Amazon in the case of deforested area. The integration was achieved using the GIS software ArcGIS. Model Builder[1] version 9.2 (Environmental Systems Research Institute, Redlands, California) was used to automate the process.

Figure 2-4 shows the process followed to integrate the dataset on annual crops with the new administrative map units. The Step 1 Model was used to combine the tabular crop data with the new administrative boundaries, using the IBGE code as a common field in both datasets. The output was a new shapefile with data on annual crops for each year from 1990 to 2006.

These shapefiles were used in the Step 2 Model to summarize the statistics for each new map unit. The keycode field (which was added

[1] Model Builder, an ArcGIS application tool, allows the automation of different tasks and processes (ESRI Software).

based on the aforementioned rules) was used as data reference in this process. If the same keycode value appeared more than once in the shapefile, then the different data values were combined into the new field. In other words, if two municipalities had the same keycode value, the model converted these municipalities into a single administrative unit and the values for each crop were summarized in the new field.

The Step 3 Model compares two tabular datasets (crop tabular data and the new shapefile attribute table), which summed each field in both tables, and the total values were compared to make sure that the data had been correctly added to the new map units.

The livestock dataset was integrated using a similar procedure, but two additional steps were required: the addition of new fields and the calculation of animal units for each year (Figure 2-5). These steps are discussed in detail in Chapter 4.

In the case of deforested areas, the IBGE municipality code was added to all pertinent tabular data, linking the dataset on deforested area with administrative map boundaries. Several adjustments were also made to the procedures for each script because these datasets only covered the Legal Amazon for the years 2000 to 2006 (Figure 2-6).

It is important to stress that care should be taken when merging the shapefile with the tabular data because, although the names of municipalities did not change, sometimes their administrative borders did.

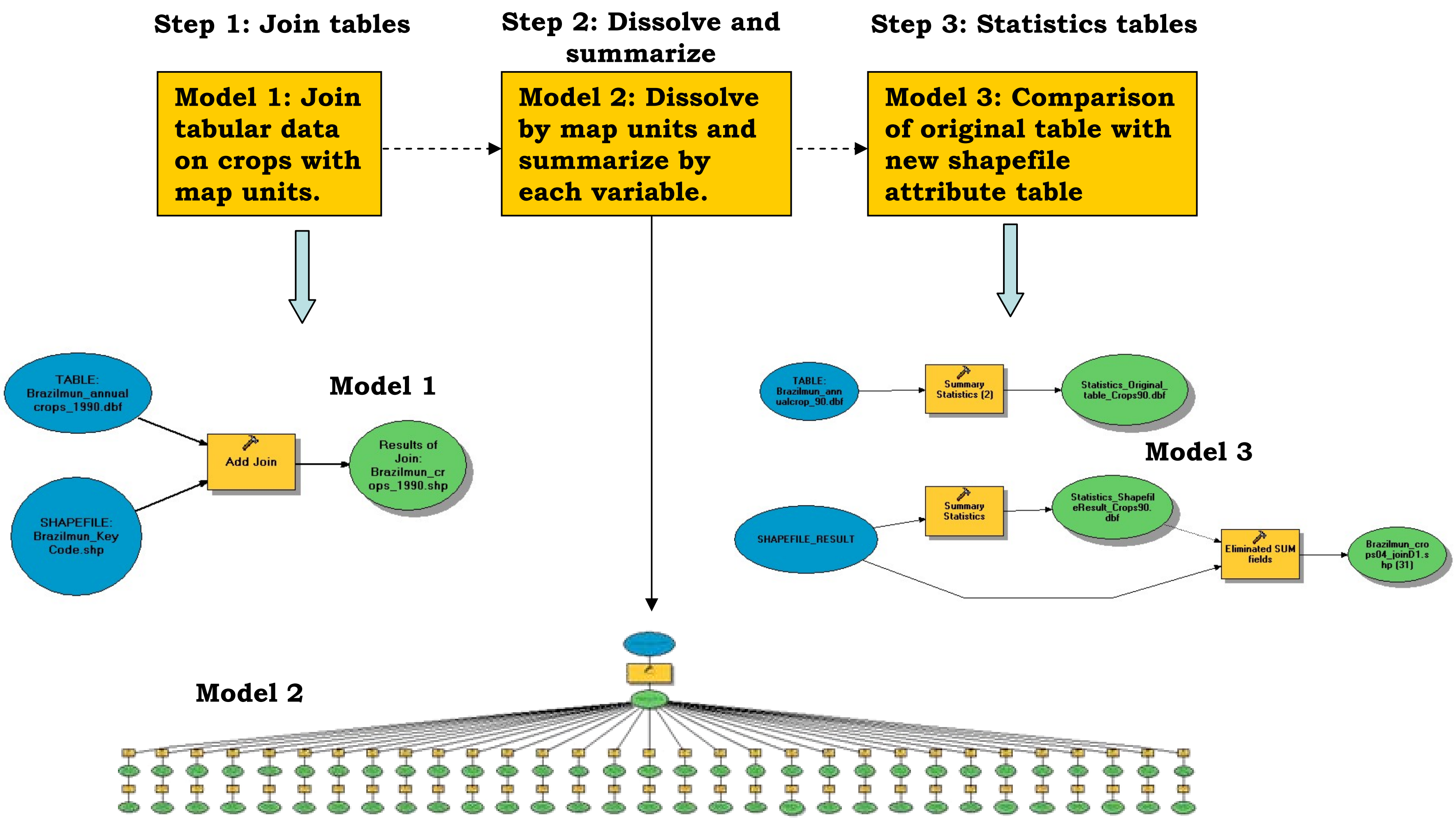


Figure 2-4. Process to combine administrative units with tabular data on crops for each year (1990 to 2006).

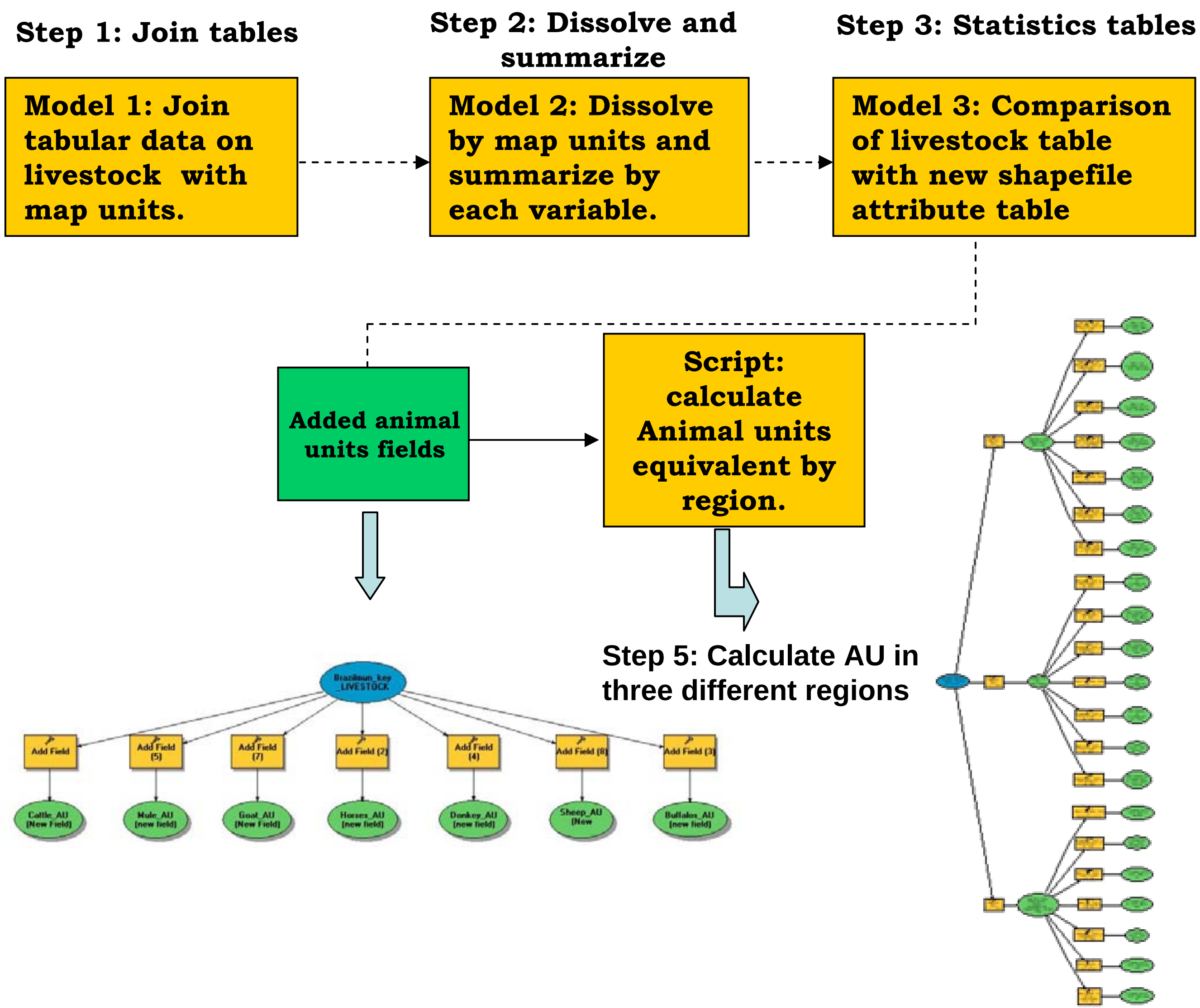


Figure 2-5. Process to combine administrative units with tabular data on livestock for each year (1990 to 2006)

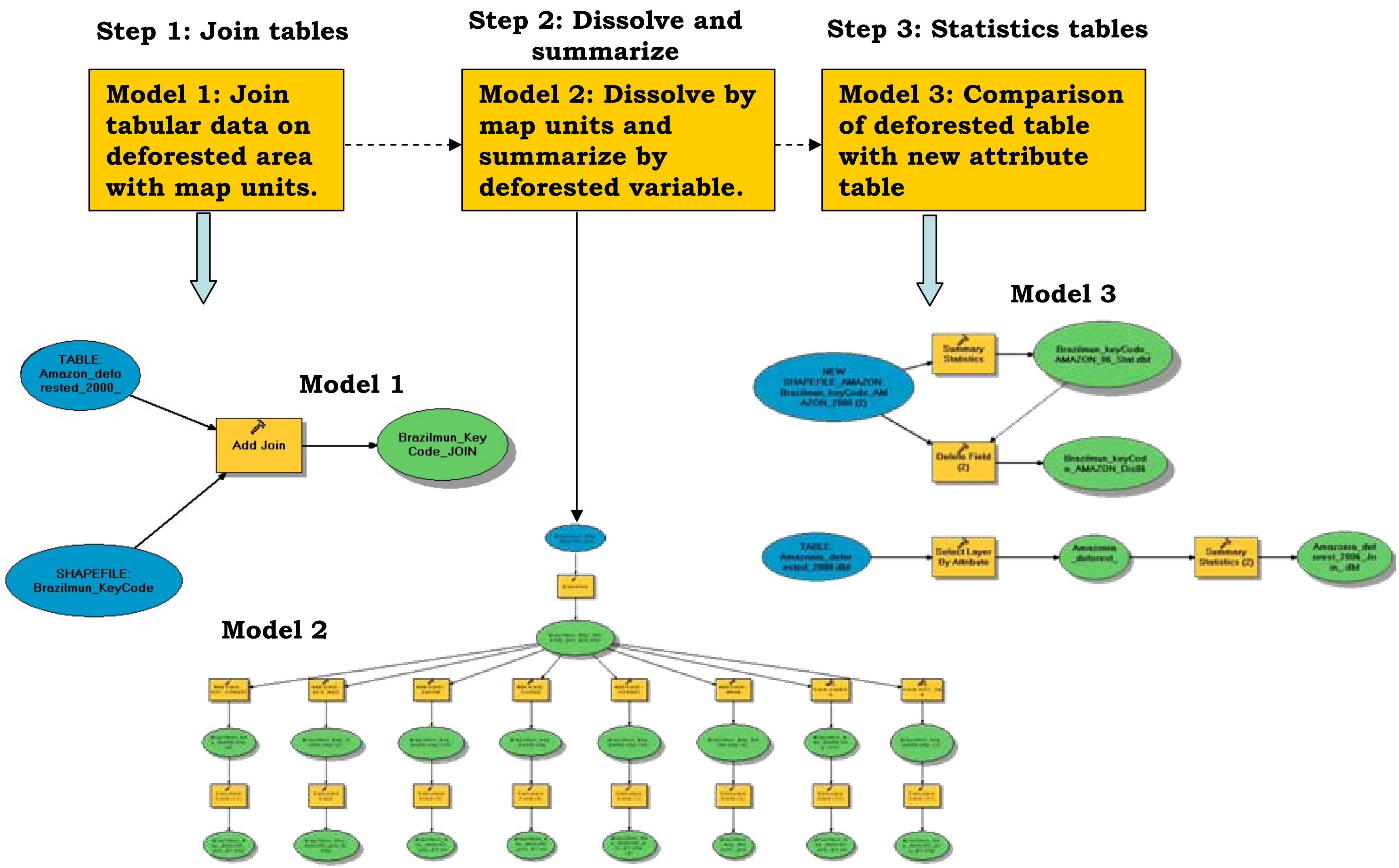


Figure 2-6. Process to combine administrative units with tabular data on deforested area for the Legal Amazon for each year (2000 to 2006).

2.4 Results

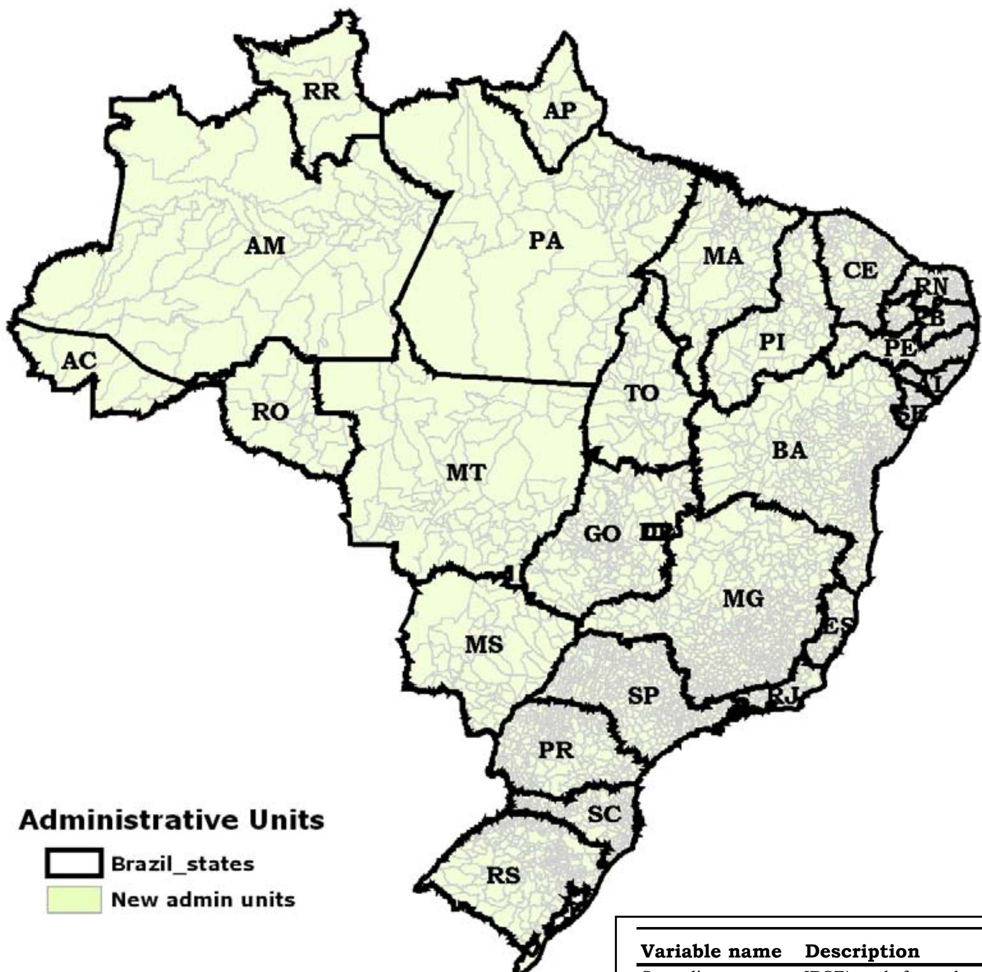
2.4.1 Consistent administrative boundaries

Despite the absence of a geographic database capable of providing timely information to conduct a comparative analysis of land use change, a consistent geographic area for the period 1990 to 2006 was generated based on the 2005 IBGE shapefile. The dataset was created using a standard coding scheme, which identified where historical changes have occurred and was linked to an administrative division map handled in a GIS. As shown in Figure 2-7, the new administrative boundaries consist of 4480 map units.

2.4.2 Integrated dataset of census statistics

Tabular census data were integrated into the new administrative division map to provide a geographic dataset that would allow the comparative analysis of land use change in Brazil from 1990 to 2006. The KEYCODE field was used as a common variable to do this integration.

Figure 2-8 summarizes the different datasets generated, which are represented in a shapefile format that contains the names of the administrative units, the codes, and the corresponding attribute table.



Variable name	Description
Geocodigo	IBGE's code for each municipality
Year	The year when a municipality was created
Mun_Name	Name of the municipality
UF_Code	Code assigned to each state
MUN_Region	Name of the region of Brazil
Mun_MesoR	Name of the meso-region of Brazil
Mun_MicroR	Name of the micro-region of Brazil
KEYCODE	Unique code assigned as identifier of a map unit

Figure 2-7. The new map of administrative units containing 4480 map units that are consistent from 1991 to 2005.

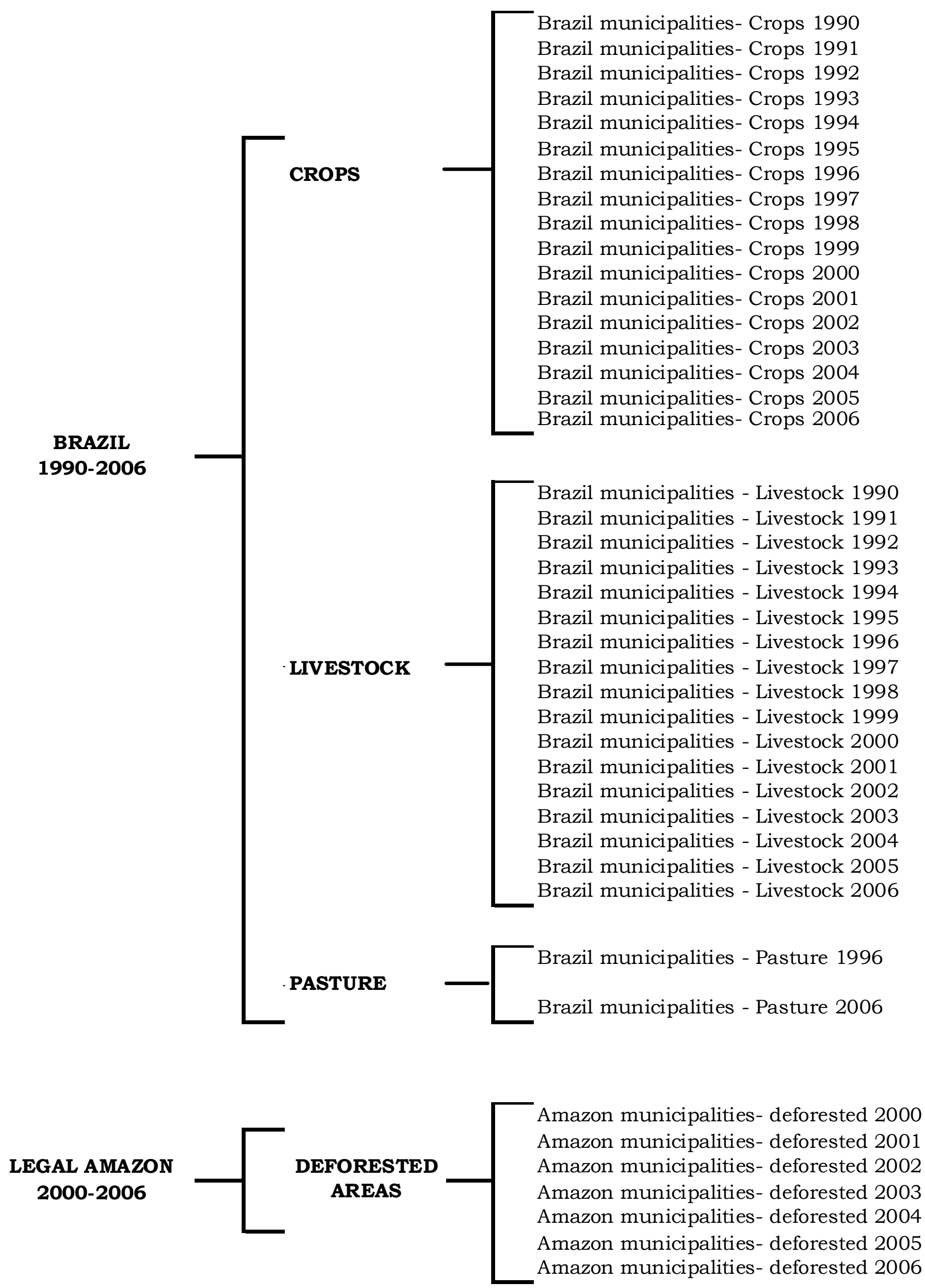


Figure 2-8. Dataset integrated into the new administrative units.

2.5 Conclusions

For many Latin American countries, agricultural censuses probably offer the most detailed information currently existing for crop and livestock production. These datasets provide reliable historical data at a high temporal resolution. These datasets, however, are organized by administrative units and are therefore poorly suited for temporal analysis because of the changes in administrative boundaries over time. Because of demographic, economic, and political changes, existing administrative boundaries are often divided, merged, or reorganized. Ignoring these changes can lead to incorrect analysis and interpretation.

This study compiled agricultural census statistics and deforestation statistics from 1990 to 2006 that are affected by such changes in administrative boundaries. To compare and analyze land use changes consistently over time, it was necessary to prepare a new consistent spatial database of administrative units.

The new administrative database for Brazil that resulted contains a consistent set of 4480 map units that represent the data available from 1990 to 2006.

The different datasets taken from the annual statistical surveys were carefully integrated into new map units. The datasets created (crops, livestock, pasture, and deforestation) for each year were then used as main source of information in the subsequence analyses conducted as part of this thesis. Whereas the newly created database was primarily constructed for the analyses that would be conducted in subsequent chapters of this thesis, it could have enormous value for other studies that have previously ignored changes in administrative boundaries (e.g. Sartoris and Igliori 2007).

CHAPTER 3

The Changing Spatial Distribution of Crops and Livestock in Brazil since 1990

3.1 Introduction

Brazil's agricultural frontier has rapidly expanded over the past decade and the importance of export crops, as compared with subsistence crops, has steadily increased since 1990 (IBGE 2006; Schnepf, Dohlman and Bolling 2001). The remarkably rapid expansion of agriculture, mainly for export commodities, has received much attention in scientific literature, within the agricultural research centres (e.g. EMBRAPA; Consultative Group on International Agricultural Research, CGIAR), and the general media, because this expansion is associated with the conversion of forest, grassland, and other areas of important biodiversity into new agricultural land (Morton et al. 2006; Brown et al. 2007; Nepstad et al. 2008). Less attention has been devoted, however, to subsistence crops, which have also been affected by this change. As a result of economic growth, production for agricultural exports has been growing at a much faster rate than the production for the domestic market, which can affect the production of staple crops and food security in the long term (Meade et al. 2004).

According to the annual crop report series of the SIDRA[1] database, hosted by the IBGE, soybeans, sugarcane, and maize were the most important annual crops in 2006, accounting for 74% of the total area cultivated. Subsistence crops accounted for the remaining 26%. The area harvested to export crops expanded by 121% from 1990 to 2006, whereas the area harvested to domestic food crops decreased by 21% (IBGE 2006). Therefore the expansion of Brazil's agricultural sector can be basically attributed to export crops, being influenced by two factors: (1) changes in the consumption patterns of countries that influence global markets (i.e., China, USA, or the European Union); and (2) new national policies that improve investment conditions, open the access to investment capital, promote favourable interest rates, create tax incentives, and implement international trade arrangements (USDA 2004; Nepstad et al. 2006; Fearnside 2001).

With the growing interest in Brazilian agriculture, recent studies have focused on understanding the drivers and spatial patterns of soybean expansion (Morton et al. 2006; Brown et al. 2005; Grau et al. 2005; Mueller 2003). However, few have focused on other traditional subsistence crops, including cassava, beans, and rice. This chapter aims to analyze the changes in geographic patterns of all major crops

[1] Acronym for the IBGE System for Automatic Retrieval (Sistema IBGE de Recuperação Automatica). Available at http://www.sidra.ibge.gov.br/.

(including subsistence crops) and livestock production in Brazil from 1990 to 2006.

3.2 Data Sources

Agricultural data obtained from censuses as well as survey statistics corresponding to the period 1990-2006 were used to analyze land use patterns and dynamics. The main source of the data for this study was IBGE's statistics database SIDRA, which includes information on agricultural and livestock production at the municipality level gathered from surveys, censuses, and aggregated databases.

IBGE also has a network of agencies across the country, located at the different municipal seats, which are responsible for monitoring the crops that are cultivated and for collecting, compiling, organizing, and disseminating information on all agricultural products. In addition, IBGE maintains a crop reporting system that involves different public and private organizations and has created different groups in each unit of the Federation that are responsible for making local estimates. This is referred to as a federative political-administrative structure. There are currently nine groups responsible for gathering and analyzing data with a defined periodicity and area coverage. For example, the group responsible for crop information was named Municipal Agricultural Production (PAM, its Portuguese acronym), and that for animal-related information was named Municipal Livestock Production (PPM, its Portuguese acronym).

Each month the reports are re-evaluated based on new information received. The statistical surveys are then transformed into aggregate datasets for on-line queries in the SIDRA internet system. The tabular data are subsequently generated and published on the IBGE's official website[2] (IBGE 2002; Palermo 2006).

The following information from SIDRA was used to conduct this analysis. The data compiled below were integrated into the municipality boundaries as described in Chapter 2.

Harvested area of crops

The IBGE-SIDRA statistical database includes planted area, harvested area, value of production, and other variables for perennial and annual crops. This study focussed on the harvested area of 31 seasonal crops (subsistence, traditional, and export) reported by each municipality[3]. Tabular data were compiled from the website for the period 1990-2006.

---

[2] SIDRA website (http://www.sidra.ibge.gov.br/)

[3] The total number of municipalities in Brazil changed constantly during the period covered by this study (from 4491 to 5564). For instance, in 1991 Brazil was divided into 4491 municipalities. In 1994 this number increased to 4974 and then jumped to 5512 in 1997. In 2001, a total of 55 new municipalities were added and, in 2005, the number of municipalities reached 5564.

Livestock

The analysis included livestock information in order to examine the changes in the extent of pasture as a key factor in the changing land cover related to livestock production. Although pasture-related information forms part of the agricultural census, no pertinent annual estimates are available. However, livestock data are available on an annual basis. Therefore, livestock data were included as a proxy for the changes in grazing area during 1990-2006.

The IBGE-SIDRA database reports the number of heads of livestock (cattle, horses, mules, buffalos, donkeys, goats, and sheep) at the municipality level. However, because not all livestock are of the same size or weight, or consume the same amount of forage, it was necessary to convert livestock data to an animal unit equivalent[4] to be able to quantify the forage demand per animal specie. In the case of Brazil, the Ministry of Agriculture developed, for each one of Brazil's regions, a standard conversion factor per animal unit equivalent (Table 3-1). The municipal livestock data were converted to animal units using the corresponding regional factor equivalent, as indicated in Table 3-1, for the 16-year period (1990-2006). Using a geographic information system (GIS), crop and livestock data for each year were compiled into a database, whose structure is presented in Table 3-2.

[4] An animal unit equivalent is a conversion factor used to determine the total number of animal units when aggregating data with more than one species (Scarnecchia 2004).

Table 3-1. Animal unit conversion factors per region in Brazil.

Animal Category	Conversion Factor per Region		
	South, Southeast Central-West	North	Northeast
Cattle	1.00	0.92	0.83
Buffalos	1.25	1.15	1.05
Horses	1.00	0.92	0.83
Donkeys	1.00	0.92	0.83
Mules	1.00	0.92	0.83
Sheep	0.25	0.22	0.19
Goats	0.25	0.22	0.19

Source: Ministerio do Desenvolvimiento Agrario (2005)

Table 3-2. Database structure for each period.

Variable	Description
Total_HA	Total harvested area in each municipality from 1990 to 2006 for all 31 annual crops: beans, barley, broad bean, cassava, cotton, castor bean, garlic, jute, linen, maize, mallow, melon, oats, onion, potato, pea, peanut, pineapple, rami, rice, rye, tobacco, tomato, triticale, sunflower, soybean, sorghum, sugarcane, sweet potato, wheat and watermelon
Total_AU	Total livestock expressed in animal units in each municipality from 1990 to 2006
Cattle_AU	Number of cattle
Horse_AU	Number of horses
Buffalo_AU	Number of buffalos
Donkey_AU	Number of donkeys
Mule_AU	Number of mules
Goat_AU	Number of goats
Sheep_AU	Number of sheep

3.3 Results

3.3.1 Changing spatial distribution of crops and livestock

This analysis used the data on harvested area for 31 annual crops, obtained from agricultural surveys conducted throughout Brazil at the municipality level. Predominant crops, in other words those crops presenting the largest harvested area in each municipality, were identified for the years 1990, 1995, 2000, and 2006 as part of the preliminary analysis of patterns of change (Figure 3-1).

In 1990, maize and soybean occupied the largest area, followed by sugarcane, rice, beans, and cassava (Figure 3-1a). In 1995, soybean and maize continued as predominant crops but soybean had expanded into new areas (i.e., southern Maranhão), whereas cotton and wheat decreased in area cultivated. A slight expansion occurred in the areas harvested to sugarcane (especially in São Paulo), rice, beans, and cassava (Figure 3-1b). In 2000, the area harvested to rice, beans, cassava, cotton, and wheat began to decline, whereas that of soybean and sugarcane continued to expand (Figure 3-1c). Soybean, in particular, showed a significant growth in Mato Grosso, Goiás, and Tocantins (Figure 3-1d).

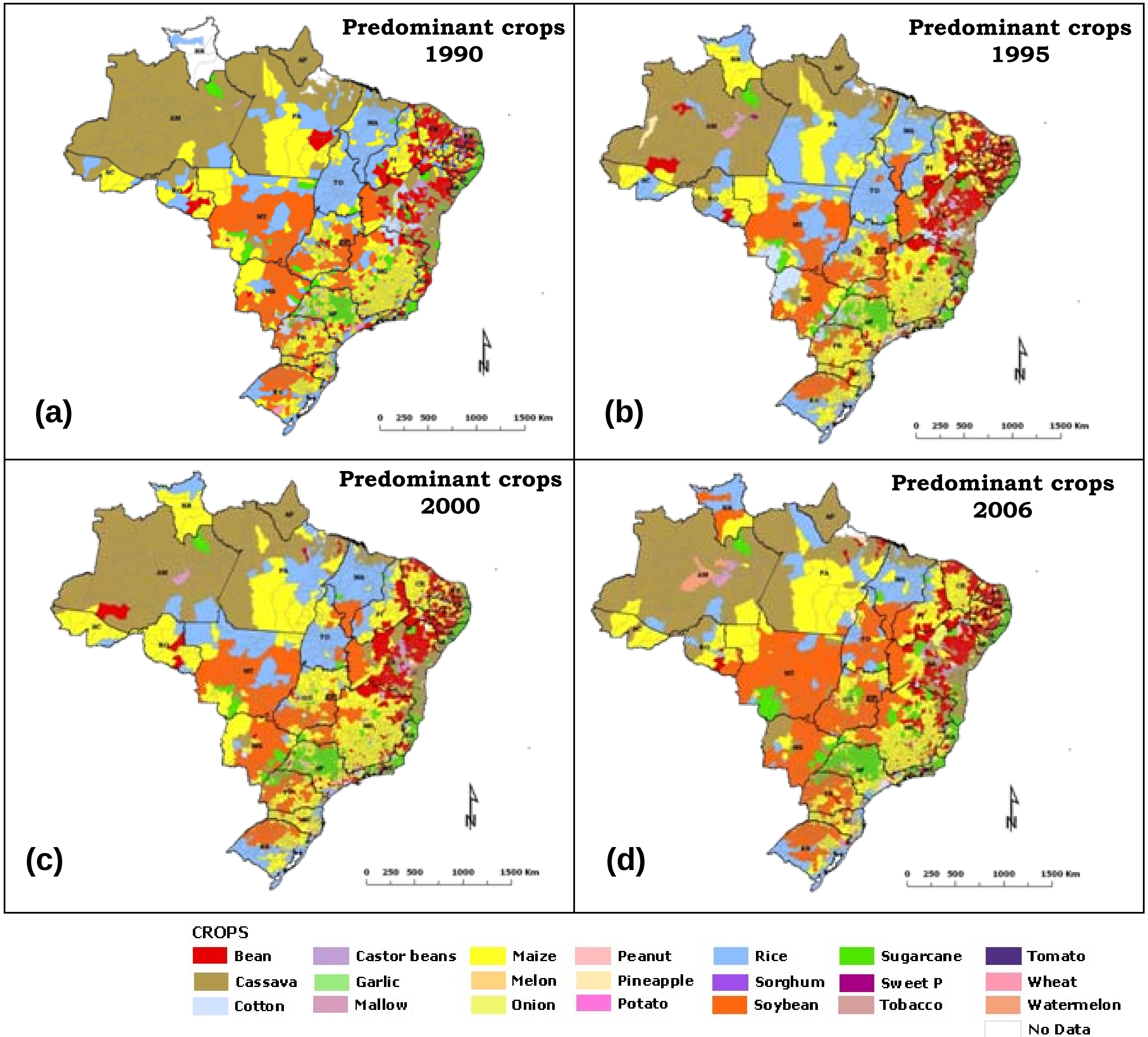


Figure 3-1. Predominant crops in each municipality from 1990 to 2006

Table 3-3, on the other hand, summarizes the percentage of change in area harvested in 31 seasonal crops in Brazil from 1990 to 2006. Soybean, maize, sugarcane, rice, beans, cassava, wheat, and cotton were the eight most important crops in terms of area harvested in Brazil in 1990. However, only soybean, maize, and sugarcane showed an increase in area harvested in 2006.

Table 3-3. Change in area of 31 seasonal crops in Brazil during 1990-2006

CROPS	Total harvested area (ha)				% Harvested area 2006	Harvested area change 1990 to 2006	% Harvested area change 1990 to 2006
	1990	1995	2000	2006			
Soybean (Soja)	11,487,303	11,675,005	13,656,771	22,047,349	40.24	10,560,046	93.46
Maize (Milho)	11,394,307	13,946,320	11,890,376	12,613,094	23.02	1,218,787	10.79
Sugar Cane (Cana de açúcar)	4,272,602	4,559,062	4,804,511	6,144,286	11.21	1,871,684	16.57
Beans (Feijão)	4,680,094	5,006,403	4,332,545	4,034,383	7.36	-645,711	-5.71
Rice (Arroz)	3,946,691	4,373,538	3,664,804	2,970,918	5.42	-975,773	-8.64
Cassava (Mandioca)	1,937,567	1,946,163	1,708,875	1,896,509	3.46	-41,058	-0.36
Wheat (Trigo)	2,680,989	994,734	1,138,687	1,560,175	2.85	-1,120,814	-9.92
Cotton (Algodão)	1,391,884	1,103,536	801,618	898,008	1.64	-493,876	-4.37
Sorghum (Sorgo)	137,758	153,961	528,061	722,200	1.32	584,442	5.17
Tabacco (Fumo)	274,098	293,425	310,462	495,706	0.90	221,608	1.96
Oats (Aveia)	193,200	165,179	182,010	323,998	0.59	130,798	1.16
Castor beans (Mamona)	286,703	76,427	208,538	151,060	0.28	-135,643	-1.20
Potato E. (Batata inglesa)	158,326	176,767	151,731	140,826	0.26	-17,500	-0.15
Peanut (Amendoim)	83,583	94,723	104,948	110,777	0.20	27,194	0.24
Triticale (Triticale)	0	0	0	101,088	0.18	101,088	0.89
Watermelon (Melancia)	67,986	79,347	80,509	92,996	0.17	25,010	0.22
Barley (Cevada)	105,067	69,458	145,507	82,177	0.15	-22,890	-0.20
Sunflower (Girassol)	0	0	0	67,829	0.12	67,829	0.60
Pineapple (Abacaxi)	33,167	44,384	60,406	66,845	0.12	33,678	0.30
Onion (Cebola)	74,646	74,676	66,505	63,314	0.12	-11,332	-0.10
Tomato (Tomate)	60,869	62,054	56,720	58,893	0.11	-1,976	-0.02
Sweet Potato (Batata doce)	62,629	55,946	43,900	44,357	0.08	-18,272	-0.16
Broad Bean (Fava)	92,137	74,261	41,179	36,857	0.07	-55,280	-0.49
Melon (Melão)	7,842	13,294	11,399	21,350	0.04	13,508	0.12
Linen (Linho)	4,061	2,855	5,321	18,679	0.03	14,618	0.13
Mallow (Malva)	21,192	6,073	3,759	12,682	0.02	-8,510	-0.08
Garlic (Alho)	17,149	12,758	13,269	10,486	0.02	-6,663	-0.06
Jute (Juta)	3,016	1,651	1,114	4,179	0.01	1,163	0.01
Rye (Centeio)	4,395	2,647	6,755	2,932	0.01	-1,463	-0.01
Pea (Ervilha)	10,798	654	1,467	1,677	0.00	-9,121	-0.08
Rami (Rami)	7,139	2,868	465	447	0.00	-6,692	-0.06
TOTAL	**43,497,198**	**45,068,169**	**44,022,212**	**54,796,077**		**11,298,879**	

Source: IBGE - 2006

Overall, these findings illustrate that soybean showed a remarkable expansion in area from 2000 to 2006, pushing into more new areas. It was also the predominant crop in several municipalities in the Brazilian states of Maranhão, Tocantins, Piaui, Rondônia, and Roraima. The other notable finding was the consistent increase in area harvested to sugarcane during the study period. This crop predominates in much of São Paulo and in several isolated areas in southern Mato Grosso, contrasting sharply with the decline observed in areas harvested to domestic food crops such as beans, rice, cassava, and wheat in almost all the years covered by this study.

As part of the analysis of changing spatial distribution over time of the most important crops as well as livestock production, the following estimates were made per municipality and per crop or livestock animal unit (AU):

- Change in crop harvested area or livestock AU from 1990 to 2006.
- Change in proportion of crop harvested area versus total harvested area from 1990 to 2006.
- Percentage change between 1990 and 2006, normalized by total harvested area.

The maps clearly illustrate the larger movement of soybeans into the Amazon region (especially Mato Grosso), and the resulting decreases and/or shifts in other crops. For instance, between 1990 and 2006, rice shows a relative reduction in area (from 3.94 to 2.97 million hectares) and a major shift northward into Mato Grosso, Para, and Rondônia (Figure 3-2). The area harvested to beans decreased from 4.6 to 4.0 million hectares, especially in the states of São Paulo, Goias, and Tocantins (Figure 3-3). The largest area harvested to cassava is located in northern Brazil, but a slight decrease in area was observed mostly in Para and Maranhão (Figure 3-4). In southern Brazil, wheat showed a substantial decline in area harvested from 2.6 to 1.5 million hectares (Figure 3-5). A decrease in area cultivated was also observed in the case of cotton—from 1.39 to 0.89 million hectares—mainly in São Paulo and Paraná. The maps, however, showed a surprising expansion into new areas, mainly in Mato Grosso (Figure 3-6).

In contrast with the aforementioned results, crops such as maize also showed growth in area, especially in western Bahia and several municipalities of Mato Grosso. Harvested area of maize increased from 11.3 to 12.6 million hectares between 1990 and 2006 (Figure 3-7). Sugarcane also presented a large increase in area cultivated (from 4.2 to 6.1 million hectares), with this expansion mainly concentrated in São Paulo (Figure 3-8). Soybean showed a remarkable expansion in area cultivated, from 11.4 to 22 million hectares, almost doubling its previous area. This expansion was concentrated in the central-western part of the country (Mato Grosso, Mato Grosso do Sul, Goiás, and Tocantins) (Figure 3-9).

The overall pattern shows a clear shift associated with soybean expansion in central-western Brazil. These results indicated that the area harvested to export crops expanded in contrast with those areas harvested to domestic food crops, which recorded a significant decline in extent.

The Brazilian livestock production system is based on native and cultivated pasture with few intensive landless systems (Carvalho 2006; Steinfeld et al. 2006). Therefore livestock numbers were analyzed as an indicator of changing pasture distribution in Brazil for the period 1990-2006 (Table 3-4).

Table 3-4. Total number of animal units per animal category for the years 1990, 1995, 2000, and 2006.

Animal category	**Total animal units**				**Percentage animal 2006**
	1990	**1995**	**2000**	**2006**	
Cattle	141,584,610	155,753,722	164,077,786	197,861,606	93.17%
Horses	5,787,045	6,054,538	5,547,335	5,452,630	2.57%
Buffalos	1,629,052	1,922,237	1,291,130	1,350,129	0.64%
Donkeys	1,129,280	1,131,824	1,044,912	1,000,488	0.47%
Mules	1,866,668	1,819,162	1,217,851	1,253,296	0.59%
Goats	2,325,782	2,207,304	1,808,175	2,018,878	0.95%
Sheep	4,534,176	4,153,792	3,219,687	3,427,127	1.61%
Total	**158,856,614**	**173,042,578**	**178,206,876**	**212,364,154**	

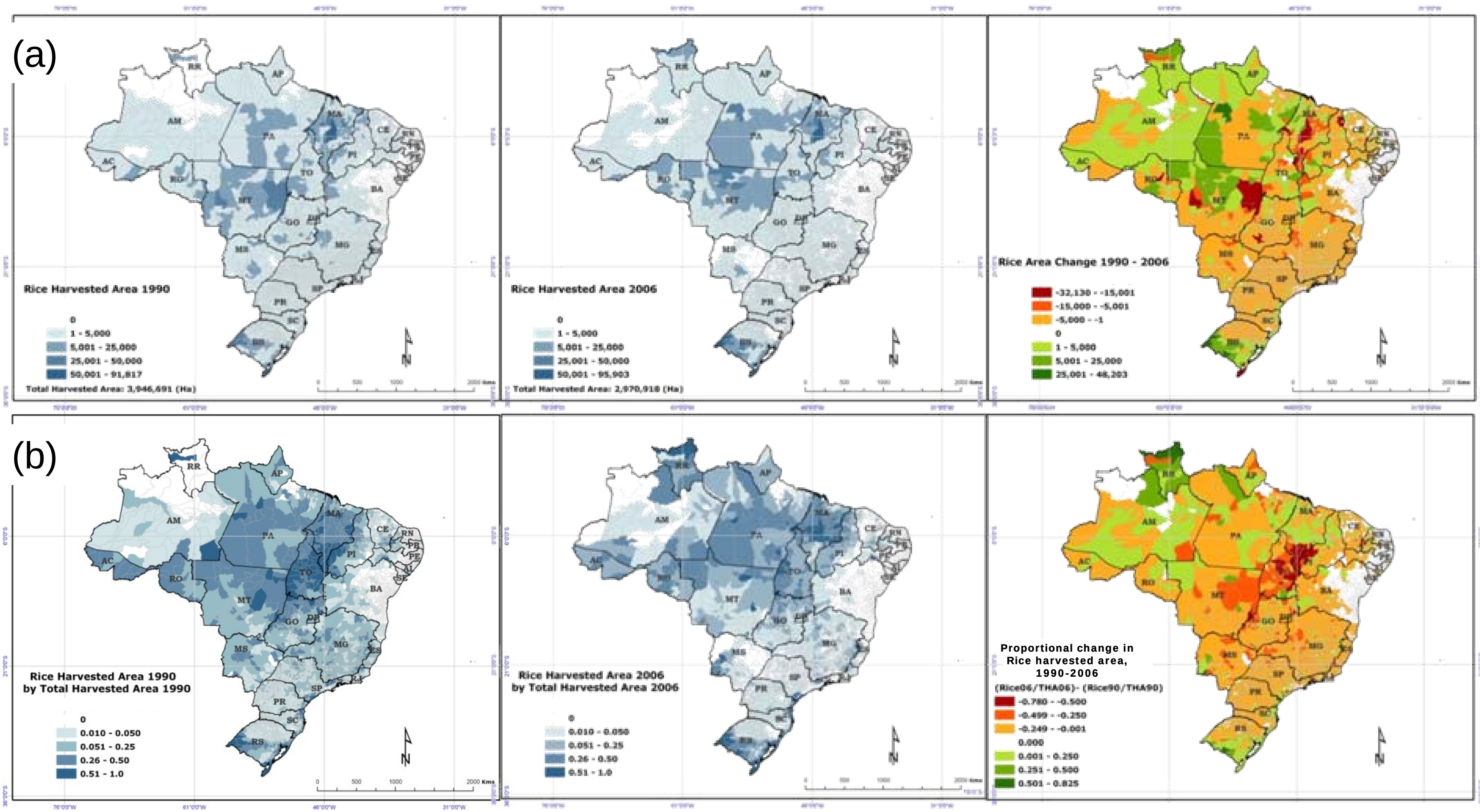


Figure 3-2. Change in spatial distribution of rice harvested area in Brazil between 1990 and 2006.
(a) Total rice harvested area in 1990, 2006, and change from 1990 to 2006 at the municipality level;
(b) same as (a), normalized by total harvested area of all crops.

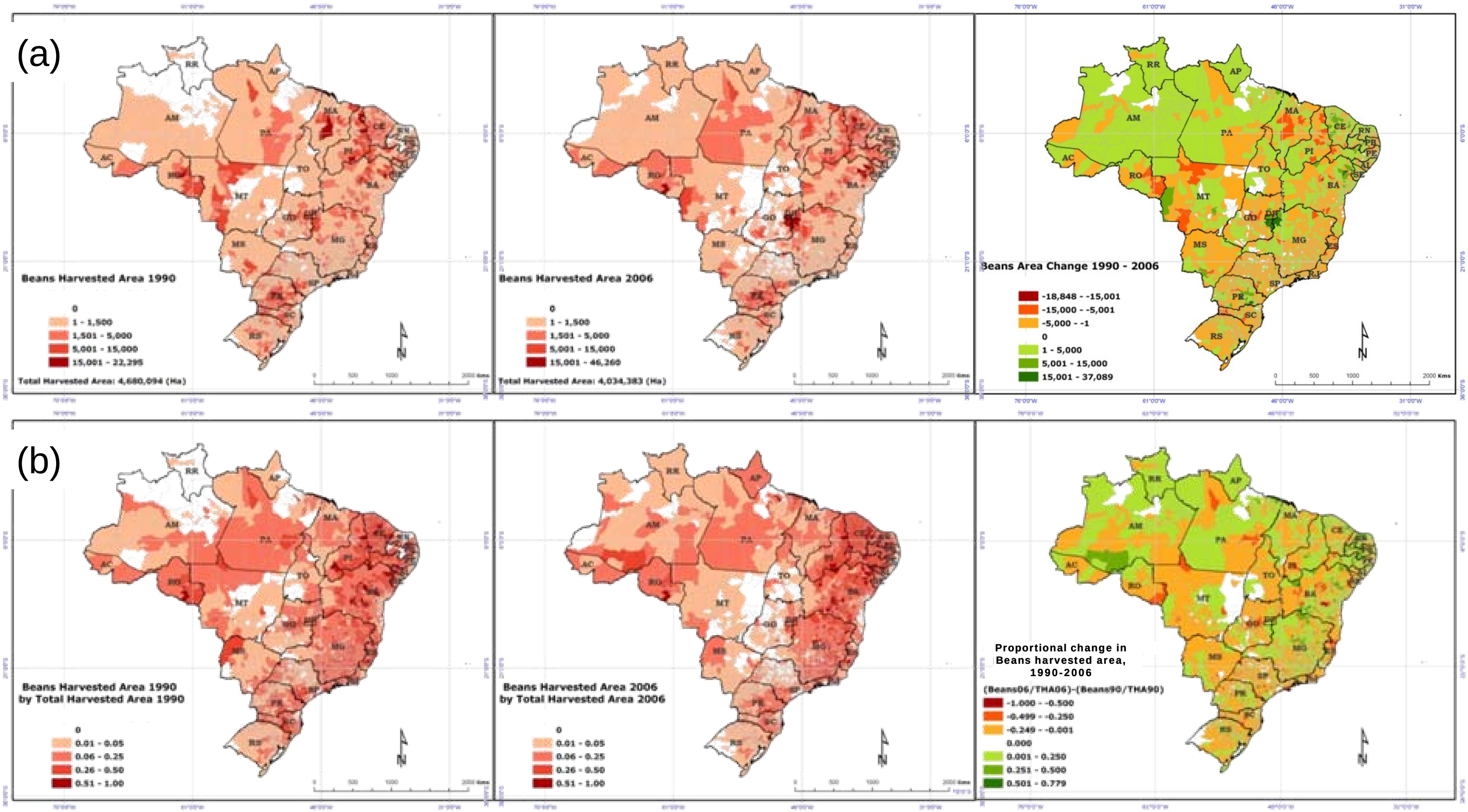


Figure 3-3. Change in spatial distribution of beans harvested area in Brazil between 1990 and 2006.
(a) Total beans harvested area in 1990, 2006, and change from 1990 to 2006 at the municipality level;
(b) same as (a), normalized by total harvested area of all crops.

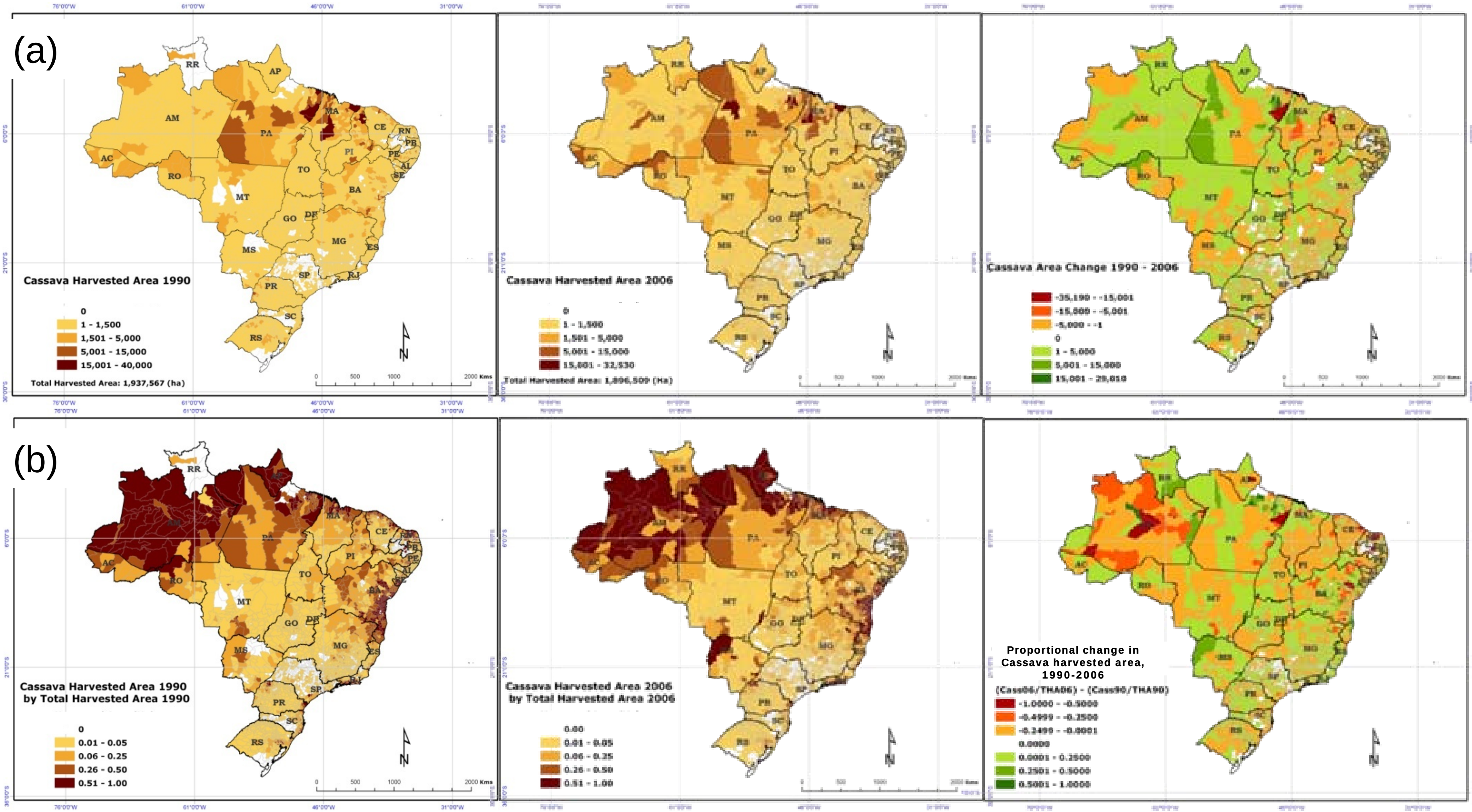


Figure 3-4. Change in spatial distribution of cassava harvested area in Brazil between 1990 and 2006.
(a) Total cassava harvested area in 1990, 2006, and change from 1990 to 2006 at the municipality level;
(b) same as (a), normalized by total harvested area of all crops.

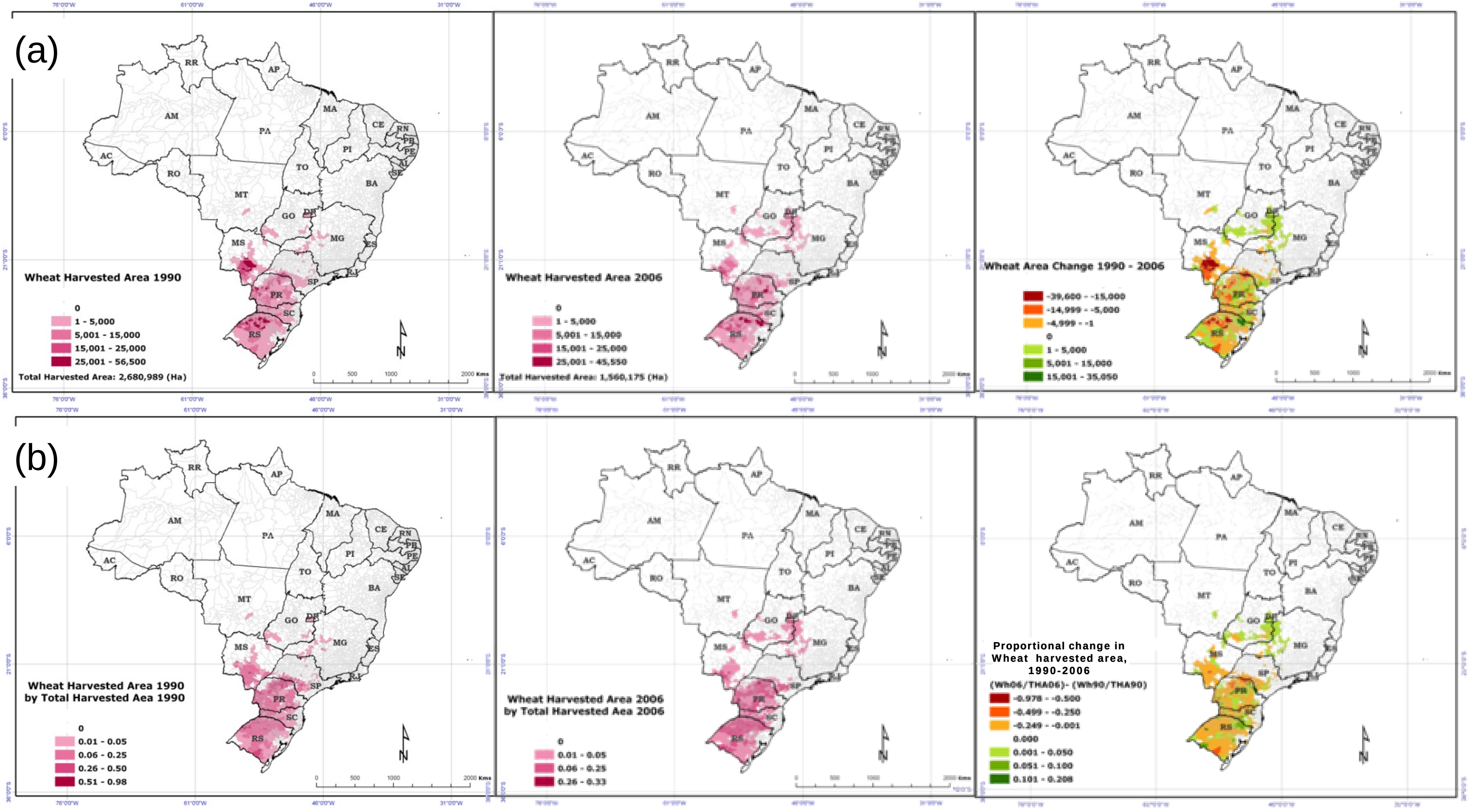


Figure 3-5. Change in spatial distribution of wheat harvested area in Brazil between 1990 and 2006.
(a) Total wheat harvested area in 1990, 2006, and change from 1990 to 2006 at the municipality level;
(b) same as (a), normalized by total harvested area of all crops.

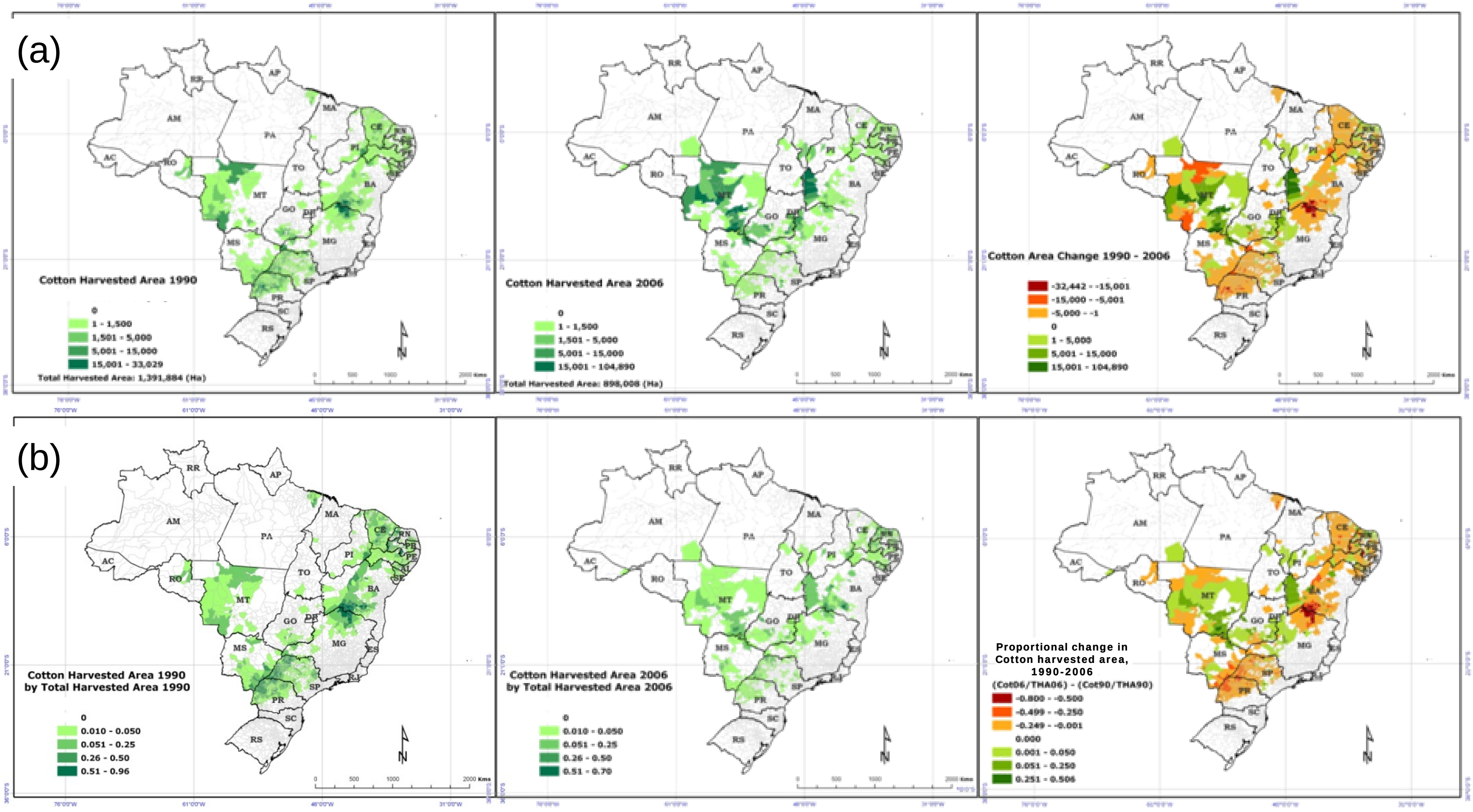


Figure 3-6. Change in spatial distribution of cotton harvested area in Brazil between 1990 and 2006.
(a) Total cotton harvested area in 1990, 2006, and change from 1990 to 2006 at the municipality level;
(b) same as (a), normalized by total harvested area of all crops.

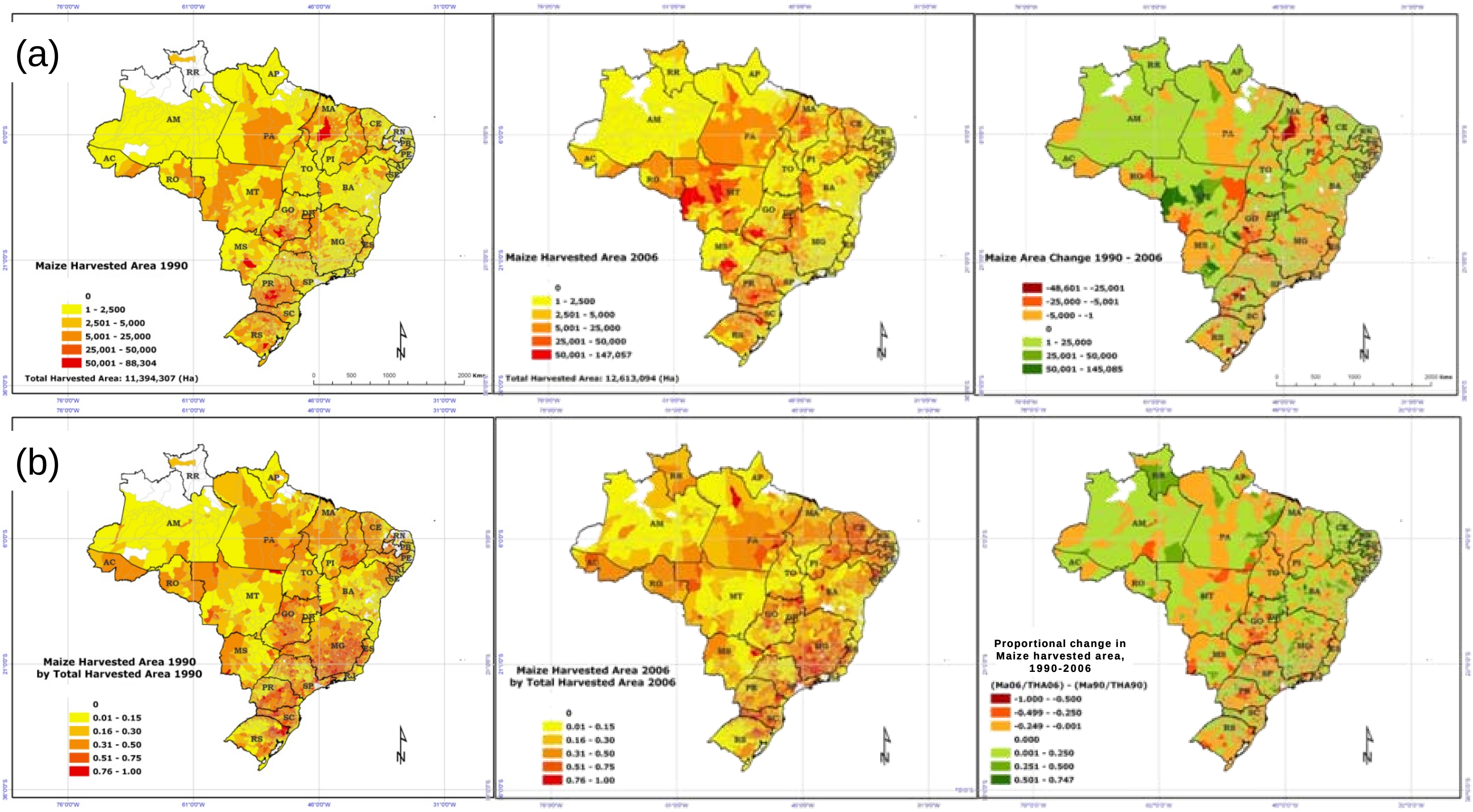


Figure 3-7. Change in spatial distribution of maize harvested area in Brazil between 1990 and 2006.
(a) Total maize harvested area in 1990, 2006, and change from 1990 to 2006 at the municipality level;
(b) same as (a), normalized by total harvested area of all crops.

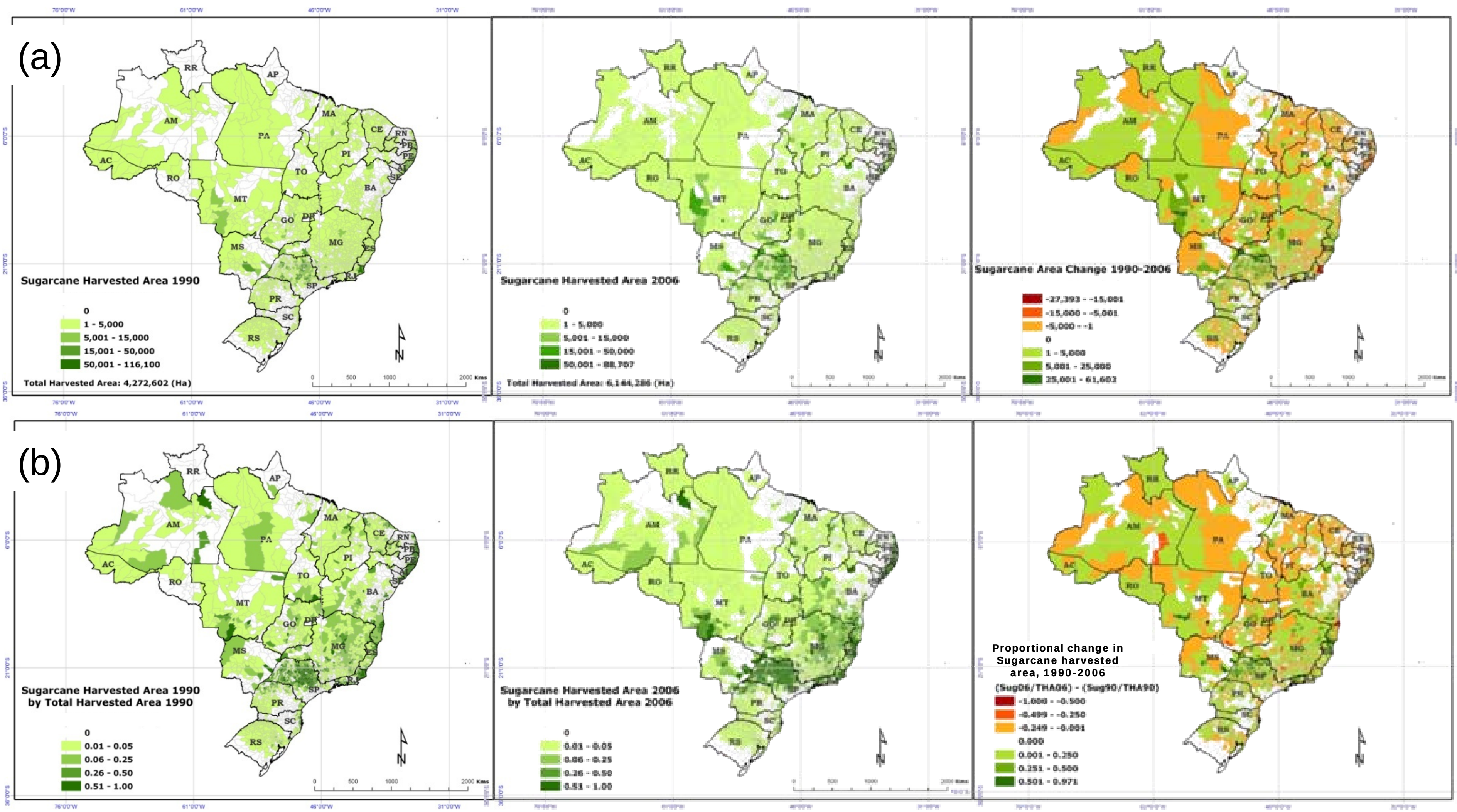


Figure 3-8. Change in spatial distribution of sugarcane harvested area in Brazil between 1990 and 2006.
(a) Total sugarcane harvested area in 1990, 2006, and change from 1990 to 2006 at the municipality level;
(b) same as (a), normalized by total harvested area of all crops.

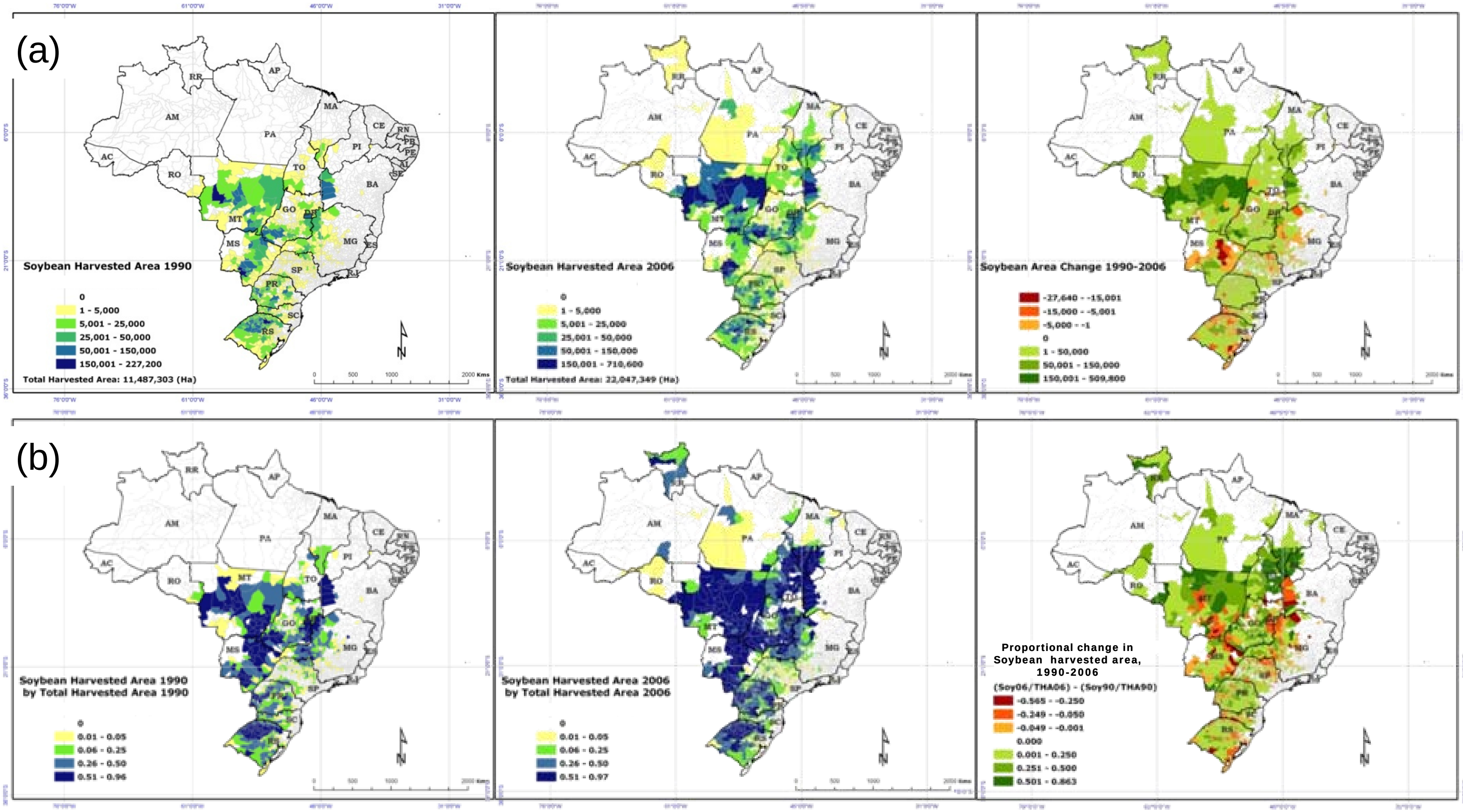


Figure 3-9. Change in spatial distribution of soybean harvested area in Brazil between 1990 and 2006.
(a) Total soybean harvested area in 1990, 2006, and change from 1990 to 2006 at the municipality level;
(b) same as (a), normalized by total harvested area of all crops.

Cattle production (in terms of numbers) ranked first in importance in the country, significantly increasing from 141 million AU in 1990 to 197 million AU in 2006. Livestock distribution in 1990 was primarily concentrated in Mato Grosso do Sul, southern Goiás, and part of Mato Grosso, whereas in 2006 a significant expansion was observed in southern Para, northern Mato Grosso, and Rondônia (Figure 3-10). A general increase in livestock production was observed, and these results suggest an increase in the area sown to pasture as well, although livestock stocking densities have also changed over time.

3.3.2 Shifts in crop growing areas and livestock

The analysis presented in this section aimed to identify the major shifts in Brazilian agriculture by studying how the area-weighted (or centre of gravity) of each crop or livestock species has changed since 1990.

Results presented in this section indicated that the most significant changes occurred in a substantial portion of the *cerrado*[1] region (specifically in the states of Mato Grosso do Sul, Mato Grosso, Goiás, Tocantins, and Maranhão) as well as in the northern part of the country (Figure 3-11). Therefore the study concentrated on the changes

---

[1] Brazil's *cerrado* region comprises a large tropical savanna, located in the central highlands. This region comprises Mato Grosso do Sul, southern Mato Grosso, Goiás, Tocantins, western Minas Gerais, and Maranhão.

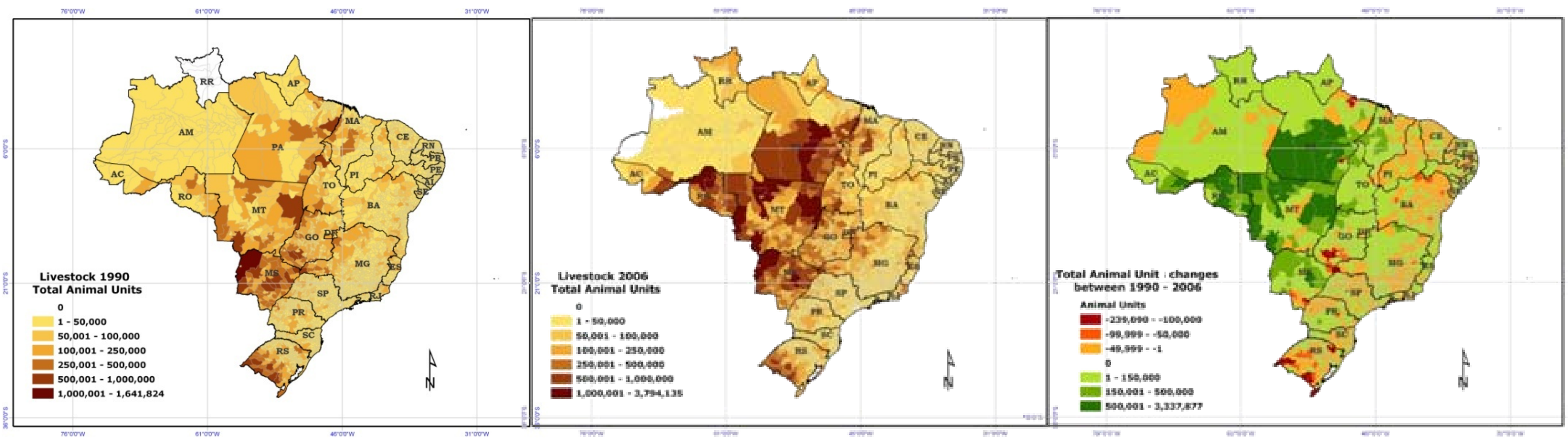


Figure 3-10. Change in spatial distribution of livestock in Brazil between 1990 and 2006. Maps illustrate total animal units in 1990; total animal units in 2006 and changes in animal units between 1990 and 2006 at the municipality level.

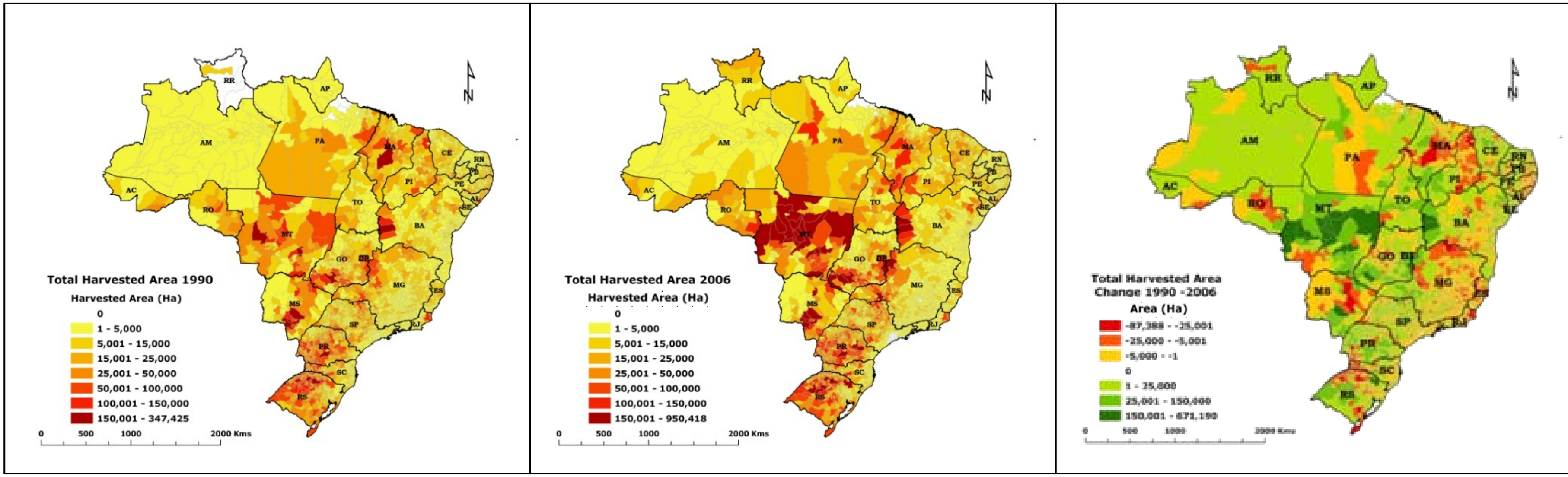


Figure 3-11. Change in spatial distribution of total harvested area in Brazil between 1990 and 2006. Maps illustrate total harvested area in 1990; total harvested area in 2006 and changes in total harvested area between 1990 and 2006 at the municipality level.

in crop and livestock distribution in the Amazon region[1] and the surrounding *cerrado* states.

The analysis involved two steps: (1) determination of the centroid of each municipality, and (2) calculation of the weighted mean centroid over the entire region under consideration, where the weights were the respective harvested areas of each crop or number of livestock in each municipality. The weighted mean centroid is therefore located nearest to those municipalities with the largest harvested area or highest livestock numbers. In other words, it identifies the "center of gravity" of crop or livestock production.

The weighted mean centroids were calculated for seven main crops[2] (maize, beans, rice, cassava, cotton, soybean, sugarcane) and for livestock animal units. The trajectory of change from 1990 to 2006 was then plotted.

The patterns of movement between 1990 and 2006 indicated that, in general, crops moved further into the Amazon region (Figure 3-12). Areas harvested to soybean and rice, which were formerly concentrated in the southern part of the country, had moved northward—214 km in the case of soybean and 192 km in the case of rice. Cotton is also an interesting case: this crop has moved 140 km to the northwest from southern Mato Grosso do Sul toward central-western Mato Grosso.

---

1 The Amazon region comprises the Brazilian states of Acre, Amapa, Amazonas, Mato Grosso, Para, Rondônia, Roraima, Tocantins, and part of western Maranhão.

2 Wheat was excluded from this analysis because its production is mainly concentrated in the southern part of the country, outside the Amazon or *cerrado* regions.

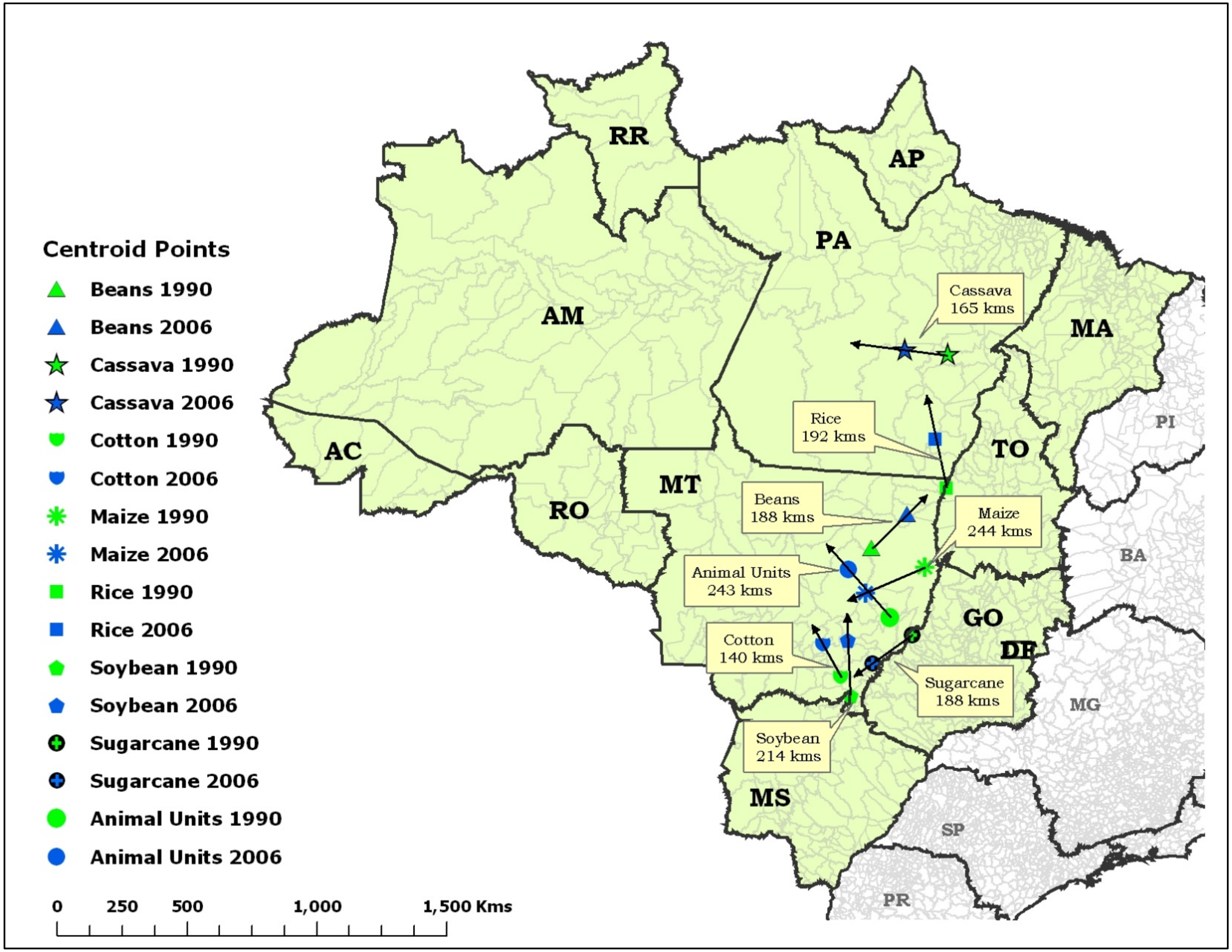


Figure 3-12. The major shifts in Brazilian agriculture between 1990 and 2006.
Each point represents the weighted-mean centroid, which is located nearest to those municipalities with the highest harvested area or livestock number in 1990 and 2006.

Beans and cassava showed a northward movement from 1990 to 2006: beans moved 188 km to the northeast and cassava, 165 km to the northwest. Maize and sugarcane remained with their centre of gravity in the southern part of the country—in the states of Mato Grosso, Goiás, and Mato Grosso do Sul, with maize moving 244 km southwest and sugarcane 188 km in the same direction. Meanwhile livestock production showed a clear movement of 243 km northwestward of Mato Grosso (Figure 3-12).

The patterns of movements from the central-west region (Goiás, Mato Grosso, and Mato Grosso do Sul) to the Amazon region are consistent with the pattern of change discussed in the previous analysis (section 3.3.1). The centre of gravity of soybean cultivation, for example, was located close to the border between Mato Grosso do Sul and Mato Grosso in 1990. However, by 2006 the crop had expanded northward from this state due to increases in area cultivated in central and northern Mato Grosso, southern Goiás, and the states of Tocantins and Maranhão, and decreases in Mato Grosso do Sul (Figure 3-13).

The centre of gravity of cotton moved northwestwards to Mato Grosso. As indicated in previous results, the area harvested to cotton decreased between 1990 and 2006. However, the pattern that emerges in Figure 3-14 indicates a decrease in the area cultivated in the southern part of Mato Grosso do Sul and a clear movement of the crop into new areas in northwest Mato Grosso.

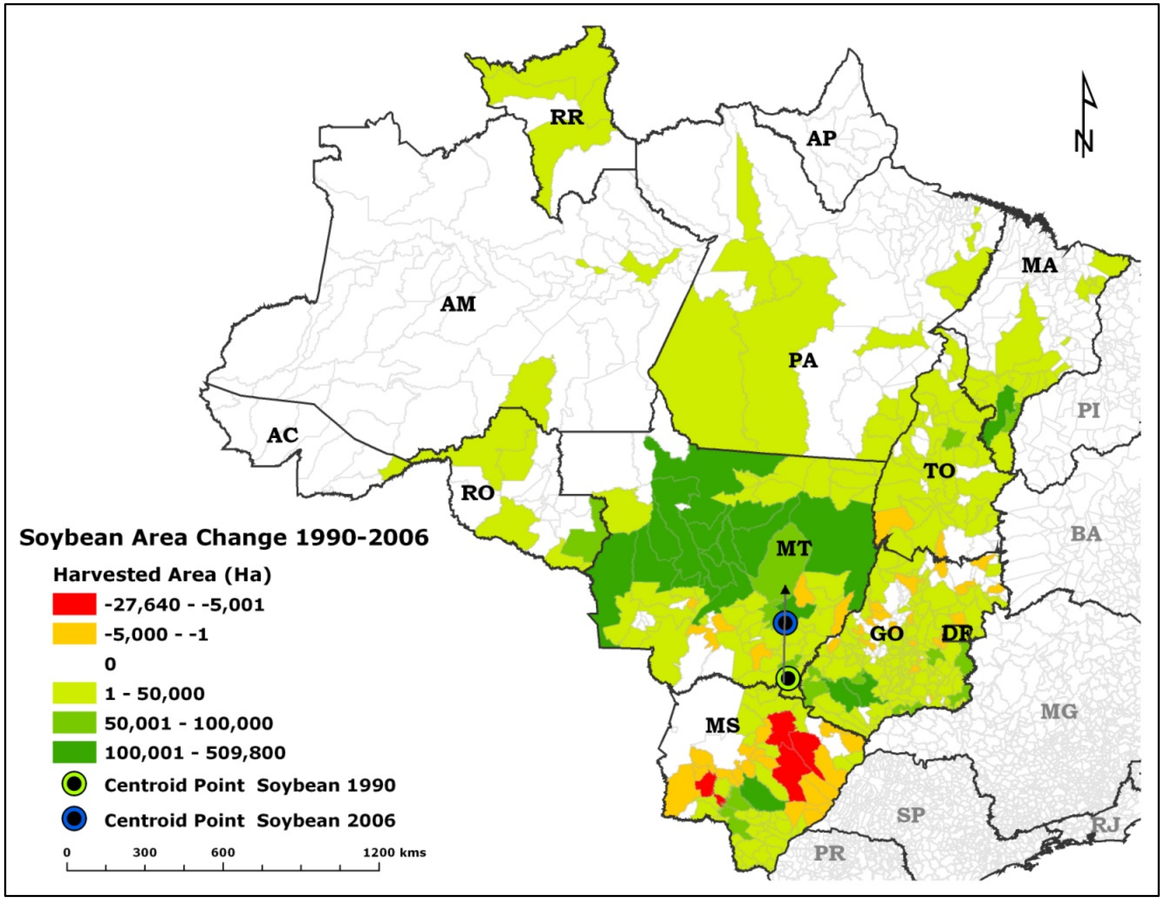


Figure 3-13. Changes in soybean areas and shift of the crop's centre of gravity in the Amazon and *Cerrado* states between 1990 and 2006.

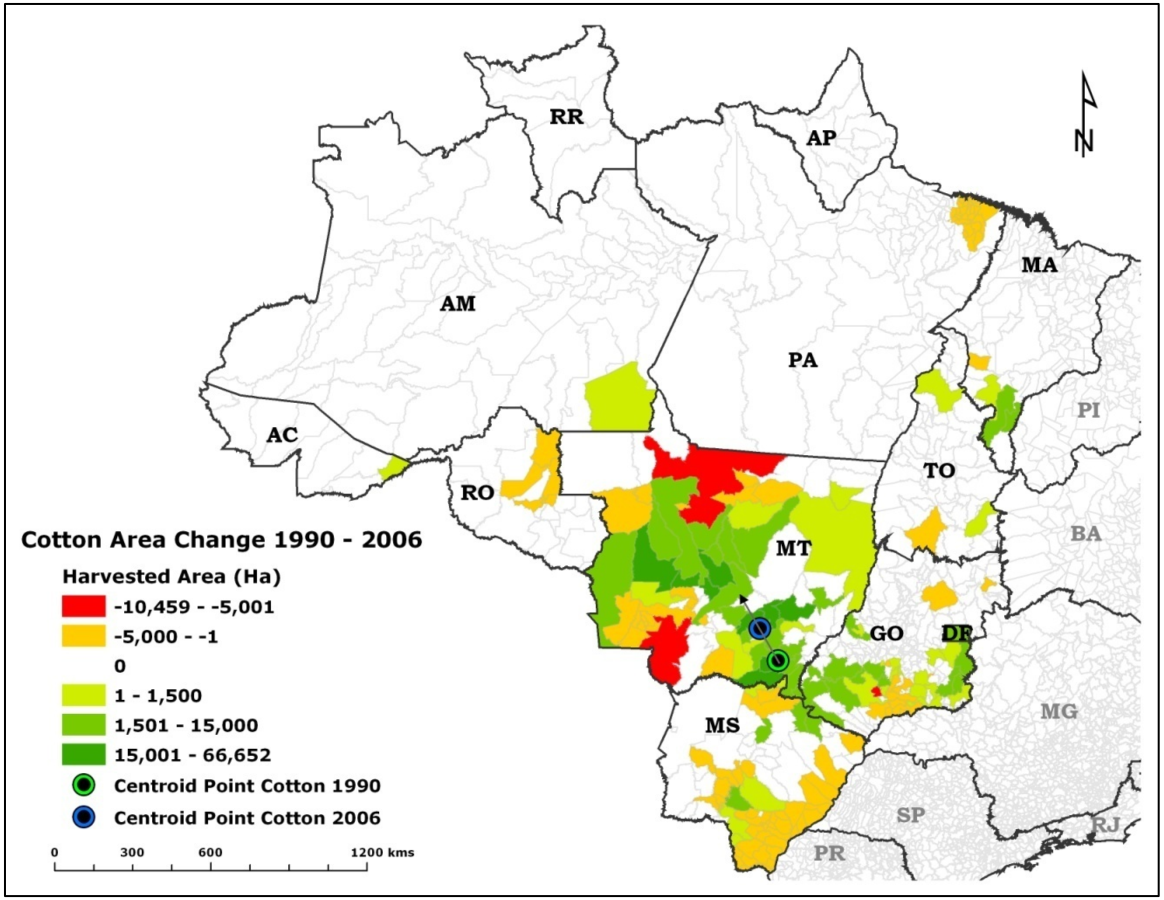


Figure 3-14. Changes in cotton areas and shift of the crop's centre of gravity in in the Amazon and *Cerrado* states between 1990 and 2006.

In the case of rice, a major shift occurred northwards into Para and northern Mato Grosso. This shift was consistent with the decrease in rice areas in Mato Grosso do Sul, southern Mato Grosso, Goiás, and Maranhão (Figure 3-15).

Beans and cassava showed an increase in area harvested in 2006, mainly in the state of Para, whereas a notable decrease was observed in the central-western states. For beans, the centroid points indicate a movement toward the northeast, where the largest areas harvested to beans are located (Figure 3-16). In the case of cassava, the largest areas were concentrated in the state of Amazonas and in northwestern Para, indicating a northwestward movement (Figure 3-17).

The centre of gravity of maize showed a movement toward the southwest, where the cultivated area increased between 1990 and 2006, whereas in the northern Brazil (Maranhão, Para, and Tocantins) this crop decreased in area (Figure 3-18). The cultivation of sugarcane, which presents its highest production in the southern part of Brazil, specifically in Sao Paulo, presents a southward movement into the states of Goias, Mato Grosso do Sul, and southern Mato Grosso. The centroid point increased the same pattern of southward movement as maize (Figure 3-19).

Regarding livestock movements between 1990-2006, Figure 3-20 shows that animal units decreased in the southern part of Goias, Mato Grosso do Sul, and Mato Grosso. Nonetheless, livestock numbers

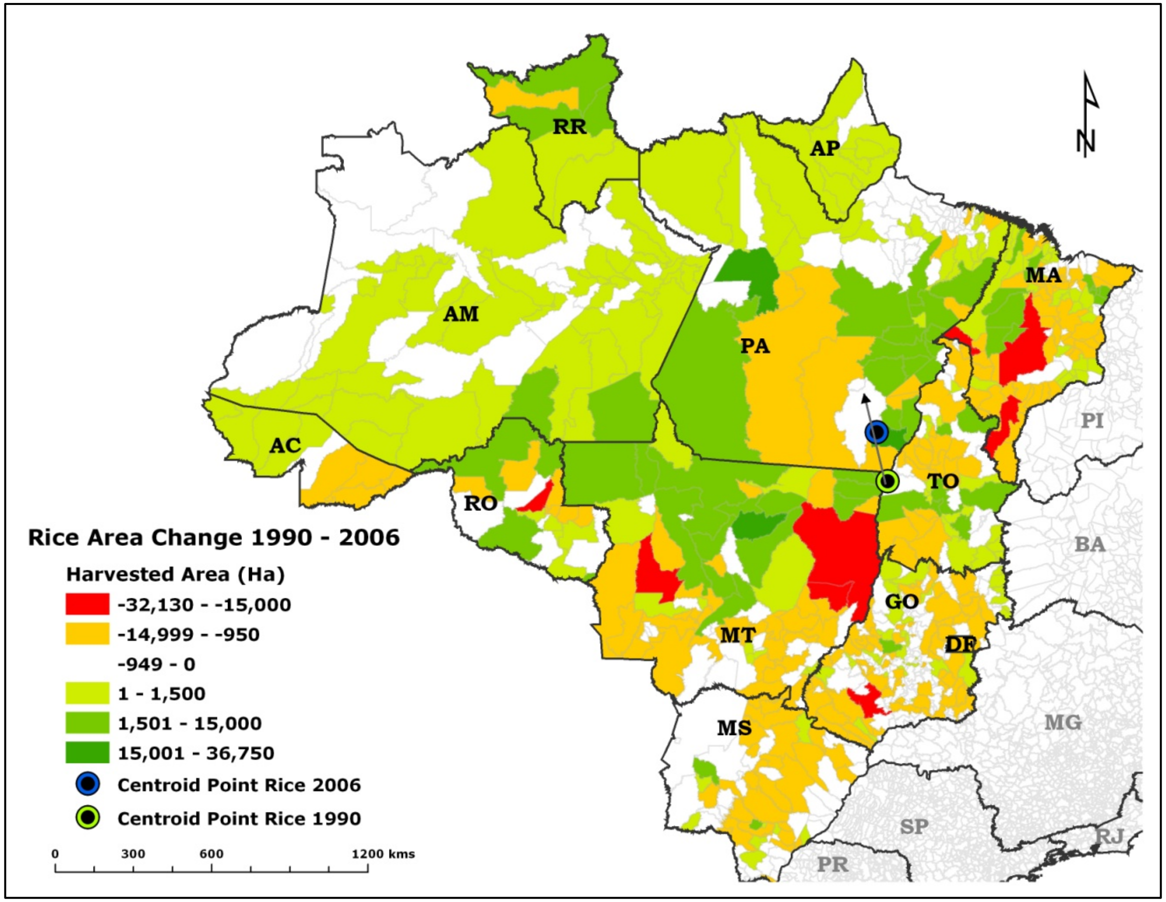


Figure 3-15. Changes in rice areas and shift of the crop's centre of gravity in in the Amazon and *Cerrado* states between 1990 and 2006.

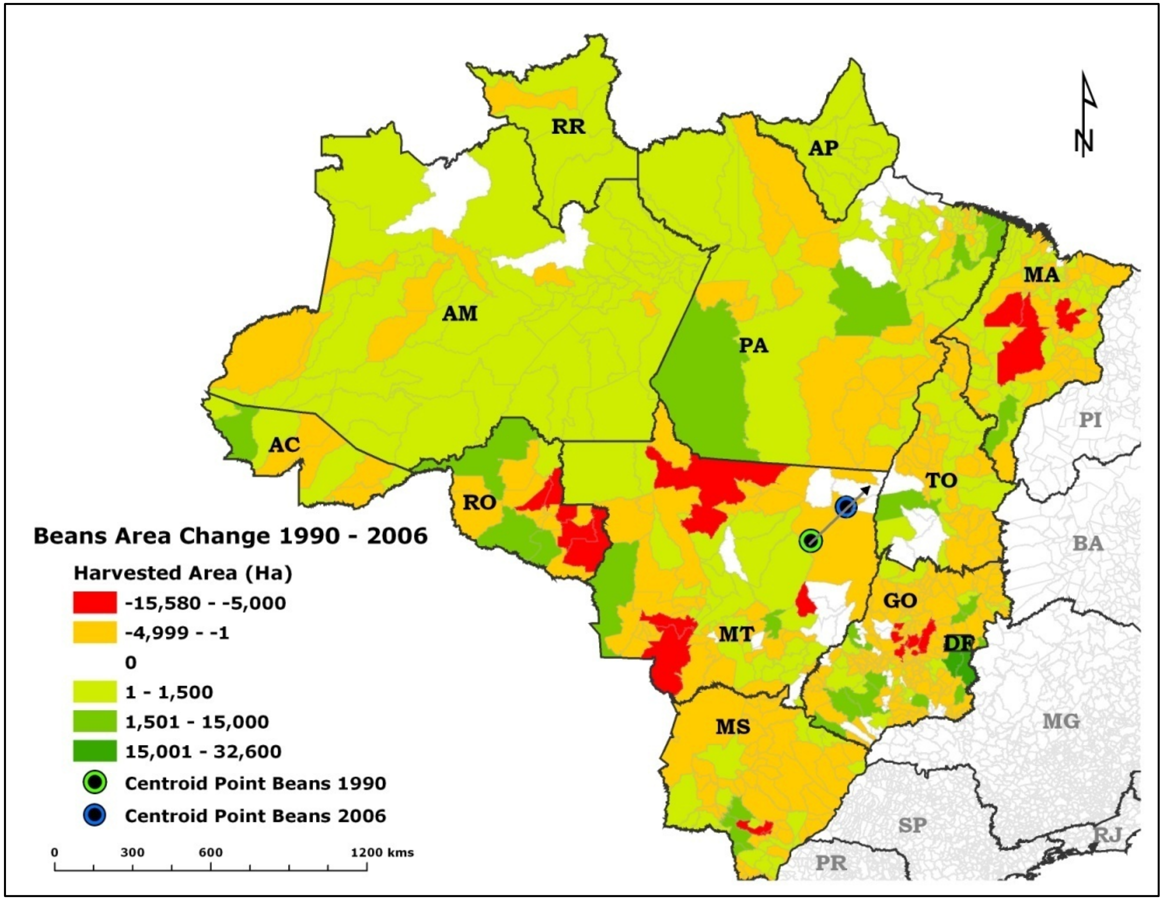


Figure 3-16. Changes in beans areas and shift of the crop's centre of gravity in in the Amazon and *Cerrado* states between 1990 and 2006.

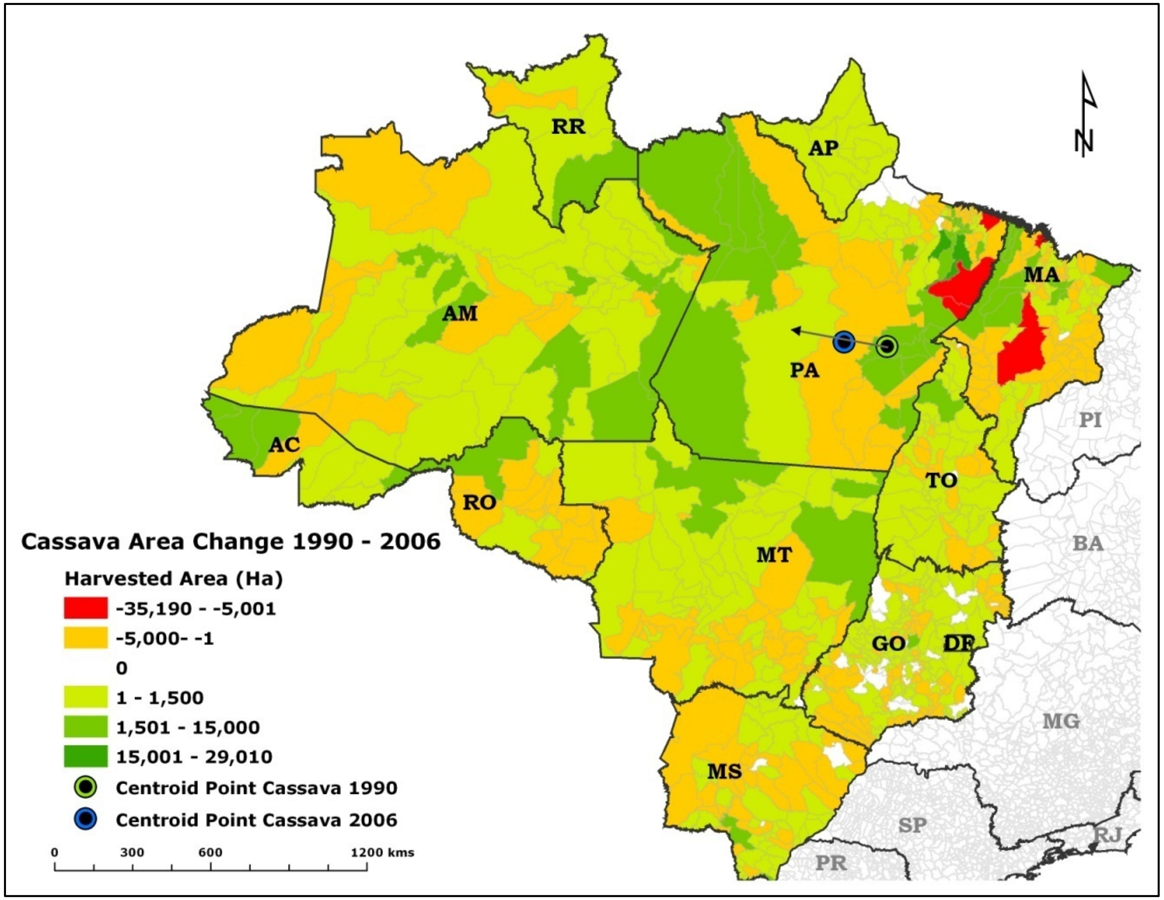


Figure 3-17. Changes in cassava areas and shift of the crop's centre of gravity in in the Amazon and *Cerrado* states between 1990 and 2006.

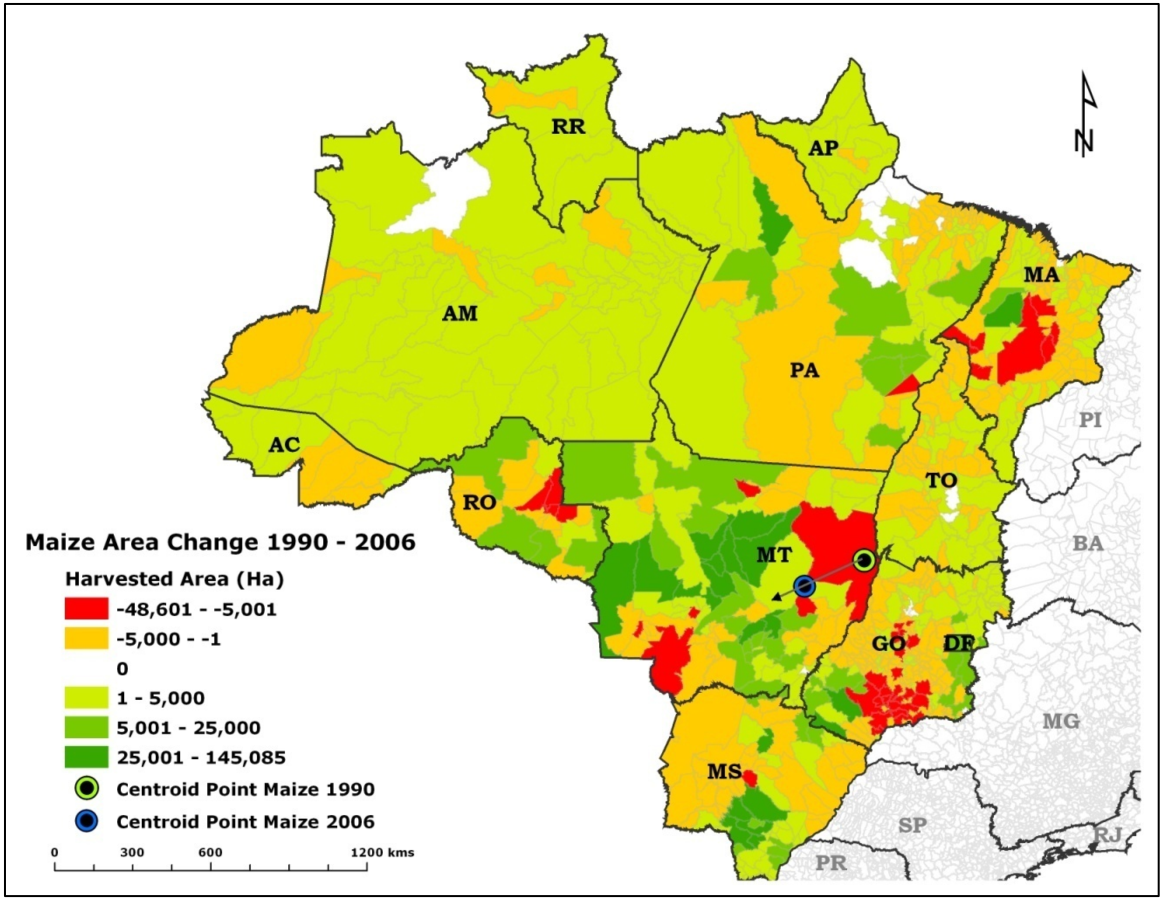


Figure 3-18. Changes in maize areas and shift of the crop's centre of gravity in in the Amazon and *Cerrado* states between 1990 and 2006.

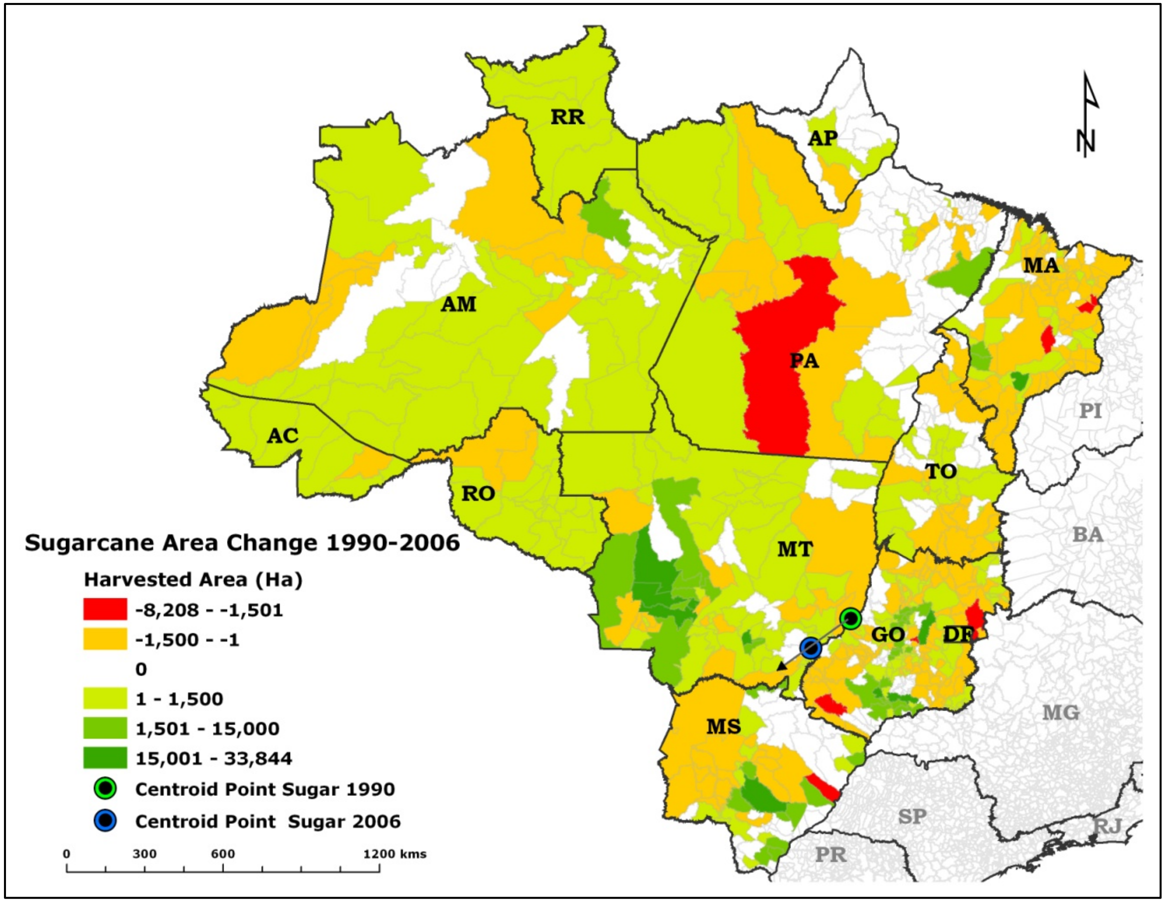


Figure 3-19. Changes in sugarcane areas and shift of the crop's centre of gravity in in the Amazon and *Cerrado* states between 1990 and 2006.

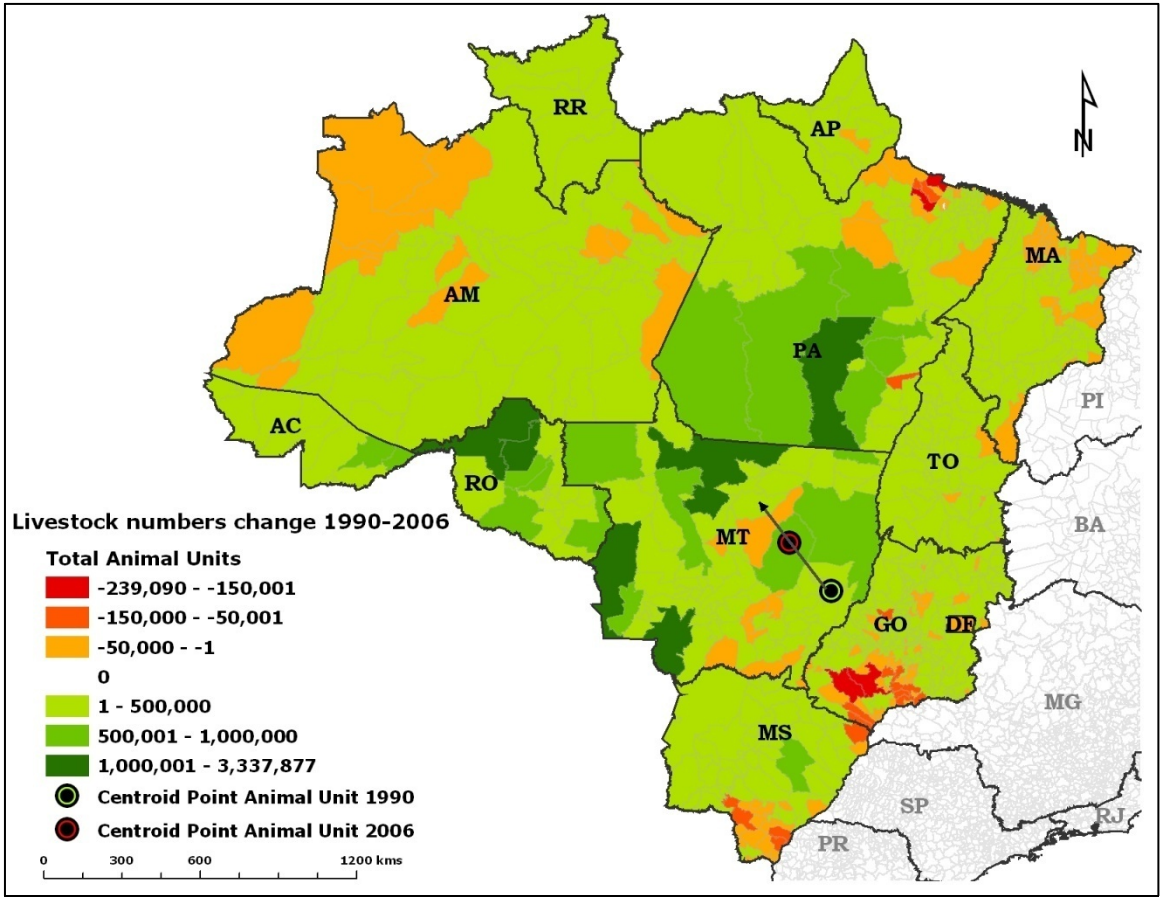


Figure 3-20. Changes in total animal units and shift of the animal unit's centre of gravity in in the Amazon and *Cerrado* states between 1990 and 2006.

increased in the northern part of the states of Rondônia, Mato Grosso, and southern Para. The centre of gravity analysis indicates that the spread of livestock in the Amazon region has moved northwest to Mato Grosso.

3.4 Conclusions

The main findings of this chapter are as follows.

1. Crops like soybean and sugarcane presented a notable expansion during the period 1990-2006. Although in different proportions, these two crops considerably increased their cultivated areas. In the case of soybean, total crop land area increased by 93.4% (10.6 million hectares), whereas sugarcane presented a 16.5% increase (1.8 million hectares).
2. In general, the area harvested to domestic food crops such as rice, beans, cassava, and wheat presented a 26% decrease in total harvested area (2.7 million hectares), possibly attributable to the increase in the area cultivated to soybeans, especially in Mato Grosso, southern Goiás, Tocantins, and Maranhão. In addition, traditional crops may also have been displaced toward other areas.
3. Livestock, especially in the case of cattle, which represents 90 percent of total animal numbers, increased by 26% during 1990-2006. Similar to crops, livestock also tended to move northwards

from southern Brazil, specifically from Mato Grosso do Sul to southern Para.

These results highlight that, since 1990, export crops such as soybeans and sugarcane have gained importance in Brazilian agriculture as compared with traditional crops, clearly evidenced by the increase in soybean in the *cerrado* region and the increase in sugarcane in the states of São Paulo, southern Goiás, and Mato Grosso. This expansion, together with the increased livestock production, has not only reduced the area harvested to traditional crops, but has also displaced these crops into new areas (generally in the north).

Although these results provide a more comprehensive understanding of the changes in spatial patterns of agricultural land use in Brazil, it also evidences the need to identify the driving forces behind this expansion and their potential impact. Deforestation in the Amazon is cause of growing concern. The next Chapter examines the impact of agricultural expansion on deforestation in this region.

CHAPTER 4

The Relationship between Agricultural Expansion and Deforestation in the Amazon Region during the Period 2000–2006

4.1 Introduction

The Amazon basin is the largest and most biological diverse rainforest in the world, covering almost half of the Brazilian territory. Its hydrographic network is a major supplier of fresh water as well (WWF 2006).

The Brazilian Legal Amazon[1] forms part of the Amazon tropical rainforest, and is a politically demarcated region located in northern Brazil. Over the last few decades, this region has become increasingly susceptible to the intense market pressure to increase agricultural exports (Fearnside 2001; Nepstad et al. 2006). It has also been affected by the opening of highways, colonization, logging and mining activities, and the expansion of the agricultural frontier (Laurance et al. 2001; Margulis 2004). During the 1980s and early 1990s, government policies

[1] The Legal Amazon refers to a politically administrative area defined in 1953 by the Brazilian Government for regional planning purposes and subsequently modified in 1966 by the military regime. The Legal Amazon extends outside of the Amazon basin and contains part of the '*cerrados'* region (non-forest vegetation such as woodlands and savannas). This area covers 5.2 million square kilometers and comprises nine states: Acre, Amazonas, Roraima, Amapa, Para, Rondônia, Mato Grosso, Tocantins, and Maranhão (WWF website: http://www.panda.org).

provided subsidized credits and substantial incentives to promote the development of the Amazon region (Fujisaka 1996). The Superintendent's Office for the Development of the Amazon Region (SUDAM, its Portuguese acronym) was the primary entity responsible for managing these incentives, giving preference to large-scale cattle production (Carvalho et al. 2002). According to the Brazilian National Institute for Space Research (INPE, its Portuguese acronym; 2007), the deforested area in the Legal Amazon has increased by 18.9 million hectares during the period 2000-2006. Several research studies conducted in the Amazon region revealed that large-scale cattle ranching was the main factor responsible for the clearing of tropical forest (Moran et al. 1994; Geist and Lambin 2001; Rudel 2005).

Deforestation in the Amazon region has been attributed to several factors, including small- and large-scale agricultural practices. A recent study conducted by Morton et al. (2006) indicated that the expansion of cropland into areas previously covered by forest has become one of the main causes of deforestation in the region, contributing to 17% of the total forest loss during 2000-2004. The study also pointed out that, between 2000 and 2003, there was a shift in deforestation dynamics in Mato Grosso, the direct conversion of forest to pasture decreasing from 78% to 66%, whereas the conversion of forest to crop areas increased from 13% to 23%.

Another study in Rondônia by Brown et al. (2005) found that the increase in land dedicated to agricultural crops was mainly due to the conversion of forestland and, to a lesser extent, the conversion of pasture areas. The expansion in the area harvested to crops in both studies was mainly attributed to soybean production.

Other studies, on the other hand, indicate that soybean expansion has occurred in areas that, at that time, were under pasture as well as in the open savannas or grasslands commonly known as "*cerrados*" (Mueller 2003). Others have argued that soybean is replacing abandoned pasture areas and is not causing new deforestation (Dross 2004; USDA 2005).

This chapter explores the association between deforestation and agricultural expansion in the Brazilian Amazon during 2000-2006. Data on annual cumulative deforestation, harvested area of crops, and estimated pasture areas at the municipality level were used as the main elements to analyze the relationship between deforestation and agricultural expansion. Although data quality and consistency are major issues, this chapter will attempt to answer the following question: what is the relationship between agricultural expansion and deforestation in the Amazon Region? It will try to examine whether soybean expansion or pasture expansion has caused deforestation.

4.2 Data Sources

This study covered the nine states comprising the Brazilian Legal Amazon (Figure 4-1). Several municipalities of Maranhão and Tocantins form part of the official borders of the Legal Amazon, which means that the dataset used in this study covered 444 municipalities of the entire region.

Figure 4-1. States comprising the Brazilian Legal Amazon and covered by this study.

The annual deforested area and the harvested area of crops from 2000 to 2006 at the municipality level for all states of the Legal Amazon were used as data sources in this study. These datasets came from the INPE[2] and the IBGE Municipal Agricultural Production (PAM).

To achieve a complete picture of land-cover change in the Amazon, it is necessary to include information on changes in pasture area in the analysis. Census data on pasture were available for 1996 and 2006 (IBGE 2006). To produce a consistent annual time series, the area under pasture was estimated for the missing years (2000-2005) based on annual livestock data available from the same source (more details below).

4.2.1 Deforested area

The INPE has been monitoring the deforestation of the Brazilian Amazon using Landsat Thematic Mapper data since 1974 to quantify deforestation rates (INPE 2007). Over the last 10 years, INPE has worked on the PRODES[3] project to develop a methodology that determines more accurately the increase of deforested areas in the Amazon. To estimate the extent of deforested areas, PRODES analyzes different Landsat scenes covering the entire Amazon region. The use of combined topographic charts at 1:100,000 scale and vegetation maps from IBGE

---

[2] The National Institute for Space Research (INPE) provided annual deforestation data for the Legal Amazon, at the municipality level, under a project known as PRODES (Amazon Deforestation Project). See website at: http://www.obt.inpe.br/prodes/.

[3] PRODES (Satellite Monitoring of Forests in the Brazilian Amazon) is the largest forest monitoring project in the world, operational since 1997 and based on LANDSAT satellite images that capture the evolution of the extent and rate of deforestation in the Brazilian Amazon. The database is available at http://www.obt.inpe.br/prodes.

helped improve the classification and image processing procedure (Câmara et al. 2006). The raster data on deforested area were further converted to a vector database at the municipality level using GIS and were made available for downloading. The data generated by the PRODES Digital Project is stored in a database described in Table 4-1.

For the purpose of this study, PRODES data for 2000-2006 were analyzed at the municipality level. In order to analyze the data consistently over time, this dataset was integrated into each new administrative map unit discussed in Chapter 2.

Table 4-1. Description of variables included in the PRODES database.

Variable	Description
UF	Name of state
MUN_Name	Name of municipality
Area_PRODES	Municipality area according to PRODES (ha)
DEF00*	Cumulative deforested area until 2000 (ha)
Per_Def_00	Percentage of deforested area until 2000
Forest_00	Forest area in 2000 (ha)
Per_For_00	Percentage forest area in 2000
Cloud_00	Area covered by clouds in 2000 (ha)
Not_Forest_00	Non-forest area in 2000 (ha)
Not_Observed_00	Area not observed in 2000 (ha)
Hydro_00	Hydrographic area in 2000 (ha)

* Cumulative deforested area and the remaining variables were collected for the years 2000, 2001, 2002, 2003, 2004, 2005, and 2006.

4.2.2 Harvested area of crops

The main data source used was the statistics database SIDRA of the Brazilian Institute of Geography and Statistics (IBGE, its Portuguese acronym) for 2000-2006, previously described in Chapter 3. The database contained information for the eight crops most cultivated in terms of area harvested in the Legal Amazon: soybean, maize, rice, cassava, cotton, beans, sugarcane, and wheat. The other crops found in lower proportions were classified as "Other crops" and grouped into a single category.

4.2.3 Area under pasture

The main sources of land use data are the agricultural censuses conducted every five years by IBGE. As such, pasture-related information is unavailable on an annual basis, except for 1996 and 2006. However, the IBGE Municipal Agricultural Production (PAM) does provide annual information on certain land use practices based on surveys of opinions of experts. This information includes livestock data at the municipality level.

Therefore, instead of simply interpolating between pasture data in 1996 and 2006 to get annual value, an annual pasture dataset was estimated for the years between 1996 and 2006 in three steps, using livestock information. First, livestock stocking density was calculated for the two years for which there was information available on both area under pasture and livestock numbers (1996 and 2006). Then the stocking density was linearly interpolated between these two dates and, lastly, pasture data were estimated for the period 2000-2005 in each municipality as a function of stocking density and livestock numbers.

Estimation of pasture area between 1996 and 2006

As indicated in Chapter 3, Brazilian livestock data were expressed in animal units using the corresponding regional factor equivalent. This quantification allowed the stocking density[4] variable to be calculated as follows:

$$SD_{(i)} = (AU_{(i)} / P_{(i)})$$

where:

$SD_{(i)}$ = livestock stocking density for each municipality (i),

$AU_{(i)}$ = total animal units, and

$P_{(i)}$ = total area under pasture, expressed in hectares.

Total animal units were obtained as in Chapter 3, by summing up individual animal numbers (cattle, horses, buffalos, donkeys, mules, goats, and sheep).

Once the stocking density for 1996 and 2006 was calculated, i.e., $SD_{(i,1996)}$ and $SD_{(i,2006)}$, stocking density was linearly interpolated for the missing years between these dates using the following formula:

[4] Stocking density is the number of animals of a specified type that can subsist per unit area. Stocking density is used in range management to optimize forage production for grazing livestock (Hersom 2005).

$$SD_{(i,t)} = SD_{(i,\ 1996)} + \left(\frac{SD_{(i,\ 2006)} - SD_{(i,1996)}}{2006 - 1996} \right) * \left(t - 1996 \right)$$

where:

$SD_{(i,t)}$ = stocking density for each municipality (i) in each period of time (t),

$SD_{(i,\ 1996)}$ = stocking density for the year 1996 for each municipality (i), and

$SD_{(i,\ 2006)}$ = stocking density for the year 2006 for each municipality (i).

This formula was applied to each administrative map unit for the missing years between 1996 and 2006.

Once the annual stocking density was calculated, the next step involved estimating the area under pasture for the years 2000-2005. The following formula was used:

$$EP_{(i,t)} = AU_{(i,t)} / SD_{(i,t)}$$

where:

$EP_{(i,t)}$ = estimated pasture for each municipality (i) in each year (t),

$SD_{(i,t)}$ = stocking density for each municipality (i) in each year (t), and

$AU_{(i,t)}$ = total animal units in each municipality (i) in each year (t).

Figure 4-2 shows a comparison between pasture estimated with the interpolation used for these calculations, based on stocking density, and the total animal units from 2000 to 2006 for the entire Amazon region. It is clear that animal units increased faster than total pasture area. This is because of increasing stocking density over the 2000-2006 period.

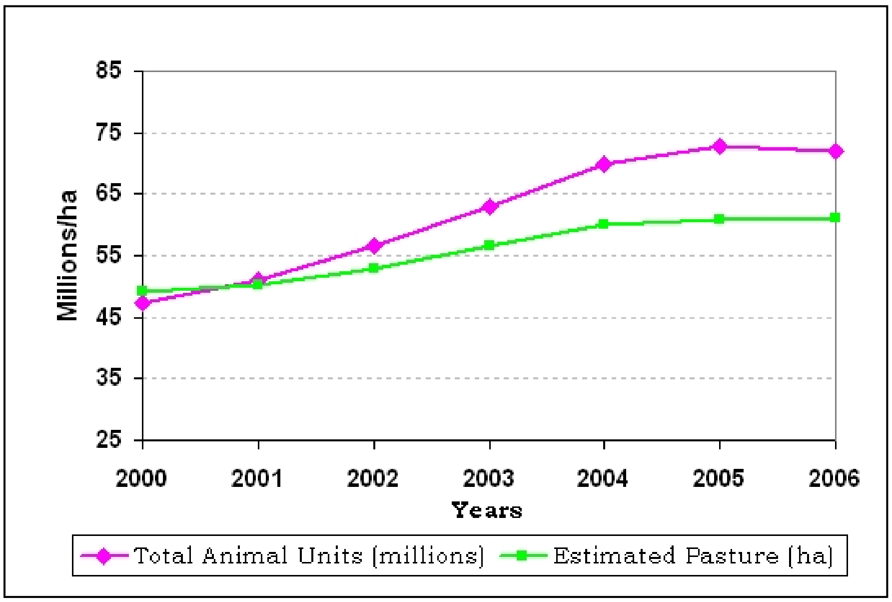


Figure 4-2. Estimated area under pasture based on stocking density calculated for the period 2000-2006.

4.3 Results

4.3.1 Changing spatial distribution of forest and crop areas across the Legal Amazon during 2000-2006

The Legal Amazon is an important agricultural zone in Brazil. Total cultivated area increased from 7.7 million hectares in 2000 to 11.6 million in 2006 (Figure 4-3a). This expansion can be mainly attributed to the increase in area harvested to soybean—from 3.0 to 6.6 million hectares—as compared with other crops (maize, rice, cassava, cotton, beans, and sugarcane) (Figure 4-3b). However, these data suggest that the Amazon region is dominated by extensive pasture areas rather than crop areas, which increased from 49 million hectares to 61 million hectares during the same period of time (Figure 4-3a).

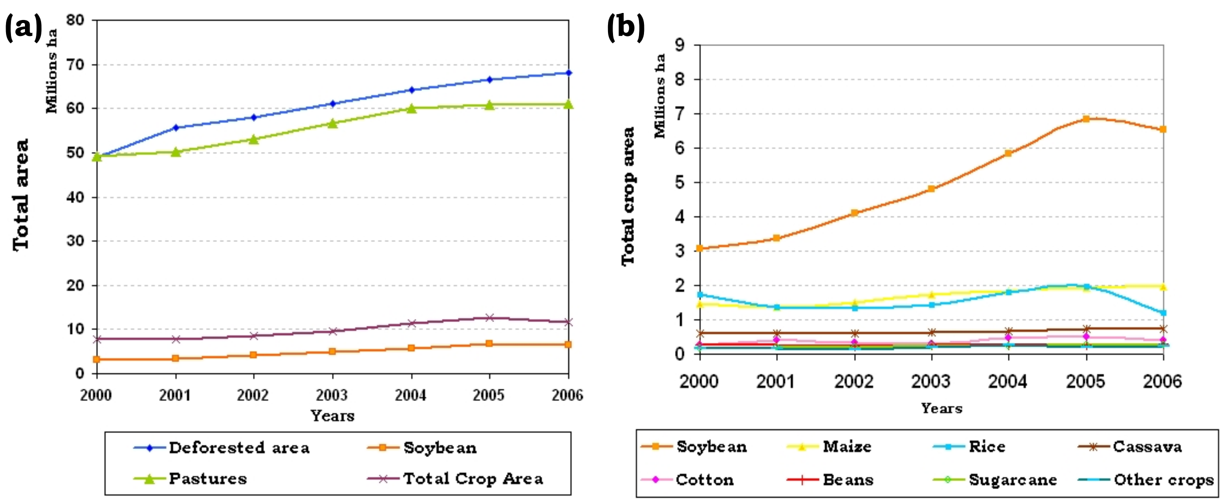


Figure 4-3. Legal Amazon areas for the period 2000-2006:
(a) Total deforested area, pasture estimation, total crop area, and area harvested to soybean.
(b) Total area harvested to soybean, maize, rice, cassava, cotton, beans, sugarcane, and other crops.

These changes over time were used as a starting point to examine the spatial pattern of change between 2000 and 2006 in the Legal Amazon.

The following variables were calculated for each municipality in the region: extent of deforestation, change in total crop harvested area, and estimated pasture area from 2000 to 2006.

The results indicate that pasture is mostly concentrated in the states of Rondônia, Mato Grosso, Tocantins, and Para. Although the overall area under pasture increased from 2000 to 2006, spatial distribution maps shows that increases were limited to Acre, Rondônia, and Para, while pasture decreased in the states of Mato Grosso and Tocantins (Figure 4-4).

Soybean increased in area harvested in the states of Mato Grosso and Tocantins, with the greatest proportion being concentrated in the state of Mato Grosso (Figure 4-5). The area harvested to soybean represented almost half of the total crop area in the Legal Amazon. As shown in Figure 4-6, total crop area increased in the states of Mato Grosso and Tocantins where soybean cultivation expanded, and decreased in the state of Para. Crops other than soybean were harvested to a lesser extent, with the areas increasing basically in northern Maranhão and in several isolated areas of the states of Rondônia and Mato Grosso, and decreasing in northern Mato Grosso and eastern Para (Figure 4-7).

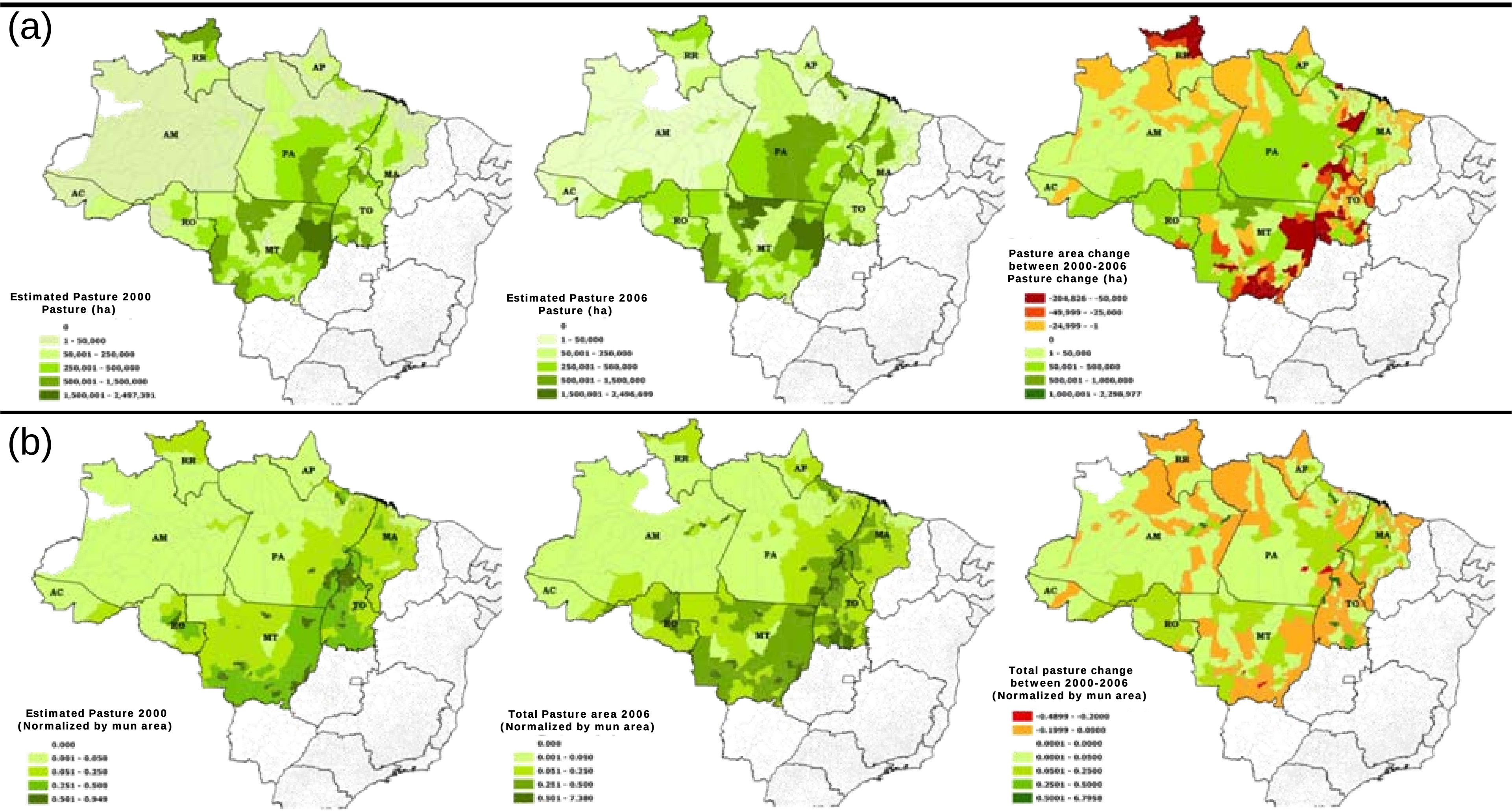


Figure 4-4. Spatial distribution of pasture areas and pasture area change between 2000 and 2006, in the Legal Amazon.
(a) Total pasture areas in 2000 and 2006
(b) Total pasture areas, normalized by municipality area in 2000 and 2006.

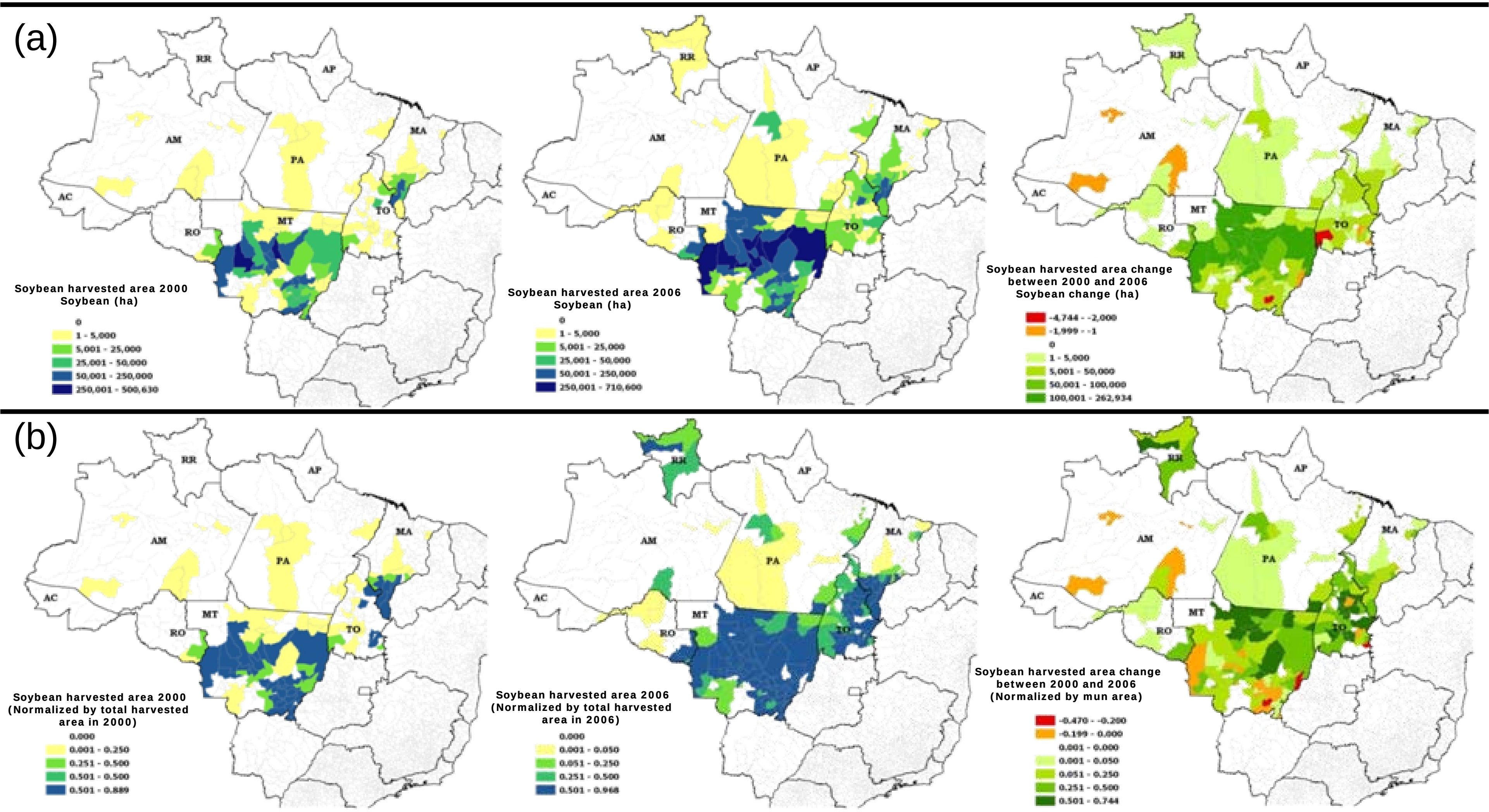


Figure 4-5. Spatial distribution of soybean areas and soybean area change between 2000 and 2006, in the Legal Amazon.
(a) Total soybean areas in 2000 and 2006
(b) Total soybean areas, normalized by municipality area in 2000 and 2006.

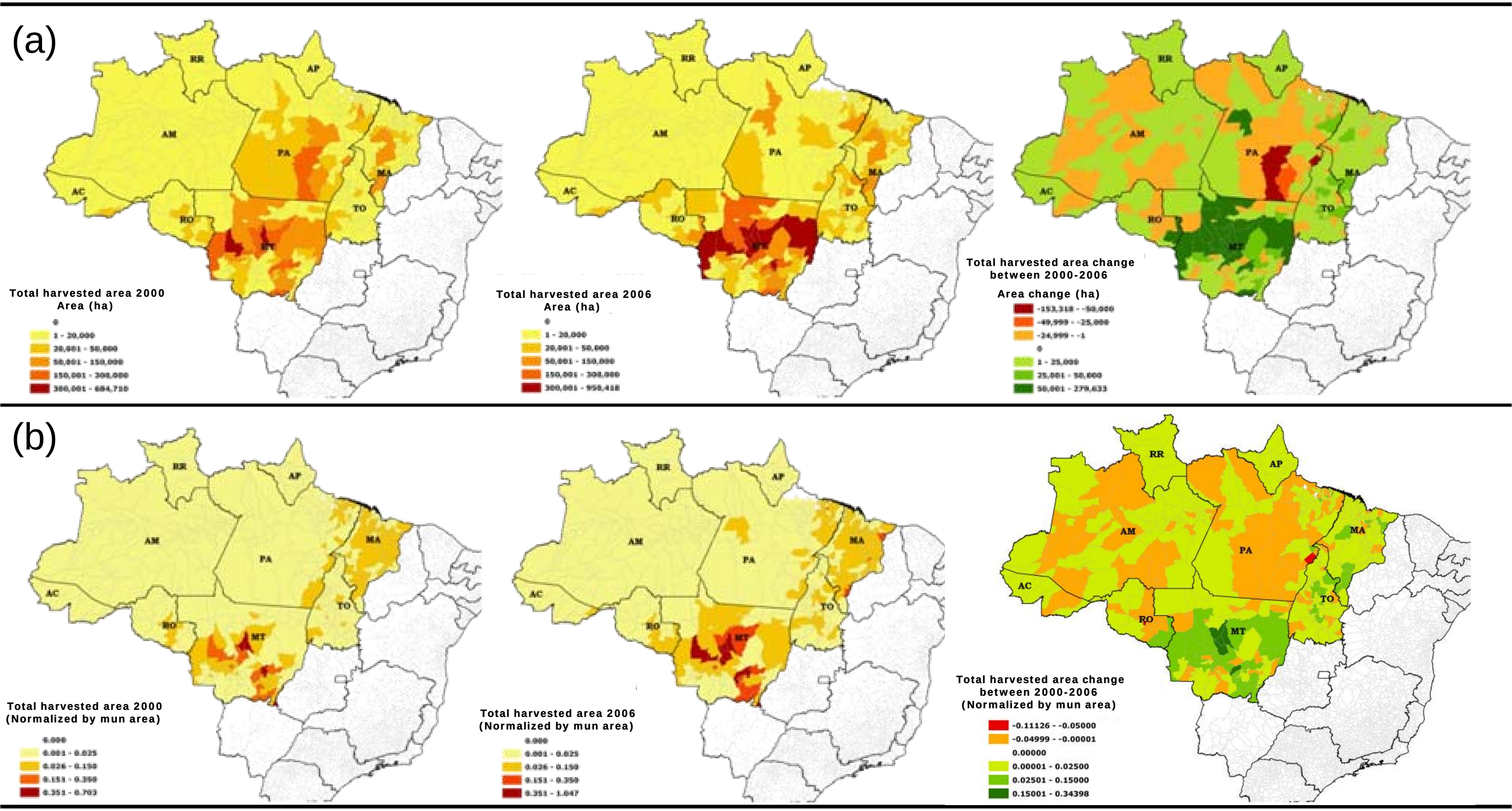


Figure 4-6. Spatial distribution of total harvested area and total harvested area change between 2000 and 2006, in the Legal Amazon.
(a) Total harvested area in 2000 and 2006
(b) Total harvested area, normalized by municipality area in 2000 and 2006.

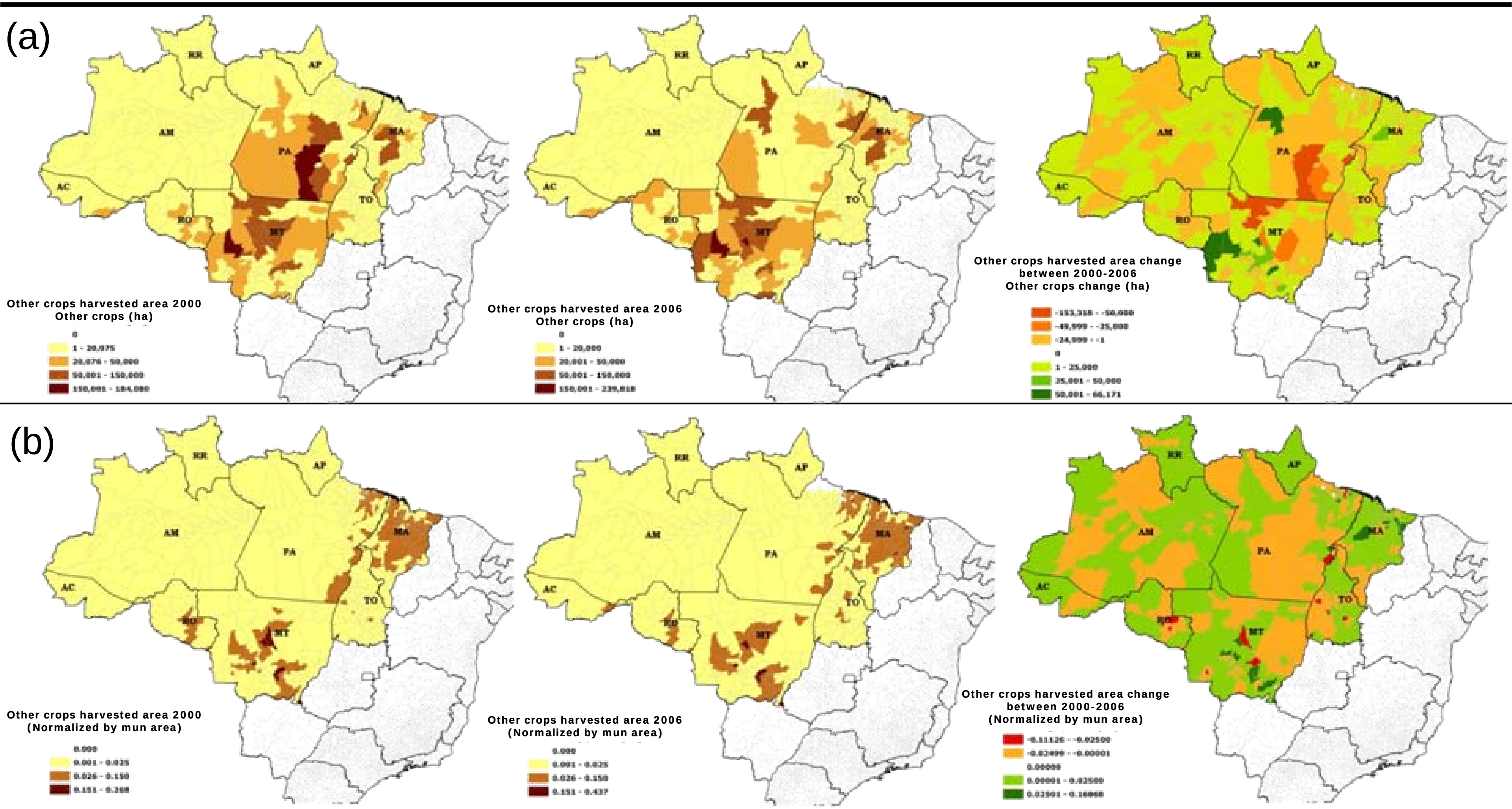


Figure 4-7. Spatial distribution of other crops harvested area and other crops harvested area change between 2000 and 2006, in the Legal Amazon.
(a) Other crops harvested area in 2000 and 2006
(b) Other crops harvested area, normalized by municipality area in 2000 and 2006.

In the case of total deforested area between 2000 and 2006, maps draw attention to the cumulative clearing of forests mainly in the states of Acre, Mato Grosso, Para, and Maranhão, where deforestation was highest, especially in the area known as the 'arc of deforestation'[1] (Figure 4-8).

4.3.2 Exploring the relationship between deforestation and agricultural areas

The previous results suggest that the area under pasture decreased in those states where the area harvested to soybean increased. Furthermore, comparison of the patterns of change for 2000 and 2006 indicated that the areas showing increases in crop and pasture coincided with those presenting the largest extent of deforestation in the Legal Amazon. In view of these results, the following question arises: Did agricultural expansion cause deforestation in the Amazon region during 2000-2006?

[1] In this case, the 'arc of deforestation' refers specifically to those areas where most deforestation currently takes place in the Amazon region—a large zone located along the eastern and southern forest margins in eastern Acre, running along Rondônia, northern Mato Grosso and Tocantins, and advancing toward eastern Para and northeastern Maranhão (http://www.eoearth.org/article/Deforestation_in_Amazonia).

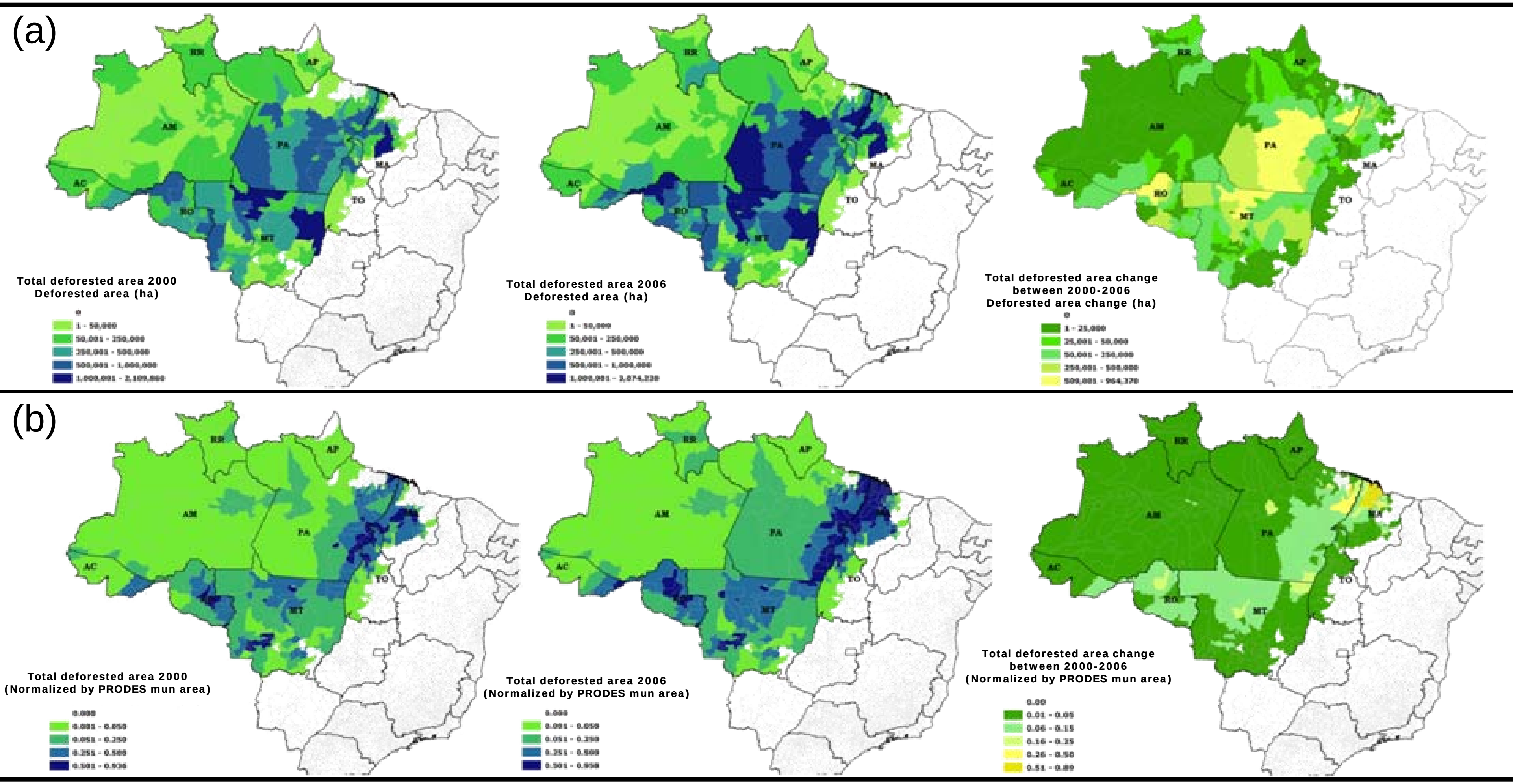


Figure 4-8. Spatial distribution of total deforested area and deforested area change between 2000 and 2006, in the Legal Amazon.
(a) Total deforested area in 2000 and 2006
(b) Total deforested area, normalized by municipality area in 2000 and 2006.

Deforestation in the Amazon is a complex process that involves multiple factors, including logging, road infrastructure, fires, population, agricultural activities, and others (Pfaff et al. 2007; Asner et al. 2005; Anderson et al. 2002; Geist and Lambin 2001). This study, however, only focused on testing whether there is a statistical relationship between the spatial patterns of agricultural expansion and deforestation.

To explore the relationship between agricultural expansion and deforestation, the changes in area between 2000 and 2006 at the municipality level were analyzed using an Ordinary Least Squares (OLS)[1] regression model. The variables considered were as follows: agricultural area (sum of total crop harvested area and estimated pasture) and total deforested area. Each variable was normalized by municipality area. The results are summarized below.

All Legal Amazon

As shown in Figure 4-9, there is a weak relationship between change in agricultural area and deforestation in the Legal Amazon. The difficulty in identifying a relationship could be attributed to two factors. First, this initial analysis considered all municipalities of the Legal Amazon (a total of 444 municipalities), although not all the land in this region is covered with forest, especially in the southern and eastern parts

[1] Ordinary least squares (OLS) estimation is the usual method of regression analysis used to determine the relationship between one or more independent variables (Gotelli 2004).

where a large proportion is under '*cerrado*' vegetation or natural savanna (Figure 4-10). Agricultural area in the cerrado region has certainly increased without replacing forest.

A second possible explanation for the low correlation is the poor quality of the data used. Data, especially on annual agricultural areas, were obtained by the IBGE Municipal Agricultural Production (PAM), based on expert surveys.

To investigate the first possibility, the analysis was repeated using those municipalities dominated by forest, which were selected using two different criteria: those municipalities with more than 70% forest cover and those with less than 50% forest. Furthermore, the analysis was repeated after identifying and removing outliers.

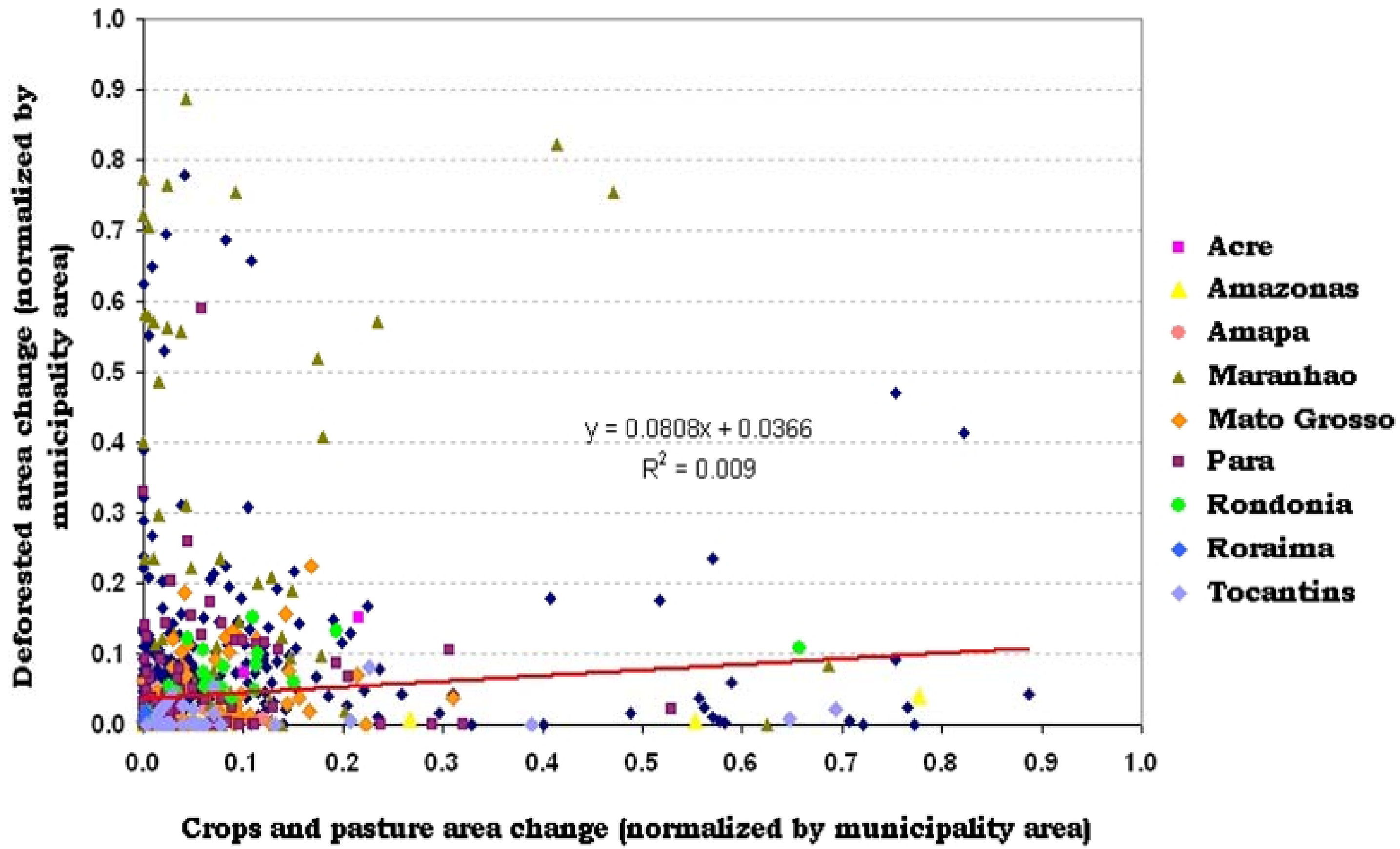


Figure 4-9. Scatter plot showing the relationship between the change in crop and pasture area and the change in deforested area between 2000 and 2006 (all states of the Legal Amazon).

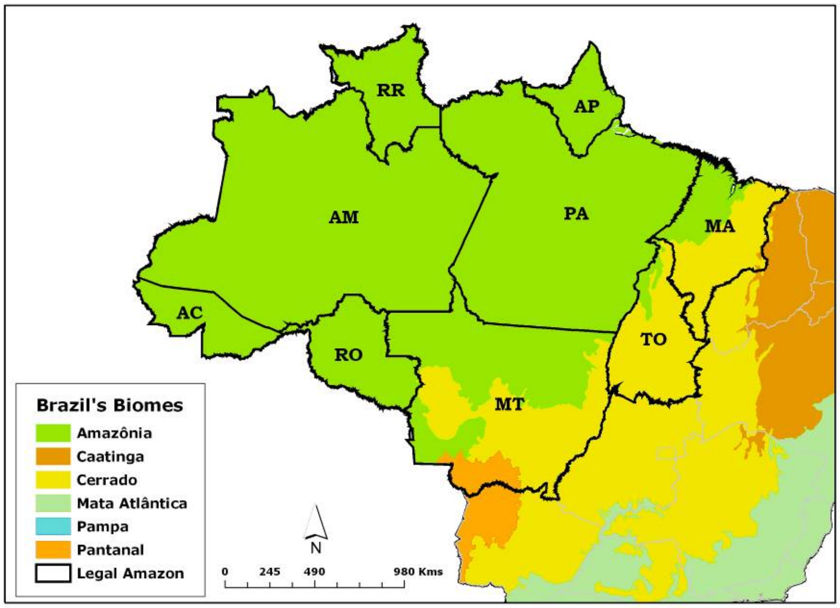


Figure 4-10. The biomes of the Legal Amazon (IBGE-MMA 2007).

Areas covered by more than 70% natural forest

The regression analysis was repeated, focusing on those municipalities in the Legal Amazon that, in 2000, were covered by more than 70% natural forest. Although 140 municipalities located in the states of Acre, Amazonas, Amapa, Maranhão, Mato Grosso, Para, Rondônia, Tocantins, and Roraima were initially selected, two states were excluded from the analysis: Tocantins, because none of its municipalities presented areas with more than 70% forest, and Maranhão, because several discrepancies were observed in the deforestation data reported by PRODES between 2000 and 2006. For example, data for some municipalities in Maranhão indicated zero deforested area in 2000, but then in 2001 this figure abruptly rises to 100% deforested area. With little literature to support such rapid deforestation, a decision was made to discard these data from the analysis because the quality of the data was suspected to be particularly poor for this state.

Figure 4-11 shows the results of the statistical OLS regression model for the remaining seven states in the Legal Amazon, including and excluding the outliers (or extreme values). Figure 4-11a shows a weak linear relationship between change in deforested area and change in agricultural area, with R^2 equal to 0.12. However, this figure also shows two obvious outliers. Figure 4-11b shows a strong relationship (R^2 = 0.50) with the outliers excluded. The outliers correspond to the municipalities of Maniquiri, located in the state of Amazonas, and Paragominas, located in the state of Para.

With the outliers excluded, linear regression analysis was performed for the 101 municipalities of the seven states in the Legal Amazon. Results indicate a strong and statistically significant relationship between change in agricultural area and change in deforested area in those municipalities covered by more than 70% forest (R^2 =0.509, p-value $\leq$ 0.001) (Table 4-2, Figure 4-11b).

Table 4-2. OLS regression analysis shows the relationship between change in deforested area and change in area under crops and pasture in municipalities covered by more than 70% forest in seven states of the Legal Amazon (2000-2006).

Regression Statistics	
Multiple R	0.714
R Square	0.510
Adjusted R Square	0.505
Standard Error	0.025
Observations	101

ANOVA

	df	SS	MS	F	Significance F
Regression	1	0.064	0.064	103.001	< 0.001
Residual	99	0.062	0.001		
Total	100	0.126			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%
Intercept	0.011	0.003	4.09	< 0.001	0.006
X Variable 1	0.823	0.081	10.15	< 0.001	0.662

	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0.017	0.006	0.017
X Variable 1	0.984	0.662	0.984

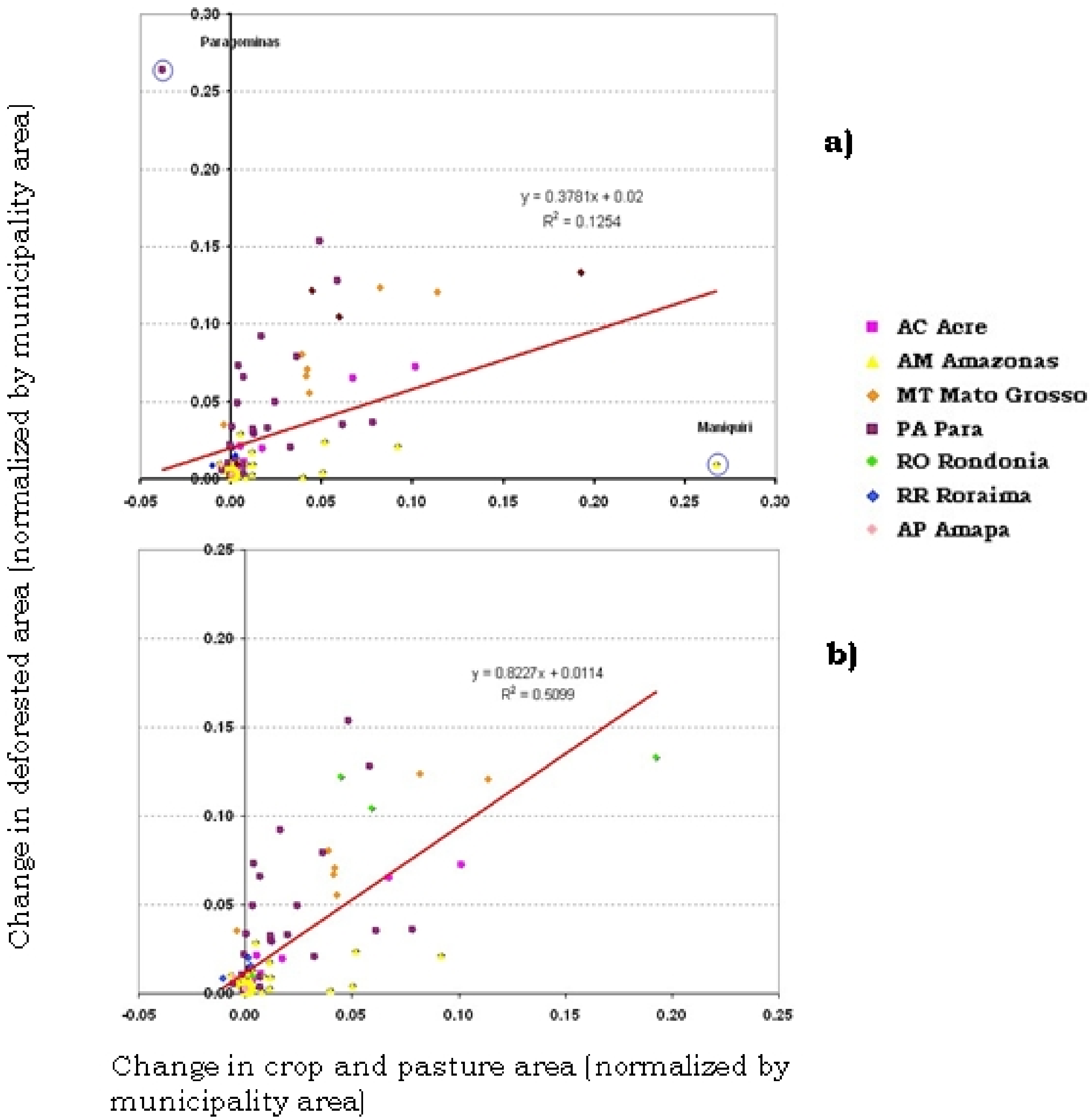


Figure 4-11. Scatter plot showing the relationship between the change in deforested area and change in area under crops and pasture in municipalities covered by more than 70% forest in seven states of the Legal Amazon (2000-2006).
(a) Outliers appear in blue circles
(b) Excluding outliers

Areas covered by more than 50% natural forest

The previous analysis was repeated for those municipalities covered by more than 50% natural forest in the Legal Amazon. The states of Tocantins and Maranhão were excluded as well as new two outliers, which correspond to the municipalities of Abaetetuba and Garrafão do Norte, both in the state of Para.

The results of the OLS regression did not differ significantly from previous results. Including outliers, the R^2 value is 0.133, whereas when outliers were excluded the R^2 value is 0.42 (Figure 4-12).

With the outliers excluded, the results of the regression analysis with 144 municipalities (excluding outliers) were analyzed and are summarized in Table 4-3. As with previous analyses, the results are strong and statistically significant (R^2 value = 0.42; p-value < 0.001). Although these results suggest that a relationship does exist between deforestation and the areas under crop/pasture in those areas covered by more than 70% or 50% forest, it is not possible to determine whether the relationship can be attributed to the expansion of crops or the expansion of pasture. This issue will be explored further in the next section.

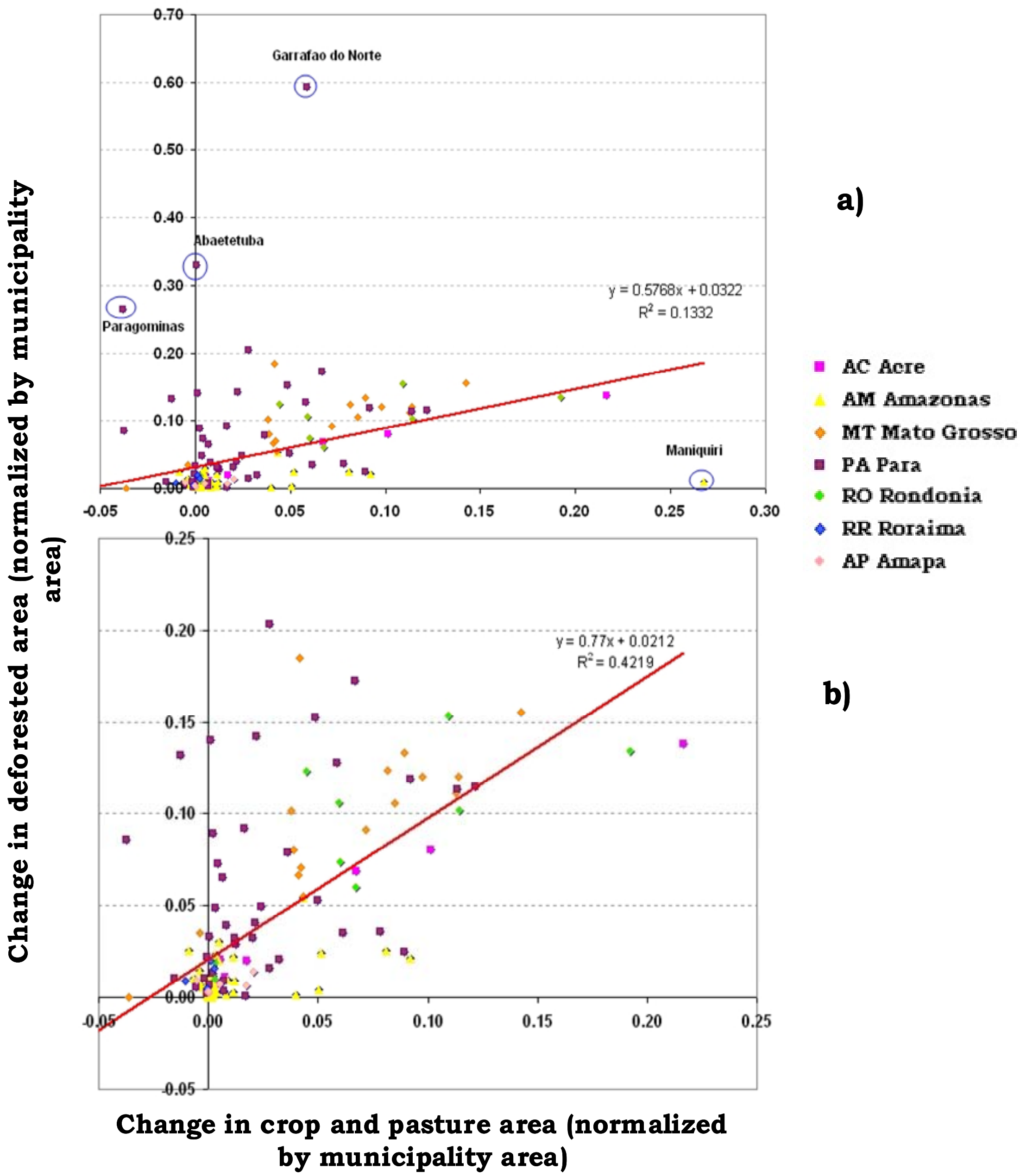


Figure 4-12. Scatter plot showing the relationship between the change in deforested area and change in area under crop and pasture municipalities covered by more than 50% forest in seven states of the Legal Amazon (2000-2006).
(a) Outliers appear in blue circles
(b) Excluding outliers

Table 4-3. OLS regression analysis shows the relationship between change in deforested area and change in area under crops and pasture in municipalities covered by more than 50% forest in seven states of the Legal Amazon (2000-2006).

Regression Statistics	
Multiple R	0.650
R Square	0.422
Adjusted R Square	0.418
Standard Error	0.038
Observations	144

ANOVA

	df	**SS**	**MS**	**F**	**Significance F**
Regression	1	0.148	0.148	103.64	< 0.001
Residual	142	0.203	0.001		
Total	143	0.351			

	Coefficients	**Standard Error**	**t Stat**	**P-value**	**Lower 95%**
Intercept	0.021	0.004	5.81	< 0.001	0.014
X Variable 1	0.770	0.076	10.18	< 0.001	0.620

	Upper 95%	**Lower 95.0%**	**Upper 95.0%**
Intercept	0.028	0.014	0.028
X Variable 1	0.920	0.620	0.920

4.3.3 Is soybean expansion causing deforestation?

As discussed in the introduction to this chapter, there are claims that soybean expansion in the Amazon is causing deforestation (Morton et al. 2006). The debate continues whether soybean expansion has occurred in areas previously under pasture or whether this crop is causing new deforestation. To test these hypotheses, OLS regression analysis was performed, considered the following aspects:

(i) Only the change in area of soybean, pasture, and deforestation between 2000 and 2006.

(ii) Only those municipalities in the Legal Amazon that were covered with more than 50% natural forest and located in those states where soybean is most cultivated (such as Mato Grosso, Rondônia, Para, and Roraima; sample points of soybean change in other states are mostly zero).

Based on the above considerations, an OLS regression analysis was performed for each of the following comparisons[2]:

- Change in deforested areas versus change in pasture areas,
- Change in deforested area versus change in soybean area, and
- Change in pasture area versus change in soybean area.

The total change in soybean, pasture, and deforestation area, from 2000 to 2006, was initially examined for the different states (Figure 4-

---

[2] For this particular analysis, the change in area was based on the slope rather than on the difference between one year and another. The following formula was applied to calculate the change in area for each variable: change in area = slope (variable x). Slope = ([x value for each year],[year]* [number of year])/(municipality area), where x is the area under pastures or area planted to soybean.

13). Of the municipalities covered with more than 50% forest, soybean expansion mainly occurred in the state of Mato Grosso, although harvested area increased in smaller proportions in the states of Para, Rondônia, and Roraima (Figure 4-13). Soybean cultivation, however, accounts for a small proportion of the total land area compared with the area dedicated to pasture and deforested area.

Figure 4-13 illustrates the same trend in Para and Rondônia. Roraima is also an exception, showing a decrease in the area under pasture in contrast with all the other states, which showed an increase in pasture areas.

The OLS regression analysis comparing deforested area with expansion in pasture shows a strong and statistically significant relationship for Mato Grosso ($R^2 = 0.48$, p-value < 0.001); a weaker, though significant relationship in Para; and a strong but less significant relationship in Rondônia (Figure 4-14). In Roraima, the relationship is negative (increasing pasture area with decreasing deforestation) but insignificant (few municipalities).

However, the change in soybean area showed no statistical relationship to deforestation (Figure 4-15), except in the case of Roraima where results were insignificant because of the few samples.

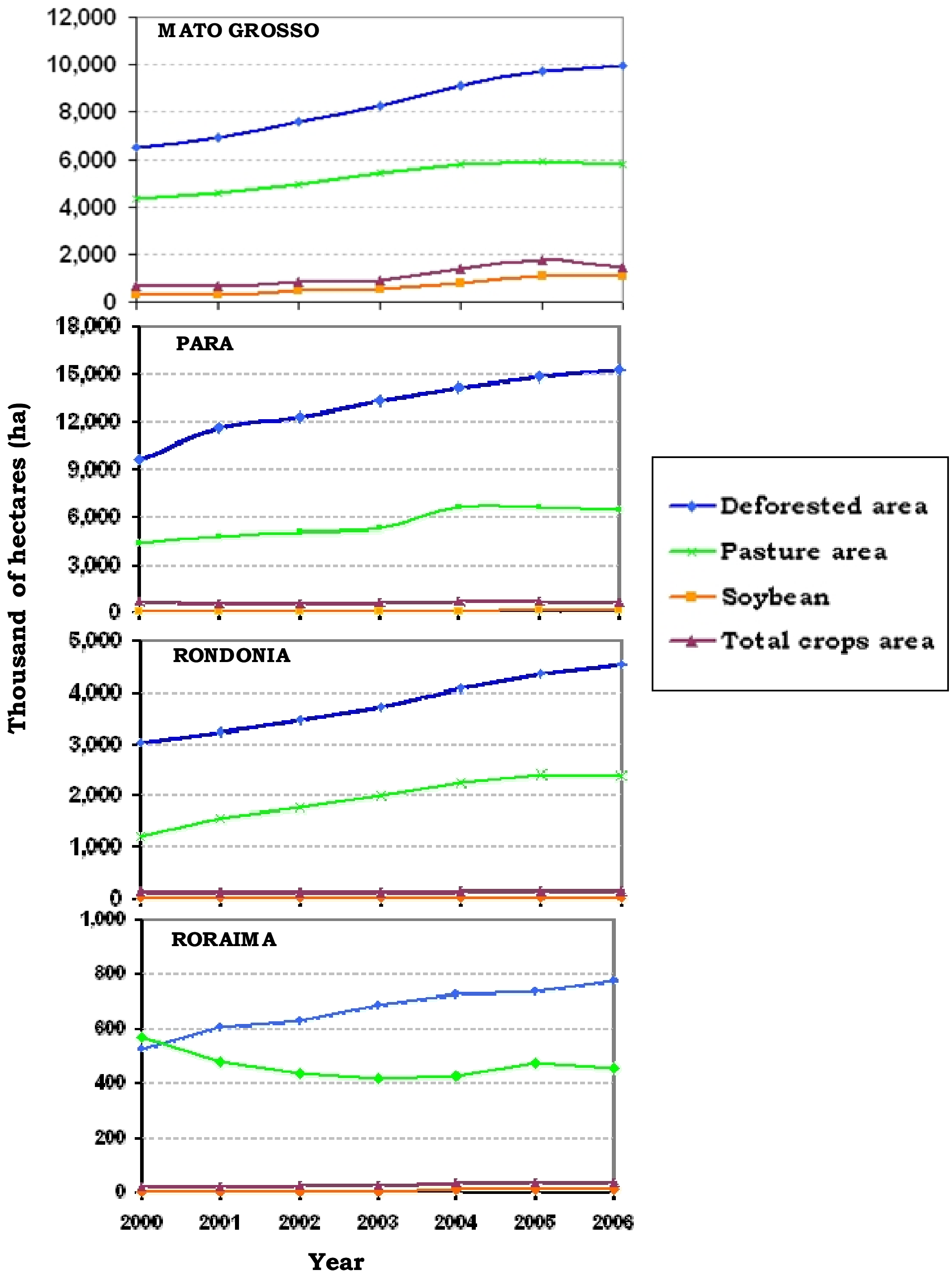


Figure 4-13. Change in area over time in the municipalities covered by more than 50% forest.

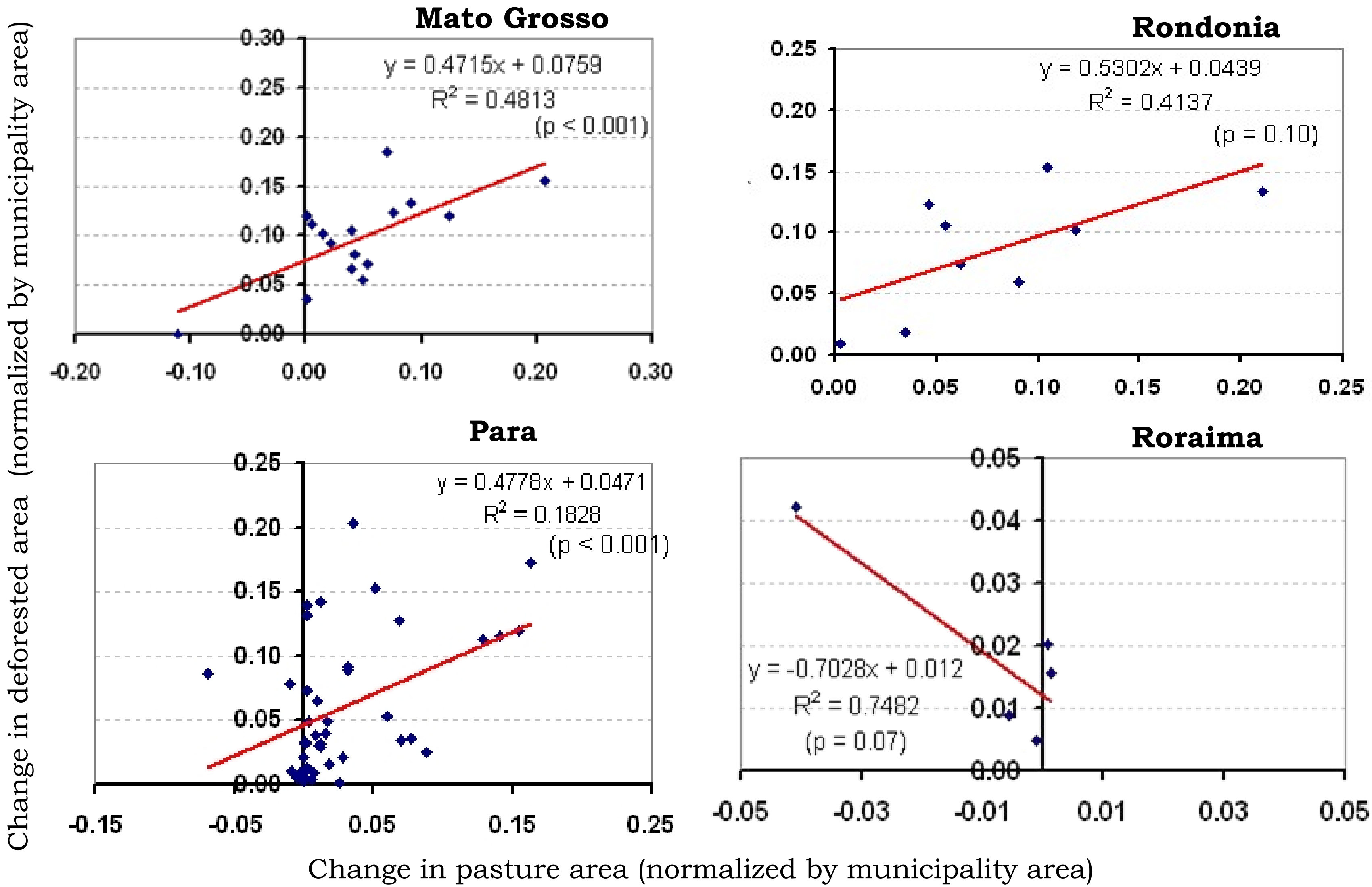


Figure 4-14. Comparison between change in deforested area with change in pasture area between 2000 and 2006 in municipalities covered by more than 50% forest.

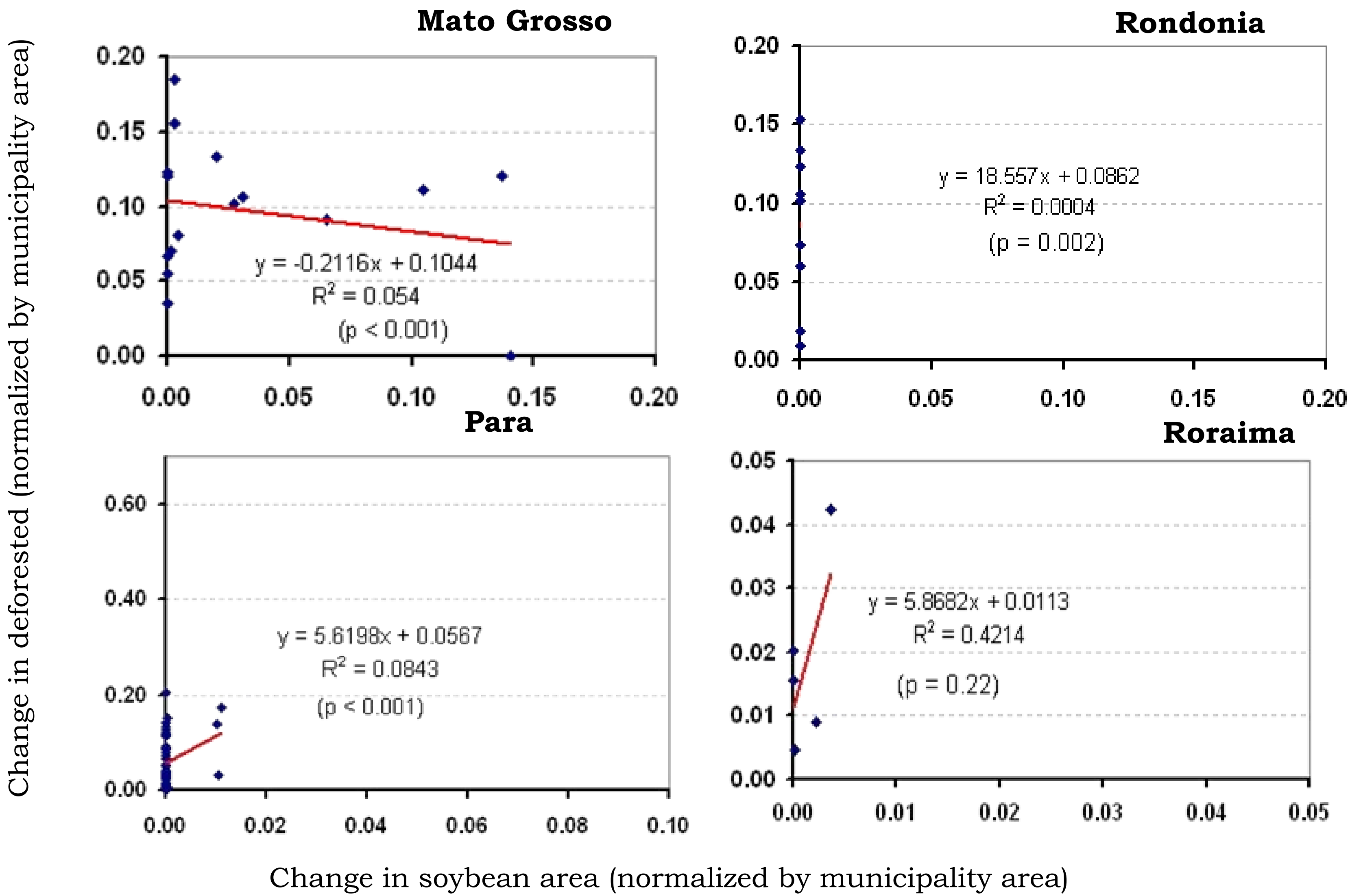


Figure 4-15. Comparison between change in deforested area with change in soybean area between 2000 and 2006 in municipalities covered by more than 50% forest.

A comparison of change in pasture area with change in soybeans indicated a strong negative relationship in Mato Grosso (R^2 = 0.43), which was also significant (p-value < 0.001). No strong or statistically significant results were obtained for the other states (Figure 4-16).

In summary, while soybean expansion showed no relationship to deforestation in any of the Brazilian states, pasture expansion appears to be related to deforestation in Mato Grosso, Rondônia, and Para. Soybean expansion, however, was negatively related to pasture expansion in Mato Grosso, implying that soybeans may be replacing pasture areas in Mato Grosso, thereby displacing pasture elsewhere, indirectly causing deforestation. In the next section, the spatial shifts in crop and pasture areas and deforestation will be explored in further detail.

4.3.4 Shift in the location of deforested and agricultural areas

To better understand the shifts taking place in both deforested and agricultural areas in the Legal Amazon, a centroid analysis was performed (as in Chapter 3).

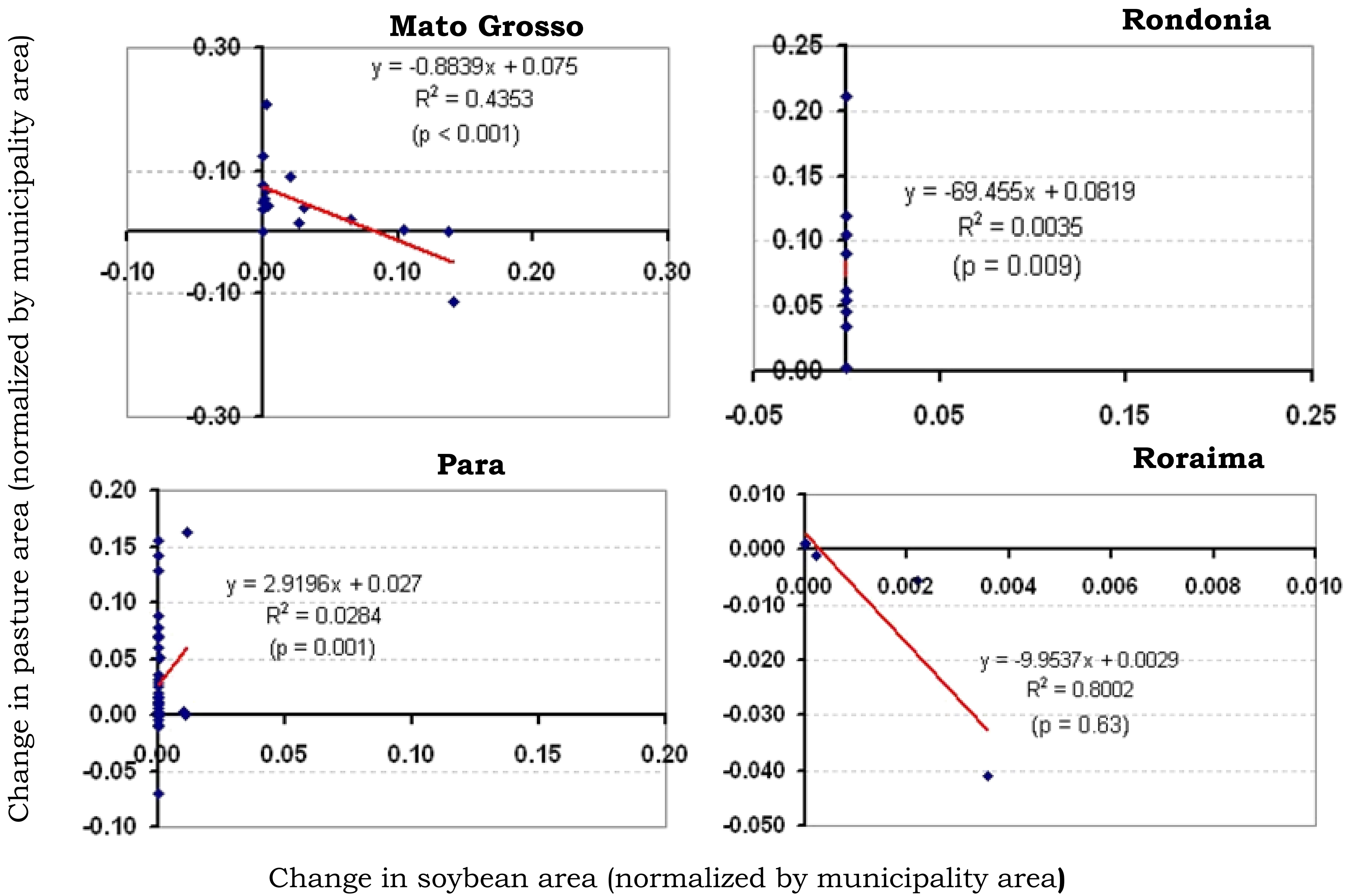


Figure 4-16. Comparison between change in pasture area with change in soybean area between 2000 and 2006 in municipalities covered by more than 50% forest).

The weighted mean centroid for 2000 and 2006 was calculated for total harvested area, total pasture area[1], total deforested area, total soybean area, and total area for crops other than soybean. The analysis was done over two scales: (1) all Legal Amazon and (2) the states of Mato Grosso, Para, and Rondônia because, according to the results of previous analyses, these were the most affected by agricultural expansion. The centroid analysis for all Legal Amazon indicates that, between 2000 and 2006, deforested areas shifted 39 km to the northeast, from northern Mato Grosso to eastern Para. Pasture area showed a northwestward movement of 87 km, from northeastern Mato Grosso to southwestern Para. In the case of soybean, the centroid analysis shows a 82 km northeastern shift, from southern to northeastern Mato Grosso. Thus, the northward shift of soybean was accompanied by northward shift of both pasture and deforestation. Total harvested area shifted 55 km toward the southwest, where the largest expansion of area harvested to soybean and maize is located. Crops other than soybean have moved slightly southward, about 7 km, from southern Para to northern Mato Grosso (Figure 4-17).

The centroid analysis by state indicates that, in the state of Mato Grosso, soybeans have shifted 45 km toward the northern part of the state, where soybean cultivation has expanded. The same holds true for total harvested area, which moved 17 km in the same direction.

[1] Total estimated pastures for 2000 as well as total pastures reported by IBGE in 2006 were taken into consideration.

Deforested area has also shifted 27 km northward, where the areas with the highest percentage of forest were located in 2000.

The area under pasture in Mato Grosso has moved 35 km toward the northwestern part of the state, where deforested areas were located between 2000 and 2006. In contrast, other crops show a movement (45 km) toward the southwestern part of Mato Grosso, where maize is grown (Figure 4-18a).

The centroid analysis for the state of Para shows a general movement towards the northern part of the state in the cases of pasture (108 km), total harvested area (159 km), and other crops (165 km). In the case of soybean, however, a 242-km northwestward movement is observed, which suggests that the largest areas harvested to soybean are extending toward the western part of the state. Deforested areas show a slight movement (14 km) toward the western part of the state (Figure 4-18b).

The centroid analysis of the state of Rondônia shows a movement of pasture (36 km) and deforested areas (21 km) from the eastern to the northwestern part of the state. In addition, total harvested area shows a movement (48 km) from the southern to the northwestern part of the state. However, other crops show a central-western movement (9 km) and soybean a slight movement (6 km) toward the southern part of the state (Figure 4-18c).

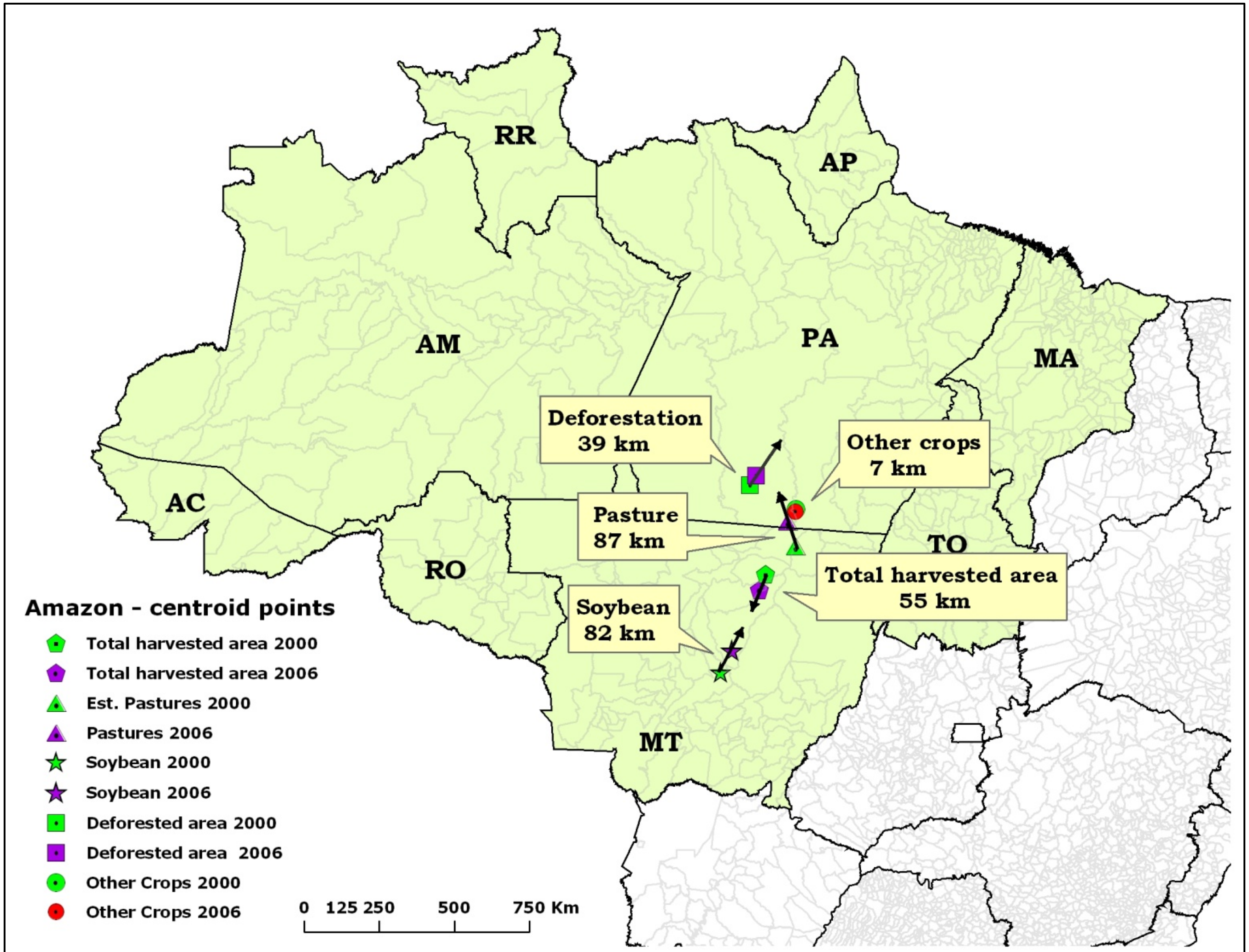


Figure 4-17. Movements of weighted-mean centroids between 2000 and 2006 for all municipalities in the Legal Amazon

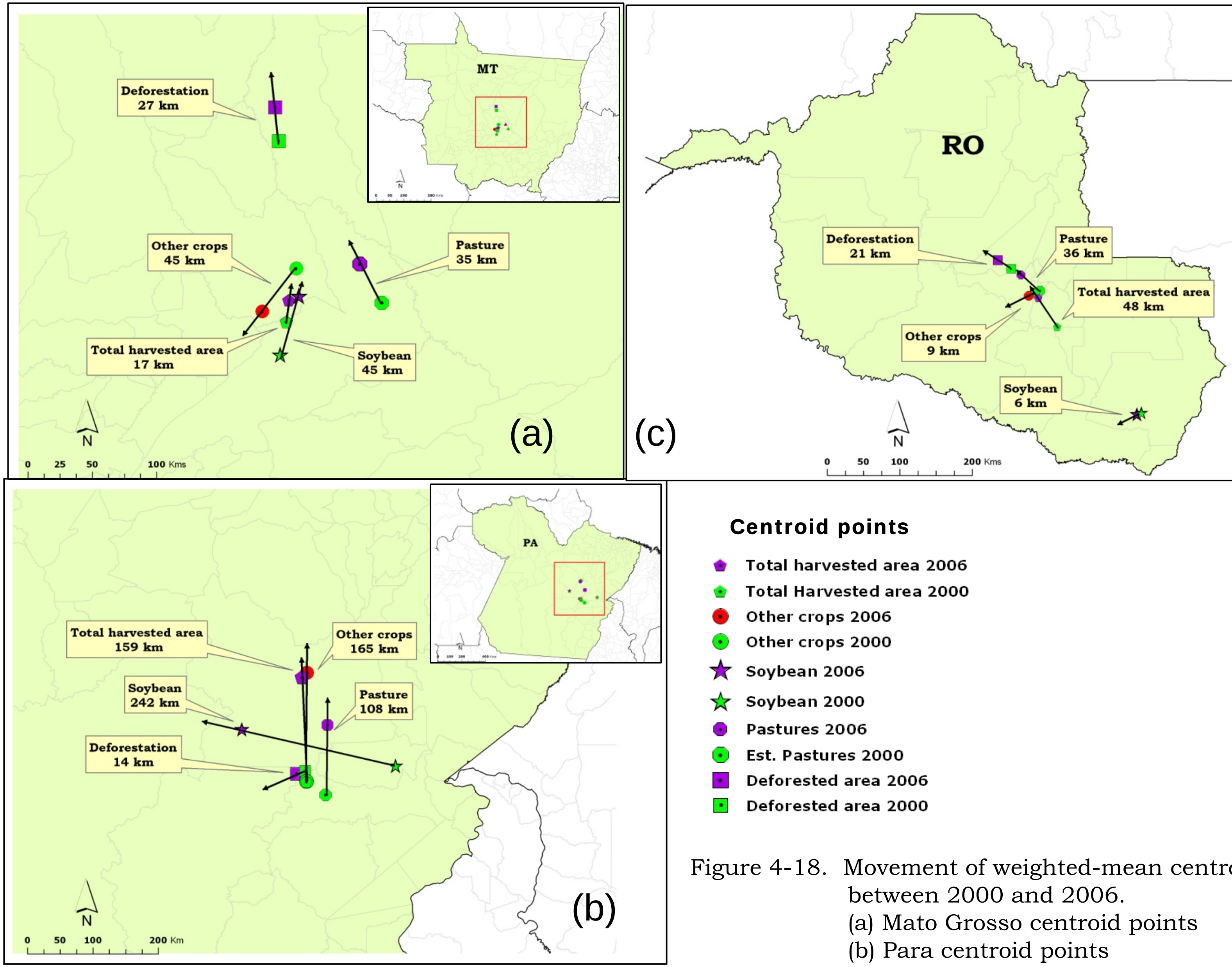


Figure 4-18. Movement of weighted-mean centroids between 2000 and 2006.
(a) Mato Grosso centroid points
(b) Para centroid points
(c) Rondonia centroin pointd

In summary, there is evidence of a northward shift of soybeans in Mato Grosso, toward the forest frontier, further displacing pasture areas northward into the forest frontier from Mato Grosso to Para, which may have lead to increased deforestation in Para. Indeed, the centroid of deforested area in Para is close to the centroid of pasture expansion.

4.4 Discussion and Conclusion

The relationship between agricultural expansion and deforestation in the Legal Amazon was analyzed was the period 2000-2006. Although the study was limited by the lack of reliable data at the municipality level and by potential inconsistencies in the data compiled, several similarities were observed between geographic patterns and the results of statistical analyses. Results, however, should be treated with caution.

Agricultural expansion in the Legal Amazon has apparently been driven mainly by soybean cultivation and pasture, although deforestation shows a stronger relationship with pasture area as compared with soybean area. Soybean, on the other hand, was related to pasture area in Mato Grosso, which suggests that the area under pasture is being replaced with soybean crops and that pasture may be being displaced to new areas, causing deforestation. In this case, there would be an indirect relationship between soybean and deforestation. The analysis of centroid movements showed a strong tendency for pasture formation to move towards the state of Para, which could explain not only the increase in soybean production in Mato Grosso but also the decrease in pasture. Furthermore, deforested areas have been increasing in the northeastern part of Para, where pasture and crop areas are increasing as well.

However, based on study results, it cannot be determined conclusively to what extent deforestation is related to pasture expansion or to crop expansion because only correlations were tested, which does not suggest causation.

Similarities are found between geographic patterns and results of statistical analyses in some cases but not in others.

1. The changes in the spatial distribution of crops suggest that, between 2000 and 2006, an increase in area harvested to soybean occurred in areas previously used for pasture, especially in the state of Mato Grosso. This was consistent with statistical results, which show that soybean areas in Mato Grosso are related to pasture rather than to deforested areas. Statistical results also show that pasture area in Mato Grosso are related to deforested area.

2. In other cases, however, results do not show much agreement between visual analysis of the spatial distribution maps and statistical analyses. For example, in the state of Para, spatial distribution maps show an increase in pasture, soybean, and deforested areas between 2000 and 2006. However, statistical

analysis shows that the correlation was weak to very weak in most cases.

3. In the case of Roraima, spatial distribution maps show an increase in soybean area in those areas presenting a decrease in pasture area. These results could suggest that the soybean area expanded into previous pasture area. These maps also show that, during the same period, Rondônia presented an increase in deforested area in the northeastern part of the state, which correlates with the expansion in pasture area. In both Roraima and Rondônia, whereas the statistical analysis does show some correlation, the sample size was too small and therefore non-significant.

In general, the analysis of geographic patterns in this study shows some evidence of a relationship between agricultural expansion and deforestation. However, more reliable data are necessary to improve the accuracy of results. Differences in geographic patterns, especially in the case of Para, suggest that deforestation could be driven by factors different from agricultural expansion. However, the analysis of the relationship between the expansion of the agricultural frontier and deforestation is extremely complex and requires that other biophysical and socioeconomic factors be included in the analysis so that results, instead of being speculative, are more accurate.

CHAPTER 5

Summary and Conclusions

This work presents the spatial analysis of agricultural land cover change in Brazil from 1990 to 2006 and examines how this change relates to deforestation in the Amazon region during 2000-2006. To perform the study, a spatial database of consistent administrative boundaries for 1990-2006 was initially created, and agriculture and deforestation census statistics for Brazil were subsequently incorporated into this database (described in Chapter 2). The resulting dataset allowed the changes in the extent of agriculture and forests in Brazil to be analyzed over time (described in Chapters 3 and 4).

The main findings were as follows:

- *Soybean and sugarcane in Brazil have undergone a significant expansion since 1990.*

Data analyses indicate that, from 1990 to 2006, soybean was the predominant crop in Brazil in terms of area cultivated. During this time period, the crop presented a remarkable growth—more than any other crop, increasing from 11.4 to 22 million hectares. This growth occurred mainly in the central-western part of the country, specifically in the states of Mato Grosso, Goias, and Tocantins. Sugarcane has also showed continued expansion in area cultivated since 1990, although to a lesser extent than soybean, increasing from 4.2 to 6.1 million hectares. Sugarcane expansion was mostly concentrated in the state of São Paulo. These findings contrast with the trends observed for other crops like rice, beans, cassava, cotton, and wheat, which not only showed a decrease in area cultivated (from 14.6 to 11.3 million hectares) but also a shift in location.

Over the last decades, the prices of soybean and sugarcane have been considerably higher than those of traditional staples such as rice, beans, and cassava. The global demand for both crops is also much higher, leading to intense market pressure to increase their agricultural expansion (Nepstad et al. 2006; Valle 2007). This expansion places subsistence crops at risk and could affect food security.

- *A distinct south-to-north shift in crops and livestock has occurred since 1990.*

Considering just the Brazilian Amazon and the surrounding cerrado regions, between 1990 and 2006 the centre of soybean cultivation moved further north, from southern to central Mato Grosso. Rice showed a relative reduction in area harvested in the southern part of the country, and maps illustrate a major shift northward into Para and northern Mato Grosso.

An interesting change was also observed in the case of cotton, which has moved northwestward into Mato Grosso. This crop has expanded rapidly into new areas in northwestern Mato Grosso, while decreasing in the southern states of Mato Grosso do Sul, Parana, and São Paulo. Cassava experienced a westward shift, its area decreasing slightly in the states of Para and Maranhão. Beans, on the other hand, have moved northeastward.

In contrast, maize and sugarcane clearly exhibited a shift towards the southwest. Maize has moved from northern Brazil (Maranhão, Para, and Tocantins) into several municipalities of Mato Grosso. Although sugarcane expansion has been concentrated in the state of São Paulo, this crop has also expanded into central-western Brazil (Mato Grosso, Mato Grosso do Sul, Gôias, and Tocantins). The overall pattern indicated that the areas of export crops (soybean and sugarcane) expanded, while domestic food crops recorded a significant decline.

During the period covered by this study, a northward shift in livestock distribution was also observed. The number of animal units decreased in Mato Groso do Sul, southern Gôias, and part of Mato Grosso, but increased significantly in southern Para, northern Mato Grosso, and Rondônia.

Export crops expansion could be attributed to the growing demand for soy products, biofuels, and meat worldwide—produce that is protected by government policies and enjoys incentives—as well as to new technologies that contribute to major improvements in agro-export products (Kaimowitz and Smith 2001; Nepstad et al. 2008; Valdes 2006). The expansion of export crops has exerted pressure on other crops, pushing them further into the Amazon region.

- *Deforestation in the Legal Amazon seems to be directly related to pasture expansion rather than to soybean, but there may be an indirect relationship to soybean expansion.*

There is a fairly strong relationship between deforestation and agricultural expansion. However, while deforestation seems to be related to pasture expansion in Mato Grosso, Rondônia, and Para, it was not related to soybean expansion in any state. Nonetheless, soybean expansion did relate negatively to change in pasture area in the state of Mato Grosso, suggesting that soybean could be forcing pastures out of Mato Grosso into other states.

- *Soybean may be pushing pastures into the Amazon region, indirectly causing deforestation.*

The centroid analysis for all Legal Amazon shows that, between 2000 and 2006, deforested areas moved 39 km to the northeast, further into Para. During the same period, soybean areas moved 82 km from southern to northeastern Mato Grosso, while pasturelands moved 87 km from northern Mato Grosso towards southern Para. The centroid of pasture expansion seems to be close to the centre of deforestation.

These combined results suggest that, in the case of the Legal Amazon, the expansion of soybean (especially in Mato Grosso) may be pushing other crops and pastureland into Para and other states. The fact that soybean is displacing pastureland into new areas may be indirectly causing deforestation.

In summary, this study provides valuable insight into the dynamics of soybean expansion in Brazil and how this expansion is related to deforestation, pasture location, and local food crops. The geographic data prepared for this study can be potentially used in future studies and by other researchers interested in examining the drivers and consequences of agricultural expansion in Brazil.

References

Andersen L.E.; Granger C.W.J.; Reis E.J.; Weinhold D.; Wunder S. 2002. The dynamics of deforestation and economic growth in the Brazilian Amazon. Cambridge. University Press, Cambridge, UK. 259 p.

Asner G.P.; Knapp D.E.; Broadbent E.N.; Oliveira P.J.C.; Keller M.; Silva J.N. 2005. Selective logging in the Brazilian Amazon. Science 310: 480-482.

Barbier E.B. 2004. Agricultural expansion, resource booms and growth in Latin America: Implications for long-run economic development. World Development 32(1):137-157.

Brown J.C.; Jepson W.E.; Kastens J.H.; Wardlow B.D.; Lomas J.M.; Price K.P. 2007. Multitemporal, moderate-spatial-resolution remote sensing of modern agricultural production and land modification in the Brazilian Amazon. GIScience and Remote Sensing 44 (2):117-148.

Brown C.; Jepson W.; Price K. 2004. Expansion of mechanized agriculture and land-cover change in southern Rondonia, Brazil. Latin American Geography. 7 p.

Brown J.C.; Koeppe M.; Coles B.; Prince K.P. 2005. Soybean production and conversion of tropical forest in the Brazilian Amazon: The case of Vilhena, Rondonia. Ambio 34(6):462-469.

Burgi M.; Hersperger A.M.; Schneeberger N. 2004. Driving forces of landscape change—current and new directions. Landscape Ecology 19:857-868.

Câmara G.; Valeriano D.M.; Soares J.V. 2006. Metodologia para o cálculo da taxa anual de desmatamento na Amazônia Legal. Instituto Nacional de Pesquisas Espaciais (INPE). 24 p.

Caporale M.A. 2004. Financial liberalization and macroeconomic policy options Brazil, 1994-2003. Texto para discussão. IE/UNICAMP N.117. 32 p.

Carvalho G.O.; Nepstad D.; McGrath D.; Vera D. M.C.; Santilli M.; Barros A.C. 2002. Frontier expansion in the Amazon: Balancing development and sustainability. Environment 44(3):32-42.

Carvalho P. 2006. A country pastures resource profile. Grassland and Pasture, Crop System-FAO. Available at www.fao.org/ag/agp/agpc/doc/counprof/Brazil/brazil.htm#1.int.

Deadman P.; Robinson D.; Moran E.; Brondizio E. 2004. Colonist household decisionmaking and land-use change in the Amazon rainforest: an agent-based simulation. Environment and Planning 31:693-709.

Dross J.M. 2004. Managing the soy boom: two scenarios of soy production expansion in South America. WWF Report. 65 p.

Dross J.M.; Bickel U. 2003. The impact of soybean cultivation on Brazilian ecosystems. Three case studies, commissioned by the WWF Forest Conversion Initiative. 33 p.

Ewers R.M.; Laurance W.F. 2006. Scale-dependent patterns of deforestation in the Brazilian Amazon. Environmental Conservation 33(3):203-211.

Fearnside P. 2005. Deforestation in Brazilian Amazonia: History, rates, and consequences. Conservation Biology 19(3):680-688.

Fearnside P. 2001. Ecosystems of South America: Status and threats. National Institute for Research in the Amazon (INPA). Manaus, Brazil. p. 345-359.

Ferreira Filho J.B.S.; Horridge M.J. 2004. Economic integration, poverty and regional inequality in Brazil. Revista Brasileira de Economia 60(4):363-387.

Foley J.A.; DeFries R.; Asner G.P.; Barford C.; Gordon B.; Carpenter S.R.; Chapin F.S.; Coe M.T.; Daily G.C.; Gibbs H.K.; Helkowski J.H.; Holloway T.; Howard E.A.; Kucharik C.J.; Monfreda C.; Patz J.A.; Prentice C.; Ramankutty N.; Synder P.K. 2005. Global consequence of land use. Science 309:570-574.

Fujisaka S.; Bell W.; Thomas N.; Hurtado L.; Crawford E. 1996. Slash-and-burn agriculture, conversion to pasture, and deforestation in two Brazilian Amazon colonies. Elsevier (59):115-130.

Geist, H.J.; Lambin E.F. 2002. Proximate causes and underlying forces of tropical deforestation. BioScience 52:143-150.

Geist H.J.; Lambin E.F. 2001. What drives tropical deforestation? A meta-analysis of proximate and underlying causes of deforestation based on subnational case study evidence. LUCC Report Series (4). 136 p.

Goldenberg J. 2006. The ethanol program in Brazil. Environmental Research Lett. 1014008. 5 p.

Graham H.D.; Gauthier H.; Mendonça de Barros J.R. 1987. Thirty years of agricultural growth in Brazil: Crop performance, regional profile and recent policy review. Economic Development and Cultural Change 36(1):1-34.

Grau R.J.; Aide T.M.; Gasparri N.I. 2005. Globalization and soybean expansion into semiarid ecosystem of Argentina. Ambio 34(3):265-266

Heyck D.; Lynn D. 2002. Surviving globalization in three Latin American communities. Broadview Press. 299 p.

Hersom M. 2005. Pasture stocking density and the relationship to animal performance. Institute of Food and Agricultural Sciences, University of Florida, USA. Document AN155. 4 p.

Houghton R.A.; Lefkowitz D.S.; Skole D.L. 1991. Changes in the landscape of Latin America between 1850 and 1985. I. Progressive loss of forests. Forest Ecology and Managements 38:143-172.

IBGE (Instituto Brasileiro de Geografia e Estadistica). 2008. Interactive maps website at http://mapas.ibge.gov.br/.

IBGE (Instituto Brasileiro de Geografia e Estadistica). 2007. Mapas Interativos – Mapa de Divisôes Territoriais, malhas municipais para os anos de 2005, 2001, 1997, 1994 e 1991. Available at http://www.sidra.ibge.gov.br/mapas_ibge/ (accessed October 2007).

IBGE (Instituto Brasileiro de Geografia e Estadistica). 2006. Agricultural production at municipality-level. Agricultural database SIDRA. Available at http://www.sidra.ibge.gov.br/.

IBGE (Instituto Brasileiro de Geografia e Estadistica). 2006. Perfil dos municipios Brasileiros. Available at http://www.ibge.gov.br/home/estatistica/economia/perfilmunic/default.shtm.

IBGE (Instituto Brasileiro de Geografia e Estadistica). 2002. Pesquisas Agropecuarias. Serie Relatorias Metodologicos. 2 edicao. Rio de Janeiro, Brazil. 96 p.

IBGE (Instituto Brasileiro de Geografia e Estadistica); MMA (Ministerio do Meio Ambiente). 2007. Mapa de biomas. Interactive maps website. Available at http://mapas.ibge.gov.br/.

INPE (Instituto Nacional de Pesquisas Especiais). 2007. Monitoring of the Brazilian Amazon forest by satellite 2000-2006. PRODES database [www document] website at http://www.obt.inpe.br/prodes/.

Kaimowitz D.; Smith J. 2001. Soybean technology and the loss of natural vegetation in Brazil and Bolivia. Agricultural technologies and tropical deforestation. CAB International 195-211. 17 p.

Kirby K.R.; Laurance W.F.; Albernaz A.K.; Schroth G.; Fearnside P.M.; Bergen S.; Venticinque E.M.; da Costa C. 2006. The future of deforestation in the Brazilian Amazon. Elsevier Futures 38:432-453.

Klein Goldewijk, K. 2001. Estimating global land use change over the past 300 years: the HYDE database. Global Biogeochemical Cycles 15(2):417-434.

Knapp R. 2003. Brazilian sugar. Horticultural and tropical products division (202). 6 p.

Lambin E.F.; Geist H.J. 2006. Land-use and land-cover change. Local process and global impacts. Springer Berlin Heidelberg New York. 222 p.

Lambin E.F.; Geist H.J.; Lepers E. 2003. Dynamics of land-use and land-cover change in tropical regions. Environ. Resource 28:205-241.

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

Laurance W.F.; Cochrane M.A.; Bergen S.; Fearnside P.M.; Delamônica P.; Barber C.; D'Angelo S.; Fernandes T. 2001. The future of the Brazilian Amazon. Science 291:438-439.

Lepers E.; Lambin E.F.; Janetos A.C.; DeFries R.; Achard F.; Ramankutty N.; Scholes R.J. 2005. A systhesis of information on rapid land-cover change for the period 1981-2000. BioScience 55(2):115-124.

Meade B.; Valdes C.; Rosen S. 2004. Brazil's food security and food assistance programs to reduce poverty. Food security assessment. Economic Research Service-USDA. GFA 15:24-34.

Margulis S. 2004. Causes of deforestation of the Brazilian Amazon. World Bank Working Paper 22. Washington D.C., USA. 100 p.

Meyer W.; Turner B.L. 1994. Changes in land use and land cover: A global perspective. Cambridge University Press. 537 p.

Moran F.F.; Brondizio E.; Mausel P.; You Wu. 1994. Integrating Amazonian vegetation, land use and satellite data. BioScience 44(5):329-338.

Morton D.; DeFries R.; Shimabukuro Y.; Anderson L.O.; Arai E.; Espiritu-Santo F.; Freitas R.; Morisette J. 2006. Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. In: Proceedings of the National Academy of Sciences of the United States of America. PNAS 103(39):14637-14641.

Mossi M.B.; Aroca P.; Fernandez I.J.; Azzoni C.R. 2003. Growth dynamics and space in Brazil. International Regional Science 26(3):393-418.

Mueller C.C. 2003. Expansion and modernization of agriculture in the Cerrado—the case of soybean in Brazil's Center-West. Department of Economics. Working Paper No. 306. University of Brasilia. 28 p.

Nepstad D.; Stickler C.; Soares-Filho B.; Merry F. 2008. Interactions among Amazon land use, forests and climate: prospects for a near-term forest tipping point. Philosophical transactions R. Soc. 1098. 10p.

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

Palermo L. 2006. The Statistical and Geoscientific IBGE's Metadata System (SIDRA) (Sistema de Metadados do IBGE – SIDRA). IBGE Working Paper. April 2006. 12 p.

Pereira M.F.; Tusi da Silveira J.S.; Lanzer E.A.; Samohyl R.W. 2002. Productivity growth and technological in the Brazilian agricultural sector. Pesquisa Operacional 22(2):133-146.

Peres C.A. 2001. Paving the way to the future of Amazonia. Trends in Ecology & Evolution 16(5):217-219.

Pfaff A.; Robalino J.; Walker R.; Aldrich S.; Caldas M.; Reis E.; Perz S.; Bohrer C.; Arima E.; Laurance W.; Kirby K. 2007. Road investments, spatial spillovers, and deforestation in the Brazilian Amazon. Journal of Regional Science 47(1):109-123.

Ramankutty N.; Foley J.A. 1999. Estimating historical changes in global land cover: Croplands from 1700 to 1992. Global Biochemical Cycles 13:997-1027.

Roberts N. 1996. The human transformation of the Earth's surface. International Social Science Journal 48(4):493-510.

Rudel T.K. 2005. Tropical forest. Regional paths of deforestation and regeneration in the late twentieth century. Columbia University Press. 0231-13195. 231 p.

Sartoris A.; Igliori D. 2007. Local economic growth in Brazil: a spatial analysis for Sao Paulo Municipalities. Department of Economics, Sao Paulo University. 13 p.

Scarnecchia D. 2004. Viewpoint: Entropy, concept design, and animal-unit equivalence in range management science. J. Range Management 57:113-116.

Schnepf R. D.; Dohlman E. and Bolling C. 2001. Agriculture in Brazil and Argentina: Developments and prospects for major field crops. U.S. Department of Agriculture, Agriculture and Trade Report. WRS-01-3. 85 p.

Steinfeld H.; Wassenaar T.; Jutzi S. 2006. Livestock production systems in developing countries: status, drivers, trends. Animal Production and Health Division, Food and Agriculture Organization, Rome. Rev. Sci. Tech. Off. Int. Epiz 25(2):505-516.

Turner B.L.; Moss R.H.; Skole D.L. (eds.). 1993. Relating land use and global land-cover change: A proposal for an IGBP-HDP core project. Report from IGBP-HDP Working Group on Land-Use/Land-Cover Change. (Report No.24) and the Human Dimensions of Global Environmental Change Programme (HDP) (Report No. 5). 65 p.

UNICA (Sao Paulo Sugarcane Agro-industry Union) 2006. The sugarcane industry. Statistics dataset. Available at http://www.unica.com.br/.

USDA (United States Department of Agriculture). 2005. Brazil: 2005/06 Soybean area projected to decline. Report: 5 p. Available at www.usda.gov.

USDA (United States Department of Agriculture). 2004. China's soybean imports expect to grow despite short-term disruptions. Outlook Report from the Economic Research Services. OCS-04J1. 14 p.

USDA (United States Department of Agriculture). 2003. Brazil: Future agricultural expansion potential underrated. Production estimates and crop assessment division. Foreign Agricultural Services Report. 8 p.

USDA (United States Department of Agriculture). 2001. A comparison of economic and agricultural settings. USDA Report: Agriculture in Brazil and Argentina: Developments and Prospects for Major Field Crops. Agriculture and Trade Report. WRS-01-3. 4-14, 11 p.

USDA (United States Department of Agriculture). 2000. Prices for bumper soybean crop hinge on China's imports. Commodity Spotlight. Agricultural Outlook. Economic Research Service-USDA. 3 p.

Valdes C. 2006. Brazil's booming agriculture faces obstacles. Economic Research Services. USDA. Amber Waves 4. 8 p.

Valle S. 2007. Losing forest to fuel cars: ethanol sugarcane threatens Brazil's wooded savanna. Available in The Washington Post, 31 July: http://www.washingtonpost.com/wp-dyn/content/article/2007/07/30/AR2007073001484.html

Vitousek P.M.; Mooney H.A.; Lubchenco J.; Melillo J.M. 1997. Human domination of Earth's ecosystems. Science 277:494-499.

Walker R.; Moran E. 2000. Deforestation and cattle ranching in the Brazilian Amazon: External capital and household processes. World Development 28 (4): 683-699.

WWF (World Wildlife Fund). 2006. Climate change impact in the Amazon. Report Michael Case, WWF Climate Change Programme. 12 p.