LÍVIA CRISTINA PINTO DIAS

PATTERNS OF LAND USE AND GREENHOUSE GASES EMISSIONS FROM BRAZILIAN AGRICULTURE (1940-2014)

Thesis submitted to the Applied Meteorology Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Doctor Scientiae*.

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APPROVED: June 14, 2017.

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Marcos Heil Costa
(Advisor)

This thesis is dedicated to everyone who participated in my educational and professional training.

"Eles não lavram, nem criam. Não há aqui boi,
nem vaca, nem cabras, nem ovelhas, nem
galinha, nem qualquer outra alimária, que
costumada seja ao viver dos homens. Nem comem
senão desse inhame, que aqui há muito, e dessa
semente e frutos, que a terra e as árvores de si
lançam. E com isso andam tais e tão rijos e tão
nédios, que o não somos nós tanto, com quanto
trigo e legumes comemos."

Letter from Pero Vaz de Caminha to El-Rei D. Manuel

(Porto Seguro - Brazil, May 1, 1500)

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BIOGRAPHY

LÍVIA CRISTINA PINTO DIAS, daughter of João Antônio Dias and Maria Aparecida Pinto Dias, was born in Santo Antônio do Monte, on June 11, 1988.

In June of 2011, I graduated in Environmental Engineering at the Universidade Federal de Viçosa (UFV).

In August of 2011, I initiated my studies at the Post-graduation Program in Agricultural Meteorology at the UFV. I concluded the Magister Degree in Agricultural Meteorology with the work entitled "Effects of land cover change on evapotranspiration and streamflow of small catchments in the Upper Xingu River Basin, Central Brazil" in July of 2013.

In August of 2013, I initiated the Doctoral Degree at the Post-graduation Program in Applied Meteorology at the UFV.

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CHAPTER 1

LIST OF SYMBOLS

ΔALU	Agricultural land use change
ΔU_{MCA}	Variation of the amount of total agricultural land use in each MCA
A	Pixel area
a	Proportions of animal by age (younger than 1 year-old, between 1 and 2 year-old and adults)
$ALU_{i,j}^{t}$	Total agricultural land use maps as a percentage of area per pixel
c	Animal category (dairy cows, adult male, adult female and young cattle)
DE	N_2O emissions from grazing animals and application of manure as fertilizers
EF	Emission factor of CH_4 by enteric fermentation
f	Proportion of animal in each animal category
F_{cn}	Factor of conversion from N to N_2O
Fl_{each}	Fraction of nitrogen lost by leaching
F_{mv}	Factor of volatilization for manure as fertilizers

F_{ov}	Factor of volatilization for other synthetic nitrogen fertilizers except urea
F_p	Fraction of manure excreted directly in pasturelands
F_{uv}	Factor of volatilization for urea
FE	Synthetic nitrogen fertilizer emissions,
fu	Fraction of urea in relation to the total synthetic nitrogen fertilizers
GF	Direct N_2O emission factor for grazing animals
i	Coordinates of rows of the pixels in the map
j	Coordinates of columns of the pixels in the map
k	Index that indicates a municipality
LE	Indirect N_2O emission from leaching
LF	Indirect N_2O emission factor for leaching
m	Index that indicate an MCA
ME	CH4 emission from enteric fermentation and manure management
MM	Emission factor of CH_4 by manure management
Nex	N excreted of annually of an animal category
NF	Direct N_2O emission factor
$NONF_{i,j \in k}^{t}$	Convert gridded non-forest maps
P	Population of animals (either dairy or cattle beef head)
p	Proportion of animal category
SN	Amount of synthetic nitrogen fertilizer delivered to the farmers
SV_{area}	Secondary vegetation area
t	Index that indicates a year
$U_{I,J}^{1940}$	Amount of total agricultural land use in a pixel from 1940
U_{MCA}^{1995}	Amount of total agricultural land use in a micro region from 1995 census data
$U_{k \in MCA}^{1995}$	Amount of total agricultural land use in a municipality k belonging a MCA from 1995 census data
U_{MCA}^{2006}	Amount of total agricultural land use in a MCA from 2006 census data

$U_{I,J}^{T}$	Estimated total agricultural land use in a pixel for the year *t*
U_{k}^{t}	Estimated total agricultural land use in a municipality *k* in the year *t*
VE	Indirect N_2O emission from atmospheric deposition
VF	Indirect N_2O emission factor for atmospheric deposition

LIST OF ACRONYMS

ABRAF	*Associação Brasileira dos Produtores de Florestas Plantadas* (Brazilian Association of Planted Forest Producers)
ANDA	*Associação Nacional para Difusão de Adubos* (National Association for the Diffusion of Fertilizers)
AFOLU	Agriculture, Forestry and Other Land Use sector
AGB	Aboveground biomass
BGB	Belowground biomass
GHG	Greenhouse gases
GWP	Global Warming Potential
IBGE	*Instituto Brasileiro de Geografia e Estatística* (Brazilian Institute of Geography and Statistics)
INPE-EM	INPE Emission Model
IPCC	Intergovernmental Panel on Climate Change
IPEA	*Instituto de Pesquisa Econômica Aplicada* (Institute of Applied Economic Research)
LULUCF	Land Use, Land Use Change and Forestry
MCA	Minimum Comparable Area
MK test	Mann-Kendall test

MATOPIBA	Acronym created from the first two letters of the states of Maranhão, Tocantins, Piauí, and Bahia
MAPA	*Ministério da Agricultura, Pecuária e Abastecimento* (Brazilian Ministry of Agriculture)
NDC	Nationally Determined Contributions
PPCDAm	*Plano de Ação para Prevenção e Controle do Desmatamento e das Queimadas no Bioma Amazônia* (Action Plan for Prevention and Control of Deforestation and Burning in the Amazonia)
PPCerrado	*Plano de Ação para Prevenção e Controle do Desmatamento e das Queimadas no Bioma Cerrado* (Action Plan for Prevention and Control of Deforestation and Burning in the Cerrado)
PNMC	*Política Nacional sobre Mudanças no Clima* (National Policy on Climate Change)
Plano ABC	*Plano Setorial de Mitigação e de Adaptação às Mudanças Climáticas para a Consolidação de uma Economia de Baixa Emissão de Carbono na Agricultura* (National Program for Low Carbon Agriculture)
PRODES	*Projeto de Monitoramento da Floresta Amazônica Brasileira por Satélite* (Program for the Annual Estimation of Deforestation in the Brazilian Amazon)
UNFCCC	United Nations Framework Convention on Climate Change

ABSTRACT

DIAS, Lívia Cristina Pinto, D.Sc., Universidade Federal de Viçosa, June, 2017. **Patterns of land use and greenhouse gases emissions from Brazilian agriculture (1940-2014).** Adviser: Marcos Heil Costa

Given the large size of Brazil, its enormous vegetation diversity and agriculture heterogeneity, the development of national agricultural and conservation policies requires an understanding of historical patterns of land use for the entire country. It is only through the lens of history that the current geographic trends in land use can be fully understood and accurate future projections made. This study analyzes the spatial patterns of the Brazilian agriculture between 1940 and 2014, with emphasis on land use and greenhouse gas emissions. I investigate the historical patterns of agricultural land use and greenhouse gases emissions in Brazil using a new historical-spatial database at spatial resolution of 30” (approximately 1 km x 1 km). Although the agriculture frontier is still expanding in the Amazon and Cerrado, rates are much lower than before, and throughout the eastern and southern part of the country, agricultural land use is actually decreasing. The production of soybean and maize increased due to increase in area and yields, but the production of sugarcane increased predominantly due to extensification. Pasturelands decreased in all regions analyzed, except in Amazonia, but the slow process of technology transference appears to be keeping the

Brazilian stocking rate of cattle close to 1.0 head/ha, indicating an inefficient livestock system. Brazil is moving slowly towards a more intensive and sustainable agriculture. Until 1975, deforestation of the Atlantic Forest and Cerrado were the main sources of CO_2 emissions. After that, Amazonia took the first position as source of CO_2 emissions. Emissions from land use change in Atlantic Forest and Pampas decreased gradually after 1975 and these biomes become a sink of CO_2 since 1990. The total agricultural emissions are decreasing because the CO_2 emissions are decreasing and they are several times larger (in CO_{2eq} terms) than the CH_4 and N_2O emissions. Brazil is heading towards the reduction of land use change emissions as proposed in the National Policy on Climate Change. About the Nationally Determined Contributions proposed in the 2015 Paris agreement, the past rates in forest restoration are more than sufficient to achieve the suggested measure proposed. The conclusion is that Brazil should be more audacious in its goals. My results provide one of the first comprehensive historical and geographically explicit overview of agricultural land use and greenhouse gases emissions in Brazil, providing clear insights to guide future territorial planning, sustainable agriculture, policy and decision-making.

RESUMO

DIAS, Lívia Cristina Pinto, D.Sc., Universidade Federal de Viçosa, junho de 2017. **Padrões de uso do solo e emissões de gases de efeito estufa pela agricultura Brasileira (1940-2014).** Orientador: Marcos Heil Costa

Dada a grande extensão do Brasil, sua enorme diversidade de vegetação e heterogeneidade agrícola, o desenvolvimento de políticas agrícolas e de conservação requer uma compreensão dos padrões históricos de uso da terra para todo o país. Somente através da lente da história que as atuais tendências geográficas no uso da terra podem ser totalmente compreendidas e projeções futuras mais precisas podem ser feitas. Este estudo analisa os padrões espaciais da agricultura brasileira entre 1940 e 2014, com ênfase no uso da terra e nas emissões de gases de efeito estufa. Os padrões históricos de uso das terras pela agricultura e emissões de gases de efeito estufa foram investigados usando uma nova base de dados histórico-espacial com resolução espacial de 30” (aproximadamente 1 km x 1 km). Embora a fronteira agrícola ainda esteja expandindo na Amazônia e Cerrado, as taxas são muito menores do que antes, e em toda a parte oriental e sul do país, a área agrícola está diminuindo. A produção de soja e milho aumentou devido ao aumento da área e da produtividade, mas a produção de cana-de-açúcar aumentou principalmente devido à extensificação. As pastagens diminuíram em todas as regiões analisadas, exceto na Amazônia, mas o lento processo de transferência de tecnologia tem mantido a taxa de lotação de bovinos perto

de 1 cabeça/ha, indicando um sistema de pecuária ineficiente. O Brasil está se movendo lentamente para uma agricultura mais intensiva e sustentável. Até 1975, o desmatamento da Mata Atlântica e do Cerrado foram as principais fontes de emissões de CO_2 pela mudança de uso da terra. Depois disso, a Amazônia tomou a primeira posição como fonte de emissões de CO_2. As emissões decorrentes da mudança do uso da terra na Mata Atlântica e nos Pampas diminuíram gradualmente após 1975 e esses biomas tornaram-se sumidouros de CO_2 desde 1990. As emissões agrícolas totais estão diminuindo porque as emissões de CO_2 estão diminuindo e elas são várias vezes maiores (em termos de CO_{2eq}) que as emissões de CH_4 e N_2O. Por outro lado, o aumento da produtividade resulta em aumento das emissões pela agricultura. Brasil está a caminho da redução das emissões por uso do solo propostas na Política Nacional sobre Mudanças no Clima. Sobre as Contribuições Nacionalmente Determinadas no acordo de Paris, em 2015, as taxas passadas de restauração florestal são mais do que suficiente para atingir a medida sugerida no acordo. A conclusão é que o Brasil deveria ser mais audacioso em suas metas. Esses resultados fornecem uma das primeiras visões históricas abrangente e espacialmente explicita do uso da terra pela agricultura e pecuária das emissões de gases de efeito estufa no Brasil, fornecendo ideias claras para orientar futuros planejamentos territoriais, a agricultura sustentável, a formulação de políticas públicas e a tomada de decisões.

GENERAL INTRODUCTION

Agriculture is one of the most important activities in Brazil since the colonial period, but a rapid transformation of this activity occurred in the last century. The first Brazilian agricultural survey, carried out in 1920, registered that cropland occupied only 6.6 Mha (IBGE, 2017). Between 1920 and 2006, Brazilian cropland increased nearly tenfold (from 6.6 to 60.5 Mha; IBGE, 2017) and native vegetation was gradually replaced by planted areas, especially in the Atlantic Forest, Cerrado and Amazonia biomes (Leite et al., 2012).

Cattle ranching is also practiced in Brazil since the 16th century for subsistence and urban supply. The amount of pasture in Brazil in 1920 was not registered in the first survey, but it is known that pastureland expanded rapidly in the Atlantic Forest, Cerrado and Pampas biomes in the 17th century and that livestock was consolidated as an export activity in the beginning of the 20th century (Teixeira e Hespanhol, 2014). Between 1920 and 2016, cattle herd increased from 35.3 to 175 million cattle heads in

Brazil, currently distributed in more than 160 Mha of pasturelands in all biomes (IBGE, 2017).

In these 100 years, there was a considerable increase in yield with the adoption of improved cultivars, irrigation, fertilizer, biocides, and mechanization. Furthermore, the country diversified its agriculture, standing out today for its large exports of soybean, maize, sugarcane, oranges, coffee and several other products (FAO, 2017). Currently, agribusiness provides about 16.5 million jobs (IBGE, 2017) and is responsible for more than 20% of the Brazilian Gross Domestic Product (CEPEA, 2016). Brazil is also one of the ten major exporters of agricultural products in the world (FAO, 2015).

It is expected that Brazil continues to increase its production and exports in the future. Recently, the Brazilian Ministry of Agriculture *(Ministério da Agricultura, Pecuária e Abastecimento* or MAPA) estimated that Brazilian grain production will increase by 29.4% and beef production by 23.3% between 2015 and 2025 (MAPA, 2015). In the same period, soybean and maize exports are predicted to increase by 51.2% and 42.1%, respectively, and beef exports by 37.4% (MAPA, 2015).

If Brazilian agriculture has been increasing its importance and participation in the international market, equally increasing is the concern about the impacts of agricultural activity on the environment. Deforestation is one of the most threatening consequences of the expansion of Brazilian agriculture. Amazon deforestation is widely studied and it is know that Amazonia biome occupation from agriculture was accelerated by the construction of a network of highways in the early 1970s (Fearnside, 2005; Barona et al., 2010; Leite et al., 2011). The deforestation of the Atlantic Forest started in the early 1500s due to extractivism and agriculture and, currently, only 7% of the original area remains (SOS Mata Atlântica, 2017). The direct relationship between agricultural area expansion and native vegetation removal in the Cerrado and Caatinga biomes has also been clearly demonstrated (Brannstrom et al., 2008; Rocha et al., 2012; Beuchle et al., 2015) as well as in the Pampas (Graesser et al., 2015) and Pantanal biomes (Harris et al., 2005).

Brazilian deforestation is closely intertwined with biodiversity loss (Chaplin-Kramer et al., 2015), alteration of the water and soil properties (Scheffler et al., 2011; Groppo et al., 2015; Hunke et al., 2015), changes in atmospheric characteristics at regional scales (Costa e Pires, 2010), and energy and water balance alterations (Anderson-Teixeira et al., 2012; Stickler et al., 2013; Dias et al., 2015). In addition, deforestation is the major source of greenhouse gas (GHG) emissions in Brazil (Leite et al., 2012; Calvin et al., 2015; Chaplin-Kramer et al., 2015).

Until 1995, deforestation caused by agricultural expansion in Brazil had already been responsible for the emission of 21 Pg-C, which corresponds to 18.1% of the original carbon stock of Brazilian vegetation (Leite et al., 2012). Houghton et al. (2000) estimates that Amazon biome emissions increased from zero before 1960 to 1.8 Pg-C between 1989 and 1998. Aguiar et al. (2012) estimates that approximately 2.1 Pg-C was emitted only in Amazon biome between 2000 and 2009. Only pasture establishment was responsible for roughly 0.95 Pg-C of the deforestation emissions in the Amazonia biome between 2003 and 2008 (Bustamante et al., 2012).

The GHG emissions from agricultural land use change in Cerrado was studied by Bustamante et al. (2012) and Noojipady et al. (2017). Bustamante et al. (2012) estimates that emissions from land use change from pastureland establishment corresponded to nearly 0.2 Pg-C between 2003 and 2008. Noojipady et al. (2017) found that cropland establishment in Cerrado was responsible for the emission of 0.18 Pg-C between 2003 and 2013, the greatest part of the emissions coming from the conversion of non-forest Cerrado physiognomies. Land use emissions estimates can be found for the other four Brazilian biomes in the Third National Communication of Brazil to the United Nations Framework Convention on Climate Change (Brasil, 2016), which covers the period between 1990 and 2010, but there is no analysis or discussions focusing exclusively in the agricultural activity.

A Brazilian emissions estimate from agricultural establishment depends on detailed historical geographic descriptions of land use and land cover change for the entire country, such as has already been done by Leite et al. (2012). They constructed the first historical-spatial description of Brazilian agriculture land use and conducted the first estimate of carbon emissions associated with agricultural land use change for the entire country from 1940 to 1995, at a spatial resolution of 5' (approximately 9 km x 9 km). However, this land use database was restricted to mapping general croplands and pastures (natural and planted), and crop-specific maps remain unavailable for Brazil. In addition, to become policy-relevant, the land use database and the carbon emissions estimates need to be updated to include more recent years. Moreover, an analysis of the agricultural contributions to climate change would be more complete if the emissions from land use and land cover change were accompanied by spatially explicit estimates of other agricultural activities emissions.

Other agricultural activities emissions represented 32% of the total national emissions in 2010 (Brasil, 2016). The CH_4 emissions from enteric fermentation were 11 Tg-CH_4, which represents 64% of the total CH_4 emissions from agriculture in 2010. The N_2O emission was 472 Gg-N_2O in 2010, being emitted mainly for the grazing animals and nitrogen fertilizer both synthetic and from animal (Brasil, 2016).

Maps have been used for a long time to store knowledge about the land surface and for geographic space management, such as the development of national agricultural and conservation policies. Maps allow the identification of spatial distribution accompanied by quantitative information. Historical maps can allow identification of when certain events happened as well as time trends. In addition, maps instigate the search for the causes of the spatial distribution.

Historical agricultural land use maps improve the understanding of the current agriculture heterogeneity and are important for contextualizing contemporary environmental problems. Recently, maps provided by remote sensing data have been improving our understanding of the Earth's surface and are essential tools in studies of the land use consequences of agriculture (Graesser et al., 2015), such as deforestation and land use change emission.

This study aims to analyze the spatial patterns of the Brazilian agriculture between 1940 and 2014. More specifically, I describe the dynamics of the conversion between natural vegetation, pasturelands and croplands (including specific crops), and spatial heterogeneity of the GHG emissions from agricultural land use change and agricultural sector. To achieve this goal, I constructed two historical-spatial database, for Brazilian agricultural land use and GHG emissions, at spatial resolution of 30" (approximately 1 km x 1 km).

In Chapter 1, I investigate the historical patterns of agricultural land use and productivity in Brazil using a historical-spatial database for Brazilian agricultural land use. This database includes yearly data on cropland areas (total cropland areas from 1940 to 2012, and soybean, maize, and sugarcane from 1990 to 2012); soybean, maize, and sugarcane yield and yearly cattle stocking rate from 1990 to 2012; and pasturelands (total, and split into natural and planted pastures from 1940 to 2012). In addition, I contrast the changes in productivity and agricultural area for soybean, maize, sugarcane and cattle to understand the extensification-intensification relationship. I also perform a yield gap analysis – the difference between average yields and the top yields (top 5%) in the main producing regions.

In Chapter 2, I analyze the spatial patterns of GHG emissions, placing these findings into the current environmental debate. For these analyses, I developed a historical-spatial database of Brazilian GHG emissions that contains the CO_2 emissions maps from agricultural land use from 1940 to 2014, CH_4 emissions maps from enteric fermentation and manure management from 1975 to 2014, and direct and indirect N_2O emissions maps from 1975 to 2014. In this study, I also analyze the Brazilian agriculture emissions through a statistical trend test of time series and from the perspective of the National Policy on Climate Change (PNMC – *Política Nacional sobre Mudanças do Clima*; Federal Law n. 12,187/2009 and Decree 7390/2010).

CHAPTER 1 - PATTERNS OF LAND USE, EXTENSIFICATION AND INTENSIFICATION OF BRAZILIAN AGRICULTURE

Dias, Lívia C. P.; Pimenta, Fernando M.; Santos, Ana B.; Costa, Marcos H.; Ladle, Richard J., 2016. Patterns of land use, extensification and intensification of Brazilian agriculture. ***Global Change Biology***, v. 22, n. 8, p. 2887-2903.

1.1.Introduction

A growing world population combined with increasing per capita income and consumption (especially of animal proteins) has stimulated discussions about how to produce enough food to meet the global demand (Godfray et al., 2010). To guarantee global food security, current production would need to be approximately doubled over the next 35 years (Tilman et al., 2011). This enormous challenge has led to a renewed focus on agricultural production in regions that have the capacity to meet this vastly increased demand.

Brazil is one of these countries with high capacity to increase agricultural production, having a generally favorable climate and vast areas that are suitable for agriculture. Indeed, Brazil is already one of the ten major exporters of agricultural products in the world (FAO, 2017) and it is expected to continue to increase production and export. Recently, the Brazilian Ministry of Agriculture (*Ministério da Agricultura, Pecuária e Abastecimento* or MAPA) estimated that Brazilian grain production will increase by 29.4% and beef production by 23.3% between 2015 and 2025 (MAPA, 2015). In the same period, soybean and maize exports (in grain) are predicted to increase by, respectively, 51.2% and 42.1%, and beef exports by 37.4% (MAPA, 2015).

In Brazil, agriculture activities have been the main driver of deforestation (Gibbs et al., 2010), a major source of greenhouse gas emissions (Leite et al., 2012; Calvin et al., 2015; Chaplin-Kramer et al., 2015), biodiversity loss (Chaplin-Kramer et al., 2015), and alteration of the water and soil characteristics (Scheffler et al., 2011; Hunke et al., 2015). Nevertheless, Brazilian grain production has roughly doubled since 2005 despite reductions in deforestation rates during the same period. Moreover, in the last five years, farmers have had financial incentives to adopt more sustainable agricultural practices through the National Program for Low Carbon Agriculture (Brasil, 2012). Such an increase in production coupled with enhanced environmental protection cautiously supports the view that Brazil has the potential for large-scale sustainable development of its agriculture to meet global food security goals.

Increasing yield without increasing the area under agriculture or causing significant environmental degradation is known as sustainable intensification, and has been proposed as one of the strategies to provide global food security (Balmford et al., 2005; Rudel et al., 2009; Strassburg et al., 2014). Achieving sustainable intensification in Brazil within a relatively short time period will be an enormous political, technological, and social challenge. As a starting point for policy development, it is essential that decision-makers have accurate information on the spatial and temporal patterns of agricultural land use and yield in the Brazilian territory. Using this information, it should be possible to identify areas and land-uses (e.g. crops, livestock) with the greatest capacity for sustainable increases in yield.

Many studies have mapped recent agricultural areas, investigating the dynamics of the conversion between natural vegetation, pasturelands, and croplands (especially soybean) in Brazil. However, many of these studies had limited spatial coverage, such as a single state (Morton et al., 2006; Rudorff et al., 2010; Macedo et al., 2012; Arvor et al., 2013), a biome (Barona et al., 2010; Sano et al., 2010; Beuchle et al., 2015; Ferreira et al., 2015) or were restricted to a limited period of time (Morton et al., 2006; Monfreda et al., 2008; Barona et al., 2010; Macedo et al., 2012; Arvor et al., 2013; Beuchle et al., 2015; Graesser et al., 2015). Given the large size of Brazil, its enormous vegetation diversity and agriculture heterogeneity, the development of national agricultural and conservation policies requires an accurate reconstruction of historical land use maps for the entire country. It is only through the lens of history that the current geographic trends in land use can be fully understood and accurate future projections made.

The first historical-spatial description of Brazilian agriculture land use for the entire country was provided by Leite *et al.* (2012), who reconstructed the agricultural areas in Brazil from 1940 to 1995, at a spatial resolution of 5’ (approximately 9 km x 9 km). However, this database was restricted to mapping general croplands and pastures (natural or planted). Crop-specific maps are required for the continued development of sustainable agriculture policy, and these remain unavailable for Brazil. Moreover, to become policy-relevant this database needs to be updated to include more recent time periods.

In addition to precise land use data, sustainable agriculture policy requires accurate information about agricultural extensification and intensification. Agricultural extensification is the increase of agriculture output through expansion of agriculture area. In contrast, intensification is the increase in productivity on existing agricultural lands – often through the use of improved cultivars, irrigation, fertilizer, biocides and mechanization – and without land conversion (Foley et al., 2011). Some scientists have argued that intensification is essential to spare natural areas (Balmford et al., 2005; Rudel et al., 2009; Strassburg et al., 2014). However, others suggest that increasing yields makes agriculture more profitable and therefore creates further financial incentives to increase the rate of conversion of natural habitat at agricultural frontiers (Ramankutty e Rhemtulla, 2012; Barretto et al., 2013; Lapola et al., 2014).

Here, the historical patterns of agricultural land use and productivity in Brazil are investigated. This analysis begin with a description of land use patterns in Brazil based on a new explicitly spatialized database of agriculture areas. This new database updated the work of Leite et al. (2012) to include more recent time periods using a higher spatial resolution and includes crop-specific area and productivity maps.

The historical distributions of cropland and pastureland were reconstructed by combining agricultural census data and remote sensing data for the whole of Brazil from 1940 to 2012 at 30" spatial resolution (approximately 1 km x 1 km). Pastureland maps are divided in planted and natural pasture from 1940 to 2012, and cropland maps are divided in the three main crops cultivated in Brazil (sugarcane, soybean, and maize) from 1990 to 2012. Together, these land uses comprise about 90% of all agricultural land use in the country (including double crops). Finally, yearly maps of soybean, maize, and sugarcane yield and yearly cattle stocking rate were provide from 1990 to 2012. The main objectives of this study are to: i) characterize agricultural land use change in Brazil and the productivity of four agricultural products (soybean, maize, sugarcane, and cattle); ii) describe the patterns of yield of soybean, maize, and sugarcane, and the stocking rate of cattle for the entire country and; iii) explore the productivity-agriculture area relationship for the three crops and cattle to better understand the dynamics of extensification-intensification, especially in the Amazon and Cerrado agricultural frontiers.

1.2. Materials and methods

1.2.1. Region of study

Brazil has 27 federal units (26 states and 1 Federal District) divided into 5 regions (Fig. 1.1). With 850 million ha of area, Brazil contains six biomes: Amazonia, Atlantic Forest, Caatinga, Cerrado (Brazilian savanna), Pampas (grasslands), and Pantanal

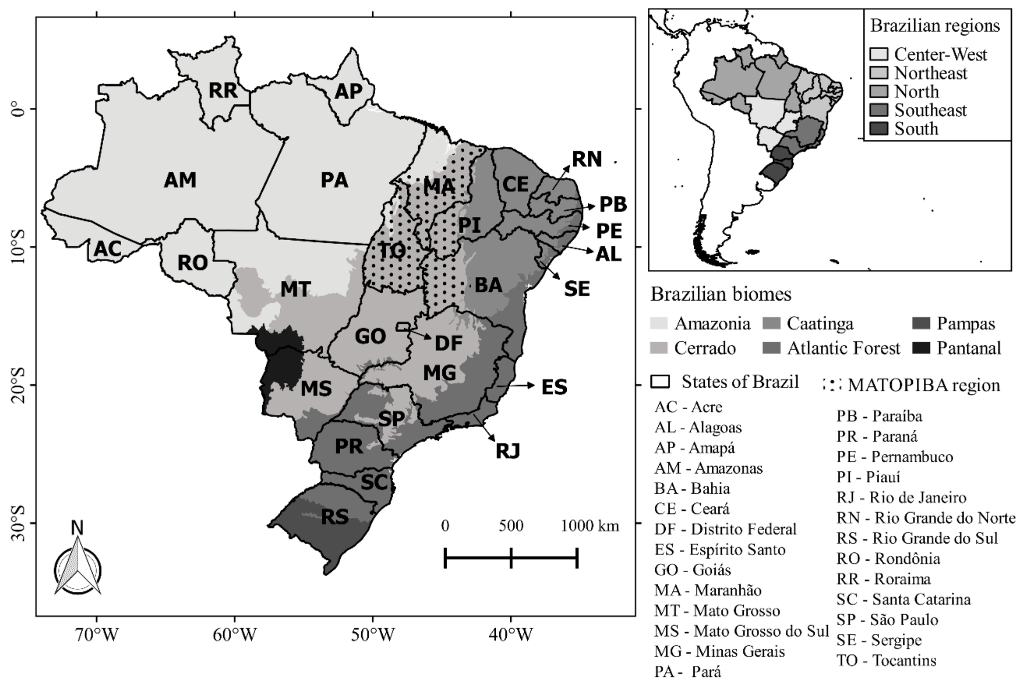

Fig.1.1: Location of the study area, with identification of the Brazilian states, regions, and biomes and the location of MATOPIBA (new agricultural frontier located in the states of Maranhão, Tocantins, Piauí, and Bahia).

(Fig. 1.1).

The most recent agricultural frontier in the country is located in the MATOPIBA region (Figure 1.1). MATOPIBA is an acronym created from the first two letters of the states of Maranhão, Tocantins, Piauí, and Bahia – although the frontier region comprises only part of Cerrado biome in these states, with an area of 7.4 million ha (Miranda et al., 2014). This new Cerrado agricultural frontier is characterized by rapid changes in land cover and land use for cropland, especially soybean, and agricultural intensification through the adoption of new technologies. However, to date there is no detailed information available on land use, productivity and the extensification-intensification relationship in this region.

1.2.2. Land use data sources

This study use a similar approach to that used in previous global (Monfreda et al., 2008; Ramankutty et al., 2008) and Brazilian (Leite et al., 2011, 2012) agricultural land use reconstructions. Specifically, this reconstruction is based on a combination of remote sensing data – to provide the land use localization – and census or inventory data – to identify type and amount of the agricultural land use.

The 30 m global forest cover change maps developed by Hansen *et al.* (2013) were used to provide the land use localization. These maps include global tree cover extent for the year 2000, with forest loss allocated annually from 2001 to 2012. Trees are defined as vegetation taller than 5 m and the tree cover is expressed as a percentage per pixel. Originally, these tree cover maps had approximately 30 m x 30 m spatial resolution, but the resolution was changed to 30” (approximately 1 km x 1 km) by summing the pixels in grid for the analysis. Starting with the inverse of tree cover in each pixel for the year 2000, which represents the non-forest areas, this 2000 non-forest map is combined with the forest loss map for each year to provide non-forest maps for 2000 to 2012.

The non-forest maps are converted into agricultural land use maps using agricultural census data provided by the Brazilian Institute of Geography and Statistics (IBGE - *Instituto Brasileiro de Geografia e Estatística*) and compiled by the Institute of Applied Economic Research (IPEA - *Instituto de Pesquisa Econômica Aplicada*). Brazilian census data were performed in 1940, 1950, 1960, 1970, 1975, 1980, 1985, 1995, and 2006 at the municipality level. In these surveys, land uses are classified in three categories: cultivated areas (the sum of permanent and temporary crops), natural pasture, and planted pasture. Permanent crops are defined as cultures that last for several seasons, while temporary crops need to be replanted after each harvest. Banana, orange, grape, and coffee are examples of permanent crops, while rice, maize, soybean, and sugarcane are examples of temporary crops. Natural pasture refers to non-planted areas where original vegetation is grass. Planted pasture is characterized by planted grass species for animal grazing, usually established after tilling, liming, and fertilizing the soil. Total agricultural land use is the sum of cultivated areas, natural pasture, and planted pasture.

It should be noted that there are differences in the definition of total agricultural land use area and cultivated area in Brazilian census data. Agricultural land use area is the area modified for agricultural purposes (livestock, cultivation or fallow areas). Cultivated areas correspond to the area planted with a specific crop in a given year. In the land use area category, double-cropped areas are counted only once, while the sum of the cultivated area of each crop planted in a municipality in a year could be greater than the land use area if the farmers of the municipality adopt double cropping.

To construct the specific area and yield crop maps, cultivated area and production of soybean, sugarcane, and maize, yearly data were obtained from the Municipal Agricultural Survey in the IBGE database at the municipality level from 1990 to 2012. From this same database, the number of cattle in each municipality is obtained, from 1990 to 2012, to construct cattle stocking rate maps.

1.2.3. Total agricultural land use data processing at the polygon scale

Although all census data were collected at the municipality level, the minimum comparable area (MCA) as unit for the historical reconstruction is used. An MCA consists of the smallest set of municipalities with a stable boundary over time. Brazil had 1,577 municipalities in 1940 and 5,572 municipalities in 2013, and new municipalities are created almost every year in the country, normally by the division of one unit into two new ones. One set of MCAs is defined for each of the following time periods: 1940-1995, 1950-1995, and 2000-2012. Firstly, 1,502 MCA polygons were defined for the period 1940-1995. However, municipalities were large in 1940 and each MCA aggregates data from several contemporary municipalities. Thus, to avoid inaccuracies due to these large MCAs, 1,823 MCA polygons were defined for the period 1950-1995. The 1940-1995 MCAs is used to create only the 1940 maps, and the 1950-1995 MCAs to create all maps in the period 1950-1995. For more recent years (2000-2012), MCA polygons were the same as the micro regions, which are the small units that aggregate municipalities with similar economic and social characteristics.

In some MCAs, the total agricultural land use from census data was greater than the MCA area. To correct for this inconsistency, the amount of total agricultural land use area that needed to be removed to match the MCA area (in percentage) was calculated and this proportion is applied to the adjusted total agricultural land use, cropland, natural pasture, and planted pasture data. In 1940, the total agricultural land use from census data was greater than the MCA area in 6 MCAs in a universe of 1,502 MCAs. Between 1950 and 1995, the number of MCAs that lost agricultural area varied from 9 to 23 in a universe of 1,823 MCAs.

Between 2000 and 2012, yearly total agricultural land use data is estimate for each municipality in two steps. Firstly, the annual increase or decrease rate between two census data is calculated for each MCA census data (Equation 1.1):

$$\Delta U_{MCA} = \frac{\left(U_{MCA}^{2006} - U_{MCA}^{1995}\right)}{U_{MCA}^{1995}} \tag{1.1}$$

where ΔU_{MCA} is the variation of the amount of total agricultural land use in each MCA, U_{MCA}^{2006} is the amount of total agricultural land use in a micro region from 2006 census data (km^2), and U_{MCA}^{1995} is the amount of total agricultural land use in a micro region from 1995 census data (km^2).

Second, this methodology consider that all municipalities in an MCA converted land use at the same annual rate as the MCA (Equation 1.2):

$$U_k^t = U_{k \in MCA}^{1995} \cdot \left[1 + (t - 1995) \cdot \frac{\Delta U_{MCA}}{(2006 - 1995)}\right] \tag{1.2}$$

where U_k^t is the estimated total agricultural land use in a municipality *k* in the year *t* (km^2) for $2000 \leq t \leq 2012$ and $U_{k \in MCA}^{1995}$ is the amount of total agricultural land use from 1995 census data in a municipality *k* (km^2). In the end of this process, these estimated data are filtered to avoid estimated land use areas greater than the polygon area. The mean area lost with this filter is 0.14% of the estimated total agricultural land use area in Brazil between 2000 and 2012.

The same process used to obtain total agricultural land use data was used to obtain the amount of cropland and natural pastureland for each municipality for 2000 to 2012. Planted pastureland for each municipality is calculated as the difference between total agricultural land use, cropland, and natural pasture data.

The planted area data for soybean, maize, and sugarcane from 1990 to 2012 are filtered to avoid individual crop areas greater than the total cropland area at each polygon. The mean individual crop area lost in this process is 0.03%, 0.02% and 0.01%, respectively, for the inventory data for soybean, maize, and sugarcane planted area in Brazil between 1990 and 2012.

1.2.4. Land use data disaggregation to 30" resolution

To convert gridded non-forest maps ($NONF_{i,j \in k}^{t}$, in km^2) into total gridded agricultural land use maps, the fraction of total agricultural land use is calculated in municipality k in year t ($2000 \leq t \leq 2012$) by dividing the estimated total agricultural land use area (U_k^t, in km^2) by the total non-forest area in the municipality ($\sum_{i,j \in k} NONF_{i,j}^{t}$, in km^2; Equation 1.3, Fig. 1.2a). Then, this fraction is multiplied by the non-forest map ($NONF_{i,j \in k}^{t}$). Finally, the result of this calculation is divided by the pixel area ($A_{i,j}$) to express the final total agricultural land use maps as a percentage of area per pixel ($ALU_{i,j}^{t}$, in %):

$$ALU_{i,j}^{t} = 100 \cdot \frac{\left(NONF_{i,j \in k}^{t} \cdot \frac{U_k^t}{\sum_{i,j \in k} NONF_{i,j}^{t}} \right)}{A_{i,j}} \quad (1.3)$$

where *i* and *j* are, respectively, the coordinates of rows and columns of the pixels in the map. The resulting maps can have agricultural land use area in a pixel greater than 100% of the pixel area, especially if the remote sensing non-forest area is lower than the census agricultural area at the municipality level.

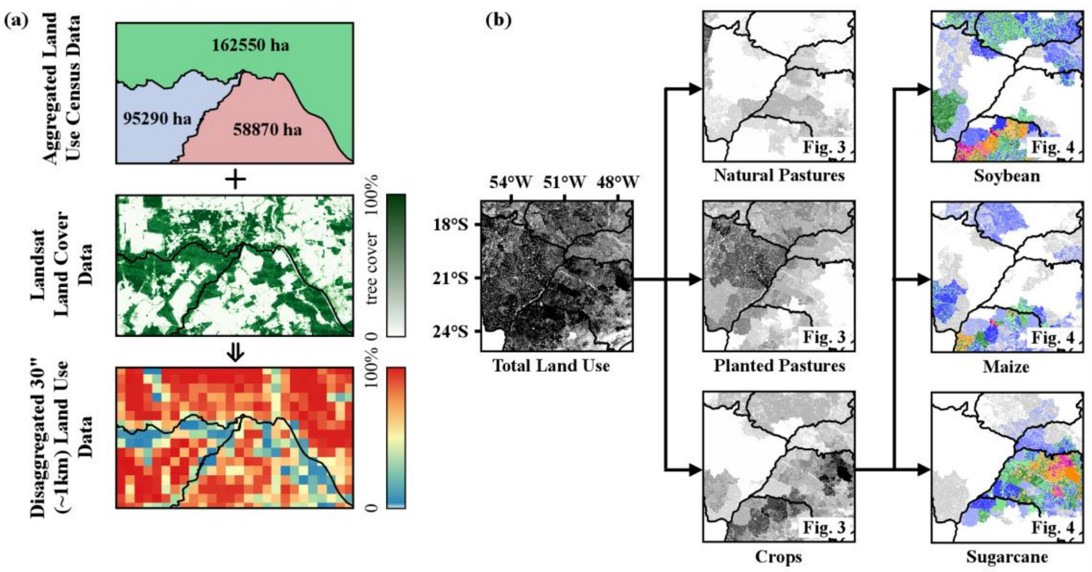

Fig. 1.2: Disaggregation and split process. To create the disaggregated 30" (~1km^2) land use data, we merge land use census data aggregated by municipality with Landsat derived land cover map (Hansen et al., 2013). Total land use maps are split into maps of croplands, natural pasturelands, and planted pasturelands. After that, croplands maps are split into maps of soybean, maize, and sugarcane planted area.

During the period of reconstruction only about 4% of the pixels have this problem. This data is corrected through an iterative procedure, using Equation 1.4, to adjust the pixel values only for MCAs with at least one pixel with land use area greater than 100% of the pixel area:

$$LU_{i,j}^{t} = 100 \cdot \frac{\left[1-\exp\left(-0.01 \cdot F \cdot ALU_{i,j}^{t}\right)\right]}{\left[1-\exp\left(-0.01 \cdot F \cdot P_{MCA\,max}^{t}\right)\right]} \qquad (1.4)$$

where $LU_{i,j}^{t}$ is the final corrected map in a year *t* (%); *F* is a factor of distribution for each micro region; and $P^t_{MCA\,max}$ *is* the maximum land use pixel value in a MCA in the $ALU^t_{i,j}$ map (in %). The intent of this equation is to compress the range of $ALU^t_{i,j}$ (from 0 to $P^t_{MCA\,max}$) into the range 0 to 100% of the pixel area through the distribution of the exceeding agricultural areas to the other pixels of the MCA. Equation 1.4 acts at the pixel level where F for each polygon is chosen in an iterative process. For a MCA with at least one pixel with agricultural land use proportion greater than 100% of the pixel area, the maximum land use pixel value in the MCA is identified. Then, the iteration is started with a very low F value ($F=10^{-9}$). The equation calculates the new proportion of agricultural land use area used in each MCA pixel. The new agricultural land use area allocated at the MCA is then calculated, and the resulting agricultural land use area is compared with the estimated agricultural land use polygon area. In each iteration, F is incremented and the equation is reapplied using the new F value. The procedure is iterated until the absolute error of the resulting agricultural land use polygon area is lower than 0.001% of the estimated land use polygon area. With this transformation, the pixels initially without deforestation remain with zero agricultural land use value and the other pixels received additional agricultural area.

For the census years of 1940 to 1995, the agricultural land use maps are obtained in a process similar to that expressed in Equation 1.3. Since remote sensing data from Hansen et al. (2013) database are not available before the year 2000, the 2000 non-forest map is used as a base for the geographical distribution of agriculture between 1940 and 1995. The fraction of total agricultural land use at the municipality k in a year t (for t = {1940, 1950, 1960, 1970, 1975, 1980, 1985, 1995}) is calculated by dividing the total agricultural land use from the census data in the year t by the total non-forest land area in the municipality in the year 2000. Then, the municipality grid cells are multiplied from the non-forest map in the year 2000 by this fraction of total agricultural land use at the municipality *k* in the year *t*. The final total agricultural land use maps are expressed as a percentage of area per pixel.

The total agricultural land use maps – for census years between 1940 and 1995 and yearly from 2000 to 2012 – are further divided into maps of cropland and pasturelands (natural and planted pasture; Fig. 1.2b) using the following procedure: (1) the proportion of cropland/pasturelands use in a municipality *k* in a year *t* is calculated by dividing the cropland/pasturelands area by the total agricultural land use area in this municipality *k* in the year *t*; (2) the total agricultural land use map in the year *t* is multiplied by the proportion of cropland/pasturelands use of that grid cell.

To complete the time series, a linear interpolation is carried out between the census years and between 1995 and 2000 for the total agricultural land use, croplands, and pasturelands maps. Finally, this same method – using the proportion of the crop specific use in a municipality *k* in the year *t* multiplied by the total cropland use of that grid cell in the year *t* – is used to split total cropland maps into soybeans, maize, and sugarcane planted area maps from 1990 to 2012.

1.2.5. Soybean, maize, sugarcane, and livestock productivity maps

The maps of agricultural productivity are constructed for 1990 to 2012. The soybean, maize, and sugarcane yield is calculated by dividing the production of the MCA by the total crop area extracted from the crop specific maps for the MCA. Finally, the productivity data for all MCA pixels is allocated. For the cattle stocking rate maps, the amount of cattle heads in the MCA is divided by the total pasture area in the MCA. The stocking rate of cattle data is eliminated from the map if the MCA has pasture area less than 100 ha. In general, one to seven MCAs had less than 100 ha between 1990 and 2012 and the mean lost area was approximately 50 ha per MCA.

Stocking rate of cattle greater than 8 head/ha occurred in a maximum of six MCAs. Stocking rate of cattle equal or greater than 8 head/ha is considered to be a high value that may be the result of overestimation of cattle herd size or underestimation of the pastureland in these MCAs. For that reason, stocking rates greater than 8 head/ha were adjusted to 8 head/ha – this maximum rate accounted for less than 0.1% of the total amount of cattle head in Brazil from 1990 to 2012.

1.2.6. Regional productivity-agriculture area relationship

To better understand the extensification-intensification relationship, four graphical summaries of data are generated, each one contrasting the area and productivity of soybean, maize, sugarcane or cattle. These figures include the productivity-agriculture area relationship for the consolidated agricultural regions and for the emergent regions of each commodity during the study period. In addition, the production isolines, expressed in millions of tons (or heads), are indicated and identify the top 5% most productive areas in the regions selected. The top 5% with the agricultural productivity maps are calculated to obtain the soybean, maize, and sugarcane yield and the stocking rate of cattle for each municipality in the year 2010 only. The top 5% most productive areas are identified by the simple process of organizing the land use area (in pixels) in increasing order and identifying the productivity value of the 95% percentile for each region studied.

1.2.7. Comparison with other land use databases

There are no other products with the temporal range and spatial scale that could fully validate this land use database. Validation was therefore achieved through comparison between three existing land use databases for the Amazon and Cerrado biomes for the most recent years.

The patterns of the total cropland and total pastures maps for 2012 were compared with the map produced by the TerraClass 2012 project (INPE, 2014) and the TerraClass Cerrado 2013 project (INPE, 2015). The TerraClass project aims to map land use and land cover changes in the Brazilian Amazon based in the land cover change maps from the PRODES project (Program for the Annual Estimation of Deforestation in the Brazilian Amazon) and remote sensing data from Landsat. This project has already produced freely available land cover maps for the years 2008, 2010, and 2012 at 30 m spatial resolution. The 16 classes of the TerraClass 2012 map were grouped in 4 categories: natural vegetation (primary and secondary forest and reforestation), cropland (annual cropland and land use mosaic), pastureland (livestock production in grass species predominance areas, livestock production in grass associated with shrubs areas, regeneration with pasture, pasture mixed with bare soil, and deforestation), and other uses (urban area, mining, not forest, water, not observed area, and other uses).

TerraClass was extended for the Cerrado biome (TerraClass Cerrado) that has one freely available land cover map for the year 2013. For adequate comparison, the 13 classes of the TerraClass Cerrado map were grouped in 4 categories: natural vegetation (natural forest and naturally not vegetated), cropland (annual crop, permanent crop, and land use mosaic), pastureland, and other uses (urban area, mining, planted forest, bare soil, water, not observed, and other uses). Finally, the Amazon and Cerrado maps, which originally have vector format, were converted to a 30” grid to be compared against this database.

In addition to TerraClass, Rudorff *et al.* (2015) describe the expansion of the first harvest soybean, maize, and cotton planted area and the land use change associated with this expansion in the Cerrado. The authors conducted a land use and land cover classification using Landsat and MODIS images for the 2000/2001, 2006/2007, and 2013/2014 crop calendar years. As the IBGE planted area data include first and second harvest and maize frequently is used as second crop, only soybean planted area can be directly compared between Rudorff *et al.* (2015) and this study database for 2001 and 2007.

1.3. Results

In the following sections, the reconstructed historical land use data and the historical productivity for soybean, maize, sugarcane, and cattle is described. Significant land use is defined as grid cells with at least 10% agricultural land use.

1.3.1. Patterns of the agricultural land use in Brazil

In 1940, total agricultural land use was 106 million ha (Fig. 1.3a) concentrated in South, Southeast and Center-West regions, especially in Rio Grande do Sul, São Paulo, Minas Gerais, Mato Grosso do Sul, and Goiás. Large areas of agricultural land use were established throughout the country until 1985, when Brazil achieved its greatest agricultural land use area (231 million ha, Fig. 1.3a). Although agriculture keeps expanding towards Center-West and North regions, total agricultural land use in Brazil started to decrease after 1985 due to abandonment or conversions to other non-agricultural land uses in the eastern region. Between 2000 and 2010, total agricultural area grew again (to 220 million ha), although not reaching 1985 levels. In this period, agriculture in Northeast region resumed its growth, especially in the states of Maranhão and Piauí.

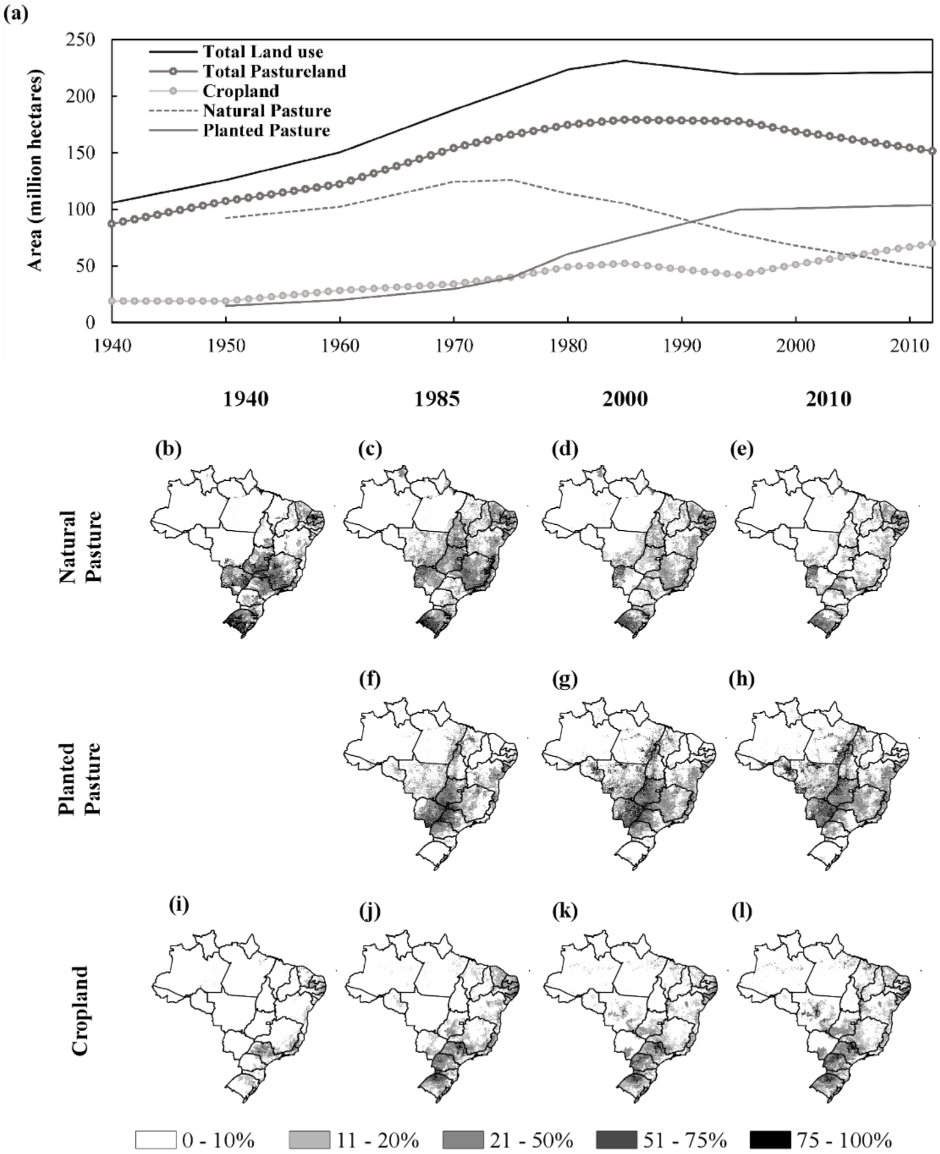

Fig. 1.3: Agricultural land use in Brazil. (a) Land use area from census data in million ha from 1940 to 2012, natural pastureland in Brazil from (b) 1940, (c) 1985, (d) 2000, and (e) 2010 in percent of the pixel area, planted pastureland in Brazil from (f) 1985, (g) 2000, and (h) 2010 in percent of the pixel area, total cropland in Brazil from (i) 1940, (j) 1985, (k) 2000, and (l) 2010 in percent of the pixel area. For the 1940s, natural and planted pastureland data are not individually available in the census data. We show the total pastureland (natural + planted) in Fig. 1.3b, with the remark that pasturelands were mostly natural at that time.

Pasturelands always contributed most to total agricultural land use, but the proportions of natural and planted pastureland dramatically change over time (Figs 1.3b-e and 1.3f-h). For 1940, natural and planted pastureland data are not individually available in the census data, therefore, the total pastureland (planted + natural) is showed in Fig. 1.3b, with the remark that pasturelands were mostly natural at that time.

Natural pasture area expanded until 1975 (Figs 1.3a and 1.3b-e), after which areas with natural pasture were replaced by more profitable planted pasture areas. Natural pastures still are predominant in the Pampas (located in southern Rio Grande do Sul) and Pantanal (located in western Mato Grosso do Sul). Planted pasture expanded during the study period (Figs 1.3a and 1.3f-h), especially in the Cerrado biome. Brazil reached peak total pasture area in 1985 (179 million ha, Fig. 1.3a), after which pastureland areas reduced due to abandonment or shifts to croplands. Between 1985 and 2010, planted pasturelands expanded in eastern Pará, Rondônia, and Acre, following the main rivers and roads in the North region.

Cropland areas experienced a gradual expansion between 1940 and 2010 (Figs 1.3a and 1.3i-l). In 1940, croplands were concentrated in northern Rio Grande do Sul, São Paulo, coastline of the Northeast region, and some parts of Minas Gerais, Rio de Janeiro, and Espírito Santo. By 1985, croplands had expanded around the previously consolidated regions and in the states of Paraná, Santa Catarina, southern Mato Grosso do Sul, and Goiás. After 1985, crops quickly increased in the interior of Brazil, extending into Mato Grosso, Goiás, eastern Bahia, some parts of Pará and Amazonas. Large areas of cropland were abandoned in the Northeast region in 1980s and 1990s probably due to the persistent drought in this region, returning between 2000 and 2010.

Although Brazilian farmers plant a diverse mixture of crops, only soybean, maize, and sugarcane are analyzed in this study (Figs 1.4a-h). These three crops account for 72% of crop area (including double cropping) and about 90% of the production of temporary crops in Brazil. Since 1990, large areas of soybean are found in South region and, in low concentration, in some parts of São Paulo, Minas Gerais,

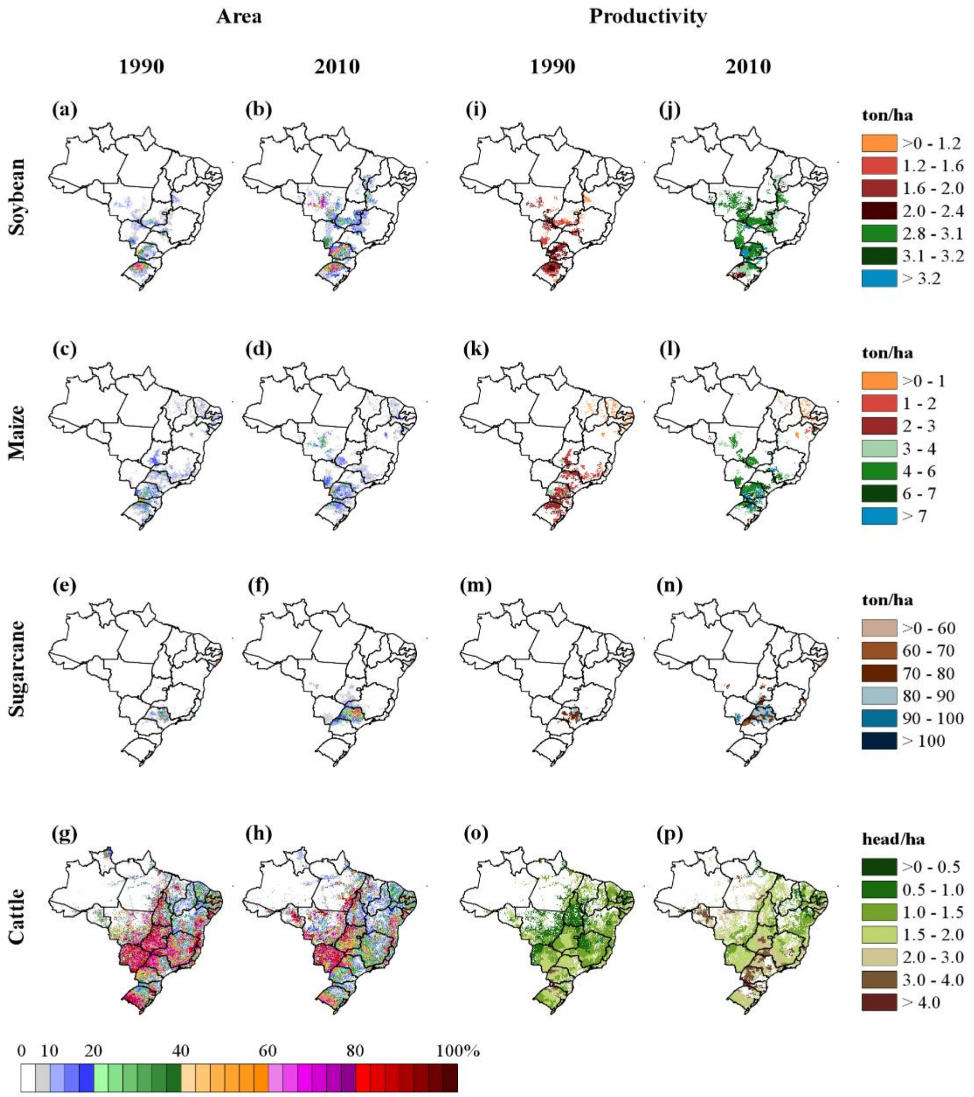

Fig. 1.4: Planted area of (a) soybean in 1990, (b) soybean in 2010, (c) maize in 1990, (d) maize in 2010, (e) sugarcane in 1990, and (f) sugarcane in 2010 in percent of the pixel area. Total pastureland area in (g) 1990 and (h) 2010 in percent of the pixel area. Yield of (i) soybean in 1990, (j) soybean in 2010, (k) maize in 1990, (l) maize in 2010, (m) sugarcane in 1990, and (n) sugarcane in 2010. Stocking rate of cattle in Brazil in (o) 1990 and (p) 2010 in head per hectare. Data are not showed in this map if the micro region had pasture area less than 100 ha and stocking rate was limited in 8 head/ha.

Mato Grosso do Sul, Mato Grosso, Goiás, and western Bahia (Fig. 1.4a). After 1990, soybean extended northward, further moving into the Cerrado and new soybean crop areas began to appear in Mato Grosso and MATOPIBA (Fig. 1.4b).

Maize is an omnipresent product in Brazilian culture and small amounts are found in almost all municipalities of Brazil, since this crop frequently is associated with subsistence agriculture. In 1990, the highest concentration of maize crops, probably for commercial purpose, lies in northern Rio Grande do Sul, Santa Catarina, Paraná, and northern São Paulo (Fig. 1.4c). Between 1990 and 2010, maize reduced in São Paulo and Minas Gerais, but new areas appeared in Mato Grosso do Sul, Mato Grosso, and in central Bahia (Figs 1.4c, d). More recently, regions with the highest concentration of soybean also have the highest concentration of maize, such as regions in center of Mato Grosso, southern Mato Grosso do Sul, southern Goiás, Paraná, and northern of Rio Grande do Sul. This indicates that maize is being grown as a second crop in these regions (Arvor et al., 2013, 2014).

By 1990, significant areas of sugarcane were found in São Paulo (Fig. 1.4e), with high concentrations in northern Rio de Janeiro and in northeast coastline (Sergipe, Alagoas, Pernambuco, Paraíba, and Rio Grande do Norte). Between 1990 and 2010, new areas mainly appeared on the periphery of previously observed sugarcane growing centers in São Paulo and Paraná (Figs 1.4g,h). In this period, low concentration of sugarcane crop areas appeared in Goiás, Mato Grosso do Sul, and Mato Grosso. Non-significant sugarcane areas can also be found in several states, probably because sugarcane is also used as livestock feed for smallholders.

The total pastureland was used in the cattle density analysis. Between 1990 and 2010, total pastureland extensification occurred in North and Center-West regions, while reductions were observed in the South, Southeast, and Northeast regions (Figs 1.4g, h).

1.3.2. Patterns of the crop productivity and cattle density

Soybean yield increased throughout the country between 1990 and 2010 with mean yield increasing from 1.7 to 2.9 ton/ha (Figs 1.4i,j). In 1990, soybean productivities at significant areas ranged from 0.57 to 2.4 ton/ha and the highest yields were found in the South and Center-West regions (Fig. 1.4i). In 2010, mean soybean yield was 2.39 ton/ha with a higher productivity of 3.4 ton/ha and a lower productivity of 1.8 ton/ha. In this year, the highest soybean yields were found especially in Paraná state (Fig. 1.4j).

Between 1990 and 2010, mean maize yield increased 2.5 ton/ha, from 1.8 to 4.3 ton/ha (Figs 1.4k,l). Mean maize yield at significant areas in 1990 was 2.2 ton/ha (ranged from 0.01 to 4.3 ton/ha) with some regions in Paraná and Goiás characterized by very high productivity (Fig. 1.4k). In 2010, maize yields ranged from 0.04 to 9.5 ton/ha. In this year, the highest maize productivities were located in South region (Fig. 1.4l) with western Bahia characterized by yields greater than 8 ton/ha.

Mean sugarcane yield increased from 60.8 to 78.3 ton/ha between 1990 and 2010 (Figs 1.4m,n). Sugarcane productivity varied substantially between São Paulo and the Northeast region. In São Paulo, mean yield increased from 76 ton/ha in 1990 to 84 ton/ha in 2010, with some regions reaching 110 ton/ha in this period. Sugarcane yield at significant areas in São Paulo ranged from 62.4 to 93.8 ton/ha in 1990 and from 70.9 to 110.8 ton/ha in 2010. In the Northeast region – especially the states of Sergipe, Alagoas, Pernambuco, Paraíba, and Rio Grande do Norte – mean productivity increased from 48 to 55 ton/ha between 1990 and 2010. Sugarcane yield in significant areas in the Northeast region ranged from 30.9 to 76.7 ton/ha in 1990 and from 32.4 to 69.1 ton/ha in 2010. A new sugarcane region in Mato Grosso do Sul had very high yield (99 ton/ha) in 2010.

Cattle stocking rate increased slowly in Brazil between 1990 and 2010 (Figs 1.4o,p). The mean cattle stocking rate was 0.82 head/ha in 1990 and 1.36 head/ha in 2010. During the study period, cattle density increased unevenly with many low productivity regions (< 1 head/ha) and a few regions with high productivity (> 4 head/ha). Between 1990 and 2010, the stocking rates of cattle were greater than 4 head/ha in Rio Grande do Sul, Paraná, Santa Catarina, and São Paulo states and in parts of the Northeast region coastline, especially in Maranhão. Stocking rate of cattle grew quickly during 2000s in Minas Gerais, Paraná, Santa Catarina, Maranhão, Goiás, Mato Grosso, Rondônia, Acre, and Pará.

1.3.3. Productivity-agriculture area relationship

The extensification-intensification relationship for soybean was analyzed in Amazonia and Cerrado biomes, South and Center-West regions, and MATOPIBA (Fig. 1.5). These regions represent nearly 83% of the soybean crop area in Brazil. The increase in Brazilian soybean production came from both increases in productivity and expansion of the crop area (Fig. 1.5a). Amazonia soybean production increased 25-fold between 1990 and 2012 (from 0.3 to 7.6 million of tons), while planted areas increased from 0.2 to 2.4 million ha and productivity grew up from 1.8 to 3.1 ton/ha. Between 1990 and 2010, the production of soybean in the Cerrado biome increased more than 5-fold (from 7.1 to 37.6 millions of tons) due to an increase in area (from 4.6 to 12.4 million ha) and a doubling in yield (from 1.5 to 3 ton/ha). MATOPIBA also showed a remarkable increase in production, area, and yield between 1990 and 2012, with soybean production increasing 28 times (from 0.26 to 7.4 millions of tons), planted area increasing from 0.4 to 2.5 million ha, and yield increasing from 0.64 to 2.9 ton/ha.

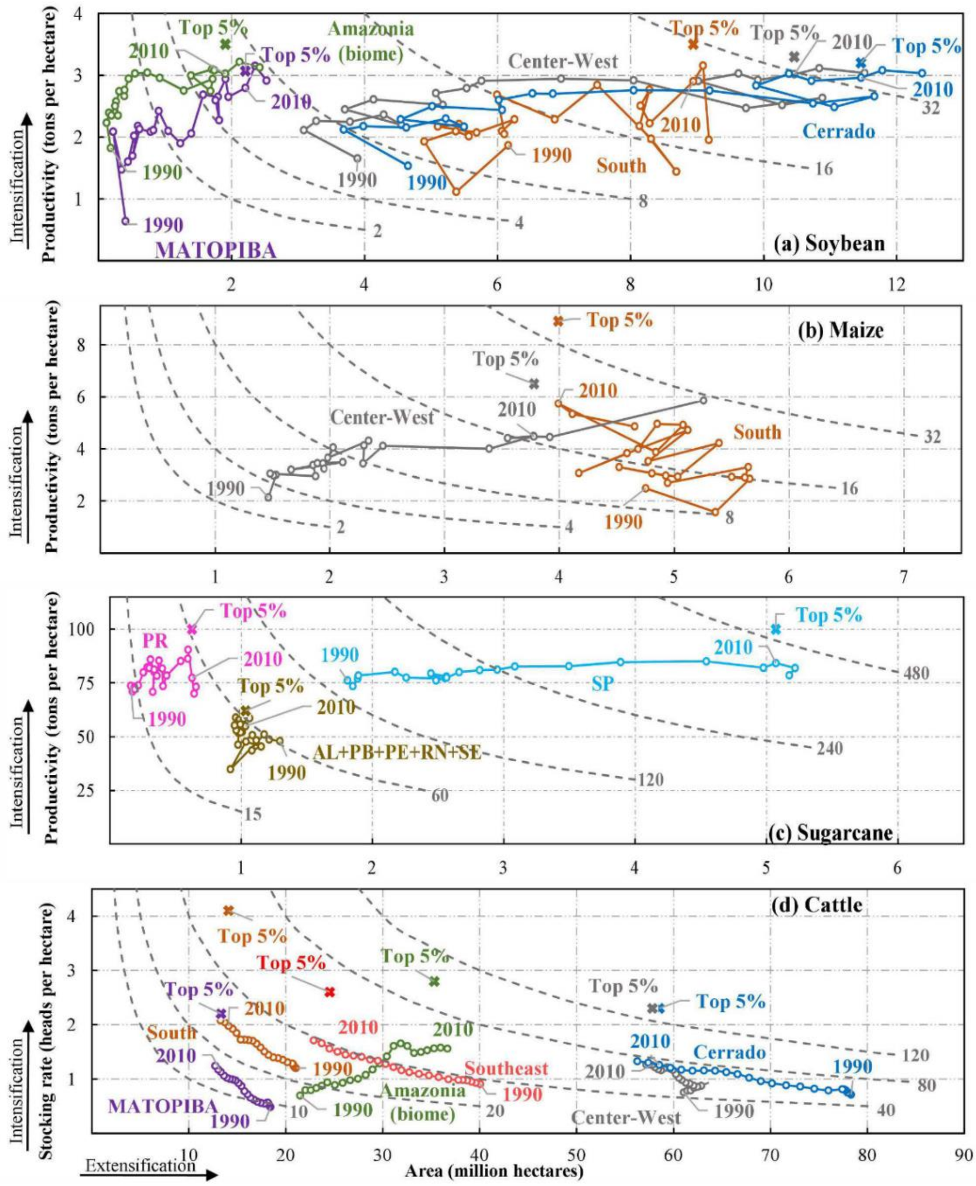

Fig. 1.5: Extensification-intensification analysis. Trends in (a) soybean planted area and yield for the Amazonia and Cerrado biomes, Center West and South regions and MATOPIBA, (b) maize planted area and yield for Center-West and South regions, (c) sugarcane planted area and yield for São Paulo and Paraná states and a region formed by the states of Alagoas, Paraíba, Pernambuco, Rio Grande do Norte, and Sergipe (AL+PB+PE+RN+SE), (d) pastureland areas and stocking rate of cattle for the Amazonia and Cerrado biomes, Center-West, South, and Southeast regions and MATOPIBA.

Soybean planted area increased in the South region by 30% (from 6.2 to 9.2 million ha) and production more than doubled (from 11.5 to 25.9 millions of tons) between 1990 and 2010. In this region, soybean production reached 28.7 millions of tons in 2011, but it decreased to 17.9 millions of tons in 2012, while the soybean planted area increased by approximately 0.9 million ha. The harvest from 2004/2005 and 2011/2012 in the South region had very low yield (about 1.4 ton/ha in 2005 and 1.9 ton/ha in 2012), probably due to climatic factors. The Center-West region had approximately 3.9 million ha of planted area in 1990 and produced 6.4 millions of tons of soybean. After 22 years, the area of soybean increased to 11.5 million ha and production increased to 35 million of tons. The Center-West curve is similar to Cerrado curve (Fig. 1.5a) due to the large overlap between the two regions.

Mean soybean yield was approximately 3 ton/ha in 2012 for all analyzed regions and, in general, the highest soybean yields (top 5%) were not dramatically higher than the average in 2010. The yield gap (difference between mean productivity and the top 5%) was lowest in Cerrado, where the mean soybean yield was only 7.5% lower than the top 5%, and was greatest in the South region, when the mean soybean yield was 17% lower than the top 5%. The mean soybean yield was 8.5%, 10% and 14% lower than the top 5%, respectively, in the Center-West region, MATOPIBA, and Amazonia biome.

Maize is produced mainly in the South and Center-West regions, accounting for nearly 66% of Brazilian maize production. In the Center-West region, maize crop area increased 3.6 times (from 1.5 to 5.3 million ha) while yield increased nearly 3-fold (from 2.1 to 5.9 ton/ha) between 1990 and 2012 (Fig. 1.5b). In this period, maize production rose from 3.1 to 30.7 millions of tons in Center-West region. Maize crop area in the South region started with 4.8 million ha in 1990, ranged between 3.9 and

5.7 million ha, and was 4.6 million ha in 2012 (Fig. 1.5b). In this region, maize yield increased from 2.5 to 4.8 ton/ha and production doubled (from 11 to 22 million of tons) between 1990 and 2012. The top 5% in South region (8.9 ton/ha) is greater than in Center-West region (6.5 ton/ha). In 2010, the mean yield was 31% lower than the top 5% in the Center-West region and was 36% lower than the top 5% in the South region.

Brazil has two main sugarcane production centers: in the Northeast region and in São Paulo/Paraná. In the context of sugarcane, the northeastern sugarcane region is formed by the states of Alagoas, Paraíba, Pernambuco, Rio Grande do Norte, and Sergipe. The two main sugarcane production centers represent nearly 70% of the sugarcane crop area in Brazil. Although mean sugarcane production in northeast Brazil ranged from 31.9 and 62.4 millions of tons, it was close to 60 millions of tons for many years between 1990 and 2010 (Fig. 1.5c). Moreover, sugarcane crop area in northeastern sugarcane region decreased by 23% (from 1.3 to 0.99 million ha) while the yield increased from 47.9 to 55.7 ton/ha, which indicates a trend of intensification. The top 5% (62 ton/ha) was very similar to the mean yield (55 ton/ha) in the northeast Brazil, suggesting that most producers were working at their maximum capacity.

In São Paulo and Paraná states, the sugarcane yield was greater than that observed in northeastern sugarcane region between 1990 and 2012. In this period, mean sugarcane yield was 79 ton/ha in the two more Southern states as compared to 51.8 ton/ha in the Northeastern states. São Paulo and Paraná experienced extensification in sugarcane planted area. São Paulo had 1.8 million ha of sugarcane area in 1990 and 5.2 million ha in 2012. In this state, sugarcane production also increased from 137.8 to 406.2 millions of tons in 22 years. Sugarcane planted area in Paraná increased by 0.5 million ha (from 0.16 to 0.66 million ha) in area and production by 36.2 millions of tons (from 11.7 to 47.9 millions of tons) between 1990 and 2012. The top 5% was 100 ton/ha in São Paulo and 95 ton/ha in Paraná state. The yield gap was greater in Paraná, where the mean sugarcane yield was 22.7% lower than the top 5%, while in São Paulo, the mean sugarcane yield was 15.9% lower than the top 5%.

Finally, the extensification-intensification relationship for cattle was studied in Amazonia and Cerrado biomes, Center-West, South, and Southeast regions and MATOPIBA (Fig. 1.5d). These regions represent nearly 95% of the pasturelands in Brazil. Both total pastureland areas and stocking rate of cattle increased in Amazonia (Fig. 1.5d). Between 1990 and 2012, cattle numbers increased 4-fold (from 14.9 to 57.2 million heads) in Amazonia biome due to an increase in pastureland area from 21.5 to 36.7 million ha and the increment of 2.5 times in stocking rate (from 0.69 to 1.56 head/ha). On the other hand, the Cerrado biome, Center-West, South, and Southeast regions and MATOPIBA show clear evidence of livestock intensification (Fig. 1.5d), with decreases in pasture areas associated to increases in stocking rates.

Pasturelands decreased in the Cerrado biome from 78.3 to 56.3 million ha while stocking rate of cattle grew from 0.7 to 1.3 head/ha, and total herd size increased from 55.8 to 74.6 million between 1990 and 2012. In the Center West region, pasturelands decreased from 61.0 to 57.2 million ha and herd size increased from 45.9 to 72.4 million, increasing the stocking rate from 0.8 to 1.3 head/ha between 1990 and 2012. The South region had the greatest stocking rate of cattle in 1990 (1.2 head/ha) and in 2012 (2.1 head/ha). During the period of study, cattle herd size in the South region was nearly constant at 27 million and pasturelands decreased from 21 to 13.3 million ha. In Southeast region, the cattle herd size remained close to 38 million during the study period, although pastureland contracted from 40 to 22.9 million ha and stock rates increased from 0.9 to 1.7 head/ha. MATOPIBA pasturelands decreased by 5.7 million ha in the 22 years analyzed (from 18.4 to 12.7 million ha) while production increased from 8.9 to 15.7 million heads and productivity gradually increased from 0.48 to 1.2 head/ha.

The yield gap was largest in the South region where the mean stocking rate of cattle in 2010 (1.97 head/ha) was 52% lower than the potential given current practices (the top 5% was 4.1 head/ha). In contrast, the lowest yield gap was found in the Southeast region, where the mean stocking rate (1.56 head/ha) was 40% lower than the top 5% (2.6 head/ha). In Amazonia, the mean stocking rate of cattle (1.56 head/ha) was 44% lower than the top 5% (2.8 head/ha). In the Cerrado biome and Center-West region, the mean stocking rate was 45% lower than the top 5% for cattle (2.3 head/ha in both areas). Finally, the mean stocking rate in MATOPIBA (1.13 head/ha) was 48% lower than the top 5% (2.2 head/ha) in 2010.

1.3.4. Intercomparison

In the TerraClass map, each pixel is classified as only one type of land use. Then, if it is indicated that there is pastureland in one pixel, 100% of the land use in this pixel is pastureland. On the other hand, the methodology used in this study produces maps with percentage of area with a land use. This methodological difference needs to be understood to compare the maps on Fig. 1.6.

The TerraClass project reports 44.2 million ha of pasturelands in Amazon in 2012 and 60 million ha in Cerrado in 2013. This study estimate that total pasture in the year 2012 was 36.7 million ha in Amazon (17% less) and 56 million ha in Cerrado (7% less). The patterns of pastureland identified in the TerraClass (Fig. 1.6a) and in the 2012 map produced in this study (Fig. 1.6b) agree in several regions. In both products, pasturelands are found near the highway that crosses Rondônia (BR-364), the

Trans-Amazonica highway (BR-230) that crosses the Pará state from east to west, and along the BR-163 that connects Cuiabá (Mato Grosso) to Santarém (western Pará). Pasturelands also are predominant in both products in eastern Acre, around the state's capital, and in Mato Grosso do Sul. In the Cerrado, the overall pattern is similar, although the pasturelands in this study maps are more widely distributed than in the TerraClass maps (Fig. 1.6). In MATOPIBA and Mato Grosso, for example, this study map indicates more pixels with a small percentage of pastureland while TerraClass has fewer pixels with 100% of use.

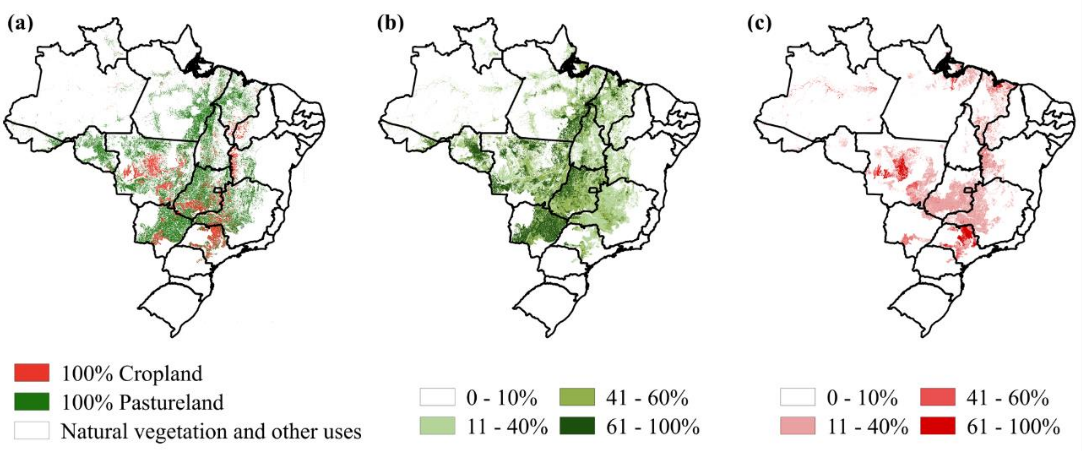

Fig. 1.6: Comparison between: (a) the TerraClass projects maps for Amazon in 2012 and Cerrado in 2013; (b) the 2012 total pastureland map and; (c) the 2012 total cropland map.

According to TerraClass project, croplands occupy 5.2 million ha in Amazonia and 24.6 million ha in Cerrado. This study estimate 8.2 million ha of cropland in Amazonia (58% more) and 24.3 million ha in Cerrado (1% less). In both TerraClass and this study products, croplands are found mainly in the center and southeastern Mato Grosso, southern Mato Grosso do Sul, southern Goiás, western Minas Gerais, northern São Paulo, southern Maranhão, southern Piauí and western Bahia (Fig. 1.6c). Croplands distribution are also more widespread in this study maps than in the TerraClass maps, especially in Goiás and Minas Gerais states.

The historical soybean planted area database produced in this study has an absolute error smaller than 10% when compared with Rudorff *et al.* (2015) report. Rudorff *et al.* (2015) found that Cerrado has 7.5 million ha of soybean planted area in 2001 and 10.1 million ha, in 2007. This study estimate 6.8 million ha of soybean planted area in the Cerrado in 2001 (9% less) and 9.8 million ha, in 2007 (3% less). In MATOPIBA, Rudorff *et al.* (2015) estimated 0.9 million ha of soybean planted area in 2001 while this study estimated 1 million ha of this crop (1% more). For the year 2007, Rudorff *et al.* (2015) estimated 1.7 million ha while this study report 1.8 million ha of soybean planted area (6% more) in the new agricultural frontier.

1.4. Discussion

This study aimed to characterize agricultural land use change and productivity in Brazil. The most general trends were probably the gradual replacement of natural pasturelands with planted pasture in several parts of the country since the 1970s and the rapid expansion of croplands since the 1980s in almost all states. In recent years, cropland and pastureland increased in Amazonia and Cerrado agricultural frontiers while agriculture areas in South, Southeast and Northeast regions decreased (mainly after 1985). Barretto *et al.* (2013) observed that agricultural contraction has mainly occurred near metropolitan areas in Southeast regions and in semi-arid region in the Northeast region.

Soybean cultivation has been considered a powerful threat to the environment in Brazil (Fearnside, 2001) and has been identified as one of the main drivers of increases in cropland areas in Latin America (Gibbs et al., 2010). Indeed, soybean areas have been quickly expanding (approximately 0.61 million ha/year between 1990 and 2012) and reached 25 million ha in 2012, 36% of the total cropland area in Brazil. Moreover, several regions with high concentration of soybean also have high concentrations of maize. These patterns may indicate double cropping practice. This hypothesis can be verified in Mato Grosso: areas that have high concentrations of soybean and maize in this study maps closely correspond to areas identified by Arvor *et al.* (2013) as “double cropping systems with two commercial crops”.

Sugarcane areas have recently increased in Brazil due to increase in the fleet of dual-fuel (ethanol-gasoline) cars (Rudorff et al., 2010). Sugarcane areas are mainly concentrated in the center and northern São Paulo state, which is responsible for approximately 60% of national production. It was observed that pasturelands (natural and planted) contracted while sugarcane expanded in these areas. These findings are consistent with Rudorff *et al.* (2010), who found that sugarcane expansion occurred mainly over pasture and summer crop areas.

West *et al.* (2014) suggested reduction in natural vegetation conversion in Brazil as a strategy for agricultural sustainability and food security. Halting deforestation by agricultural expansion seems a wise strategy to avoid losses in productivity, especially in a climate change future (Lapola et al., 2011; Oliveira et al., 2013). However, it is not a simple task. Despite public efforts against deforestation, this study estimated that 13 million ha of new agricultural areas were established between 2006 and 2012, of which 55% replaced Amazon rainforest and 24% replaced Cerrado. For a future that combines environmental protection with enhanced food security, Foley *et al.* (2011) suggests that agricultural expansion needs to stop. However, the authors highlight that diverse strategies need to be combined, such as closing yield gaps, and that no single solution will be sufficient. Identifying appropriate suites of potential strategies will require detailed analysis of historical trends in ecosystem services and the interaction between productivity and expansion of agricultural areas.

Although Brazilian agriculture has been historically known for extensification of agriculture at the expense natural vegetation (especially in the Amazonia and Cerrado biomes), data from recent years indicate that extensification has slowed and intensification is increasing. For example, soybean extensification was accompanied by intensification in all regions analyzed. The increase in soybean planted area in Center-West and South regions coincided with pastureland contraction in these regions, which may imply that soybean crop may have advanced over pasture areas (as demonstrated by Macedo *et al.* (2012) for Mato Grosso). In contrast, an increase in soybean planted area in MATOPIBA coincided with pastureland contraction, but in this case soybean planted areas have advanced mainly over native vegetation (Rudorff et al., 2015). The increment in soybean planted area was proportionally greater than the increment in yield, but the new soybean crop areas had similar yield than the adjacent and consolidated areas.

Maize experienced extensification and intensification in the Center-West region, but not in the South region. Part of the area increment in the Center-West is probably due to the adoption of double cropping, and not conversion of natural vegetation into maize. São Paulo and Paraná states clearly experienced sugarcane extensification, characterized by increases in area and little increase in yield. Low increases in yield probably occurred because, in general, new sugarcane producers adopt adjacent practices allowing them to quickly reach sugarcane yields similar to consolidated areas.

Cattle density increased approximately 21% between 1990 and 2012, but the slow process of technology transfer appears to be keeping the Brazilian cattle stocking rate near to 1.0 head/ha in several parts of the country. Such low values are indicative of an inefficient livestock system (Lapola et al., 2014). Livestock intensification is possible, as demonstrated by some regions that recently reached high cattle stocking rates. Further research is needed to identify the current management in the most productive regions and to assess if these farms are sustainable and whether their practices are transferable.

Anthropic activities have extensively modified the Earth's surface and land use change is one of the most obvious manifestations (Foley et al., 2005). Evaluating human impact on the environment and designing strategies for sustainable development requires spatially accurate descriptions of land use changes and identification of their drivers. Land use change significantly influences a variety of global processes. For example, the conversion of native vegetation to agriculture can change atmospheric characteristics at regional scales (Costa e Pires, 2010), alter energy and water balance (Anderson-Teixeira et al., 2012; Stickler et al., 2013), modify soil characteristics (Scheffler et al., 2011; Hunke et al., 2015), cause biodiversity loss (Chaplin-Kramer et al., 2015; Newbold et al., 2015) and disrupt important ecosystem services. Ramankutty & Foley (1998) suggest that accurate land use databases can be used directly within climate and ecosystem models. Indeed, this land use database could be used for a wide range of research, such as meteorology, hydrology, agronomy, ecology, conservation, economy, and territorial planning. In addition, these analyses provide insights into the extensification-intensification relationship and new information on Brazil's newest agricultural frontier (MATOPIBA).

Although this study provide a basic yield gap analysis – the relationships between average yields and the top yields – a more extensive analysis of the spatial and temporal variability of yields is a priority that will be explored in future studies. Yield gap analysis is a powerful tool to analyze deficits in agricultural technology and closing this gap could have a dramatic impact on food security (Godfray et al., 2010; Foley et al., 2011; Mueller et al., 2012).

To characterize the agricultural land use change in Brazil and productivity of four agricultural products (soybean, maize, sugarcane, and cattle), agricultural census data and remote sensing data is merged for the whole country from 1940 to 2012 at 30” spatial resolution. This “data fusion” technique was first developed by Ramankutty and Foley (1998) and has subsequently been subject to several modifications and improvements. Leite *et al.* (2011) merged a satellite-derived land classification for 2000 at a spatial resolution of 5’ (approximately 10 km x 10 km; Ramankutty et al., 2008) with census data to analyze the geographic patterns of agricultural land use in Brazilian Amazon. This methodology has been validated by Leite *et al.* (2011) who concluded that the combination of census data and remote sensing data provide maps that are consistent with independent estimates of changes in land cover. More recently, Leite *et al.* (2012) used the same methodology to reconstruct geographically explicit changes in agricultural land use for the entire Brazilian territory.

The methodology of this study was able to generate high-quality land use and productivity maps for Brazil between 1940 and 2012. The reconstructed changes in land use patterns are consistent with the history of agricultural geography in Brazil and the land use reconstruction produced in this study had the same pattern as previously described by Leite *et al.* (2012). Nevertheless, some uncertainties and inaccuracies still need to be clarified.

Firstly, the Hansen *et al*. (2013) database contains maps of global tree cover for the year 2000, with forest loss allocated annually from 2001 to 2012. These tree cover maps have approximately 30 m spatial resolution and trees are defined as vegetation taller than 5 m. Tropek *et al.* (2014) claim that the definition of “forest” as trees taller than 5 m in height is problematic because monocultures, such as *Eucalyptus*, are considered forest. Moreover, it is not clear if this satellite-based product considers permanent cultures, such as orange, mango and guava, as forested or deforested areas. Tropek *et al.* (Tropek et al., 2014) also identified some areas with vegetation lower than 5 m (such as pineapple, banana and soybeans) that were wrongly considered forests, although Hansen *et al.* (2014) argues that rigorous statistics are used to validate the maps. Nevertheless, Hansen *et al.* (2013) database provide annual non-forest maps for the entire Brazil.

Remote sensing captures only the top of the vegetation and provides relatively little information about land use (Leite et al., 2012). In addition to the remote sensing data, this study methodology used agriculture surveys and estimated data, which introduced other inaccuracies. First, annual total agricultural land use, cropland and pastureland data are estimated for municipalities based on the micro region growth rate. Although it is a reasonable assumption, since a micro region is an administrative unit that aggregates municipalities with similar characteristics, each municipality could have a different agricultural development rate. Second, the trend between 1995 and 2006 census data was extrapolated to estimate annual data between 2007 and 2012. Until a new agricultural census data is completed, it will not be possible to verify the real error introduced by this step. Furthermore, the agricultural census data is another possible source of error because it cannot be independently verified. These inaccuracies due to the use of the agriculture surveys and estimated data are one of the main causes of the difference between the amount of pastureland and cropland in TerraClass and this study database.

Another intrinsic error is that agricultural census data is allocated in all land areas considered as non-forest (no trees) in the smallest administrative unit used to create the maps. Thus, the methodology cannot avoid allocating agriculture to unsuitable areas, such as urban areas, rivers, beaches, dunes, wetlands and small dams. The Hansen *et al.* (2013) database may underestimate or overestimate forest loss and this directly influences how the census data are spatialized. Underestimated forest loss areas are corrected by the procedure of Equation 1.4 applied to 4% of the pixels located in approximately 2,000 municipalities. In overestimated forest loss areas (areas where forest cover or leaf area index is lower) such as several Cerrado, Caatinga, Pampas, and Pantanal phytophysionomies, the census data are widely distributed in an AMC. This widespread distribution causes the difference between the land uses pattern in TerraClass map (Fig. 1.6a) and this study database (Fig. 1.6b and 1.6c). Due to this possible allocation of agriculture into unsuitable areas and widespread distribution, the maps produced in this study, while appropriate for large-scale patterns analysis, should not be employed in analysis of smaller areas than the AMC used to produce the maps.

Additionally, the agricultural reconstruction between 1940 and 1999 is primarily derived from the 2000 map. In this procedure, the methodology implicitly consider that agricultural areas have never occupied areas wider than the ones with agricultural activities in 2000. For example, if there was agriculture in a region in the past that has been abandoned to vegetation recovery, it would not contain agriculture areas in the year 2000 and it would not be possible to correctly reconstruct agriculture in this region.

Future research efforts should also focus on the development of higher quality agricultural maps. Remote sensing can identify spatial patterns of land cover, but has difficulties distinguishing between land uses or specific crops, at least at the large-scale. This problem may be partially alleviated by merging high-resolution satellites data, national inventories, and “field truths”. The moderate resolution multispectral

MODIS plus Landsat 8 data and data from the recently launched Sentinel-2A could provide robust crop mapping over time and space. In addition to the national survey data, new ancillary information is also required to create and validate the land use classification, such as geo-referenced land use surveys of farmers. Future research will involve even higher volumes of data and will therefore demand considerable computational power. Fortunately, massive cloud-based computational platforms for Earth observation data processing should soon allow us to better identify and monitor croplands and pasturelands.

CHAPTER 2 - GREENHOUSE GASES EMISSIONS FROM LAND USE AND AGRICULTURE IN BRAZIL FROM 1940 TO 2014

2.1. Introduction

Agriculture is responsible for an important amount of global greenhouse gases (GHG) emissions. Between 2000 and 2010, the global agriculture sector was responsible for the emission of ~5.4 Pg-CO_{2eq} year^{-1} while the land use change GHG emissions accounted for ~4.9 Pg-CO_{2eq} year^{-1} (Smith et al., 2014). In total, Agriculture, Forestry and Other Land Use (AFOLU) sector emitted ~1/4 of the total anthropogenic GHG emissions, mainly from deforestation, livestock, soil and nutrient management (Smith et al., 2014). Globally, AFOLU sector emissions are only smaller than emissions from fossil fuel combustion and industrial processes.

Different from the global picture, the largest source of GHG emissions in Brazil is land use change, which historically is associated with expansion of agricultural area (Leite et al., 2012; Brasil, 2016; Chapter 1). Between 2000 and 2005, the total land use change emission accounted for ~2.1 Pg-CO_2 year^{-1} (73% of the national total) while the agriculture sector was responsible for ~0.36 Pg-CO_2 year^{-1} (13% of the national total). Even after intense efforts to control deforestation – especially in the Amazonia biome – land use change emissions is still larger than the agriculture sector emissions. Between 2005 and 2015, Brazilian land use change accounted for ~1.2 Pg-CO_{2eq} year^{-1} (55% of the national total) while the agriculture sector was responsible for ~0.41 Pg-CO_{2eq} year^{-1} (19% of the national total, Observatório do Clima, 2017). Land use change and agriculture sectors were responsible for ~68% of the national emissions in 2015 and, therefore, agriculture activity is the main target activity for actions to mitigate GHG emissions in Brazil.

Although agriculture is historically the main driver of deforestation in Brazil, not all land use change is caused by agriculture. To quantify the agricultural land use emissions truly provides information about the contribution of this activity to GHG emission and allows the formulation of actions to minimize emissions directed to specific social actors.

Leite et al. (2012) conducted the first historical estimate of carbon emissions associated with agricultural land use change between 1940 and 1995. They reconstructed the historical agricultural land use for entire Brazil and estimated carbon emissions using a simple bookkeeping model that substitutes the natural biomass for the agriculture biomass (or the opposite) as agriculture area increased (or decreased). For a shorter period, Noojipady et al. (2017) estimated annual carbon emission from cropland extensification in the Cerrado biome between 2003 and 2013. These authors analyzed cropland expansion using satellite data and carbon emission was estimated using two different approaches: one based on satellite data and a second based on aboveground biomass and root:shoot ratios.

These previous studies analyzed only the land use change emissions from the agriculture activity. Here, agriculture activity is defined as the management of a diverse range of activities, such as raising livestock, cropping and forestry. On the other hand, agriculture sector is one of the Intergovernmental Panel on Climate Change (IPCC) divisions from anthropogenic emission (IPCC, 1996) and this data is also important to understand the emissions from agriculture.

In addition to the carbon emitted by land use change, other GHG emissions from agriculture sector were included in the study of Bustamante et al. (2012). In this study, Brazilian GHG emissions from cattle ranching were estimated between 2003 and 2008, while emissions from land use change were estimated for Amazon and Cerrado biomes using the INPE-Emission Model (INPE-EM; Aguiar et al., 2012). For the entire country, the GHG emissions from burned areas were estimated using remote sensing data (MODIS data) and enteric fermentation emissions were calculated using agriculture survey data.

As mentioned earlier, Brazilian agriculture activity is an important contributor to the national emission balance. However, previously published estimated emissions from agriculture are aggregated by states, biomes or national totals (Aguiar et al., 2012; Bustamante et al., 2012; da Mata et al., 2015; Brasil, 2016; Noojipady et al., 2017). The Third National Communication, which is the official estimate of GHG emissions, reports emissions aggregated by states and national total from 1990 to 2010. A dataset with historical and explicitly spatialized agricultural activity emission is essential to understand the national heterogeneity and to identify the regions with larger emissions. Moreover, a historical-spatial agriculture emission database can allow the identification of regions with difficulties to improve their production practices over the time, which can become priority areas for investments to reduce agricultural emissions.

In this study, I analyze the spatial patterns of GHG emissions, placing these findings into the current land use policy and sustainable agriculture debate. For these analyses, I developed a historical-spatial database of Brazilian GHG emissions at a spatial resolution of 30” (approximately 1 km x 1 km). This database contains the CO_2 emission maps from agricultural land use from 1940 to 2014, CH_4 emissions maps from enteric fermentation and manure management from 1975 to 2014, and direct (synthetic nitrogen fertilizers, nitrogen from grazing animals and nitrogen from manure used as fertilizers) and indirect (atmospheric deposition and leaching) N_2O emissions maps from 1975 to 2014. In this study, I also analyze the Brazilian agriculture emissions through a statistical trend test of time series and from the perspective of the National Policy on Climate Change (PNMC – *Política Nacional sobre Mudanças do Clima*; Federal Law n. 12,187/2009 and Decree 7390/2010).

2.2. Methodology

2.2.1. CO_2 balance from agricultural land use

2.2.1.1. Carbon storage in the vegetation

With 8.5 million km^2 of area, Brazil contains six biomes: Amazonia, Atlantic Forest, Caatinga, Cerrado (Brazilian savanna), Pampas (grasslands), and Pantanal (Fig. 1). The country is divided into 27 federal units, being 26 states and 1 Federal District, and into 5 regions (Fig. 2.1).

An original vegetation map represents the past vegetation before the anthropic land use ise established. To produce an original vegetation map, I firstly use the vegetation map produced by RadamBrasil project. RadamBrasil was the first effort to map

Brazilian vegetation through an extensive field survey and remote sensing analyses during the 1970s. This vegetation map has preserved areas (80% of the Brazilian territory), anthropized areas (18% of the Brazilian territory) and water bodies (2% of the Brazilian territory) in the 1970s. Preserved areas have their vegetation classified according to the classification system of Brazilian vegetation (IBGE, 2012). For the anthropized areas, a likely vegetation type is indicated based on the observations and experiences of the RadamBrasil researchers, but without specification of the sub-divisions of the Brazilian classification system. To produce an original vegetation map, I suggest the missing sub-divisions of the vegetation type in the anthropized areas using the description in the Technical Manual of the Brazilian Vegetation (IBGE, 2012).

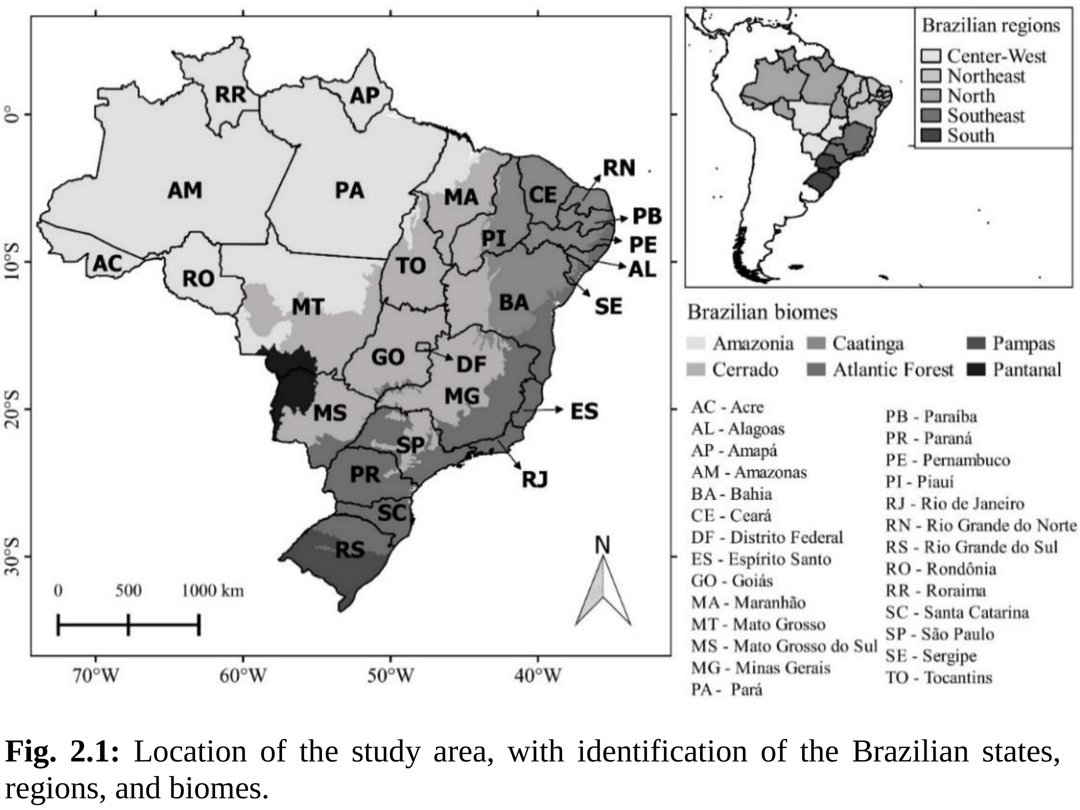

Fig. 2.1: Location of the study area, with identification of the Brazilian states, regions, and biomes.

According to the Technical Manual of the Brazilian Vegetation (IBGE, 2012), the sub-divisions of the vegetation types for forest physiognomies can be inferred from latitude and altitude. I use the Shuttle Radar Topography Mission (SRTM) elevation data to calculate mean altitude at 1 km x 1 km spatial resolution throughout Brazil and these data was used as a mask for the vegetation type classification. For non-forest physiognomies, I classify the vegetation according to the dominant phytophysiognomy class near the missing vegetation type area.

To produce the biomass map, I assign the carbon stock values of each vegetation physiognomies of the original vegetation map to four different pools (aboveground and belowground carbon stocks, dead wood, and litter). The carbon stock values for each vegetation physiognomies were obtained from the Land Use, Land Use Change and Forestry (LULUCF) Reference Report of the Third National Communication of Brazil to the United Nations Framework Convention on Climate Change (UNFCCC; Bustamante *et al.*, 2015). In addition, I use the aboveground and belowground living biomass values from Nogueira et al. (2008) for four transition vegetation types: contact zone between rainforest and woody oligotrophic vegetation of swampy and sandy areas, contact zone between rainforest and seasonal forest, contact zone between savanna and seasonal forest, and contact zone between savanna and rainforest. Before I assign these values to the four transition vegetation types of the original vegetation map, I transform living biomass in carbon stocks using the ratio 0.47. The distribution of biomass over Brazil is presented in Fig. 2.2.

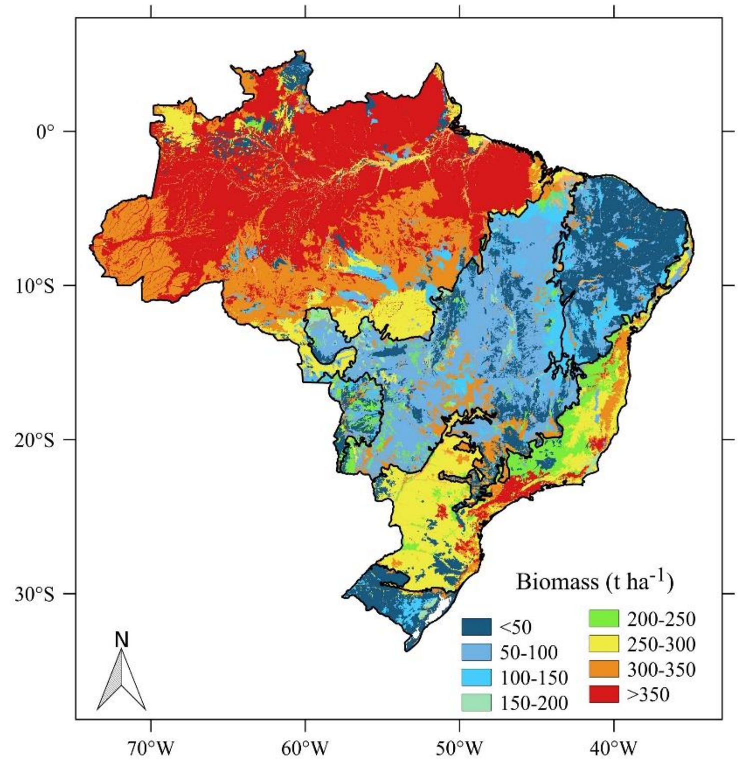

Fig. 2.2: Brazil's original total biomass (aboveground and belowground carbon stocks, dead wood, and litter) map.

2.2.1.2. Area occupied by agriculture in Brazil

In this study, I use the explicitly spatialized database of Brazilian agriculture developed in Chapter 1. This database includes maps of total croplands, natural pastureland and planted pastureland for the period of 1940 to 2014 at spatial resolution of 30" (approximately 1 x 1 km). The map unit is hectare (ha) per pixel and sum of the cropland, natural pastureland and planted pastureland data is the total agriculture land use in Brazil.

The patterns of historical land use in Brazil described in Chapter 1 can be summarized as follows. In 1940, total agricultural land use was concentrated in the eastern and southern parts of the country. Total agricultural land use was 106 million ha in 1940, achieved its largest area in 1985 (231 million ha), and was 221 million ha in 2014. In general, agriculture has expanded northwestward, in the Amazon and Cerrado biomes, while agricultural land use is actually decreasing in the eastern and southern parts of the country due to abandonment or conversions to other non-agricultural land uses (Chapter 1).

Pasturelands have always been the most important contributor to total agriculture land use in Brazil, but natural pasturelands were gradually replaced by more profitable planted pastures, since 1975 (Chapter 1). The sum of natural and planted pasturelands is the total pastureland. Total pastureland was 87 million ha in 1940, achieved its greatest area in 1985 (179 million ha), and was 148 million ha in 2014. Between 1985 and 2014, pasturelands decreased in all Brazilian biomes, except in Amazonia. The cropland also expanded northwestward, although also occurred extensification in consolidated crop areas in South and Southeast regions. Croplands increased from 19 million ha in 1940 to 73 million ha in 2014.

2.2.1.3. Calculations of CO_2 emissions and sinks

The carbon balance due to changes in agricultural land use involves knowledge about the dynamics of land use change, biomass in original vegetation, and emission factors of each component of the carbon cycle. To integrate all these elements, I designed an emission model based on the generic INPE-EM modelling framework (version 1.0; Aguiar et al., 2012; Fig.2.3). INPE-EM is an adaptation for spatially explicit environments of the bookkeeping model developed initially by Houghton et al. (2000). My emission model has a similar structure, but adapted to use the database presented in Chapter 1. Because this framework was previously described by Aguiar et al. (2012), I name the variables and parameters following Aguiar et al. (2012), whenever possible, to facilitate comparison between the two studies.

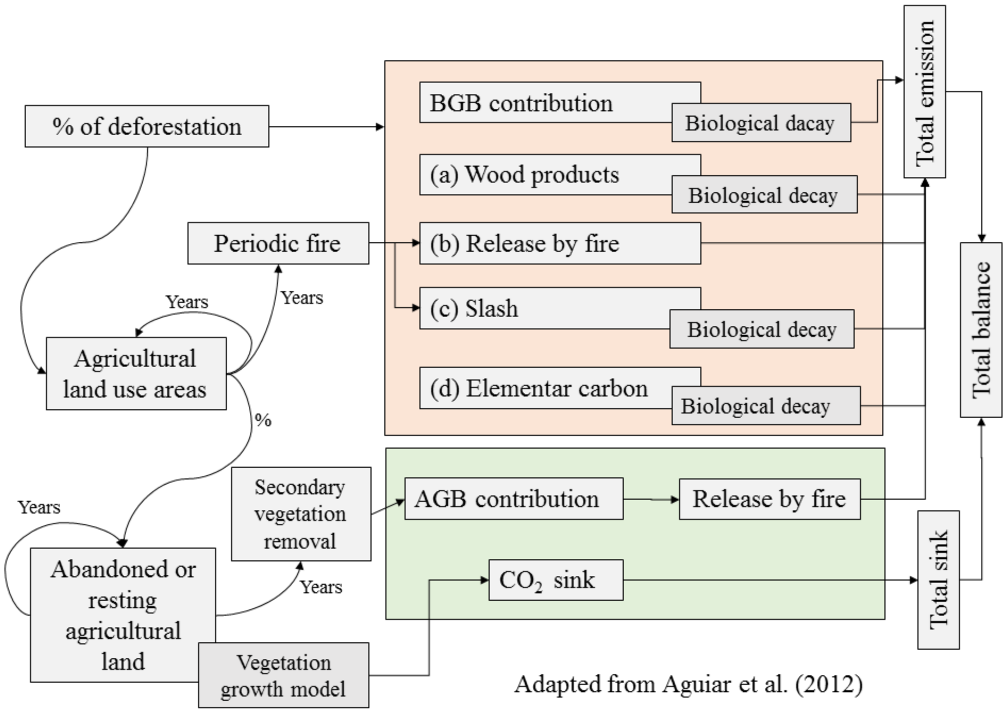

Fig. 2.3: INPE-EM conceptual model schematic representation.

My emission model has three independent modules (*Primary Forest Loss*, *Secondary Forest Growth* and *Secondary Forest Loss*) and the process of sources and sink of carbon between the compartments is gradual. The *Primary Forest Losses* module represents the process of clear-cut deforestation of primary vegetation. In this case, belowground carbon stocks (BGC) is released to the atmosphere at a decaying exponential rate (biological decay, *decayRateBGB*) and the aboveground carbon (AGC) can follow four possible paths: 1) part of AGC becomes wood products (*precWoodProducts*) and their carbon is released to the atmosphere at a decaying exponential rate (*decayRateWoodProducts*); 2) part of AGC is released immediately to the atmosphere after a fire event (*percFireFirstYear*); 3) part of AGC remains on the ground to decompose (*percSlash*) and their carbon is released to atmosphere at a decaying exponential rate (*decayRateSlash*); and 4) after fire, part of AGC remains on the ground as elemental carbon (*percElementalCarbon*) and their carbon is released to the atmosphere at very slow rates (*decayRateElementalCarbon*). In addition, I include in the *Primary Forest Losses* module the process of re-burn slash left in the ground from deforestation (*slashFireCycle*) once every 3 years, such as described in Aguiar et al. (2012).

This first module also represents the fate of the litter and dead wood carbon. Both carbon pools can follow three possible paths: 1) part of litter/dead wood biomass is released immediately to the atmosphere after a fire event (*percLiterFire/perWoodFire*); 2) part of litter/dead wood remains on the ground to decompose (*percLitterDecomposition/ percWoodDecomposition*) and their carbon is released to the atmosphere at a dacaying exponential rate (*decayRateSlash*); and 3) part of litter/dead wood remains in the soil as elemental carbon (*percElementalCarbon*) and their carbon is released to the atmosphere at very slow rates (*decayRateElementalCarbon*).

The *Secondary Forest Growth* module represents the dynamics of secondary vegetation in abandoned agricultural areas. In this module, the secondary vegetation growth and CO_2 sequestration occurs following a vegetation growth curve (*modelRegrow*) suggested by Houghton et al. (2000). In this vegetation growth curve, secondary vegetation recovered 70% of their original carbon stock in the first 25 years and the remaining 30% over the next 50 years. My model was constructed so that the grid cells may have areas with secondary vegetation at different ages. For example, if agricultural land use area decreases in 10% of the pixel area in the year *t*, secondary vegetation starts to grow in this area. If agricultural land use area decreases in additional 5% of the pixel area in the year *t+1*, the same grid cell will support 1 year-old secondary vegetation in 10% of its area and a newer secondary vegetation will start to grow in 5% of its area. My model supports as many new secondary vegetation areas as necessary with different ages in each grid cell.

Part of the reduction in agricultural areas can be explained by increasing urban areas, which can be detected using the 1 km x 1 km night light map from the year 2012 made by the NASA Earth Observatory and available at https://visibleearth.nasa.gov/view.php?id=79765. Although some points of lights may be not city lights, I consider that these detected lights can indicate some other anthropic occupation – such as mining operations, illuminated roads or lights from small rural villages – and secondary vegetation growth is also limited in these cases. To avoid secondary vegetation growth in urban areas, I exclude the vegetation growth in the pixels with any light points identified in the night light map.

Secondary vegetation can also be removed, which is represented in the *Secondary Forest Loss* module. In this module, all aboveground and belowground carbon present in the secondary vegetation removed is released immediately to the atmosphere, such as after a fire event.

Based on the difference between agricultural land use area in the time *t* and *t-1*, the model goes through the different modules for each grid cell. If agricultural land use area change (ΔALU) is positive and the secondary vegetation area (SV_{area}) is equal to zero in the grid cell, the model executes only the *Primary Forest Loss* component for this pixel in the year *t*.

When the grid cell has some secondary vegetation area, these areas are primarily removed if it occurs an expansion of the agricultural area. Among the secondary forest growth areas, the youngest ones are priority for removal. Then, if $\Delta ALU > 0$ and $SV_{area} > 0$ and $\Delta ALU \leq SV_{area}$, the model executes the *Secondary Forest Loss* component removing the youngest secondary forest until the removed area is equal to the area of expansion of agriculture. The remaining secondary forest remains growing according to the *Secondary Forest Growth* module. If ΔALU > 0 and SV_{area} > 0 and ΔALU > SV_{area}, the model executes the *Secondary Forest Loss* module, removing all secondary vegetation in the grid cell, and the *Primary Forest Loss* module, removing the area corresponding to ΔALU – SV_{area}. Finally, if $\Delta ALU \leq 0$, the model executes only the *Secondary Forest Growth* component.

Grid cell CO_2 balance in year *t* is equal to the sum of the CO_2 emission by primary and secondary forest losses, the CO_2 sink by secondary vegetation growth – that has negative signal – and old emissions that correspond to a percentage of carbon that are being released to the atmosphere at a decaying exponential rate.

To account for old emissions in the year of 1940, I initialize the model in the year of 1840, performing a spin up of 100 years. For this, annual agricultural land use maps were constructed for the period between 1840 and 1939 using a simple linear algebra. I considered that agricultural land use is equal to zero in 1840 and that the amount of land use gradually increased until 1940 as expressed in Equation 2.1:

$$U_{i,j}^{t} = (t - 1840)\left[U_{i,j}^{1940}/(1940 - 1840)\right] \qquad (2.1)$$

where *i* and *j* are, respectively, the coordinates of rows and columns of the pixels in the map, $U_{i,j}^{t}$ is the estimated total agricultural land use in the year *t* (km^2) for $1840 \leq t \leq 1939$ and $U_{i,j}^{1940}$ is the amount of total agricultural land use from 1940 (km^2). This spin up influences mainly the emissions estimated in the first 15 years (1940-1954). In 1940, the old emissions estimated during the spin up accounted for 35% of the total. The spin up influence decreased to 1% of the total estimated emissions in 1955 and 0.06% in 2014.

The parameters values described by Aguiar et al. (2012) are suitable for the Amazon biome and Bustamante et al. (Bustamante et al., 2012) also used them to estimate the emissions of the Cerrado. Since the Atlantic Forest also is a tropical forest formation with timber potential and similar deforestation processes, I considered that the Amazon biome parameters can also be used for the Atlantic Forest.

Recently, da Mata et al. (2015) developed a GHG emission study for the Caatinga biome using the INPE-EM framework. These authors suggested parameters for Caatinga based in the study of Andreae and Merlet (2001), which determined emission factors from biomass burning for Savanna and Grasslands. I considered that these parameters also can be used for Pampas and Pantanal biomes, which are natural pasturelands with very low timber potential and fire is frequently used for pastureland renovation. Table 2.1 summarizes the parameters used in this study.

2.2.2. CH_4 emissions from enteric fermentation and manure management

First, I create maps of heads of beef cattle per pixel and heads of dairy cow per pixel from 1975 to 2014. I obtain the number of cattle and dairy cows, in heads, in each municipality from the Municipal Livestock Survey from the Brazilian Institute of Geography and Statistics (IBGE – *Instituto Brasileiro de Geografia e Estatística*) database, from 1975 to 2014. Although all census data were collected at the municipality level, the unit used for the historical reconstruction was the minimum comparable area (MCA). An MCA consists of the smallest set of municipalities with a stable boundary overtime. This procedure is necessary since new municipalities are created almost every year in Brazil and there are not annual municipal maps available. I defined one set of MCAs for each of the following periods: 1823 MCA polygons for the period 1975-1989 and 558 polygons for the period 1990–2014. For the recent years

(1990-2014), MCA polygons are the same as the micro regions, which are the small units that aggregate municipalities with similar economic and social characteristics.

Table 2.1: The bookkeeping model parameters for Amazonia, Atlantic Forest, Cerrado, Caatinga, Pantanal, and Pampas biomes. AGB and BGB are acronyms for aboveground biomass and belowground biomass, respectively.

Parameter	Description	Biome	
		Amazonia Atlantic Forest Cerrado	Caatinga Pantanal Pampas
percWoodProducts	Percentage of AGB that become wood products	15%	0%
percFireFirstYear	Percentage of AGB that released immediately to the atmosphere after a fire event	42.5%	80%
percSlash	Percentage of AGB that remain on the ground to decompose	42.5%	18%
percElementalCarbon	Percentage of AGB that will remain on the ground as elemental carbon	2%	2%
percLitterFire	Percentage of litter that released immediately to the atmosphere after a fire event	50%	50%
percLitterDecomposition	Percentage of litter that will remain in the soil as burnt remains	50%	50%
percWoodFire	Percentage of dead wood that released immediately to the atmosphere after a fire event	50%	50%
percWoodDecomposition	Percentage of dead wood that will remain in the soil as burnt remains	50%	50%
decayRateBGB*	Biological decay of BGB	0.7	0.7
decayRateWoodProducts*	Biological decay of wood products	0.1	0.1
decayRateSlash*	Biological decay of slash	0.4	0.05
decayRateElementalCarbon*	Biological decay of elemental carbon	0.001	0.001
slashFireCycle	Number of years between re-burn slash left in the ground from deforestation	3	-

*dimensionless

The amount of beef cattle is obtained by the difference between the number of cattle and the number of dairy cows. The number of dairy cows is greater than the number of beef cattle only in two MCAs in the year of 1977 and in one MCA in the years of 1992 and 1994. In these cases, I consider the number of beef cattle equal to zero.

To geographically distribute the heads of beef cattle, I first calculate the stocking rate of beef cattle in the MCA *m* (polygon) in the year *t* by dividing the amount of beef cattle heads in the MCA *m* in the year *t* by the total pasture area (in hectare) in the MCA *m* in the year *t* (*t* = [1975, 2014]). Then, I multiply the total pasture area in each MCA grid cell (in hectare) in the year *t* by the stocking rate of beef cattle at the MCA *m* in the year *t*. The final number of beef cattle maps are expressed in heads per pixel. This same method is used to calculate the heads of dairy cow per pixel maps from 1975 to 2014.

I estimate the methane emission by enteric fermentation and manure management from 1975 to 2014 based on the Methane Emissions from Enteric Fermentation and Animal Manure Management Reference Report of the Third National Communication of Brazil to the UNFCCC (Berndt et al., 2015). The Reference Report methodology uses the Intergovernmental Panel on Climate Change (IPCC) Guideline 1996 Tier 1 approach complemented with emission factors developed for national conditions based in information from expert consultations and literature. For example, to calculate the emission factors, it is considered that each Brazilian state has particularities related to the predominant gender, breed and age of animals, quantity and quality of feed, degree of digestibility of the digested mass, the conditions of breeding system, and climate.

Beef cattle data are subdivided in adult males, adult females, and young cattle. This subdivision is done according to the Reference Report (Berndt et al., 2015) which defines federal units proportions (p_{ci_ut}) of animal in category c for each federal unit and the emission factors by enteric fermentation and manure management (EF_{ci_ut}, MM_{ci_ut}) from 1990 to 2010. I use the proportions of the years 1990 and 2010, respectively, for the period 1975-1990 and 2010-2014. Then, the annual CH4 emissions by enteric fermentation of cattle and manure management per pixel are calculated for four animal categories (dairy cows, adult male, adult female and young cattle), according to Equation 2.2:

$$ME_{it} = \sum_c \left(P_{it}\, p_{ci_ut}\right)\, \left(EF_{ci_ut} + MM_{ci_ut}\right) 10^{-6} \quad (2.2)$$

where ME_{it} is the enteric fermentation and manure management emissions in the pixel *i* in the year *t* (in Gg-CH_4), P_{it} is the population of animals (either dairy or cattle beef heads) in the pixel *i* in the year *t* (in head $year^{-1}$), EF_{ci_ut} is the emission factor of CH_4 by enteric fermentation of an animal category *c* in the pixel *i* belonging to the federal unit u in the year *t* (in kg-CH_4 $head^{-1}$ $year^{-1}$), and MM_{ci_ut} is the emission factor of CH_4 by manure management of an animal category *c* in the pixel *i* belonging to the federal unit u in the year *t* (in kg-CH_4 $head^{-1}$ $year^{-1}$). For the category of dairy cow, f_{ci_ut} is equal to 1 and 10^{-6} is the conversion factor from kg to Gg.

2.2.3. N_2O emissions from agricultural soils

According to IPCC Guideline, N_2O emissions can be distinguished in direct and indirect emissions. Direct emissions analyzed in this work includes synthetic fertilizers, nitrogen from grazing animals and nitrogen from manure used as fertilizers. Indirect emissions take place from the atmospheric deposition of NO_x and NH_3 or after nitrogen is lost from leaching or runoff (IPCC, 1996).

Direct and indirect emissions of N_2O are estimated on the instructions detailed on the Nitrous Oxide Emissions from Agricultural Soils and Manure Management Reference Report of the Third National Communication of Brazil to the UNFCCC (Alves, 2015). The Reference Report methodology uses the IPCC Guideline 1996 Tier 1 approach complemented with emission factors developed for national conditions based in information from expert consultations and literature.

2.2.3.1. Direct emissions

Synthetic nitrogen fertilizers are important substances to improve crop yield, but they are a considerable source of N_2O emissions. I obtain synthetic nitrogen fertilizers data from 1975 to 1989 from Lapido-Loureiro et al. (2009), who collected the apparent use of synthetic nitrogen fertilizers for the whole Brazil. Between 1990 and 2006, the amount of synthetic nitrogen fertilizers delivered to the farmers for each federal unit – except North region that has aggregated values for the entire region – are obtained in the annex of the Nitrous Oxide Emissions from Agricultural Soils and Manure Management Reference Report of the Third National Communication of Brazil to the UNFCCC (Alves, 2015). For the period between 2007 and 2014, I obtain the amount of synthetic nitrogen fertilizer delivered to the farmers for each federal unit from the National Association for the Diffusion of Fertilizers (ANDA - *Associação Nacional para Difusão de Adubos*) available at the IBGE database.

To estimate fertilizer data for each federal unit/North region between 1975 and 1989, I calculate the proportion of synthetic nitrogen fertilizer used for each federal unit/North region in 1990 in relation to the total amount of synthetic nitrogen fertilizer used in the whole country in this year. After that, I multiply this proportion for each federal unit by the annual total amount of synthetic nitrogen fertilizers used in Brazil according to Lapido-Loureiro et al. (2009). Then, I obtain the annual amount of synthetic nitrogen fertilizers delivered to the farmers for each federal unit/North region between 1975 and 1989.

In Brazil, only ~1.6% of the fertilizer is used in pasturelands and, among the crops, the largest consumers of fertilizers are maize, sugarcane, coffee and cotton (ANDA, 2009). Soybean planted area represents 41% of the total cropland area in Brazil in 2014, but currently they are not fertilized with nitrogen because the biological fixation of nitrogen is able to supply the nutritional demand of this crop (Sediyama et al., 2015). Although other legume crops also can present biological fixation of nitrogen, such as peanut and beans, they represent a small area in relation to the total cropland in Brazil (less than 7%). Then, the difference between total cropland (the sum of permanent and temporary crops) and soybean planted area maps are used as base for the geographic distribution of synthetic nitrogen fertilizers data.

This procedure can result in inaccuracies in the beginning of the time series. Vargas et al. (1982) reported that, in 1982, nitrogen fertilization in soybean was still widely used because it was the agronomical recommendation of the time and because there was a low availability of fertilizers without nitrogen on the market. However, both soybean planted area and synthetic nitrogen fertilizer use were low in the beginning of the time series, so probably the assumption that soybean is not fertilized with nitrogen during the whole period will not dramatically alter the results.

Total cropland (from 1975 to 2014) and soybean (from 1990 to 2014) maps were developed in Chapter 1. For the period before 1990, soybean planted area maps were developed using the same approach to that used in Chapter 1 (Section 1.2.5).

Nitrogen fertilizers delivered to the farmers maps are obtained in two steps. First, I calculate the fertilizer application rate in the federal unit u in the year t by dividing the amount of synthetic nitrogen fertilizer delivered to the farmers (in tons) in the federal unit *u* in the year *t* by the difference between cropland area and soybean planted area (in hectare) in the federal unit *u* in the year *t* (*t* = [1975, 2014]). Then, I multiply the federal unit grid cells from the total pasture area (in hectare) in the year *t* by the fertilizer application rate at the federal unit *u* in the year *t*. The final synthetic nitrogen fertilizer maps are expressed in tons per pixel.

The main synthetic nitrogen fertilizer used in Brazil is urea, and it is the nitrogen fertilizer more susceptible to losses by volatilization of NH_3 when applied to soil (Alves, 2015). Then, the Reference Report suggest annual fractions of urea in relation to the total synthetic nitrogen fertilizer (fu_t) between 1990 and 2010. I use the fraction of the years 1990 and 2010, respectively, for the period 1975-1990 and 2010-2014. Different factor of volatilization for urea (F_{UV}, 30%) and other synthetic nitrogen fertilizers (F_{OV}, 10%) are also proposed for Alves (2015). The annual emission of N_2O is estimated according to Equation 2.2:

$$FE_{it} = [SN_{it}\ fu_t\ (1 - F_{UV}) + SN_{it}\ (1 - fu_t)\ (1 - F_{OV})\ ]\ F_n\ NF\ 10^{-6} \qquad (2.2)$$

where FE_{it} is the synthetic nitrogen fertilizer emissions in the pixel *i* in the year *t* (in Gg-N_2O), SN_{it} is the amount of synthetic nitrogen fertilizer delivered to the farmer in the pixel *i* in the year *t*, F_n is the conversion factor from N to N_2O (44/28), NF is the direct N_2O emission factor (0.01 kg-N_2O kg-N^{-1}) and 10^{-6} is the conversion factor from kg to Gg.

The geographic distribution of the N_2O emission by grazing animals and by application of manure as fertilizers are based in the beef cattle and dairy cow maps obtained as explained in Section 2.2.2. Beef cattle data are subdivided in younger than 1 year-old, between 1 and 2 year-old and adults according the federal units proportions

(a_{ci_u}) defined in the Reference Report (Berndt et al., 2015). I use the f_{ki_j} values of the years 1990 and 2010, respectively, for the period 1975-1990 and 2010-2014. The annual emission of N_2O is estimated according to Equation 2.4:

$$DE_{it} = \sum_c \left(P_{it}\, a_{ci_u}\, Nex_c \right) \left[(1 - F_{MV}) \left(1 - F_{p\, i_u t} \right) NF + F_{p\, i_u t}\, GF \right] F_n\, 10^{-6} \tag{2.4}$$

where DE_{it} is the N_2O emissions from grazing animals and application of manure as fertilizers in the pixel *i* in the year *t* (in Gg-N_2O), P_{it} is the population of animals (either dairy or cattle beef heads) in the pixel *i* in the year *t* (in head year^{-1}), Nex_c is the total N excreted annually by an animal category *c*, F_{MV} is the factor of volatilization for manure as fertilizers (20%), $F_{p\, i_u t}$is the fraction of manure excreted directly in pasturelands in the pixel *i* belonging to the federal unit *u* in the year *t*, NF is the direct N_2O emission factor (0.01 kg-N_2O kg-N^{-1}), GF is the direct N_2O emission factor for grazing animals (0.015 kg-N_2O kg-N^{-1}), and F_n is the factor of conversion from N to N_2O (44/28). For the category of dairy cow, $f_{ci_u t}$ is equal 1 and 10^{-6} is the conversion factor from kg to Gg.

2.2.3.2. Indirect emissions

The geographic distribution of the N_2O emission from atmospheric deposition and leaching are based in the beef cattle and dairy cow maps obtained as explained in Section 2.2.2 and in the synthetic nitrogen fertilizers maps obtained as explained in Section 2.2.3.1. I use the $p_{ci_u t}$ and fu_t values of the years 1990 and 2010, respectively, for the period 1975-1990 and 2010-2014. The annual indirect emission of N_2O from atmospheric deposition and leaching are estimated, respectively, according to Equations 2.5 and 2.6:

$$VE_{it} = \left[SN_{it}\ fu_t\, F_{UV} + SN_{it}\,(1 - fu_t)\, F_{OV} + \sum_c \left(P_{it}\, p_{ci_u t}\, Nex_c\, F_{MV}\right)\right] F_n\, VF\, 10^{-6} \quad (2.5)$$

$$LE_{it} = \left[SN_{it} + \sum_c (P_{it}\ p_{ci_u t}\ Nex_c)\right]\ F_{leach}\ LF\ F_n\ 10^{-6} \quad (2.6)$$

where VE_{it} is the annual indirect N_2O emissions from atmospheric deposition in the pixel *i* in the year *t* (in Gg-N_2O), LE_{it} is the annual indirect N_2O emissions from leaching in the pixel *i* in the year *t* (in Gg-N_2O), SN_{it} is the amount synthetic nitrogen fertilizer delivered to the farmer in the pixel *i* in the year *t*, fu_t is the fraction of urea in relation to the total synthetic nitrogen, F_{UV} is the factor of volatilization for urea (30%), F_{OV} is the factor of volatilization for other synthetic nitrogen fertilizers (10%), P is the population of animals (either dairy or cattle beef heads) in the pixel *i* in the year *t* (in head year^{-1}), $p_{ci_u t}$ is the proportion of beef cattle in 3 different ages (younger than 1 year-old, between 1 and 2 year-old and adults), Nex is the total N excreted annually by an animal category *c*, F_{MV} is the factor of volatilization for manure as fertilizers (20%), F_{leach} is the fraction of nitrogen lost by leaching (30%) , F_c is the factor of conversion from N to N_2O (44/28), VF is the indirect N_2O emission factor for atmospheric deposition (0.01 kg-N_2O kg-N^{-1}), LF is the indirect, N_2O emission factor for leaching (0.025 kg-N_2O kg-N^{-1}) and 10^{-6} is the conversion from kg to Gg.

2.2.4. Statistical analysis of the time series

To summarize the spatial patterns of the GHG emissions, all estimated emissions are converted to CO_2 equivalent (CO_{2eq}) following the Global Warming Potential from the IPCC Second Assessment Report (GWP SAR) for a period of 100 years for each gas, using the weights 1 to CO_2, 21 to CH_4 and 310 to N_2O, as adopted by the Third Brazilian National Communication.

The Mann-Kendall (MK) trend test is used to identify the trend of each GHG time series (CO_2, CH_4 and N_2O) and for the sum of all agricultural activity emissions in two periods: 1975-1994 and 1995-2014. As explained previously, in the Section 2.2.1.2, agriculture achieved the highest land use area in 1985 (231 Mha). After that, agricultural area decreased until 1995, reaching 219 Mha, and return to increase between 1995 and 2006, reaching 220 Mha. Then, I expected different trends in these two periods.

The MK test is a nonparametric test that considers the stability hypothesis of a time series. The null hypothesis (H_0) is that there has been no trend in emissions over time, that is, the observations are randomly ordered in time, and the alternative hypothesis (H_1) is that there has been an increasing or decreasing monotonic trend over time.

Considering that each grid cell has a time series with N terms, the Y_t value for the year *t* is compared with all subsequent data values (u > t). If Y_t value is higher than a data value from an earlier time period, the signal is positive and the statistic S is incremented by 1. If Y_t value is lower than a data value from an earlier time period, the signal in negative and the statistic S is decremented by 1. The final value of S is the net result of all these increments and decrements found by the comparison between the terms. The mathematical equations of MK test statistic S are defined as (Equations 2.7 and 2.8):

$$signal(Y_u - Y_t) = \begin{cases} +1 & if\ (Y_u - Y_t) > 0 \\ 0 & if (Y_u - Y_t) = 0 \\ -1 & if\ (Y_u - Y_t) < 0 \end{cases} \quad (2.7)$$

$$S = \sum_{t=1}^{N-1} \sum_{u=t+1}^{N} signal(Y_u - Y_t) \quad (2.8)$$

For $N \geq 10$, the statistic S is approximately normally distributed with mean equal zero (E(S) = 0) and variance (*Var(S)*) is calculated according to Equation 2.9:

$$Var(S) = \frac{N(N-1)(2N+5)}{18} \tag{2.9}$$

The presence of a statistically significant trend is evaluated using the statistic Z, according to Equation 2.10:

$$Z = \begin{cases} \frac{(S-1)}{\sqrt{Var(S)}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \frac{(S+1)}{\sqrt{Var(S)}} & if\ S < 0 \end{cases} \tag{2.10}$$

In a bilateral test, H_0 is rejected for a level of significance α if the absolute value of Z is greater than the value of the $Z_{\alpha/2}$ of a standard normal cumulative distribution tables. In this work, the significance level $\alpha = 0.05$ was considered. If H_0 is rejected, the S statistic indicates whether the trend is increasing (S> 0) or decreasing (S <0). In this study, the MK test is applied in each grid cell.

2.2.5. Comparison with the PNMC goals

To analyze the Brazilian agriculture emissions from the perspective of the PNMC, I calculated the land use change emissions for 2020 in a “business as usual” scenario (scenario BAU) and in a scenario where there is a reduction of 80% in Amazon deforestation and 40% in Cerrado deforestation as proposed by the PNMC (scenario PNMC). These projections are calculated according to the methodology described in the Annex of the Decree 7390/2010, which regulates the PNMC.

Here, positive agricultural land use area change ($\Delta ALU > 0$) is considered deforestation. The Amazon deforestation rate in 2020 is the mean deforestation rate between 1996 and 2005. The 2020 projected emissions in the BAU scenario for the Amazon biome is a result of the multiplication of the deforestation rate in 2020 by the mean biomass per hectare.

Similar procedure is used for the Cerrado biome. The Cerrado deforestation rate in 2020 is the mean deforestation rate between 1999 and 2008. The 2020 projected emissions in the BAU scenario for the Cerrado biome is a result of the multiplication of the projected deforestation rate in 2020 by the mean biomass per hectare.

The projected emission in PNMC scenario for the Amazon and Cerrado biomes are the product of the projected deforestation rate in 2020 for each biome, reduced by 80% and 40%, respectively, by the mean biomass per hectare in the biome. The factor of conversion from C to CO_2 is 3.67.

There is no goal of reduction on CO_2 emission for the other biomes (Atlantic Forest + Caatinga + Pampa + Pantanal). According to de Decree 7390/2010, emissions in 2020 are equal to the emissions in 2005. The sum of the projected emissions for Amazonia, Cerrado and the other biomes is the Brazilian land use change emissions from 2020 for each scenario.

2.3. Results

2.3.1. Land use carbon emissions and sinks

Original carbon content of native vegetation of Brazil's biomes amounted to 96.4 Pg-C: 68.3 Pg-C for the Amazon biome, 11.2 Pg-C for the Cerrado, 13.1 Pg-C for the Atlantic Forest, 2.4 Pg-C for the Caatinga, 0.84 Pg-C for the Pantanal, and 0.45 Pg-C for the Pampas. Leite et al. (2012) estimated that the Brazilian original vegetation biomass ranges from 82 to 149.6 Pg-C, range that comprehends my estimated original biomass. The biomass of the Amazonia and Atlantic Forest biomes estimated in this study is within the range estimated by Leite et al. (2012), which is 68.4 ± 17.1 Pg-C and 17.6 ± 6.2 Pg-C, respectively. For the Pampas, Caatinga and Cerrado, my biomass estimative is, respectively, 65%, 29% and 47% lower than that used by Leite et al. (2012). On the other hand, the Pantanal biomass estimated in this study was greater (~29%) than that estimated by Leite et al. (2012).

My estimate of the original carbon content is different from this obtained from Leite et al. (2012) because different methodologies were used to make the original biomass maps. While Leite et al. (2012) combined the RadamBrasil and IBGE (2004) vegetation maps, I used only the RadamBrasil vegetation map because it has more preserved areas than the later vegetation maps. In addition, Leite et al. (2012) used the carbon stock on vegetation from the Second National Communication of Brazil to the UNFCCC while I used the data from the Third National Communication. For the Third National Communication, new biomass allometric equations and other data obtained in the literature, such as the diameter at breast height and tree height, were included.

My original aboveground biomass map has biomass values larger than that presented by Saatchi et al. (2011). Similar observation was also made by Aguiar et al. (2012). According to Aguiar et al. (2012), maps based on field data have higher estimate of biomass due to interpolation into the phytophysionomies polygon. At the same time, the difference between my original aboveground biomass map increase since remote sensing based maps tend to underestimate the biomass due to the scale of analysis and the sensitivity of the method.

Until 1985, the biomes with the larger deforestation rates ($\Delta ALU > 0$) were Cerrado and Atlantic Forest (Fig. 2.4a). After 1985, deforestation rate in Cerrado and Atlantic forest decrease while there is an increase in the areas with vegetation growth ($\Delta ALU < 0$; Fig. 2.4b). In this period, Amazon has the largest deforestation rate.

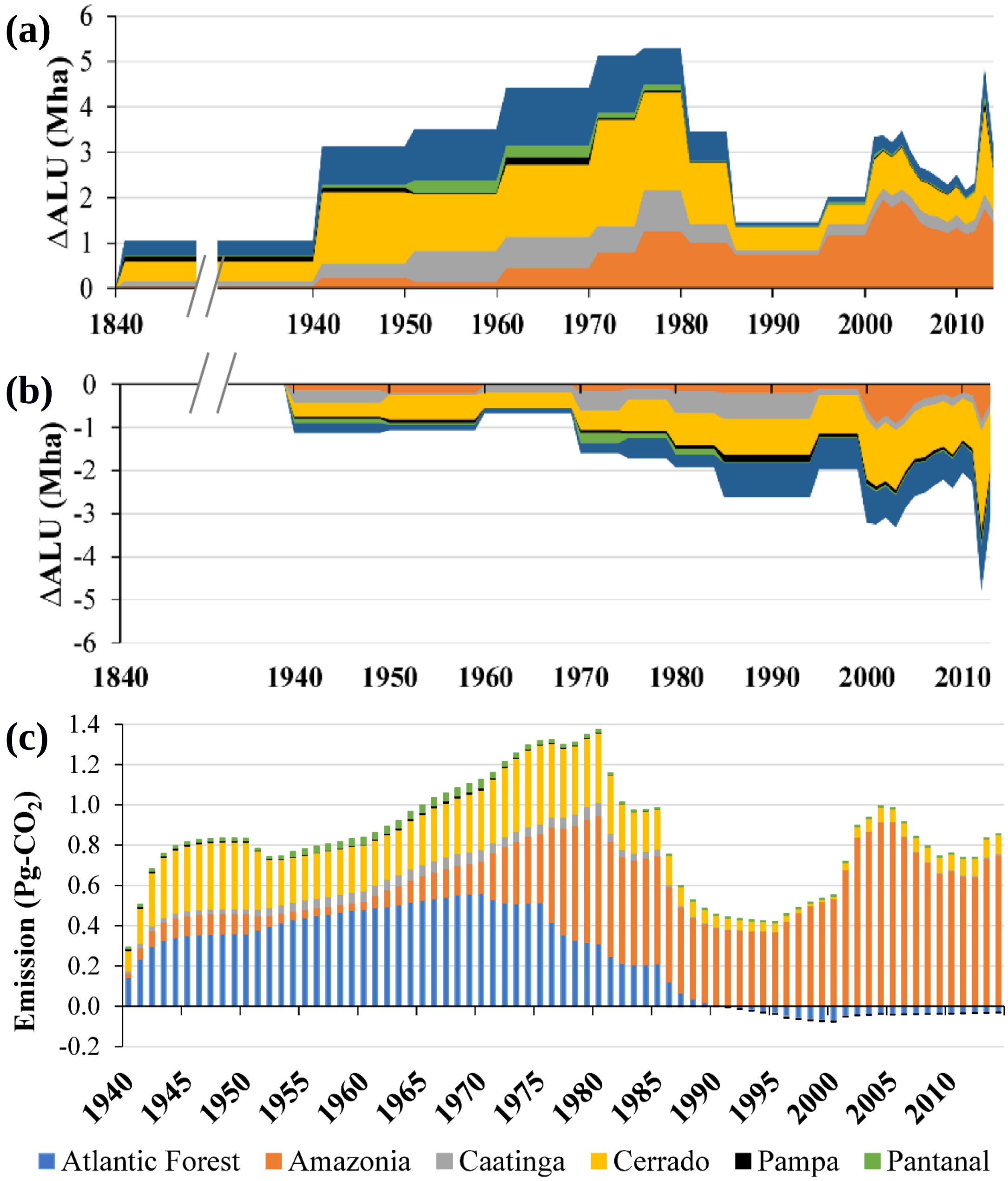

Fig. 2.4 Change in agricultural area results in (a) deforestation from agriculture expansion (ΔALU > 0) in million hectares, (b) secondary vegetation grow from agriculture abandonment (ΔALU < 0) in million hectares, and (c) CO_2 emission between 1940 and 2014 for each biome.

The periods with constant rates of changes in the agricultural area in Fig. 2.4a and 2.4b is a result of the simple linear regression (Section 1.2.4 in Chapter 1) that was performed to produce the data between the years of the agricultural census, which was used to produce the agricultural land use maps.

The estimated Brazilian agricultural land use emissions are presented in the Fig. 2.4c and Table 2.2. Before 1940, 28 Pg-CO_2 were emitted in the entire country. The greatest Brazilian land use emission from agriculture expansion occurred in 1980, when emissions reached 1.4 Pg-CO_2. After that, agricultural land use emissions decreased until 1995, reaching the lowest value since 1940 (0.38 Pg-CO_2).

The methodology used to produce the agricultural land use maps explain why there is not a peak of emission in 1995, despite the high Amazonian deforestation in this year according to the PRODES project (Program for the Annual Estimation of Deforestation in the Brazilian Amazon). According to the agricultural survey, there was a decrease in agricultural area between 1985 and 1995, leading to the decrease in emissions, which reached in 1995 the lowest value since 1940.

The high emissions in 2013 and 2014 also stand out in Fig. 2.4c, and need to be carefully analyzed. The detection of the tree cover may have been influenced by the switch of the remote sensing platform to Landsat 8, which is in orbit since 2013 and has a different combination of spectral bands and a higher radiometric resolution when compared with its predecessors. This higher radiometric resolution may have changed the sensitivity of the algorithm to detect areas occupied by anthropic activities. It cannot be ruled out the possibility that these more recent data of land use change are more accurate than the previous ones.

Until 1975, Atlantic Forest and Cerrado were the main source of land use change emissions (Fig. 2.4c). After that, Amazonia took the first position as a source of CO_2 emissions. Emissions from land use change in Atlantic Forest and Pampas decreased gradually after 1975 and these biomes become a sink of CO_2 since 1990 (Fig. 2.4c and Table 2.2). All biomes had areas that behaved like sinks of CO_2 (Table 2.3). Although

Cerrado has more areas with vegetation growth (Fig. 2.4b), the Atlantic Forest biome has a larger biomass and stood out as the main region of CO_2 sink in the country since 1990 (Fig. 2.4c and Table 2.3). Between 1991 and 2014, Atlantic Forest biome was responsible for the sink of 0.10 Pg-CO_2 year^{-1}, which represents 53% of the total CO_2 sink in Brazil (0.19 Pg-CO_2 year^{-1}, Table 2.3).

Table 2.2: Net emissions of CO_2 associated with agriculture for biomes and Brazilian regions

Biome	Net Emissions (Pg-CO_2)				
	Until 1940	**1941-1965**	**1966-1990**	**1991-2014**	**1941-2014**
Amazonia	2.0	1.9	9.8	15	27
Atlantic Forest	14	10	8.4	-1.1	18
Caatinga	1.1	0.95	1.0	0.049	2.0
Cerrado	10	6.5	6.5	0.97	11
Pampas	0.92	0.15	0.10	-0.055	2.0
Pantanal	0.56	0.52	0.41	0.13	1.1
Center-West	6.3	5.2	7.2	4.7	17
North	1.9	1.1	7.2	10	18
Northeast	3.0	3.7	4.8	1.8	10
South	4.9	3.5	3.6	-0.056	7.1
Southeast	12	6.7	3.5	-1.6	8.5
Total	28	20	26	15	61

Before 1940, the larger emissions occurred in South and Southeast regions, coastline of the Northeast region, Goiás and Mato Grosso do Sul states (Fig. 2.5a and Table 2.2). Between 1945 and 1965, emissions were spread over the national territory, although large emissions centers in western São Paulo, northern Paraná and southern Bahia can be observed (Fig. 2.5b-c).

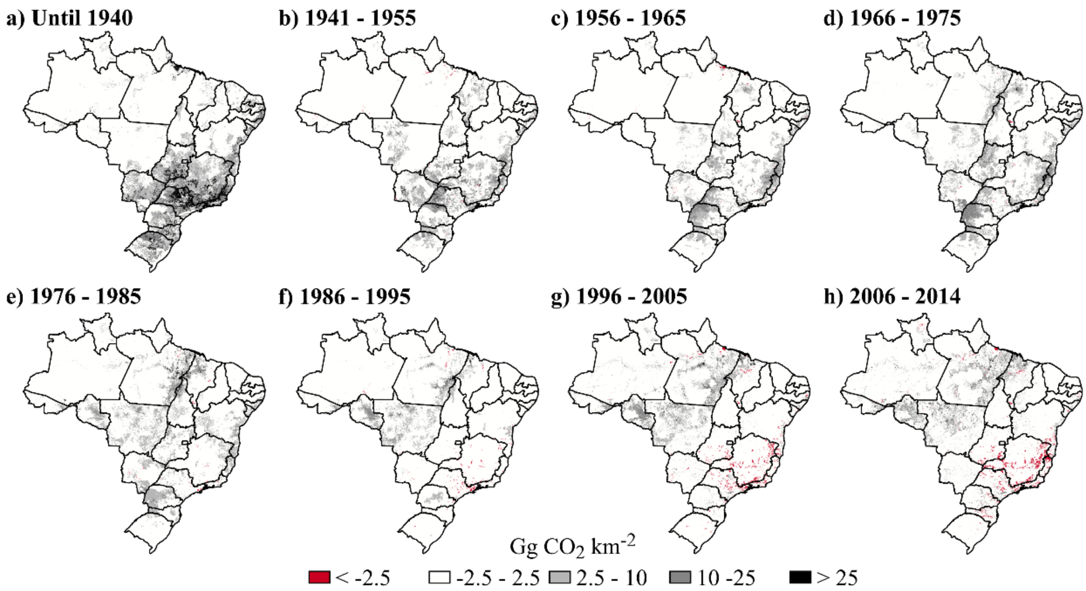

Fig. 2.5: The distribution and intensity of total CO_2 emissions from land use change caused by agricultural activity in Brazil (a) until 1940, (b) between 1941 and 1955, (c) between 1956 and 1965, (d) between 1966 and 1975, (e) between 1976 and 1985, (f) between 1986 and 1995, (g) between 1996 and 2005, and (h) between 2006 and 2014. The map data corresponds to the sum of the emissions during the period.

In 1970, the Brazilian government announced the National Integration Program (*Programa de Integração Nacional*) that aimed at extending the highway network northward. Between 1966 and 1975, new centers of emissions can be found as consequence of the occupation in Tocantins and eastern Pará, where the Belém-Brasília (BR-010) highway is located (Fig. 2.5d). New centers of emissions can be found in Rondônia and Acre, which are connected by the Cuiabá-Porto Velho (BR-364) highway, and central Pará, crossed by the Trans-Amazonian (BR-230; Fig. 2.5e) between 1976 and 1985 (Fig. 2.5e). Emission along the Cuiabá-Santarem (BR-163) highway, which is located in center of Pará, is evident in Fig. 2.5e.

From 1985 onwards, emissions are concentered in Center-West and North regions (Fig 2.5f-h and Table 2.2). On the other hand, emissions decreased in South, Southeast and Northeast regions while CO_2 sink increased between 1985 and 2014 (Fig. 2.5f-h and Table 2.2). In the last 30 years of study, the larger sinks of CO_2 are concentered in eastern Goiás, southern Bahia and the Southeast region (Fig. 2.5f-h).

Table 2.3: Emissions of CO_2 associated with agriculture expansion and sinks of CO_2 associated with agriculture contraction for biomes and Brazilian regions

Biome/ Region	Until 1940	1941-1965	1966-1990	1991-2014	1941-2014
	(Pg-CO_2)	(Pg-CO_2 yr^{-1})			
Sources					
Amazonia	2.0	0.084	0.39	0.63	0.36
Atlantic Forest	14	0.40	0.35	0.054	0.27
Caatinga	1.1	0.039	0.044	0.012	0.032
Cerrado	9.8	0.27	0.27	0.096	0.22
Pampas	0.91	0.0064	0.0044	0.001	0.0041
Pantanal	0.55	0.022	0.018	0.0075	0.016
Center-West	6.3	0.22	0.29	0.22	0.24
North	2.0	0.052	0.29	0.42	0.26
Northeast	3.0	0.15	0.2	0.11	0.15
South	4.9	0.14	0.15	0.022	0.11
Southeast	12	0.27	0.15	0.022	0.15
Total	28	0.84	1.1	0.83	0.91
Sinks					
Amazonia	0.0	-0.0096	-0.0056	-0.019	-0.011
Atlantic Forest	0.0	-0.0068	-0.013	-0.10	-0.039
Caatinga	0.0	-0.0011	-0.0024	-0.01	-0.014
Cerrado	0.0	-0.0076	-0.014	-0.054	-0.026
Pampas	0.0	-0.00034	-0.00056	-0.0033	-0.0014
Pantanal	0.0	-0.00052	-0.0014	-0.0021	-0.00013
Center-West	0.0	-0.006	-0.0068	-0.028	-0.013
North	0.0	-0.0076	-0.0044	-0.019	-0.010
Northeast	0.0	-0.0039	-0.0072	-0.031	-0.0097
South	0.0	-0.0026	-0.0030	-0.024	-00097
Southeast	0.0	-0.0056	-0.015	-0.087	-0.036
Total	0.0	-0.026	-0.036	-0.19	-0.082

2.3.2. Emissions from enteric fermentation and manure management

Between 1975 and 1984, the regions with highest emissions are western São Paulo, northern Paraná, central Goiás and Pampas (located in southern Rio Grande do Sul; Fig. 2.6a). In this period, emissions of CH_4 were concentered in Atlantic Forest and Cerrado biomes (Table 2.4). The CH_4 emissions increased in the entire country and new centers of emissions are found in Rondônia, Pará and Roraima between 1985 and 1994 (Fig. 2.6b).

Between 1995 and 2004, emission from enteric fermentation and manure management increased in Acre and eastern Pará (Fig. 2.6c). Emission in the Amazonia biome more than doubled (from 7.9 to 17 Pg-CO_2) in the period 1995-2004 in relation to the period 1985-1994 (Table 2.4). The highest emissions for the period from 2005 to 2014 are found in Rio Grande do Sul, Paraná, São Paulo, Mato Grosso do Sul, Rondônia, Goiás, eastern Pará and Atlantic coastline in Southeast and Northeast regions (Fig 2.6d).

Table 2.4: Emissions of CH_4 from enteric fermentation and manure management for biomes and Brazilian regions

Biome	Net Emissions (Tg-CH_4)				
	1975-1984	1985-1994	1995-2004	2005-2014	1975-2014
Amazonia	3.6	7.9	17	28	56
Atlantic Forest	25	27	28	29	108
Caatinga	6.7	7.6	6.3	6.9	28
Cerrado	21	30	35	38	123
Pampas	5.6	5.9	6.0	6.1	24
Pantanal	1.7	1.8	2.4	2.8	8.7
Center-West	16	24	32	36	108
North	3.4	6.9	13	21	45
Northeast	12	14	13	15	54
South	13	15	16	17	61
Southeast	19	20	20	20	80
Total	63	80	94	110	347

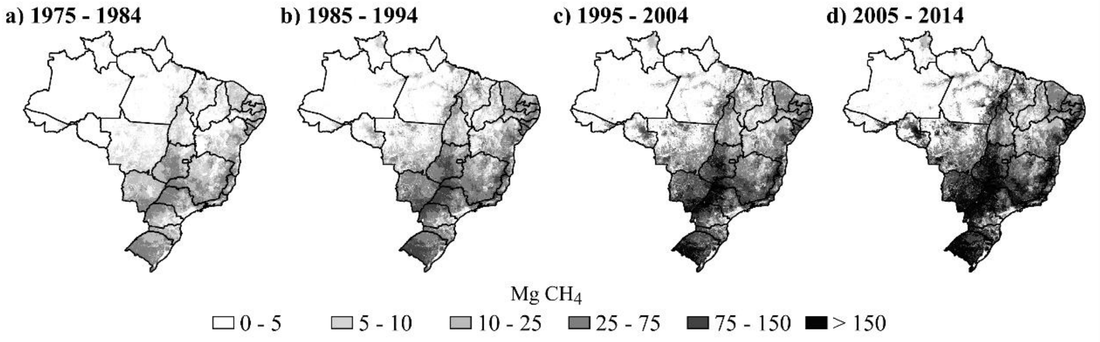

Fig 2.6: The distribution and intensity of CH_4 emissions from enteric fermentation and manure management for the period (a) 1975-1984, (b) 1985-1994, (c) 1995-2004, and (d) 2005-2014. The map data corresponds to the sum of the emissions during the period.

2.3.3. Direct N_2O emissions from agricultural soils

Although it still accounts for a small portion of total agricultural activity GHG emissions in Brazil, N_2O emissions from synthetic nitrogen fertilizers have been quickly increasing (Fig. 2.7 and Table 2.5). Between 1975 and 2014, South and Southeast concentered the greatest part of the synthetic fertilizers emissions (Table 2.5).

Table 2.5: Emissions of N_2O from synthetic nitrogen fertilizer for biomes and Brazilian regions

Biome	Net Emissions (Tg-N_2O)				
	1975-1984	1985-1994	1995-2004	2005-2014	1975-2014
Amazonia	0.00060	0.0012	0.0089	0.018	0.028
Atlantic Forest	0.048	0.062	0.10	0.17	0.39
Caatinga	0.0047	0.0062	0.0099	0.017	0.038
Cerrado	0.024	0.032	0.065	0.13	0.25
Pampas	0.0061	0.0089	0.013	0.029	0.058
Pantanal	0.00010	0.00020	0.0011	0.0044	0.0059
Center-West	0.0069	0.010	0.033	0.078	0.13
North	0.00020	0.00020	0.0024	0.0058	0.0087
Northeast	0.0086	0.011	0.019	0.034	0.073
South	0.025	0.034	0.060	0.11	0.23
Southeast	0.043	0.055	0.088	0.14	0.33
Total	0.084	0.11	0.20	0.37	0.77

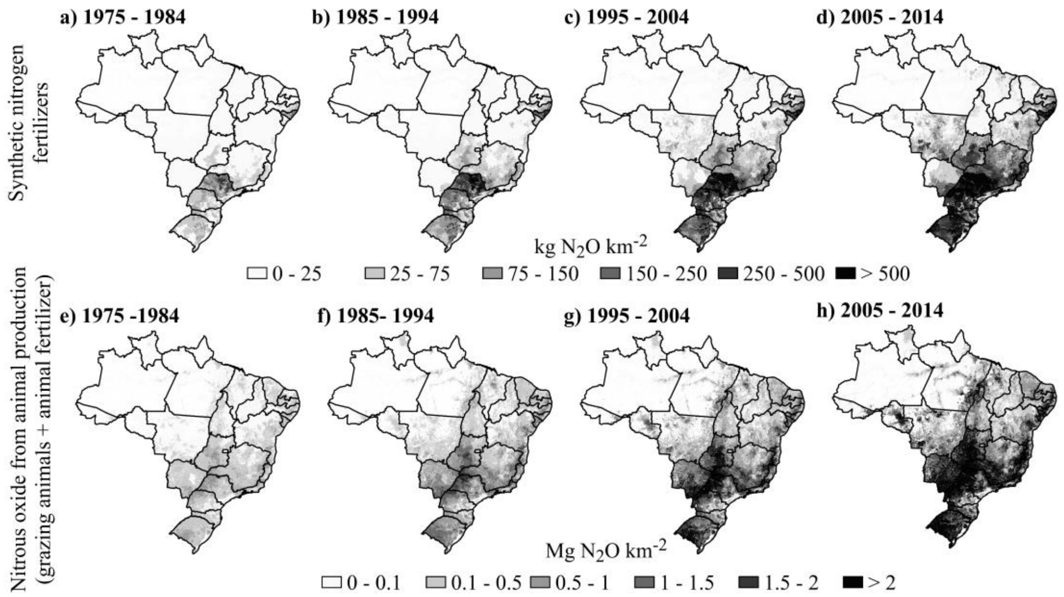

Fig. 2.7: The distribution and intensity of N_2O emissions from synthetic nitrogen fertilizers used in agriculture for the periods (a) 1975-1984, (b) 1985-1994, (c) 1995-2004, and (d) 2005-2014, and from grazing animals and manure used as fertilizes for the years of (e) 1975-1984, (f) 1995-1994, (g) 1995-2004, and (h) 2005-2014. The map data corresponds to the sum of the emissions during the period.

Since 1975-1984, São Paulo state presents the highest centers of N_2O emissions (Fig. 2.7a). Between 1985 and 1994, emissions from synthetic nitrogen fertilizers increased in Goiás and Northeast region, especially in Alagoas (Fig. 2.7b). Emissions also increased in entire South region, center of Goiás, Mato Grosso, Mato Grosso do Sul and central Bahia between 1995 and 2004 (Fig. 2.7c). Between 1996 and 2014, the highest emissions were found in South and Southeast regions, central Goiás and Alagoas (Fig 2.7d).

N_2O from animal production, which is the sum of the emission from grazing animals and the use of manure as fertilizer, are the main direct N_2O emission from agricultural soils. N_2O emissions from grazing animals represents ~96% for the total emissions from animal production, while the use of manure as fertilizer represents ~4% of those total.

Between 1975 and 1984, N_2O emissions from animal production was spread over the national territory (Fig 2.7e), but Southeast and Center-West regions stood out with the greatest total emissions in the period (Table 2.6). High emissions can be found in northern Paraná, western São Paulo, Mins Gerais and central Goiás between 1985 and 1994. In this period, N_2O emissions from animal production substantially increased in North and Center-West regions (Fig. 2.7f). For 1995-2004, emissions in Acre, Rondônia, Pará and northern Mato Grosso become more intense (Fig. 2.7g). Rio Grande do Sul, São Paulo, Paraná, Mato Grosso do Sul, Goiás, Minas Gerais, Rondônia, eastern Pará and Atlantic coastline in Southeast and Northeast regions stood out as the main N_2O emissions between 2005 and 2014 (Fig 2.7h).

Table 2.6: Emissions of N_2O from grazing animals and manure used as fertilizers for biomes and Brazilian regions

Biome	**Net Emissions (Tg-N_2O)**				
	1975-1984	**1985-1994**	**1995-2004**	**2005-2014**	**1975-2014**
Amazonia	0.051	0.12	0.23	0.39	0.79
Atlantic Forest	0.34	0.37	0.39	0.41	1.5
Caatinga	0.090	0.10	0.093	0.11	0.39
Cerrado	0.30	0.42	0.49	0.54	1.7
Pampas	0.067	0.070	0.069	0.069	0.27
Pantanal	0.023	0.025	0.032	0.039	0.12
Center-West	0.22	0.33	0.44	0.52	1.5
North	0.052	0.11	0.19	0.31	0.65
Northeast	0.16	0.19	0.18	0.22	0.76
South	0.17	0.18	0.20	0.21	0.75
Southeast	0.28	0.29	0.29	0.30	1.2
Total	0.87	1.1	1.3	1.6	4.8

2.3.4. Indirect N_2O emissions from agricultural soils

Indirect N_2O emissions from atmospheric deposition of nitrogen volatilized from synthetic nitrogen fertilization applied in crop fields and animal manure are presented in Fig. 2.8a-d and Table 2.7.

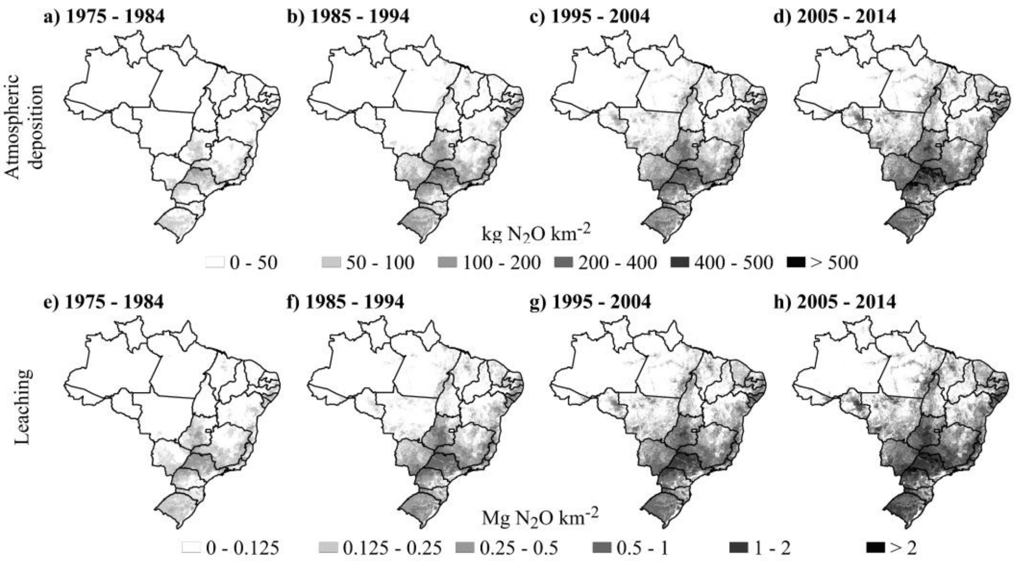

Fig 2.8: The distribution and intensity of N_2O emissions from atmospheric deposition for the period (a) 1975-1984, (b) 1985-1994, (c)1995-2004, and (d) 2005-2014, and from leaching or runoff for the period (e) 1975-1984, (f) 1985-1994, (g) 1995-2004, and (h) 2005-2014. The map data corresponds to the sum of the emissions during the period.

Table 2.7: Emissions of N_2O from atmospheric deposition for biomes and Brazilian regions

Biome	Net Emissions (Tg-N_2O)				
	1975-1984	1985-1994	1995-2004	2005-2014	1975-2014
Amazonia	0.0070	0.016	0.034	0.058	0.11
Atlantic Forest	0.059	0.068	0.080	0.10	0.31
Caatinga	0.014	0.016	0.015	0.019	0.063
Cerrado	0.048	0.066	0.083	0.11	0.30
Pampas	0.011	0.012	0.013	0.017	0.053
Pantanal	0.0031	0.0034	0.0046	0.0064	0.018
Center-West	0.031	0.048	0.068	0.090	0.24
North	0.0070	0.014	0.026	0.043	0.090
Northeast	0.024	0.029	0.029	0.039	0.12
South	0.030	0.035	0.043	0.058	0.17
Southeast	0.050	0.055	0.063	0.079	0.25
Total	0.14	0.18	0.23	0.31	0.86

Between 1975 and 1984, the centers with the greatest emissions were concentered in northwest of São Paulo and northwest of Paraná (Fig. 2.8a). Lower emissions were found in Rio Grande do Sul, Minas Gerais, Goiás, Rio de Janeiro, Espírito Santo and Northeast region coastline. For the period 1985-1994, N_2O emissions from atmospheric deposition intensified in São Paulo, Paraná and center of Goiás (Fig. 2.8b). New emission regions stood out in Mato Grosso, Rondônia, eastern Pará, Tocantins and Maranhão between 1995 and 2004 (Fig 2.8c). Between 2005 and 2014, São Paulo and Paraná stood out with the highest emissions (Fig 2.8d). Between 1975 and 2014, Southeast, South and Center-West regions had the greater indirect N_2O emissions from atmospheric deposition (Table 2.7).

Leaching is the largest source of indirect N_2O emission. The amount of N_2O emitted from leaching is growing quickly in Brazil since 1975 (Table 2.8). During the period of study (1975-2014), Southeast and Center-West regions had the greatest emissions (Table 2.8), as well Atlantic Forest and Cerrado biomes.

Between 1975 and 1984, N_2O emissions from leaching were concentered in Rio Grande do Sul, Paraná, Southeast region, Goiás, and southern Bahia (Fig. 2.8e). Between 1985 and 1994, emissions increased in Tocantins, east of Pará, Maranhão, southern Mato Grosso, Mato Grosso do Sul, Rondônia, and central Bahia (Fig. 2.8f). São Paulo and central Goiás stood out as regions with the highest indirect N_2O emissions from leaching between 1995 and 2004 (Fig. 2.8g). Finally, indirect N_2O emissions from leaching increased in all previously stablished areas between 2005 and 2014 (Fig. 2.8h).

Table 2.8: Emissions of N_2O from leaching for biomes and Brazilian regions

Biome	Net Emissions (Tg-N_2O)				
	1975-1984	1985-1994	1995-2004	2005-2014	1975-2014
Amazonia	0.026	0.059	0.13	0.22	0.43
Atlantic Forest	0.22	0.25	0.30	0.38	1.2
Caatinga	0.050	0.059	0.057	0.070	0.24
Cerrado	0.18	0.25	0.31	0.40	1.1
Pampas	0.041	0.045	0.049	0.064	0.19
Pantanal	0.012	0.013	0.017	0.024	0.066
Center-West	0.12	0.18	0.26	0.34	0.89
North	0.026	0.053	0.098	0.16	0.34
Northeast	0.088	0.11	0.11	0.15	0.45
South	0.11	0.13	0.16	0.22	0.62
Southeast	0.19	0.21	0.24	0.29	0.92
Total	0.53	0.68	0.86	1.2	3.2

2.3.5. Total emissions

Net emissions from land use change is the largest source of GHG from agricultural activity among the sources analyzed (Fig. 2.9a), but emissions from agriculture sector increased between 1975 and 2014. Total emissions from agriculture was 1.5 Pg-CO_{2eq} in 1975 and raised to ~1.6 Pg-CO_{2eq} in 1980. After 1980, total emissions decreased, reaching the lower value (0.6 Pg-CO_{2eq}) in 1995. Until 2014, emission values increased, reaching 1.1 Pg-CO_{2eq} (Fig 2.9a).

GHG emissions from agriculture sector was 11% of the total emission in 1975 and accounted between 30 and 40% of the total emissions between 1985 and 2014 (Figure 2.9b). Between 1991 and 2014, emissions from agricultural sector accounted for 0.29 Pg-CO_2 year^{-1}.

The CH_4 emission has been constantly increasing in a growing rate of 3.2 Tg-CO_2 between 1975 and 2014 (Fig. 2.9c), reaching 0.23 Pg-CO_2 in 2014. Enteric fermentation emissions is 41-times larger than manure management emissions. Enteric fermentation is also the largest source of GHG from agricultural sector among all sources analyzed.

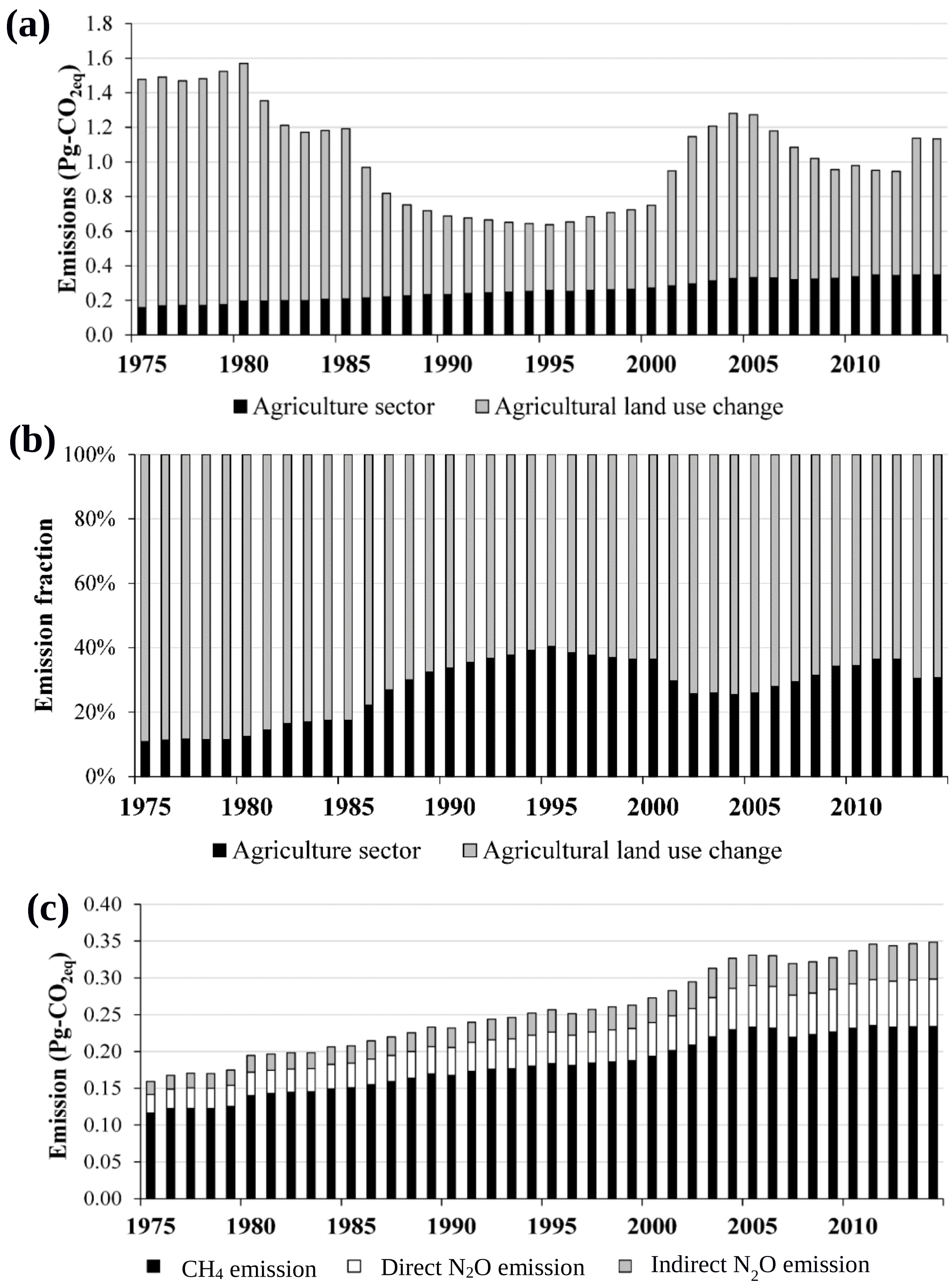

Fig. 2.9: Emissions from agriculture sector (CH_4 and N_2O) from 1975 to 2014 (a) with the estimated emissions from land use change, (b) in terms of relative participation in the total agricultural emissions, and (c) disaggregated in CH_4, direct and indirect N_2O emissions.

The total N_2O emissions (direct + indirect) have been increasing in a rate of 1.8 Tg-CO_2, reaching 0.12 Pg-CO_2 in 2014. The N_2O direct emissions are ~40% greater than the indirect emissions during all period of study (Fig. 2.9c).

2.3.6. Trend analysis in emissions data

The overarching result is that emissions due to changes in land use are decreasing, while emissions due to agriculture sector are increasing (Fig. 2.10). Between 1975 and 1994, agricultural land use change (CO_2) emissions decreased in entire Brazil, except Mato Grosso do Sul, Mato Grosso, Rondônia, and Pará (Fig. 2.10a). The national CH_4 (Fig. 2.10b) and N_2O (Fig. 2.10c) emissions increased, except in eastern Brazil. Because the CO_2 emissions area several times larger than the CH_4 and N_2O emissions, the total agricultural emissions are also decreasing (Fig. 2.10d). Eastern Mato Grosso is a special case where the decrease in the CO_2 emissions and the increase in the CH_4 and N_2O have the same magnitude, causing no trends in this region (Fig. 2.10d).

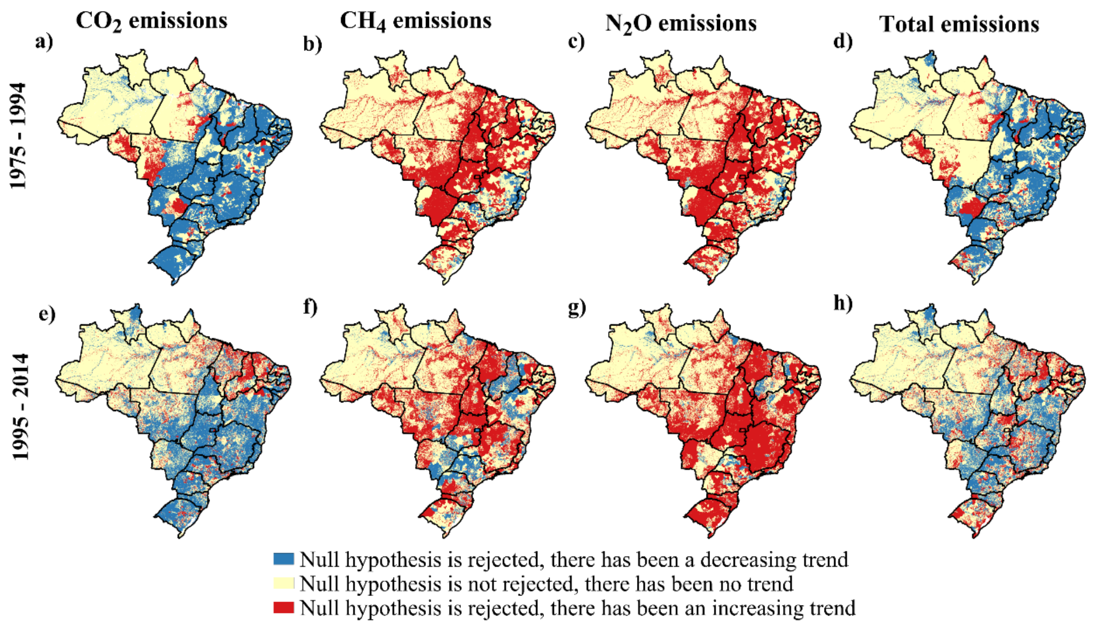

Fig 2.10: Mann-Kendall trend test for the period between 1975 and 1994 for (a) CO_2, (b) CH_4, (c) N_2O, and (d) total emissions (in terms of CO_{2eq}) and for the period between 1995 and 2014 for (e) CO_2, (f) CH_4, (g) N_2O, and (h) total emissions (in terms of CO_{2eq}).

The agricultural land use change emissions also decreased in the most part of the Brazilian territory between 1995 and 2014. Increasing trends are found in Northeast region, except Bahia (Fig. 2.10e). On the other hand, CH_4 emissions increased in the entire country. Decreasing trends are found in Paraná, São Paulo, Mato Grosso do Sul, southern Goiás, Bahia and Piauí (Fig 2.10f). N_2O emission are predominantly increasing in Brazil (Fig. 2.10g).

Total emissions are decreasing in Brazil between 1995 and 2014, but more areas are increasing when compared with the 1975-1994 period. Increasing emissions are found in Rio Grande do Sul, western Minas Gerais, western Mato Grosso do Sul, northern Goiás, and part of the Northeast region (Fig. 2.10h). Moreover, the ratio of emissions by changes in land use to emissions by the agriculture activity decreased from 4.6:1 in 1975-1994 to 2.1:1 in 1995-2014.

2.3.7. Future emissions according to PNMC goals

For 2005, Amazonian deforestation rate were similar in PNMC (1.9 Mha $year^{-1}$) and this study (1.8 Mha $year^{-1}$; Table 2.9). However, my estimate deforestation rate in 2020 is 17% lower than the 2005 deforestation rate for Amazon while PNMC estimates the Amazonian deforestation rate 5% greater than the 2005 deforestation rate. For the Cerrado, my estimated deforestation rate in 2005 is 56% lower than the rate considered in the Decree. Both this study and PNMC have estimated an increase of less than 10% in the rate of deforestation by 2020 (Table 2.9).

Using the mean biomass of 132 Mg-C ha^{-1} for Amazonia and 56 Mg-C ha^{-1} for Cerrado, the official (PNMC) estimated emissions in 2020 according to the BAU scenario are 0.95 Pg-CO_2 for Amazonia and 0.32 Pg-CO_2 for Cerrado (Table 2.9 and Fig. 2.11a-b). The sum of the official estimated emissions in 2020 for Atlantic Forest,

Table 2.9: Summary of the estimated emissions in 2020 for the PNMC data and this study data

Biome	PNMC data and scenarios					This study				
	Deforestation (Mha/year)		Mean Biomass (Mg-C/ha)	Emissions ($Pg\text{-}CO_2$)		ΔALU (Mha/year)		Mean Biomass (Mg-C/ha)	Emissions ($Pg\text{-}CO_2$)	
	2005	2020*		BAU*	2020*	2005	2020*		BAU*	2020*
Amazonia	1.9	2.0	132	0.95	0.19	1.8	1.5	162	0.89	0.18
Cerrado	1.4	1.5	56	0.32	0.19	0.69	0.70	54	0.14	0.085
Atlantic Forest				0.079**	0.079**				0.074**	0.074**
Caatinga				0.038**	0.038**				0.012**	0.012**
Pampas				-	-				0.00091**	0.00091**
Pantanal				0.016**	0.016**				0.0072**	0.0072**
Total				1.4	0.52				1.1	0.36

*scenarios.

** According to de Decree 7390/2010, these estimated emissions in 2020 are equal to the emissions in 2005.

Caatinga and Pantanal are 0.13 Pg-CO_2. Deforestation rate in Pampas was not considered in the Decree 7390/2010. The final reduction in the Brazilian emission stipulated for 2020 is 63% (from 1.4 to 0.52 Pg-CO_2; Table 2.9 and Fig. 2.11c).

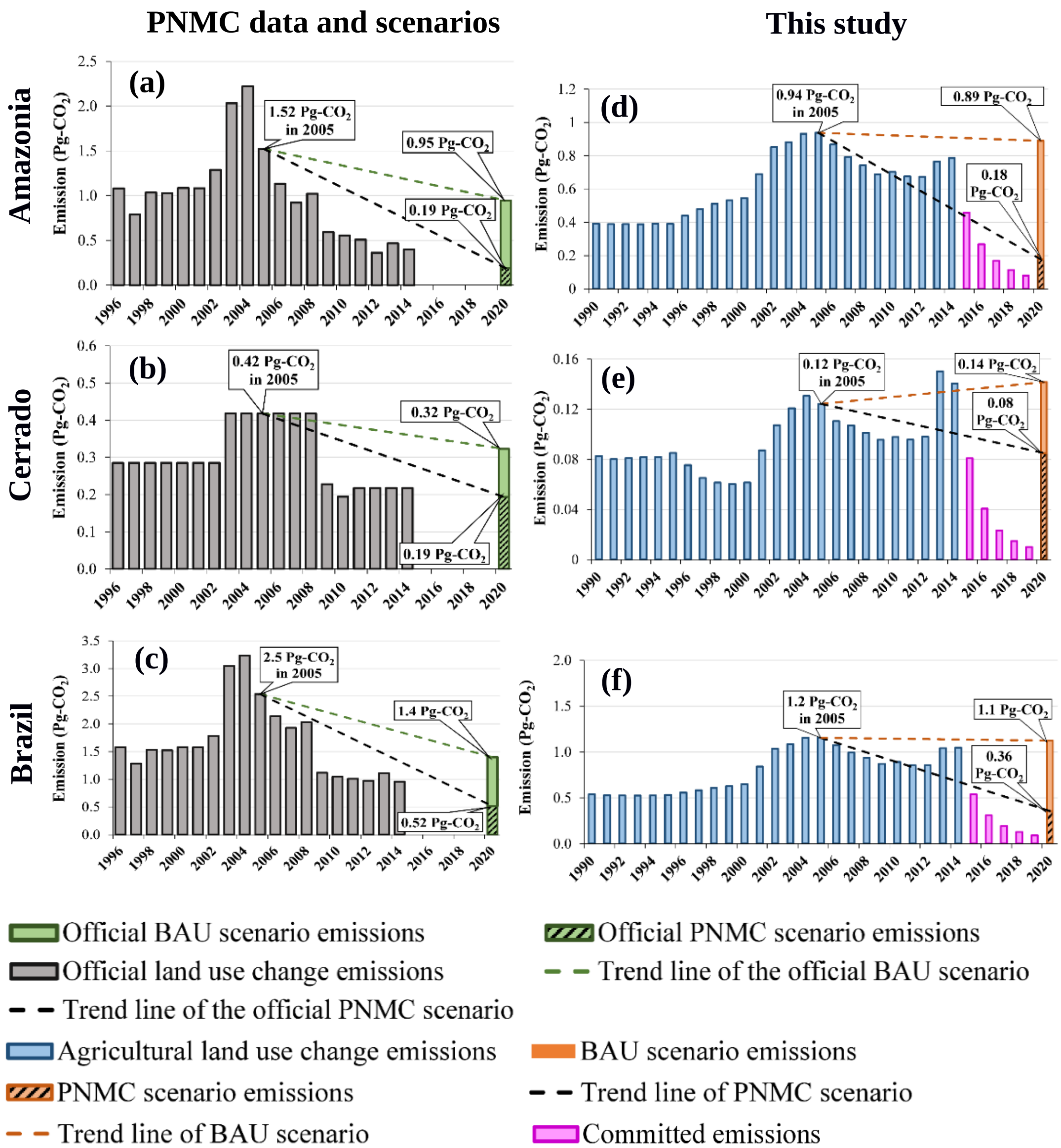

Fig. 2.11: Land use change emissions according the Third Edition of the Annual Estimates of GHG Emissions Report (in gray), emissions projected according a "business as usual" scenario for 2020 (BAU scenario, in green) and emissions projected according the PNMC goals for the year 2020 (in green and hatched) for (a) Amazon, (b) Cerrado, and (c) Brazil and agricultural land use change emissions of this study of ΔALU>0 (in blue), committed emissions from pre-2015 deforestation (in purple), emissions projected according a BAU scenario (in orange) and emissions projected according the PNMC goals (in orange and hatched) for the year 2020 for (d) Amazon, (e) Cerrado, and (f) Brazil.

In BAU scenario, Amazon emissions decrease from 0.94 Pg-CO_2 in 2005 to 0.89 Pg-CO_2 in 2020 (Fig. 2.11d). With reduction of 80% in Amazon deforestation (PNMC scenario), emissions decrease from 0.94 Pg-CO_2 in 2005 to 0.18 Pg-CO_2 in 2020. Between 2006 and 2010, estimated emissions from agriculture land use change were below the trend line, while between 2011 and 2014, the emissions were above the trend line (Fig. 2.11d).

The Cerrado emissions according to BAU scenario increase from 0.12 Pg-CO_2 in 2005 to 0.14 Pg-CO_2 in 2020 (Fig. 2.10e). With reduction of 40% in Cerrado deforestation (PNMC scenario), emissions in 2020 are targeted to increase only to 0.08 Pg-CO_2. Similar to Amazonia, estimated emissions from agriculture land use change were below the trend line between 2006 and 2012 (Fig. 2.11e), but above in 2013 and 2014.

The methodology used to estimate the official emissions considers that all biomass removed in a year is released immediately to the atmosphere. In this study, part of the lost biomass is released to atmosphere immediately and the rest released at a decaying exponential rate. Because of these differences between the methodologies, I estimate that the BAU scenario emissions of this study is lower than the official BAU scenario emissions. This is evident, for example, when comparing my Amazonian emission estimates (Fig. 2.11d) and the official ones (Fig. 2.11a) between 2002 and 2004.

In addition to the different method to calculate CO_2 emissions, I estimate both the emissions for Caatinga and Pantanal and the Cerrado deforestation rate lower than that informed in the Decree 7390/2010. Then, I estimate that the agricultural land use change emission in BAU scenario will be 1.1 Pg-CO_2 (Table 2.9), which is lower than the 1.4 Pg-CO_2 reported in the Decree 7390/2010.

In BAU scenario, Brazilian emissions decrease from 1.2 Pg-CO_2 in 2005 to 1.1 Pg-CO_2 in 2020 (Fig. 2.10e). With reduction of 80% in Amazon deforestation and 40% in Cerrado deforestation (PNMC scenario), emissions in 2020 decrease from 1.2 Pg-CO_2 in 2005 to 0.36 Pg-CO_2. The reduction on Amazon and Cerrado deforestation will lead to a reduction on 70% of the emissions projected for the BAU scenario and 60% of the emissions reported in the Decree 7390/2010.

Between 2006 and 2011, estimated emissions from agriculture land use change in Brazil were below the trend line (Fig. 2.11f). Between 2012 and 2014, my estimated land use emissions for the entire Brazil were about 25% larger than the limit, but ~44% lower than the emission projected for a future without intervention to reduce deforestation (Fig. 2.11f). As previously discussed (Section 2.3.1), the detection of the tree cover may have been influenced by the switch of the remote sensing platform to Landsat 8, which is in orbit since 2013 and has a different combination of spectral bands and a higher radiometric resolution when compared with its predecessors. This higher radiometric resolution may have change the sensitivity of the algorithm to detect areas disturbed by anthropic activities. It cannot be ruled out the possibility that these more recent data of land use change are more accurate than the previous ones.

According to my methodology, the sum of the committed emissions between 2015 and 2020 is 0.56 Pg-CO_2 in Amazonia and 0.29 Pg-CO_2 in the Cerrado (Fig. 2.11d-e). The whole country was, in 2014, already committed to 1.32 Pg-CO_2 and, in order to emissions stay below the trend line of the PNMC scenario, countrywide deforestation can not exceed 3.2 Mha between 2015 and 2020 (0.93 Mha in Amazonia, 1.5 Mha in Cerrado, and 0.47 Mha elsewhere; Fig. 2.11f).

2.4. Discussion

Land use change and agriculture sectors were responsible for ~68% of the national emissions in 2015 and, therefore, agriculture activity is the main target activity for actions to mitigate GHG emissions in Brazil. In relation to previous studies, this work expands the estimates of GHG emissions from agricultural land use beyond Amazonia and Cerrado, providing annual data for the entire Brazil from 1940 to 2014. This work also complements the Third National Communication data, presenting the spatial explicit disaggregation data and updating to include a larger time period.

Land use emissions were concentrated in the Atlantic Forest and Cerrado until 1975. After that, regions sources of emissions moved from west, following the agriculture expansion. Nowadays, Atlantic Forest and Pampas are sinks of CO_2 considering the agricultural land use.

Leite et al. (2012) estimated that 59.8 Pg-CO_2 (16.2 Pg-C) was emitted until 1985. In this period, I estimated that 73.9 Pg-CO_2 was emitted throughout the country. The difference between my estimate and Leite et al. (2012) is caused by the differences in the original biomass map and in the land use change maps. Although land use change maps in this study and in Leite et al. (2012) were obtained with the same methodology, they are based on different land cover maps.

As reported by Leite et al. (2012), approximately 45% of these emissions came from Atlantic Forest biome deforestation. From 1970 onwards, I estimated that emissions in Amazon accounted from 36% to 60% of the agricultural land use change emissions in Brazil, which is a similar than the estimate emissions from 36% to 65% reported by Leite et al. (2012).

After 1985, it is important to remember the source of agricultural land use data used to interpret the results. In Chapter 1, I reconstructed the historical agricultural land use database based on a combination of remote sensing and agricultural census data. According to the agricultural census data, the area occupied by pasturelands and croplands in Brazil grew until 1985, when it reached 231 Mha. Between 1985 and 1995, there was a decrease in the agricultural area, which reached 219 Mha. Finally, although there was an increase in the agricultural area between 1995 and 2006, the amount of agricultural area in 2006 did not reach the values of 1985. In 2014, the agricultural area was 221 Mha (Chapter 1).

This 10 Mha of agricultural area abandoned between 1985 and 2006 may have had several destinations. One of them is that this area was used for urban expansion. Thus, I use a remote sensing product – the night light map – to reduce the influence of urban areas growth in the calculation of sources and sinks from land use change in this study. Another possible destination for areas abandoned by agriculture is forestry. According to the Brazilian Association of Planted Forest Producers (ABRAF – *Associação Brasileira dos Produtores de Florestas Plantadas*), areas with planted forests grew at a rate of approximately 95,000 ha $year^{-1}$ between 2000 and 2006, and planted forests covered 5.4 Mha in 2006 (ABRAF, 2007). In addition, the MapBiomas project recently accounts a gain of 2.7 Mha of secondary vegetation in Atlantic Forest biome between 2001 and 2015 (MapBiomas, 2017).

Although forestry is based on tree growth – mainly *Eucalyptus* and *Pinus* – and implies in carbon sink, the biomass of forestry trees are smaller than the secondary vegetation in Atlantic Forest. Santana et al (2008) and Gatto et al. (2011) reported that *Eucalyptus* biomass in Southeast and South Brazil varies from 5 Mg ha^{-1} (one year-old) to 290 Mg ha^{-1} (10 year-old), values generally lower than the original biomass found in Atlantic Forest (Fig. 2.2). Since forestry areas have replaced agricultural areas and they are mistakenly considered as secondary vegetation in my study, it is possible that the reported carbon sink is being overestimated in some areas.

Farmers are also reforesting and/or abandoning areas where secondary vegetation is growing, as the bookkeeping model emissions suppose. According to the agricultural census data, the amount of natural forests within rural properties increased from 89 Mha in 1995 to 95 Mha in 2006. The North region was the only region where the amount of natural forests within the agricultural properties decreased, from 26 Mha to 22 Mha. On the other hand, the Northeast, Southeast and South regions had the highest increases in native vegetation areas (6.2, 2.1 and 1.4 Mha, respectively). Natural forest areas for the Central West region remained at approximately 31 Mha between 1995 and 2006. These data confirm my results, which show that a carbon sink is observed for the period between 1996 and 2005 for the Caatinga, Atlantic Forest and Pampas biomes. These biomes are located in the Brazilian regions where there was an increase in native forests within agricultural establishments according to IBGE survey.

This increase in native vegetation was also reported by ABRAF. According to ABRAF, the amount of native forest in Brazil has been increasing mainly for the Atlantic Forest, in the states of Minas Gerais, Espírito Santo, Rio de Janeiro, Bahia, Mato Grosso do Sul, Paraná, Rio Grande do Sul, and Santa Catarina (ABRAF, 2007, 2013). In ABRAF associated agricultural properties, native vegetation occupied 1.3 Mha in 2006 (ABRAF, 2007) and 2.1 Mha in 2012 (ABRAF, 2013).

These findings can be a positive sign for the several Brazilian efforts to reduce deforestation and increase forest restoration. The Forest Code is the main environmental legislation in Brazil and, based in this legislation, Atlantic Forest, central Cerrado and the Amazon have large areas that require restoration (Soares-Filho et al., 2014). The first Brazilian biome to have a strategy to combat deforestation was the Amazon. The Action Plan for Prevention and Control of Deforestation and Burning in Amazonia (PPCDAm – *Plano de Ação para Prevenção e Controle do Desmatamento e das Queimadas no Bioma Amazônia*) was prepared by a working committee instituted in the Decree July 3, 2003. After 3 years, the Federal Law n.11,428/2006 – the "Atlantic Forest Law" – was instituted to provide measures to protect the Atlantic Forest. More recently, federal government has instituted the Action Plan for Prevention and Control of Deforestation and Burning in the Cerrado (PPCerrado – *Plano de Ação para Prevenção e Controle do Desmatamento e das Queimadas no Bioma Cerrado*; Decree September 15, 2010). The decrease in Amazonian deforestation and the possibility of areas being reforested in the Cerrado and Atlantic Forest to comply with existing legislation shows the importance of expanding plans of action and legislation for other biomes to protect them and, consequently, reduce Brazilian GHG emissions.

Between 2003 and 2008, my estimate of the emission of CO_2 due to total agricultural land use change was 5.09 Pg-CO_2 in Amazonia. This value is similar to the 5.14 Pg-CO_2 estimated by Aguiar et al. (2012) and higher than the 3.5 Pg-CO_2 emission related to pastureland establishment according to Bustamante et al. (2012). On the other hand, I estimate an emission of 0.32 Pg-CO_2 in the Cerrado between 2003 and 2008, which is much lower than the 0.82 Pg-CO_2 estimated by Bustamante et al. (2012). My estimated agricultural land use emission for the Cerrado biome between 2003 and 2013 (0.51 Tg-CO_2) was also lower than the amount of CO_2 emission from cropland establishment (0.66 Pg-CO_2) estimated by Noojipad et al. (2017).

Despite the large reduction in Amazonian deforestation rates after 2004, I found a difference of only 0.35 Pg-CO_2 between the estimates for the period 2002 to 2005

(3.5 Pg-CO_2) and 2006 to 2014 (3.2 Pg-CO_2). The same pattern was found by Aguiar et al. (2012) who explains that the differences are not so high because the model considers residual emissions. Aguiar et al. (2012) land use change was 3.7 Pg-CO_2 between 2002 and 2005 and 2.8 Pg-CO_2 between 2006 and 2009.

Estimates of carbon emissions from land use change are considered the most complex and uncertain among all emission estimates (Ramankutty et al., 2007; Aguiar et al., 2012). The results of the land use change emission modeling strongly depend on the input data used, mainly from the biomass maps (Houghton et al., 2000; Nogueira et al., 2008; Fearnside et al., 2009; Aguiar et al., 2012; Ometto et al., 2014).

In this study, the uncertainties related to the biomass map are related to the difficulty to correctly identify the original phytophysiognomy in polygons where there was not a complete vegetation classification made by RadamBrasil. For many polygons, RadamBrasil indicates a likely vegetation type, but without the determination of all the sub-division of the Brazilian classification system, I classify the vegetation according to the dominant phytophysiognomy class near the missing vegetation type area. This methodology is acceptable for small areas, but for large polygons, the identification of plant phytophysiognomy becomes a significant source of uncertainty.

Another source of uncertainty is the assumption that the biomass value inside the polygon of a phytophysiognomy is completely homogeneous, as well as to consider that all the polygons of a phytophysiognomy located in a biome have the same values of biomass. In the natural environment, the vegetation biomass is heterogeneous, even for the same phytophysiognomy, and variations in forest biomass occur, for example, for different terrain orientations and incident solar radiation, for different pluviometric regime, and for different soil types and fertility.

In addition to the uncertainties regarding biomass maps, it is necessary to better understand the fate of the suppressed biomass, such as how much biomass is immediately released by fire or how much becomes wood product. Ramankutty et al. (2007) and Aguiar et al. (2012) highlighted that the proportion of biomass burnt in the first year is the most uncertain parameter and it is crucial for the estimates. When the emissions are modeled for the whole country, the uncertainties related to both the lack of knowledge about the emission processes, and the primary and secondary forest parameters in each biome, become more evident.

The data related to enteric fermentation, manure management, synthetic nitrogen fertilizers, grazing animals, manure used as fertilizers, atmospheric deposition and leaching produced in this work agree with the national inventory data. This can be demonstrated using a simple linear regression analysis (i.e., emissions computed in my maps aggregated in national totals versus national emissions computed on the national inventory) to characterize the slope and coefficient of determination (r^2). The regression slope ranged from 0.893 (from synthetic nitrogen fertilizers emissions) to 1.011 (from atmospheric deposition) and all r^2 are ~0.99. Similar results can be found when emissions computed in my maps aggregated in totals for each state are compared with emissions computed for each state on the national inventory.

Brazil has one of the largest herds of beef cattle in the word. The herd size in Brazil increased from 102.5 million heads in 1975 to 212.4 million heads in 2014, triggered by the increase in demand for livestock products. At the same time, cattle production in Brazil is predominantly pasture-based, which promotes high CH_4 emission. Then, recent increases in the amount of cattle heads directly reflect in increasing Brazilian CH_4 emissions, as can be observed in the estimate from enteric fermentation emissions.

Center-West region is the main source of CH_4 emissions in the country, especially Goiás and Mato Grosso do Sul states.

Nitrous oxide emissions can occur by synthetic or animal fertilizers. The use of synthetic fertilizers has grown quickly in the country. Between 1975 and 1994, the use of synthetic fertilizer was ~22,500 t $year^{-1}$. From 1995 to 2014, this rate rose to ~140,000 t $year^{-1}$. In addition, the increased consumption has been associated with an inefficient use of nitrogen synthetic fertilizer between 1970 and 2011 (Pires et al., 2015). Synthetic fertilizer is a relevant and increasing source of N_2O emission, but the grazing animal emissions is the largest sources, accounting for 96% of the direct N_2O emission.

One of the motivations of this study is that a historical-spatial agriculture emission database can allow the identification of regions with difficulties to improve their production practices over the time, which can become priority areas for investments or polices to reduce agricultural emissions. I could detect that the Northeast region, eastern Minas Gerais, Goiás and Rio Grande do Sul states should be objects of deeper analyses to establish emission reduction strategies because these regions present positive trend in the MK trend test. Northeast region presented increasing trend in land use emissions from 1995-2014. Investments in eastern Minas Gerais, Goiás and Rio Grande do Sul states should focus to reduce or mitigate agricultural sector emissions.

To compare all emissions from agricultural activity, conversion factors need to be defined. In this work, I chose the metric Global Warming Potential (GWP) because it is adopted by the official national inventories and most of the research literature. The GWP is an index that allows comparisons of the radiative forcing of a unit of different GHG emissions in a chosen time period. The scientific community has questioned this metric since GWP is not directly related to a temperature limit. In addition, their use would erroneously emphasize the importance of short-lived GHGs in the atmosphere, especially methane. Then, this metric may not adequately represent the relative contribution of different GHGs to climate change and would provide inadequate mitigation policies.

The Global Temperature Potential (GTP) is an index that allows comparison of GHG emissions by their contributions to the change in average Earth's surface temperature in a given time period. Then, the GTP is supposed to better reflect the real contribution of different greenhouse gases to climate change. When applied in my results, the GTP metric reduces the relative importance of the enteric fermentation emissions of cattle, but increases the relative importance of the emissions from grazing animals and manure used as fertilizer. For example, grazing animals and manure used as fertilizer (N_2O) emission was 43 Gg-CO_{2eq} in GTP (while 49 Gg-CO_{2eq} in GWP) and enteric fermentation and manure management (CH_4) emission was 56 Gg-CO_{2eq} in GTP (while 234 Gg-CO_{2eq} in GWP) in 2014. For these conversions, the GTP AR2 metric used considered a period of 100 years for each gas, using 1 to CO_2, 5 to CH_4 and 270 to N_2O.

Brazil stands out in the international stage for being frequently present in the discussions on climate and for undertaking GHG emissions reduction commitments considered ambitious. The UNFCCC was drafted during the United Nations Conference on Environment and Development hosted in Rio de Janeiro in 1992 (Rio 92). In 2002, Brazil voluntarily ratified to the Kyoto protocol and, in 2009, the PNMC was instituted (Federal Law n. 12,187/2009 and Decree 7390/2010). The PNMC stablished the goal of reducing between 36.1% and 38.9% of Brazilian projected emissions by 2020. My analysis with this new methodology indicates that Brazil is indeed heading toward to the reduction of land use change emissions proposed in the PNMC, although this may be revised pending confirmation of the 2013-2014 data.

2.5. Conclusions

The overarching conclusion is that emissions due to changes in land use are decreasing, while emissions due to agriculture sector are increasing. This conclusion could already be drawn from national communications data, but spatial patterns were not available. One of the most important Brazilian environmental goals is achieve zero deforestation in 2030. Then, emissions from the agricultural sector are expected to exceed emissions from land use in a near future. While it is apparently not possible to avoid CH_4 and N_2O emissions from agriculture, it is possible to reduce emissions, either by improvement in cattle breeding or feeding, or more efficient manure composting.

The Brazilian Nationally Determined Contributions (NDC) after the 2015 Paris agreement is to reduce emissions by 37% until 2025 and by 43% until 2030 in relation to the total emissions in 2005. NDC suggested measures to reduce total emissions include forest restoration of 12 Mha by 2030. To achieve this NDC suggested measure, it is necessary a vegetation growth rate of 0.8 Mha year^{-1}. According to the results of this study, there was vegetation growth in 41 Mha in all biomes between 2000 and 2014. This represent a rate of 2.7 Mha year^{-1} in forest restoration, which is already 3.5 times larger than the rate necessary to achieve the NDC suggested measure. The current trends in secondary forest growth in the Atlantic Forest biome is 0.73 Mha year^{-1} and, only in this biome, 11 Mha new secondary forest areas emerged between 2000 and 2014. The NDC suggested measures aim to be a sink of CO_2 and reduce total emissions. My analysis suggests that Brazil can go further and reverse the carbon sign for agriculture with recuperation of the degraded vegetation and abandoned areas.

Future research efforts should focus on the individual inclusion of forestry, pasture and crops CO_2 sink. Historical cropland and pastureland maps are already available (Chapter 1). The TerraClass for Amazonia and Cerrado (INPE, 2014, 2015) and the recent MapBiomas (MapBiomas, 2017) dataset can be used to delimitate forestry areas throughout the country. If these data are included in the calculations, the emissions can be quantified separately by conversion of native vegetation to forestry, pastureland and crops. Future research may include an understanding of the relationship between biomass re-growing and historical land use, which can be critical for modeling secondary vegetation. In a near future, my emission model can also incorporate soil carbon stock, which is an important sink of carbon in agricultural systems that can dramatically change the results of this study, but few consolidated data is available about this process.

CHAPTER 3 - GENERAL CONCLUSIONS

3.1. Thesis overview

Brazilian agriculture has been historically known for its extensification – which is the increase of agriculture output through expansion of agriculture area over natural vegetation. An alternative to increase production is to increase agricultural productivity without increasing the area under agriculture or causing significant environmental degradation, which is known as sustainable intensification. However, implementation of sustainable intensification will require, among other things, accurate information on the spatial and temporal patterns of Brazilian agriculture.

In the Chapter 1, I investigate the historical patterns of agricultural land use and productivity in Brazil using a new historical-spatial database for Brazilian agricultural land use at spatial resolution of 30” (approximately 1 km x 1 km) for the period 1940-2012. This study led to three main conclusions. First, the agriculture frontier is still expanding in the Amazon and Cerrado, but agricultural land use is actually decreasing while agricultural productivity is quickly increasing in the entire country.

Second, the production of soybean and maize increased due to increase in area and yields, but the production of sugarcane increased predominantly due to extensification. Third, pasturelands decreased in all regions analyzed, except in Amazonia, but the low Brazilian stocking rate of cattle indicate an inefficient livestock system.

In the Chapter 2, I analyze the spatial patterns of CO_2 emissions from land use change for the period 1940-2014 and CH_4 and N_2O emissions from agriculture for the period 1975-2014, using a historical-spatial database of Brazilian GHG emissions at spatial resolution of 30” (approximately 1 km x 1 km). This study led to three main conclusions. First, Atlantic Forest and Cerrado were the main source of land use change emissions until 1975 and, after that, Amazonia leads as source of CO_2 emissions while emissions in Atlantic Forest and Pampas decreased gradually. Second, the overarching result is that emissions due to changes in land use are decreasing, while emissions due to agriculture are increasing. Third, although the increasing agriculture emissions, the total agricultural emissions are decreasing because the CO_2 emissions area several times larger than the CH_4 and N_2O emissions.

These results provide one of the first comprehensive historical overview of agricultural land use, productivity and GHG emissions in Brazil, providing clear insights to guide future territorial planning, sustainable agriculture, policy and decision-making.

3.2. Conclusions

Brazilian agriculture is becoming more sustainable since agricultural areas have been decreasing and production is increasing, especially for livestock. Since 1985, when Brazil has reached the largest agricultural area, pastures decreased from 179 Mha to 160 Mha while cattle increased from 128 to 211 million heads.

In general, there is also a trend of reduction in the GHG emissions because of the decrease of the CO_2 emissions from deforestation, which results in an increase in the global livestock efficiency considering the ratio cattle head/GHG emissions. However, Brazil is a spatially heterogeneous country. In the eastern and southern part of the country, agricultural land use is actually decreasing. However, pasturelands continues to expand in Amazonia, although rates are much lower than before. Cutting deforestation in the Amazon, where 93% of emissions from deforestation happens, is the main challenge to reduce Brazilian emissions today.

Although a deeper analysis of the spatial and temporal variability of yields is necessary, our results clearly demonstrate that closing the yield gaps can increase the Brazilian agriculture production without increasing the area under agriculture. On the other hand, intensification decreases emissions due to changes in land use, while emissions due to agriculture sector increase.

Brazilian cropland is in expansion of area and yield. My analysis indicates that the past increase in yield as consequence of the investment of agricultural technologies, such as fertilization. Consequently, there was an increase in N_2O emissions in the entire country. Pastureland occupy large areas in Brazilian territory and cattle ranching is the main source of GHG emissions. Livestock intensification also results in an increase of the CH_4 and N_2O emissions because of the increase in the amount of cattle heads. The current sink of CO_2 due to $\Delta ALU < 0$ (~0.19 Pg-CO_{2eq} year^{-1} for the period 1991-2014; Table 2.3) is still not sufficient to neutralize the emissions from the agriculture sector (~0.29 Pg-CO_{2eq} year-^{1} for the period 1991-2014).

Zero deforestation, and thus zero CO_2 emissions from land use change, will not be reached in the short term. However, there are real possibilities of reversing the carbon sign for agriculture in Brazil in a near future with recuperation of the degraded vegetation and abandoned areas. The decreasing in agricultural area on the eastern side of the country and the growth of secondary vegetation have already transformed the Atlantic Forest from the largest source to the largest carbon sink. To zero net emissions from both deforestation and the agricultural sector, it is necessary to both halt deforestation and increase by 50% the sink of CO_2 from regrowth.

Until 2011, estimated land use change emissions in Brazil were aligned to the goals established by PNMC. However, since 2012 the estimated emissions were higher than the trend line of the PNMC goal. Due to pre-2015 land use change, Brazil is already committed to emissions of 1.32 Pg-CO_2, which are being released to atmosphere at a decaying exponential rate. In order to emissions stay below the trend line of the PNMC scenario, total deforestation between 2015 and 2020 can not exceed 3.2 Mha in the country.

The 2000-2014 data indicates that the past forest restoration is more than sufficient to achieve the 12 Mha of restoration suggested by the Brazilian NDC. In fact, mean deforestation was 2.89 Mha $year^{-1}$ while restauration was 2.79 Mha $year^{-1}$ in the last 15 years. However, forest restoration is occurring in regions with lower biomass than where deforestation is happening. Thus, zero net deforestation does not imply in zero net emissions.

3.3. Recommendations for future research

For the study described in the Chapter 1, future research efforts should focus on the development of higher quality agricultural maps. The moderate resolution multispectral MODIS plus Landsat 8 data and data from the recently launched Sentinel-2A could provide robust crop mapping over time and space. In this perspective, the MapBiomas dataset (MapBiomas, 2017) can be an important tool for future agricultural analysis. MapBiomas is an annual mapping of Brazilian land use that has been developed in a massive cloud-based computational platform for Earth observation data processing. This dataset and the national agricultural census that is going to be made in 2018 should soon allow us to better analyze the current patterns of Brazilian agriculture.

The study present in the Chapter 2 could receive an improvement that was not possible during the execution of this work. Pastureland and croplands are CO_2 sinks once they produce biomass, but it was not considered in the carbon balance bookkeeping model. It is necessary an extensive literature review to determine the biomass values throughout the Brazilian territory, including the presence and biomass of degraded pasturelands in the different regions. In addition, the emission model can incorporate soil carbon stock, which may be an important sink of carbon in agricultural systems. Future research may also include an understanding of the relationship between biomass re-growing and historical land use, which can be critical for modeling secondary vegetation.

National spatialized statistics on beef production per year is essential to calculate the ratio between protein/calories and deforested area or CO_{2eq} emitted. The same calculation of GHG emission per product unit may be done for crop carbon in a future research to verify the carbon efficiency of the agriculture production.

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