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MODELING THE INTERPLAY BETWEEN GLOBAL AND REGIONAL DRIVERS ON AMAZON DEFORESTATION

Elói Lennon Dalla Nora

Doctorate Thesis Course Graduate in Earth System Science, guided by Drs. Ana Paula Dutra de Aguiar, and David Montenegro Lapola, approved in April 2, 2014.

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( ) maioria simples

(X) unanimidade

Aluno (a): ***Elói Lennon Dalla Nora***

São José dos Campos, 02 de Abril de 2014

“*Essentially, all models are wrong, but some are useful*.”

George Edward Pelham Box

(In Portuguese)

Dedico a minha esposa, Denise Martini.

Sem você nenhuma conquista seria plena.

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(In Portuguese):

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ABSTRACT

Tropical deforestation is historically one of the largest drivers of biodiversity loss and carbon emissions globally. The growing demand for food, fiber and biofuels along with market's globalization is expected to add further pressure on tropical deforestation in the coming decades. In this sense, a number of models have been proposed to explore future deforestation trends, particularly in the Amazon. However, none of these models plausibly captured the general trajectory of land cover change that has been observed in this region. This thesis provides evidence that previous modeling approaches were not able to consistently represent the forces that shape land use dynamics in the Amazon. In general they are restricted by either global or regional drives of land cover change. Therefore, an alternative modeling approach should be taken to explore cross-scale interactions such as the world demand for resources and land use regulations. The main objective of this thesis is to explore an innovative modeling approach for the Amazon which allows simulating how the global demand for agricultural commodities and different regional land use policies could affect future deforestation trends inside and outside the Brazilian Amazon, paying special attention to leakage effects over the Cerrado. A global economic model was taken to integrate supply and demand factors at both global and regional scales. Then a spatially explicit land-use model is used to explore future patterns of land cover change over the Brazilian Amazon and Cerrado biome. Leakage effects are simulated in two different ways, regarding land demand and land allocation. In the first case, leakage effects are determined by changes on the relative land rents of different land use types mediated by changes on regional land use policies. In the second case, leakage effects are simulated based on Spatial Lag technique for land demand allocation which accounts for the spatial dependence of the deforestation. Based on this approach six contrasting multi-scale scenarios are explored focusing on deforestation rates and spatial pattern analysis for both Amazon and Cerrado. Our results revealed that Amazon conservation might not be the end of deforestation in Brazil once it can lead 43% increase over the Cerrado cleared area up to 2050. Massive land cover changes would be expected throughout the Cerrado biome, especially on the Midwest region and over the emerging agricultural frontier of MATOPIBA (acronym formed by the first letters of the Maranhão, Tocantins, Piauí and Bahia Brazilian states). Biofuels targets compliance can further press land cover changes over this region revealing that productivity gains will be decisive for both Amazon and Cerrado conservation. In summary, biodiversity conservation and emissions reduction in Brazil will depend on broader land use policies and land use efficiency. Otherwise, managing a transition towards a more sustainable land use can become utopian.

MODELAGEM DA INTERAÇÃO ENTRE FATORES GLOBAIS E REGIONAIS SOBRE O DESMATAMENTO DA AMAZÔNIA

RESUMO

O desmatamento nos trópicos é historicamente uma das maiores causas da perda de biodiversidade e emissões de carbono em nível mundial. A crescente demanda por alimentos, fibras e biocombustíveis, juntamente com a globalização dos mercados, deve pressionar ainda mais o desmatamento nos trópicos durante as próximas décadas. Neste sentido, uma série de modelos tem sido proposta para explorar tendências futuras de desmatamento, especialmente na Amazônia. Entretanto, nenhum destes modelos conseguiu capturar de forma plausível a trajetória geral de mudança da cobertura da terra observada nesta região durante a última década. Esta tese fornece evidências de que as abordagens de modelagem anteriores não foram capazes de representar de forma consistente as forças que moldam a dinâmica de uso da terra na Amazônia. Em geral, estas abordagens são limitadas ou por fatores determinantes globais ou fatores regionais de mudança. Neste caso, uma abordagem de modelagem alternativa deveria ser adotada para explorar interações entre escalas como a demanda mundial por recursos e as regulamentações de uso da terra. Assim, o objetivo geral deste trabalho é explorar uma abordagem de modelagem de uso da terra inovadora para a Amazônia, que permita simular como a demanda mundial por commodities agrícolas e diferentes políticas regionais de uso da terra podem afetar as tendências futuras de desmatamento dentro e fora da Amazônia, com especial atenção para os efeitos de deslocamento de demanda sobre o Cerrado. Um modelo econômico global foi adotado para integrar fatores de oferta e demanda em escala global e regional. Então, um modelo de uso da terra espacialmente explícito é utilizado para explorar padrões futuros de mudança da cobertura terra sobre a Amazônia Brasileira e o Cerrado. Mudanças indiretas de uso da terra são simuladas de duas maneiras diferentes, em relação à demanda e alocação de terras. No primeiro caso, os deslocamentos são determinados por alterações na renda relativa (land-rents) dos diferentes tipos de uso mediados por mudanças em políticas regionais de uso da terra. No segundo caso, os efeitos de deslocamento são simulados com base em regressão espacial (Spatial-Lag) para alocação de demanda por terra a qual captura a dependência espacial do desmatamento. Com base nesta abordagem seis cenários contrastantes de multi-escala são explorados com foco em taxas de desmatamento e análise de padrões espaciais para Amazônia e Cerrado. Os resultados revelaram que a conservação da Amazônia pode não ser o fim do desmatamento no Brasil, uma vez que isso pode levar a um aumento de 43% sobre a área desmatada no Cerrado até 2050. Extensas modificações no padrão de cobertura da terra seriam esperadas ao longo deste bioma, especialmente na região Centro-Oeste e sobre a fronteira agrícola emergente MATOPIBA (sigla formada pelas primeiras letras dos estados do Maranhão, Tocantins, Piauí e Bahia). O cumprimento de metas para biocombustíveis pode pressionar ainda mais as mudanças de cobertura da terra sobre esta região revelando que ganhos de produtividade serão decisivos para a conservação da Amazônia e do Cerrado. Em síntese, a conservação da biodiversidade e redução de emissões no Brasil dependerá de políticas de uso da terra mais amplas, além de melhoria na eficiência do uso da terra. Caso contrário, a gestão de uma transição para um uso da terra mais sustentável pode se tornar utópica.

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LIST OF ABREVIATIONS

AEZs - Agro-Ecological Zones
BC - Brazil Central Bank
BMC - Brazil Monetary Council
BT - Biofuel Targets
CET - Constant Elasticity of Transformation
CGE - Computable General Equilibrium
CLUE - Conversion of Land Use and its Effects
CNI - National Confederation of Industry
Db - Deforestation baseline
DNIT - National Department of Transport and Infrastructure
EM - Economic Models
EMBRAPA - Brazilian Agricultural Research Corporation
FAO - Food and Agriculture Organization of the United Nations
GA - Global Approach
GAM - Green-Amazon Scenario
GCE - Green-Cerrado Scenario
GDP - Gross Domestic Product
GIS - Geographic Information System
GTAP - Global Trade Analysis Project
IA - Intra-regional Approach
IBAMA - Brazilian Institute of Environment and Renewable Natural Resources
IBGE - Brazilian Institute of Geography and Statistics
INPE - Brazilian National Institute for Space Research
IPCC - Intergovernmental Panel on Climate Change
IPEA - Institute of Applied Economic Research
LRs - Legal Reserves
LuccME - Modeling Framework
MAGNET - Modular Applied GeNeral Equilibrium Toolbox
MCA - multi-Criteria Analysis

MDIC - Brazilian Ministry of Development, Industry and Foreign Trade
MMA - Brazilian Ministry of Environment
MT - Mato Grosso State
PA - Pará State
PAs - Protected areas
PPCDAm - Action Plan for Prevention and Control of the Amazon Deforestation
PROBIO - National Project for Public-Private Integrated Actions for Biodiversity
RAM - Red-Amazon Scenario
REDD+ - Reducing Emissions from Deforestation and Forest Degradation
RO - Rondônia State
SEAB-PR - Secretary of Agriculture of the State of Paraná
TerraME - Modeling Environment
TOPODATA - Geomorphometric Database of Brazil
USDA - United States Department of Agriculture

CONTENT

1 INTRODUCTION

Tropical deforestation is historically one of the largest drivers of biodiversity loss and carbon emissions globally (GIBBS et al., 2010). However, the causes and agents of deforestation in the tropics have evolved over time, especially in the Amazon (RUDEL et al., 2009; PACHECO et al., 2011). From 1960s to 1980s, small-scale farmers, in many cases supported by federal programs of colonization, along with large infrastructure projects, were the main drivers of the Amazon deforestation (BECKER et al., 2001; MACHADO, 2002). More recently, deforestation trends have been shown to be more complex, involving social, political and economic factors acting at multiple scales (LAPOLA et al., 2010; LAMBIN; MEYFROIDT, 2011; MEYFROIDT et al., 2013).

The expansion of international trade for instance, turn Amazonian land use systems sensitive to distant driving forces such as market's demand and price fluctuations (RUDEL et al., 2009; LAMBIN; MEYFROIDT, 2011). Since the 2000s there is an observed increasing correlation between domestic prices and those ones practiced in the international markets (SOLOGUREN et al., 2012). Amazon exports also boosted in this period (MDIC, 2013) and the growing demand for grains, beef and biofuels is expected to keep playing an important role on land use decisions in the coming decades (USDA, 2012).

Nevertheless, several measures have been taken by the Brazilian government to curb Amazon deforestation since mid-2000s (ASSUNÇÃO et al., 2012; BOUCHER et al., 2013; DALLA-NORA et al., 2014). The strengthening of command and control strategies and the adoption of conditional credit policies became important mechanisms for law enforcement (ASSUNÇÃO et al., 2013). In addition, the extensive expansion of the protected territory reduced the availability of public lands without destination (MMA, 2013), a historic source of illegal deforestation (SERRA; FERNANDEZ, 2004; BORRAS et al., 2012). All this measures, along with previous land use policies regarding private properties (Brazilian Forest Code), may then impose major constraints on further agricultural expansion in the Amazon.

At the same time, if land availability or policy interventions can limit the Amazon's suitability for agricultural purposes, distant drivers can lead to a geographic displacement of land use (MEYFROIDT et al., 2013). Since the advent of the conservation policies introduced by mid-2000s, Brazilian exports from agribusiness more than double up to 2012 (MDIC, 2013). It means that land demand for agricultural commodities was not neutralized during this period, but perhaps replaced by productivity gains or further land-use/cover changes elsewhere (MACEDO et al., 2012; BARRETTO et al., 2013; GARRETT et al., 2013).

This process raise concerns about the unintended effects of region-focused policies such as land demand displacements (AGUIAR, 2006), particularly, over the neighbor biome Cerrado (Brazilian savanna). It's lower level of protected areas coverage (12%) and needs for legal reserves on private properties (up to 35%), along with the relative suitability for mechanized croplands in this region (93%), suggests that Cerrado could continue to be a deforestation hotspot in Brazil (SPAROVEK et al., 2010; LAPOLA et al., 2013). In fact, agribusiness in Cerrado already responds for the largest share of grains, beef and sugarcane production of the country (IBGE, 2006). Its proximity to consumption centers and improved infrastructure also strengthens the Cerrado attractiveness for agribusiness (FERREIRA et al., 2012). Besides, the remaining Brazilian biomes either face a high degree of land occupation (RIBEIRO et al., 2009) or have low aptitude for agricultural expansion (FAO, 2006).

Despite its lower forest coverage and standing biomass, the Cerrado plays fundamental ecosystem services as carbon storage (CARVALHO et al., 2010) and as a biodiversity hotspot (MARRIS, 2005). The Cerrado also feeds three of the major water basins in South America: the Amazon, Paraguay and São Francisco rivers (VALENTE et al., 2013). The functioning of the Amazonian ecosystems is also tightly linked with the biological integrity of this biome (MALHADO et al., 2010). Nevertheless, Cerrado is currently among the 25 hotspots for conservation in the world due to its high deforestation risk (MYERS et al., 2000).

In practice, land demand displacements over the Cerrado were not verified till now, and although it is hard to detect such indirect land-use/cover changes, it’s a plausible scenario still unexplored. Previous modeling studies were not able to integrate the major forces that shape land use dynamics in the Amazon (LAURANCE et al., 2001; SOARES-FILHO et al., 2006; AGUIAR, 2006; WASSENAAR et al., 2007; NEPSTED et al., 2008; LAPOLA et al., 2011). In general they are restricted by either global (GDP growth, population growth, market's demand) or regional (distance to roads, past deforestation trends, presence of protected areas) drives of land cover change (DALLA-NORA et al., 2014). Also, scenarios' formulation was quite simplistic which compromised their ability to explore contrasting pathways (AGUIAR et al., 2014; DALLA-NORA et al., 2014). In this sense, this thesis intends to explore an innovative modeling approach for the Amazon which allows representing the interplay of regional and global drivers of land cover change. Thus, we can explore future scenarios of land cover change in the Amazon and over the Cerrado taking into account the dynamics of different driving forces acting at multi-scales. For this purpose, we run a global economic model along with a regional spatially explicit land use model adjusted in such a way as to represent land use systems as open systems.

1.1 Objective, Thesis Structure and Content

The main objective of this thesis is to explore an innovative modeling approach for the Amazon which allows simulating how the global demand for agricultural commodities and different regional land use policies could affect future deforestation trends inside and outside the Brazilian Amazon, paying special attention to leakage effects over the Cerrado.

Three main points are addressed:

(a) Review of previous land use models used to explore land cover changes in the Amazon in order to analyze their consistence with the land use dynamics observed in this region.

(b) Modification of a global economic model in order to represent Brazilian sub-regions, consistent with the Brazilian Amazon and Cerrado distribution, and so simulate a set of regional land use policies in combination with global forces. The regional dynamics are calibrated and validated on the periods 2000-2005 and 2005-2010.

(c) Simulation of contrasting land-cover change scenarios exploring the interaction between land demand for agricultural commodities and biofuels along with regional land use regulations on Brazilian Amazon and Cerrado up to 2050.

The first working hypothesis is that improved economic and spatial models can better represent the forces that shape land use dynamics in the Amazon regarding previous approaches. The second working hypothesis is that Amazon conservation might not be the end of deforestation in Brazil due to leakage effects on other regions.

This thesis was written as a collection of two papers related to a core theme. The first paper explores the “a” point stated above, whilst the second one describes the last two points aforementioned. A brief description of the structure of each chapter is presented below.

Chapter 2: This chapter aims to review and analyze the general structure of the land use models that have most recently been used to explore land cover changes in the Amazon. Based on this review, the primary limitations inherent to this type of model and the extent to which these limitations can affect the consistency of the projections are analyzed. Finally, we discuss potential drivers that could have influenced the recent dynamic of the land use systems in the Amazon and derived the unforeseen land cover change trajectory observed in this period. We close the chapter synthesizing the primary challenges for the new generation of land use models in the Amazon.

Chapter 3: In this chapter we analyze how the global demand for agricultural commodities and biofuels along with regional land use regulations could affect future deforestation trends inside and outside the Brazilian Amazon based on a set of multi-scale scenarios. For that, a global economic model has been taken to integrate supply and demand factors at both global and regional scales. Then a spatially explicit land-use model is used to explore future patterns of land cover change over the Brazilian Amazon and Cerrado biome. Our results are discussed under the light of the thesis hypotheses and point out possible ways to manage a transition towards a more sustainable land use in Brazil.

2 LAND USE CHANGE MODELS FOR THE AMAZON[1]

2.1 Introduction

Land cover change is one of the major drivers of global environmental change (TURNER II et al., 2007). Concentrated in tropical regions (GIBBS et al., 2010), such changes raise great concern about the sustainability of the goods and services provided by these ecosystems (CARPENTER et al., 2005). The growing demands for food, fiber and energy along with markets globalization could also further pressure the dynamics of tropical land use systems in the coming decades (LAMBIN; MEYFROIDT, 2011). In this context, a number of models have been proposed to explore future trajectories of land use and cover change in tropical forests, particularly in the Amazon (AGUIAR, 2006; SOARES-FILHO et al., 2006; WASSENAAR et al., 2007; MALHI et al., 2008; LAPOLA et al., 2011; DAVIDSON et al., 2012).

The future of the Amazon rainforests may never have been as heavily discussed by the scientific community as over the last decade since the advent of these models (LAURANCE et al., 2001; NEPSTAD et al., 2008). The scientific literature today has accumulated numerous projections derived from several models, scales and resolutions (SOARES-FILHO et al., 2004; AGUIAR, 2006; SAMPAIO et al., 2007; LAPOLA et al., 2010). However, despite the significant improvement of these models through the adoption of more sophisticated analysis methods and expansion of the processes and factors considered, projections of land cover change in the Amazon are still surrounded by uncertainties.

None of the change projections currently available in the literature plausibly captured the overall trajectory of land use and cover change that has been observed during the

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[1] This chapter is an adapted version of the paper:
DALLA-NORA, E. L.; AGUIAR, A. P. D.; LAPOLA, D. M.; WOLTJER G. Why have land use change models for the Amazon failed to capture the amount of deforestation over the last decade?. **Land Use Policy**, v 39, 403-411, 2014.

last decade in the Amazon (LAURANCE et al., 2001; AGUIAR, 2006; SOARES-FILHO et al., 2006; NEPSTAD et al., 2008; LAPOLA et al., 2011). After a long period of projections of massive deforestation, Amazon forest loss dropped dramatically to levels never previously recorded (INPE, 2013). A combination of regional policies to combat illegal deforestation along with a period of decrease in agricultural commodity prices, also marked by pressure from civil society on the government and productive sectors, have been suggested as the primary drivers for the deforestation slowdown observed since 2004 (ASSUNÇÃO et al., 2012; MACEDO et al., 2012; BOUCHER et al., 2013) - 84% through 2012 – (INPE, 2013).

Such inconsistency between projections and reality may be directly linked to the ways that these trajectories have been simulated, especially with regard to the quantity of change. In this sense, it is appropriate at this moment to analyze what exactly we have learned about land use models during the last decade, what went wrong and what we still need to do to add relevance, credibility and legitimacy to this type of tool (ALCAMO, 2008). For this purpose, a synthesis of the scientific knowledge that has been accumulated through the development of different models and projections is still missing in the literature on land use science.

Therefore, in the present study we seek to review and analyze the general structure of the land use models that have been used most recently to explore future change trajectories in the Amazon, focusing on those with regional coverage (Amazon basin or Brazilian Amazon). This review initially discusses the functional structure on which most of the spatially explicit land use models are based, paying special attention to aspects related to the estimated quantity of change. Based on this discussion, the primary limitations inherent to this type of model will be analyzed, as will the ways in which these limitations can affect the change trajectories projected for the Amazon. Finally, the authors discuss potential drivers that could have influenced the recent dynamic of the land use system in the Amazon and produced the unforeseen trajectory of land cover change observed in this period. In a complementary way, the primary challenges of the new generation of land use models for the Amazon are synthesized.

2.2 General structure of spatially explicit land use models

Despite the diversity of land use models found in the literature (VERBURG et al., 1999; PONTIUS et al., 2001; SOARES-FILHO et al., 2002; SCHALDACH et al., 2011; AGUIAR et al., 2012), it is possible to identify a common functional structure that is valid for most of the available cases (VERBURG et al., 2006). As illustrated in Figure 2.1, the main similarity is related to the partition between the land demand calculation (the magnitude or quantity of change) and the land allocation (the spatial distribution of change, including the potential calculation). In both cases, these projections are computed based on a number of driving factors, a portion of which are related to the quantity of change, and others of which are related only to its spatial distribution (certain factors can be important for both the demand calculation and the allocation process).

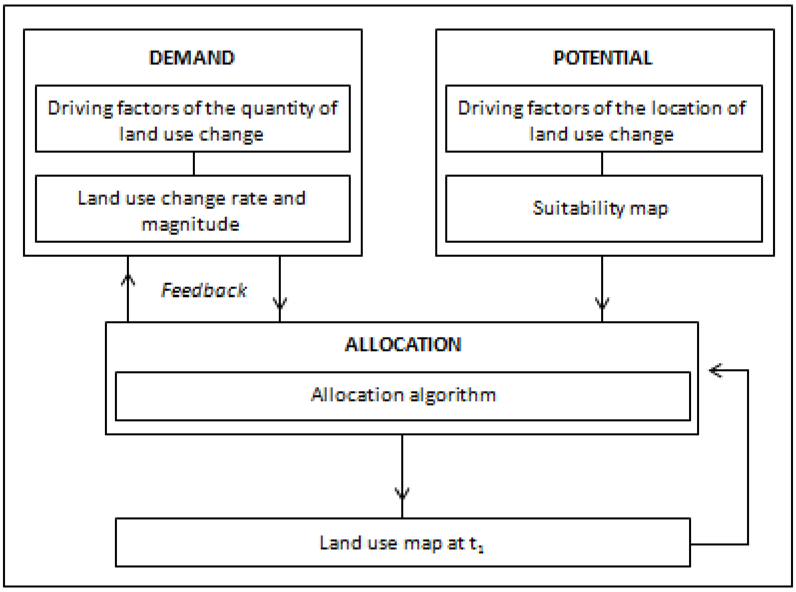

Figure 2.1 - General structure of spatially explicitly land use models.
Source: Adapted from Verburg et al. (2006).

Based on the interpretation of one or more spatial driving factors, assumed to be determinant for the location of land use and cover change, suitability maps or transition probability maps are produced (Figure 2.1). These maps indicate the suitability or propensity of a given location for a specific land use type in relation to other regions. There are several established approaches to performing this procedure; however, suitability maps based on empirical analyses and multi-criteria analysis (MCA) are the most frequent ones observed in the literature (PONTIUS et al., 2001; SOARES-FILHO et al., 2002; SCHALDACH et al., 2011).

In addition to the suitability map, the pattern of land use and cover change is also influenced by the land demand projected for each land use type in a given time period. Several methods have been used to perform such estimates, most of them following a top-down approach in which the amount of change is based on the interaction of a specific set of land use drivers (VERBURG et al., 1999; PONTIUS et al., 2001; SOARES-FILHO et al., 2002; SCHALDACH et al., 2011; AGUIAR et al., 2012). However, the assumptions involved in each method, as well as the drivers considered in the land demand calculation may differ significantly from one application to another, as discussed in the next section. The attention devoted to the land demand calculation in this review is justified by the fact that this calculation is one of the most uncertain components and therefore the most controversial output in regard to land use models produced for the Amazon.

2.2.1 Quantity of change in Amazon land use models

The land demand calculation is one of the most critical aspects of land use modeling exercises in the Amazon. As illustrated in Figure 2.2, none of the previous studies were able to plausibly capture the general trajectory of land cover change observed in this region during the last decade. Most of them assumed that land cover change in the Amazon would keep increasing or stabilize at high levels. However, in 2012 deforestation rates reached 4,571 km^2, which means a decrease of 84% over the period since 2004 (27,772 km^2), one of the highest levels ever recorded in a single year (INPE, 2013). The same trend of overestimated projections is noted regarding the alternative or non-baseline scenarios (Figure 2.3), as in most cases only some degree of variation over the same baseline future is simulated.

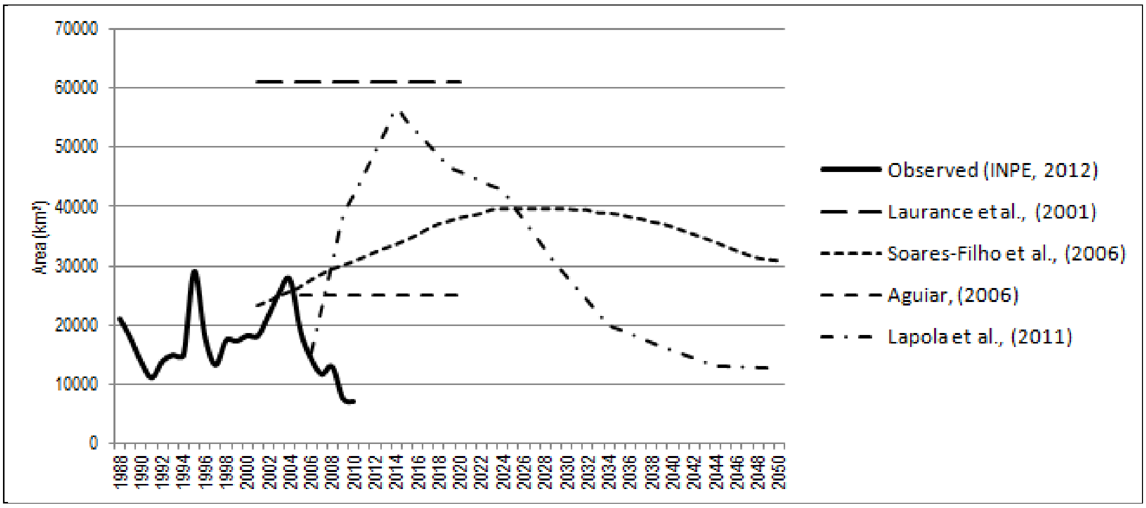

Figure 2.2 - Yearly forest loss area observed (1988-2010) and projected (2000-2050) for the Amazon in baseline trajectories.

Although such models did not aim to categorically match the observed rates of land cover change, the differences illustrated in Figure 2.2 and Figure 2.3 may be directly related to the way that land demand rates have normally been estimated for the Amazon. Comparing modeling exercises developed for this region can identify two main approaches for land demand estimates: (i) the global approach and (ii) the intra-regional approach (Figure 2.4). In the first case, the land demand calculation is based primarily on the dynamics of global driving factors, such as economic growth, population growth, per capita consumption of agricultural products and international trade policies (LAPOLA et al., 2010; LAPOLA et al., 2011), which may vary according to the assumptions made for different scenarios. This approach also includes biophysical aspects, such as climatic and agricultural aptitude conditions in the land demand calculation, which are highly dependent on the geographic location of the modeled area and directly related to the productivity issue.

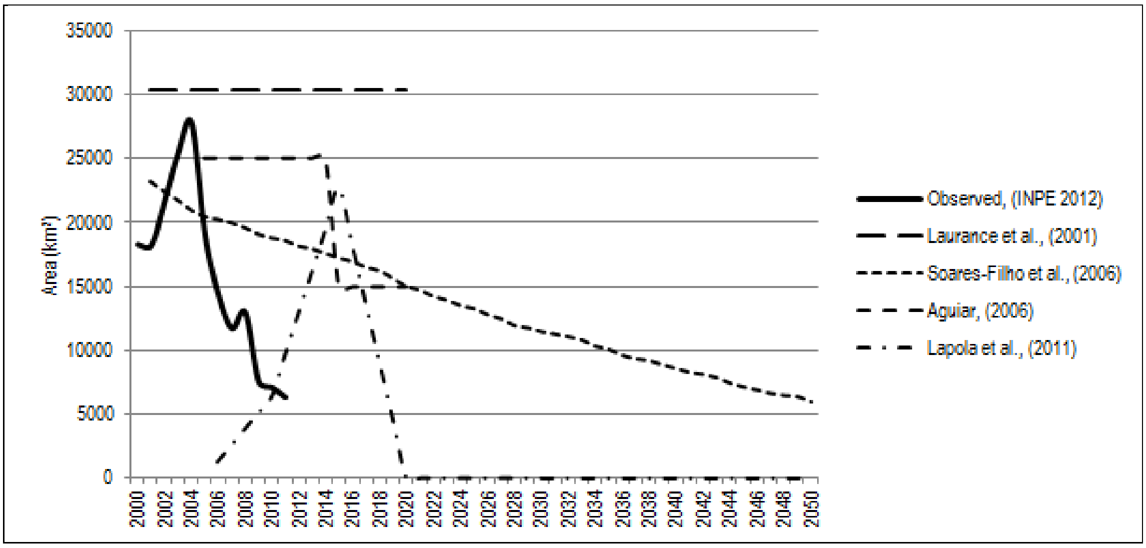

Figure 2.3 - Yearly forest loss area observed (2000-2010) and projected (2000-2050) for the Amazon in alternative or non-baseline trajectories.

Essentially, the estimates of land demand calculated for the Amazon using the global approach are given by the production/productivity relationship based on the interaction of socioeconomic and biophysical factors, both having global coverage (LAPOLA, 2011). In this approach, the estimates of agricultural and livestock production are calculated from partial equilibrium global economic models, which use projections of economic growth (GDP) and demographic growth as fundamental information to estimate the future dynamics of the agricultural sector of a given Amazonian region (LAPOLA, 2010). The global approach also allows the inclusion in the land demand calculation of political (trade barriers, subsidies) and technological (management practices, conversion efficiency) factors which are sometimes expressed only indirectly through changes in prices or productivity.

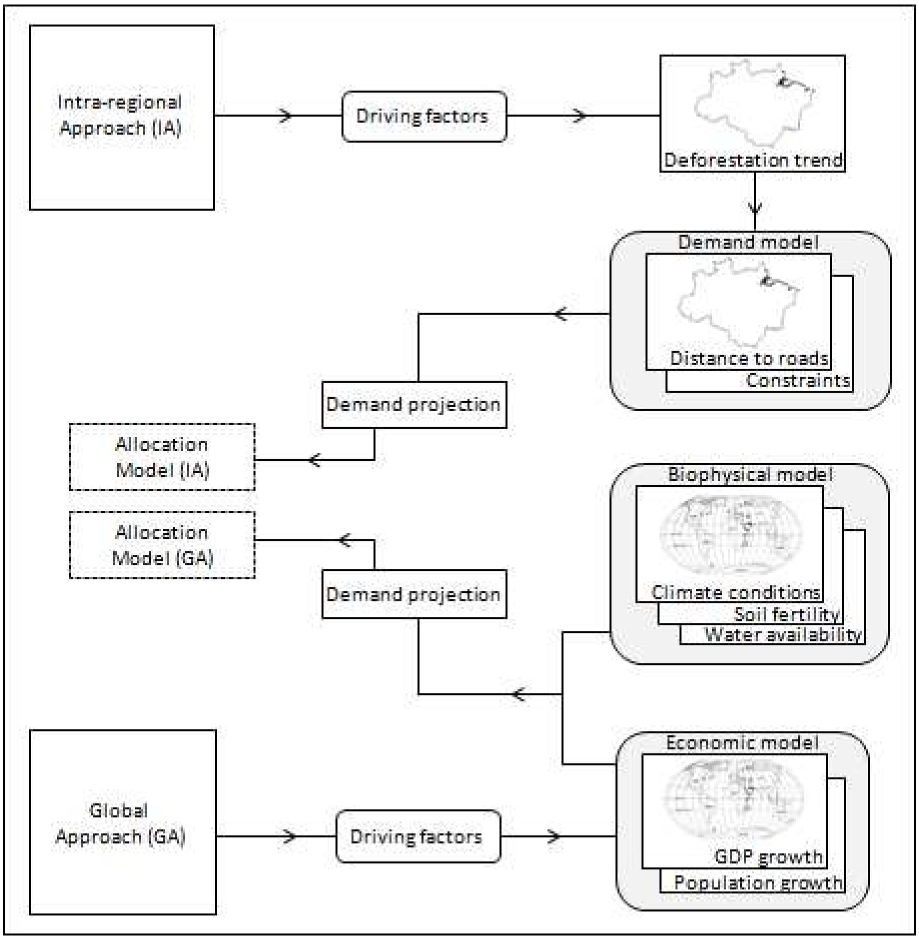

Figure 2.4 - Main approaches used to calculate land demand in the Amazon: the global approach and intra-regional approach.

In the second case, the intra-regional approach, land demand is traditionally calculated based on the dynamics of local and regional factors, such as the distance to roads and other infrastructure projects (existing and planned) and the presence of constraints (primarily protected areas). In most cases, this approach also includes in the land demand calculation a baseline factor that is related to historical deforestation averages in the Amazon as a whole or for specific sub-regions, over temporal horizons ranging from 5 to 25 years ago (LAURANCE et al., 2001; AGUIAR, 2006; SOARES-FILHO et al., 2006; NEPSTAD et al., 2008). Thus, the calculation of land demand using the intra-regional approach can be abridged by the following expression:

$$\textit{Land demand} = Db_{xt0}\,(Pe_{xt}/Ct)$$

where Db represents the average deforestation observed for region x over time horizon t0, and Pe represents the deforestation pressure resulting from the creation and paving of roads (and other infrastructure projects) in region x and time t. The term Ct is usually used to represent the presence of constraints, existing and planned, for each region x and time step t, which are assumed in the equation to be deforestation contention factors.

In this approach, the parameterization of land demand drivers, such as the distance to roads and other infrastructure projects, is based on the deforestation rates observed in the vicinity of similar projects constructed in the Amazon in the past (LAURANCE et al., 2001; SOARES-FILHO et al., 2006). In practice, this parameterization means that for each infrastructure project modeled for the Amazon in the future, a land cover change rate is attributed that corresponds to the average value of cleared area observed in the vicinity of projects of the same type in the past. Thus, the number of projects and their respective areas of influence, added to the baseline factor Db, constitute the gross amount of land demand for a given region and period, which can be fully allocated if there is available area or partially allocated based on the presence of constraints and other allocation rules inherent to each scenario (e.g., protection rules, such as the minimum area of remaining forest in each cell).

Based on this approach, Soares-Filho et al. (2008) proposed an alternative intra-regional model for the land demand calculation that projects future change rates through econometric regression. This model shares the assumptions made in the traditional intra-regional method of the land demand calculation previously described (historical data, distance to roads and protected areas). However, in this case, the proposed model seeks to capture the relationship between the annual deforestation rates recorded in the Amazon at the municipal level with the cattle growth rates and rates of agricultural area expansion. From these relationships, the gross land demand values are projected as a function of the potential future growth rates of cattle and agricultural area. These rates are exogenous to the model and can be set on the basis of historical growth averages recorded for the region or assumptions made for different scenarios. The main difference between these approaches for purposes of future land demand projections lies in the replacement of the traditional baseline factor (Db) by agricultural and livestock growth rates.

In these two examples of intra-regional approaches the land demand calculation does not directly include any form of international pressure or productivity factors (although the observed deforestation, which is used to estimate future land demand rates could indirectly include these external pressures). The global approach, in turn, does not capture the dynamics and magnitude of intra-regional drivers in the definition of future land demand rates for the Amazon. These limitations, along with model assumptions, prevent land use models from fully representing the forces that shape the dynamics of the region as discussed in more detail in section 2.3. In addition, these modeling exercises were also quite simplistic regarding their scenarios formulation approach (AGUIAR at al., 2014) since institutional changes (the social and governmental reaction against high deforestations rates) were never considered. In most cases, only some degree of variation along the same baseline future is simulated without really envisioning contrasting futures.

2.3 Analysis of model results in the context of recent land use dynamics in the Amazon

As previously described in section 2.2, most land use models used in modeling exercises for the Amazon present as their main common characteristic the structural partition between land demand and land allocation (besides in the real world, they might not be interdependent). This condition requires a clear differentiation between the spatial drivers of change, i.e., the local or proximate causes that are directly linked to the land use and cover change pattern (soil fertility, topography, infrastructure projects, etc.) and the underlying driving factors, usually spatially remote and acting at higher hierarchical levels, such as economic (price of agricultural commodities, access to rural credit), institutional (environmental policies, trade agreements) and technological (management practices, conversion efficiency) factors, which are critical for the definition of the quantity of change (KAIMOWITZ; ANGELSEN, 1998; GEIST; LAMBIN, 2002).

However, the structural division between demand and allocation appears in certain cases to have been used in such a way that contradicts the definitions of direct and underlying driving factors, particularly in the intra-regional approach of the land demand calculation. In this approach, most of the projections made for the Amazon adopt spatial driving factors (e.g., distance to roads and other infrastructure projects) as criteria to estimate future land demand rates (LAURANCE et al., 2001; SOARES-FILHO et al., 2006). To these drivers, the use of historical deforestation rates was added, for both (i) the parameterization of the impacts of new infrastructure projects and (ii) to define the baseline factor (Db). However, these historical deforestation rates were recorded under economic, political and social contexts that were completely different from the current ones and therefore unlikely to recur in the future. Today, land cover change in the Amazon is the outcome of local and distant driving factors interaction, mediated by different institutional arrangements (RUDEL et al., 2009; PACHECO et al., 2011; LAMBIN; MEYFROIDT, 2011).

During the 1970s and 1980s, Brazil’s military government believed that the implementation of large infrastructure projects was one of the best strategies for the development and occupation of the Brazilian Amazon (BECKER et al., 2001; MACHADO et al., 2002; SERRA; FERNADEZ, 2004). All of these projects had adverse environmental and social impacts (NEPSTAD et al., 2000), the implications of which can still be observed in the present, but do not reflect the current political, institutional, and economic conditions of Brazil or the Amazon. There is no doubt that the presence of new roads increases accessibility, which reduces transportation costs and increases the regional attractiveness for economic activities creating local markets that can generate more demand for land (PFAFF, 1999; ALVES, 2002). However, the reestablishment of development standards like those ones observed in the past is highly unlikely because the development processes acting in the Amazon today are completely different (CÂMARA et al., 2005).

In the other hand, the global approach to calculate land demand relies on the dynamics of global driving factors supported primarily by markets and price movements (LAPOLA et al., 2011). This means that the land demand calculation is performed in many cases disregarding the dynamics of the main local and regional underlying drivers such as institutional, political and social issues acting in the region that have a role that is as important as that played by global driving factors in defining land demands. In the last decade, for instance, it is argued that the main factor responsible for the maintenance of the deforestation slowdown process in the Amazon was the regional policies adopted by the Brazilian government (ASSUNÇÃO et al., 2012; MACEDO et al., 2012; BOUCHER et al., 2013), even under a period of favorable economic conditions (Figure 2.5).

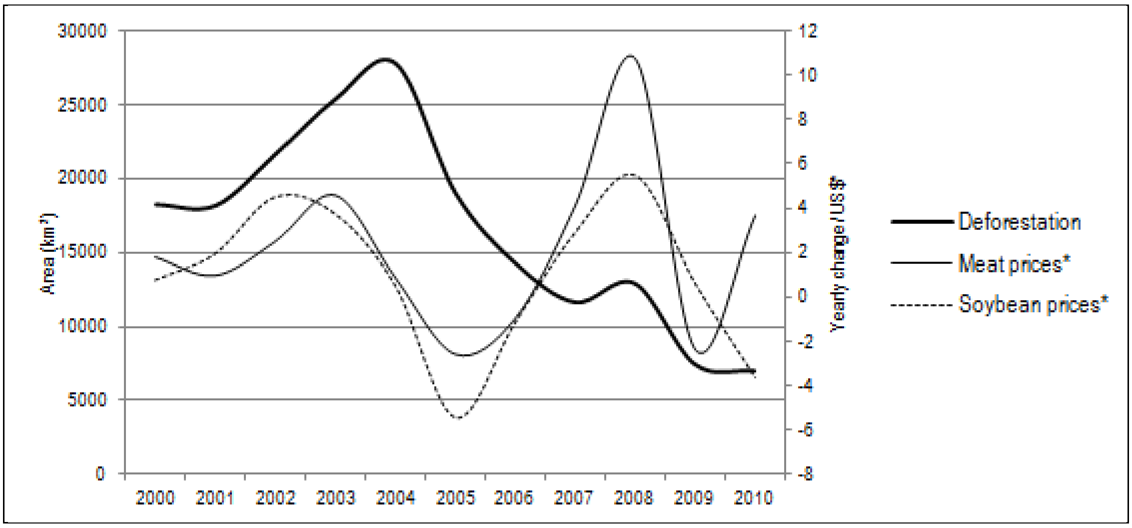

Figure 2.5 - Evolution of annual deforestation rates in the Brazilian Amazon (INPE, 2013) and yearly change in domestic prices of beef and soybeans (SEAB-PR, 2013) during the period from 2000-2010.

Prices of agricultural commodities certainly impose pressure for land use and cover change, but after 2004 it clearly cannot be taken as the only driver to explain the trajectory of Amazon deforestation. As can be seen in Figure 2.5, if Amazon deforestation was purely a result of price movements and other economic factors, we would expect that the slowdown in deforestation would be conjunctural and temporary, that is, deforestation would fluctuate according to the economic cycle, which did not actually occur. In this sense, regional policies adopted from 2004 may have played an important role in the maintenance of the deforestation slowdown process.

During this period several measures were taken to improve and extend the capabilities of monitoring, enforcement and land management in the Brazilian Amazon (BRAZIL, 2004). These measures were further supplemented through actions such as the creation of new protected areas, restrictions on rural credit access, lockout of illegally deforested farms and accountability of productive chains that buy products from illegal deforestation (BRAZIL, 2007).

These measures, although recent, yielded two remarkable moments in the recent trajectory of Amazon deforestation. After the release of PPCDAm in 2004 and the publication of Decree 6321 in 2007, around 240 new protected areas were created in the Brazilian Amazon (distributed among units of strict protection, sustainable use and indigenous lands) covering an area of approximately 810,000 km^2 (Figure 2.6). This increment represents a 65% increase in the area of conservation units that were created from 2000-2004 (490,000 km^2), which altogether currently cover around 55% of the remaining forests in the Brazilian Amazon (MMA, 2013).

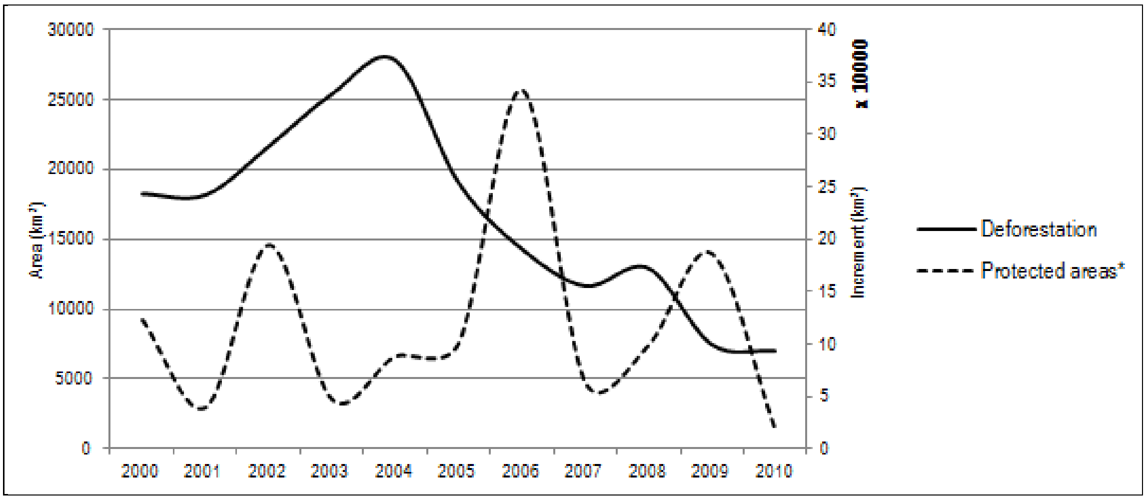

Figure 2.6 - Evolution of annual deforestation rates (INPE, 2013) and increment of protected areas in the Brazilian Amazon (MMA, 2013) during the period from 2000-2010.

Creation of protected areas in the Amazon has always been one of the key strategies adopted for biodiversity conservation (DRUMMOND et al., 2009). However, recent studies showed that the presence of these areas can also have a positive effect on deforestation reduction and thus could represent an important mechanism for reducing emissions of greenhouse gases (SOARES-FILHO et al., 2010). In this sense, the turning points observed in Figure 2.6 resulted mainly from the efforts of the Brazilian government to implement the measures published in 2004 and 2008 which envisaged broad expansion of the protected areas network in the Amazon as a strategy for containment of deforestation.

Restrictions on rural credit in the Brazilian Amazon municipalities also represented another important front against deforestation (BRAZIL MONETARY COUNCIL, 2008). The lack of control over the fate of the rural credit allowed public resources to be used in many cases to finance illegal activities in the Amazon. This happened due to the lack of criteria that took into account the environmental situation of rural properties as a prerequisite for obtaining credit, which ended funding new deforestation for agricultural expansion and enabling the consolidation of illegally occupied areas. During the period from 2000-2004 that preceded the launch of PPCDAm and Decree 6321, 81.3% (US$

6.6 billion) of the total credit granted for this region (US$ 8.1 billion) was allocated for the states of Pará, Rondônia and Mato Grosso, which accounted for 85.7% (95,308 km^2) of the total deforestation (111,210 km^2) recorded in the Brazilian Amazon during this period (INPE, 2013).

In this sense, after 2004 there was a significant cut in rural credit granted for the Brazilian Amazon municipalities as a whole (-65%) and particularly for those located in the states that concentrated the highest deforestation rates (-77%), as illustrated in Figure 2.7. The adoption of Resolution 3545 of the National Monetary Council in 2008, derived from Decree 6321, strengthened this line of action by setting new environmental standards in order to have access to rural credit in the Amazon municipalities, especially for those denoted Priority Municipalities. This measure allowed the Brazilian government to concentrate efforts in key municipalities, maintaining control over credit access in such regions, and resume the financing of regularized activities in other regions (Figure 2.7).

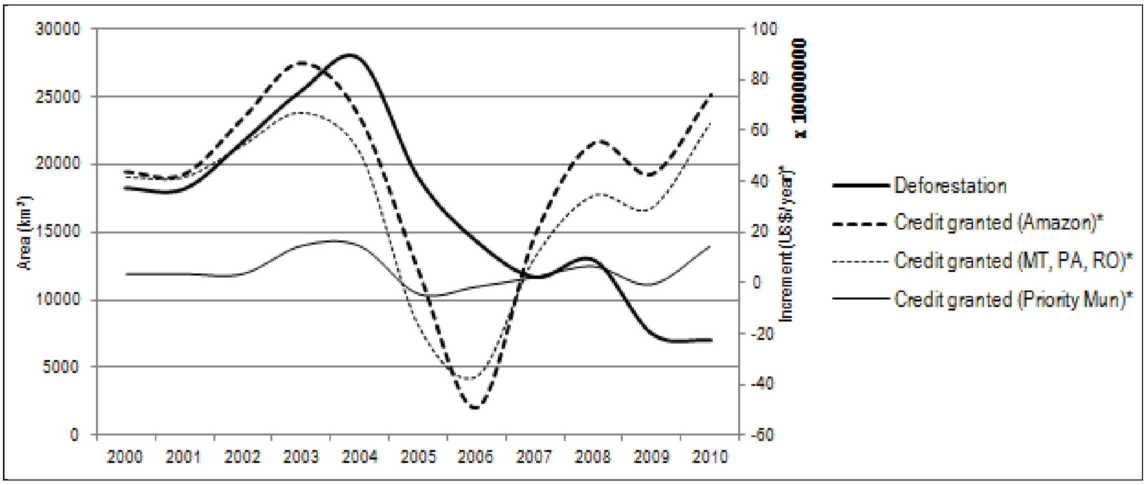

Figure 2.7 - Evolution of annual deforestation rates (INPE, 2013) and increment of rural credit granted (i) in the Brazilian Amazon (BRAZIL CENTRAL BANK, 2013), (ii) in the Amazon States that concentrate the greatest part of Amazon deforestation (MT, PA, RO) and (iii) in the Priority Municipalities for the period from 2000-2010.

The intensification of command and control actions represented one of the most important strategies to combat illegal deforestation in the period from 2004-2010 (ABDALA, 2008). During this period there was an increase of 70 times in the number of notices of violation issued by environmental agencies (increment of 8823 fines for illegal deforestation) compared to the period preceding the launch of Decree 6321 and PPCDAM (Figure 2.8). The intensification of these measures is largely due to improvements in the quality and coverage of the deforestation monitoring system by satellite imagery in the Amazon, as well as further integration among the agents involved in the monitoring and enforcement agencies (IPEA, 2011).

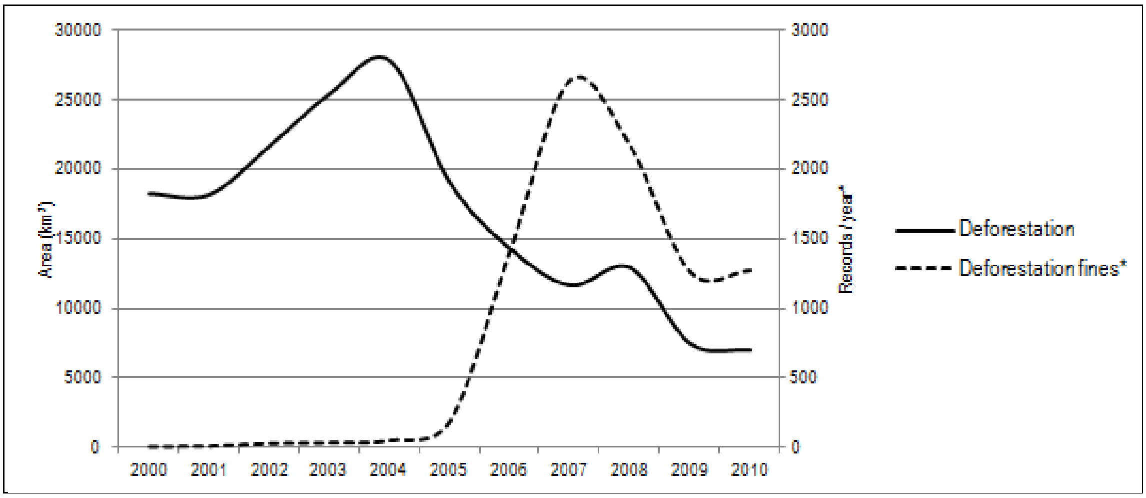

Figure 2.8 - Evolution of annual deforestation rates (INPE, 2013) and records of tax assessments in the Brazilian Amazon (IBAMA, 2012) during the period from 2000-2010.

The new possibilities of administrative penalty, promoted by Decree 6514 (BRAZIL, 2008), derived from Decree 6321, also allowed the enforcement actions to act on undercapitalization of violators. Thus, more than fines (an often inefficient form of repression given the difficulty of finding the true party responsible for illegal activities and the low payment rate), the command and control actions promoted from 2004 also began to act in blocking properties, products (cattle, wood) and equipment related to illegal activities. This change in the form of tax assessment has made command and control actions more efficient, especially in the cases of land grabbing, historically one of the key drivers of illegal deforestation and violence in the Amazon (BORRAS JR et al., 2012).

The strategy of focusing the crackdown on priority municipalities (BRAZIL, 2004) also was an important mechanism for optimizing the command and control actions. Besides, the area of these municipalities represents a relatively small part of the Brazilian Amazon; in 2007, for example, they accounted for over 50% of total deforestation. In this sense, the definition of priority areas allowed field activities to focus on strategic locations while still impacting deforestation rates for the region as a whole. In recent years, deforestation rates have fallen more significantly in these municipalities than in other regions. Between 2008 and 2009, for example, deforestation in the 43 priority municipalities fell 67%, while the decrease recorded for the Brazilian Amazon over the same period was 46%.

In summary, the effectiveness of regional policies generated a greater demand by producers and civil society for the regulation of their activities, which seems to have been decisive for the immediate reduction of deforestation rates observed over the last decade in the Amazon. Complementary actions such as the incentive created by Norway’s pledge of up to US$1 billion in results-based compensation through the Amazon Fund; the strong and concerted pressure exerted by Brazilian civil society on the government and the soy and beef industries; and the positive response by those industries, resulting in the 2006 soy and 2009 beef moratoria were also important to curb Amazon deforestation (BOUCHER et al., 2013). Ultimately, these processes reinforces the idea that Amazonian land cover change dynamics depend significantly on the behavior of local and regional factors along with intentional forces, which still need to be better understood and addressed in land use models.

2.4 Challenges of the new generation of land use models

The complex nature of the land use system in the Amazon indicates the need to adopt an innovative modeling framework to represent the forces that shape land use dynamics in this region. As discussed above, the recent trajectory of land use and cover change in the Amazon differs widely from that observed in the past. Today, it is strongly linked to the behavior of complex drivers such as international markets and regional policies (RUDEL et al., 2009; PACHECO et al., 2011; LAMBIN; MEYFROIDT, 2011). In this sense, a central challenge for the new generation of land use models consists of the expansion and integration of key driving factors from different scales adjusted in such a way as to represent land use systems as open systems.

However, it is important to keep in mind that model improvement is not meant to increase its predictive ability. Since certain aspects of human behavior, especially social feedbacks or political changes, are hard to predict, land use models are not as useful for forecasting the future as other type of models (climate models, ecosystem models). Besides, their own results can influence future developments. In this sense, model improvement regards (but is not restricted to) the challenge of improving its capacity to represent the factors that influence land cover change, and ultimately, its capacity to explore alternative policy scenarios.

That said, the integration of global and regional models could contribute to amend the structure and internal consistency of the Amazon land cover change scenarios (Figure 2.9). Global economic models (EM), in particular, have the potential to integrate supply and demand factors, taking into account current and forthcoming political and socioeconomic pressures on agricultural sectors, though not in detail. However, such models offer the necessary flexibility to develop sub-national level regions and integrate underlying regional drivers of land cover change to estimate land demand (WOLTJER et al., 2013).

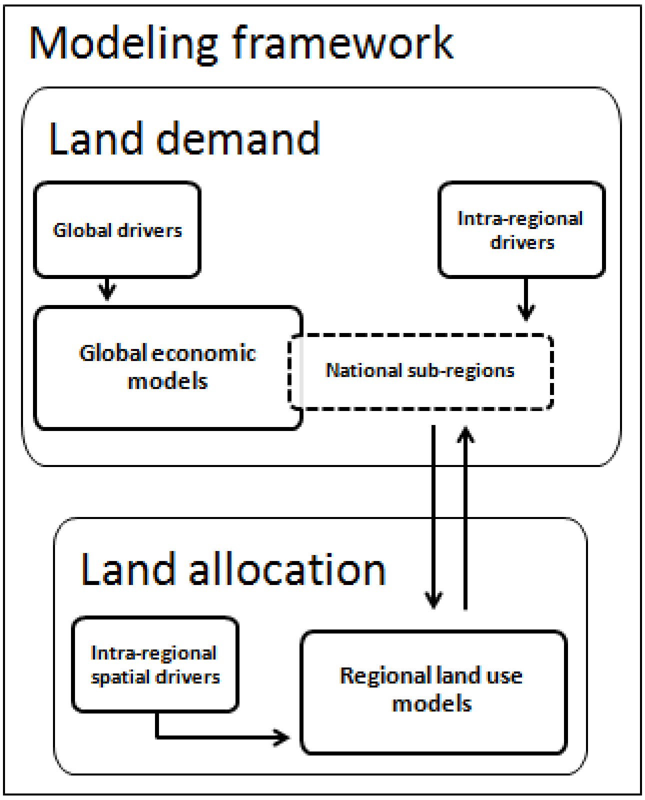

Figure 2.9 - Modeling framework for integrated land use change projections at global and intra-regional levels.

Through this approach, Amazon land-use policies such as those presented in this paper (or derived from scenario assumptions) could be taken into account when projecting land demand changes, where land demand is defined as the combination of land supply and land demand factors, mediated by land use policies. In previous land use modeling studies this balance between land demand and policies could not be properly implemented due to the limitations described in section 2.3. With a new approach that integrates demand factors and stylized supply factors in one macro-economic model, supply factors determine land availability and relative rents of different land use types and thus indirectly commodity prices either as a consequence of global or regional drivers. In addition, this approach would also create the possibility of including well-known Amazon land use transitions such as forestland-to-pastureland-to-cropland (MACEDO et al., 2012; BARRETTO et al., 2013) in a stylized manner.

The creation of new PAs policy, for instance, could be implemented as the reduction of land available for transition into agricultural land. In practice, it means that as new PAs are created, land availability decreases, affecting land prices and ultimately land rents. Other drivers such as rural credit access and command and control actions could be treated as law enforcement mechanisms and simulated through the protection of public and private PAs (BRAZIL, 2012). Finally, new roads could be modelled as a reduction in transport cost that increases the accessibility of the region (PFAFF, 1999; ALVES, 2002) and with this also land rents.

All the regional policies described above could be calibrated taking into account the period from 2000-2012. Data on changes in the Amazon PAs network are provided by the Brazilian Ministry of Environment (MMA, 2013), while data on rural credit granted are available through the Brazilian Statistical Yearbook of Rural Credit (BC, 2013). Data on command and control actions could be derived from the Annual Assessment of Violation Notices by Deforestation issued by the Brazilian Environmental Agency (IBAMA, 2012) while the location and extent of Amazonian built and planned roads are provided by the National Department of Transport and Infrastructure (DNIT, 2013).

On the other hand, the regional spatially explicit land use models available for the Amazon have the potential to define the most suitable places to allocate EM-derived land demand projections based on several spatial drivers such as land aptitude, climate conditions, infrastructure resources and constraints. In addition, regional models could provide detailed space-time analysis of the land cover transitions and the change hotspots. The outputs of the land demand allocation could also feedback to the economic model through land use elasticities or land availability under different scenarios.

This coupling would represent a fundamental improvement in the structure and consistency of such models, which ultimately is going to determine their potential as a tool to explore future scenarios and support decision-making. The ability to represent

Amazon land use systems as open and human-driven systems is also a central challenge for designing more efficient land use polices. Otherwise, the oversimplification of land use drivers and scale issues can prevent the potential of this tool to be fully developed.

2.5 Conclusions

Land use models enriched the discussion of processes and driving factors of land cover change in the Amazon while also acting as a warning which to some extent mobilized public opinion and decision making in the Amazon. However, despite the scientific soundness of this tool, model assumptions and simplifications still prevent land use models from fully representing the forces that shape land use dynamics in the Amazon. In addition, the formulation of the scenarios in previous studies was also quite simplistic, which compromised their ability to explore contrasting scenarios.

The recent trajectory of land use and cover change in Amazon differs widely from that observed in the past. Today, it is strongly linked to the behavior of complex drivers acting at both global and regional scales connected through an extensive network of market flows, information and capital. Therefore, representing Amazonian land use systems as open systems became a central challenge for the new generation of land use models.

This does not mean that model improvement will necessarily lead to precision or accuracy in the prediction of the future. Due to the broad uncertainties underlying the land use system, land use models are not meant to predict the future. Sound land use models are useful for representing plausible ways in which the future could unfold in the context of scenario development, and explore the effects of changes in certain factors. In this sense, the integration of flexible economic models and regional spatially explicit land use models is a possible way to increase the internal consistency of the modeling exercises and ultimately enhance their potential to represent future scenarios and support decision making.

3 MODELLING GLOBAL AND REGIONAL DRIVERS OF DEFORESTATION IN THE AMAZON AND THE POTENTIAL EFFECTS ON THE CERRADO[2]

3.1 Introduction

Land cover change in the tropics is one of the major drivers of global environmental change (GIBBS et al., 2010; TURNER II et al., 2007). Brazilian Amazon, in particular, stands out as the most active agricultural frontier in the world (FAO, 2006a). However, the forces that lead these changes are moving over time. Today, Amazonian land use systems became sensitive to distant drivers such as markets demand and price movements as never before (DALLA-NORA et al., 2014; LAMBIN; MEYFROIDT, 2011; MEYFROIDT et al., 2013; PACHECO et al., 2011; RUDEL et al., 2009). Only in the period 2000-2011, the exports of soybeans and beef from the Amazon region increased 4 and 28 times, respectively (MDIC, 2013).

At the same time, growing demand for agricultural commodities, associated to the lack of control on land appropriation, also adds pressure on land supply, and deforestation rates began to increase quickly reaching 27,000 km^2 in 2004, one of the highest levels ever recorded in one single year (INPE, 2013a). This situation raised great concerns about the future fate of Amazon rainforests and the Brazilian government faced it adopting several measures to curtail illegal deforestation (BRAZIL, 2004; 2007; 2009). After improvements on deforestation monitoring systems (INPE, 2013b), which allowed the intensification of command and control actions (IBAMA, 2012) along with restrictions on rural credit access (BC, 2013) and a wide expansion of the protected areas network (MMA, 2013) deforestation rates dropped 84% (4500 km^2 in 2012) since 2004 (INPE, 2013), as discussed in the previous chapter.

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[2] This chapter is an adapted version of the paper:
DALLA-NORA, E. L.; AGUIAR, A. P. D.; LAPOLA, D. M.; WOLTJER G. Amazon conservation might not be the end of deforestation in Brazil. **Journal of land use science**, (submitted).

Protected areas (PAs) *per se* have always been one of the key strategies adopted for biodiversity conservation, and after 2004, 240 new PAs with 810.000 km^2 of coverage were created (MMA, 2013). This increment represents an increase of 65% over the PAs extent created in the period 2000-2004, which altogether cover 55% of the Brazilian Amazon remaining forests currently (DALLA-NORA et al., 2014). Taking into account that 80% of the areas off public lands must be kept with native vegetation cover - the so called Legal Reserves-LRs (BRAZIL, 2012) - the strategy of creating new PAs is also contributing to close the agricultural frontier in the Amazon. But, supposing land supply could be saturated in the Amazon or stricter land use policies could turn agribusiness unviable in this region, where else the growing demand for food, fiber and biofuels could be allocated in Brazil?

The lower level of protected areas (12%) and needs for LRs (from 20% to 35%), along with its relative suitability for mechanized croplands (93%) suggests that the neighbor-biome Cerrado (Brazilian savanna) could continue to be a deforestation hotspot in Brazil. In fact, agribusiness in Cerrado already responds for the largest share of grains, meat and sugarcane production of the country (IBGE, 2006). Its proximity to consumption centers and improved infrastructure also strengthens its attractiveness for agribusiness (FERREIRA et al., 2012). Besides, the remaining Brazilian biomes already are in advanced degree of land occupation (RIBEIRO et al., 2009) or have low aptitude for agricultural expansion (FAO, 2006b).

Nevertheless, the potential benefits achieved through the environmental policies adopted for the Amazon could trigger side effects over the most biologically rich savanna in the world. The measures taken after 2004 probably prevented that market demands were allocated in the way they would be in the absence of these measures, avoiding further deforestation directly (ASSUNÇÃO et al., 2012) or through the encouragement of well-known land use transitions like the pastureland-to-cropland movements (BARRETTO et al., 2013; MACEDO et al., 2012). However, it does not mean the growing demand for agricultural commodities is being stabilized. Although land demand displacements over the Cerrado were not verified till now, it’s a plausible scenario still unexplored. Previous land use modeling studies were not able to integrate the global and regional forces that shape land use dynamics in the Amazon (LAPOLA et al., 2011; LAURANCE et al., 2001; SOARES-FILHO et al., 2006). In this sense, the objective of this work was to analyze how the growing demand for agricultural commodities and the current state of the Amazon land use policies could affect the deforestation rates in the Amazon and over the Cerrado biome in a near future. To do so, we adopted an innovative approach to the region modeling land use systems as open systems through the use of global and regional models. Based on this approach we explored six different multi-scale scenarios focusing on deforestation rates and spatial pattern analysis for both regions.

3.2 Material and Methods

The central idea behind the modeling protocol presented in this work is to represent Amazonian land use systems as open systems. It means to model land-use systems taking into account direct and underlying land use drivers acting at both global and regional scales. This approach also envisage exploring intra-regional dynamics between the Amazon and Cerrado biomes (Figure 3.1) owed of the unintended effects of policy interventions adopted to combat Amazon deforestation and promote biodiversity conservation (Table 3.1).

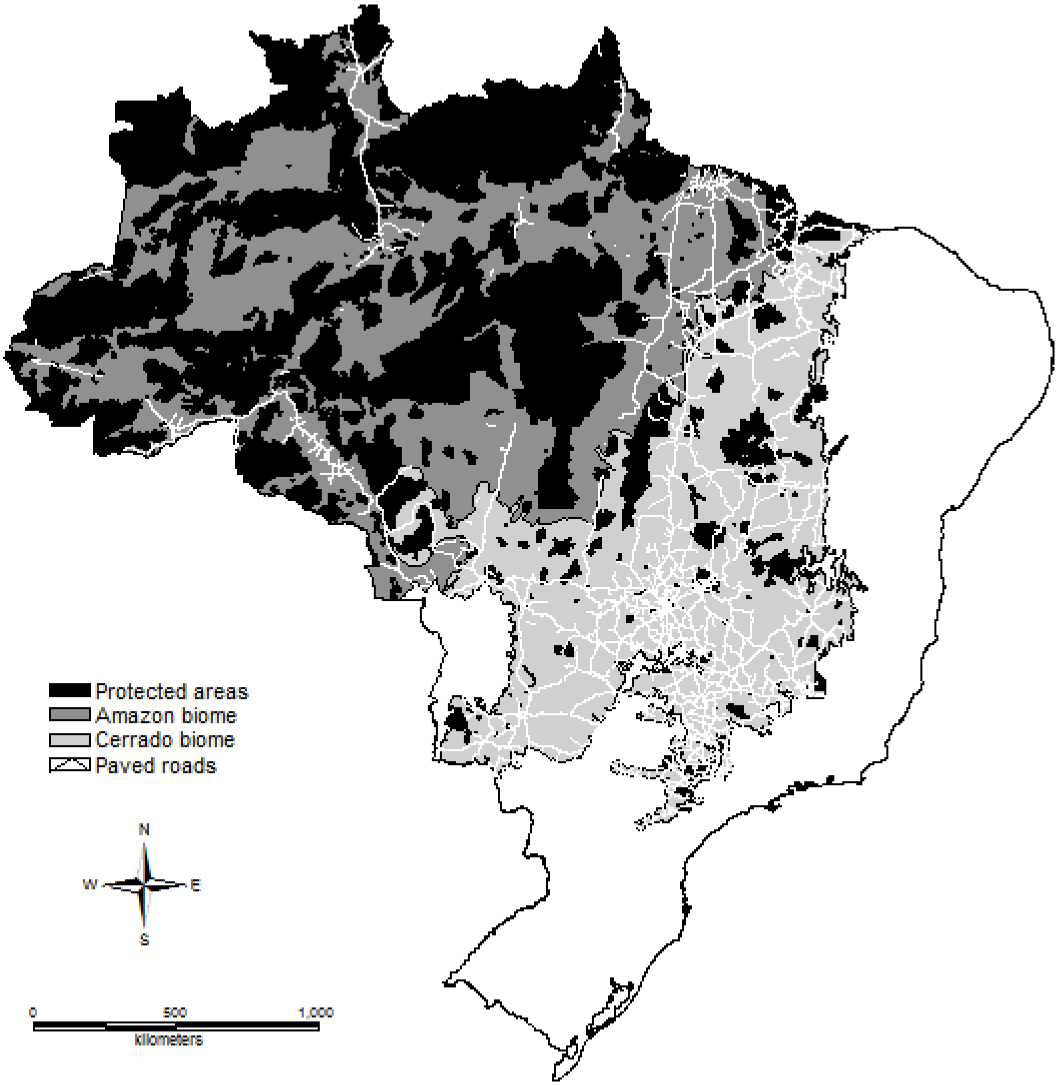

Figure 3.1 - Location of the study area with the Amazon and Cerrado biomes differentiation along with the current extent of PAs network and paved roads over both regions.

To do so, a global economic model was taken to integrate supply and demand factors at both global and regional scales taking into account current and potential socioeconomic and institutional pressures on agricultural sectors. Also, a spatially explicit land-use model was run to explore current and potential land cover patterns throughout the Amazon and Cerrado biomes. Basically, land demand or deforestation projections were derived from an economic general equilibrium model and allocated on space at annual time-steps through regional and spatially explicit land use models as discussed in sections 3.2.1 and 3.2.2, respectively.

3.2.1 Land demand

Land demand projections were performed based on the model MAGNET (WOLTJER et al., 2013; WOLTJER, 2013b), a Global Computable General Equilibrium Model (CGE)[3] in which land cover changes depend on the relative rents of different land use types[4], and so indirectly on changing prices of commodities as a consequence of both global and national drivers. Its modular set-up also offered the necessary flexibility to develop sub-national level regions (Figure 3.2) and integrate key regional drivers of land use change to estimate land demand. Land demand is defined here not in the economic manner as the demand factors, but in economic terms as land use that is a combination of land supply and land demand factors. In the rest of this chapter we use land demand as the land use from the economic model that is used as an input for the land allocation models.

National land demand is split over Agro-Ecological Zones (FISCHER et al., 2002), as defined in the GTAP-8 Land Use and Land Cover Database (BALDOS; HERTEL, 2012), the geospatial database consistent with the economic GTAP 8 database used in

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[3] Computable general equilibrium (CGE) models are a class of economic models that describe the behavior of the whole economy in an integrated manner. CGE models use a social accounting matrix approach that describes all sectors and commodities in an economy consistently. This implies that interdependencies between sectors are taken into account. For example, if a biofuels policy reduces the import of crude oil of a country, this influences the exchange rate of this country and therefore import and export prices of all other commodities. The CGE approach is especially useful when the expected effects of policy implementations are complex and materialize through different transmission channels.

[4] In classical economics, land is considered one of the four factors of production (along with capital, labor and entrepreneurship). Income derived from ownership or control of land is referred to as land rent. Land rent is the difference between the sales revenues derived from the use of land and the payments to the other production factors.

MAGNET. Such strategy allowed the isolation of the Amazon biome from the Cerrado biome and both of them from the rest of the county. It also allowed to implement in a stylized manner a set of regional policies suggested in the literature (ASSUNÇÃO et al., 2012; 2013; DALLA-NORA et al., 2014, MACEDO et al., 2012) as the key underlying drivers of the Amazon land cover change during the last decade (see Table 3.1).

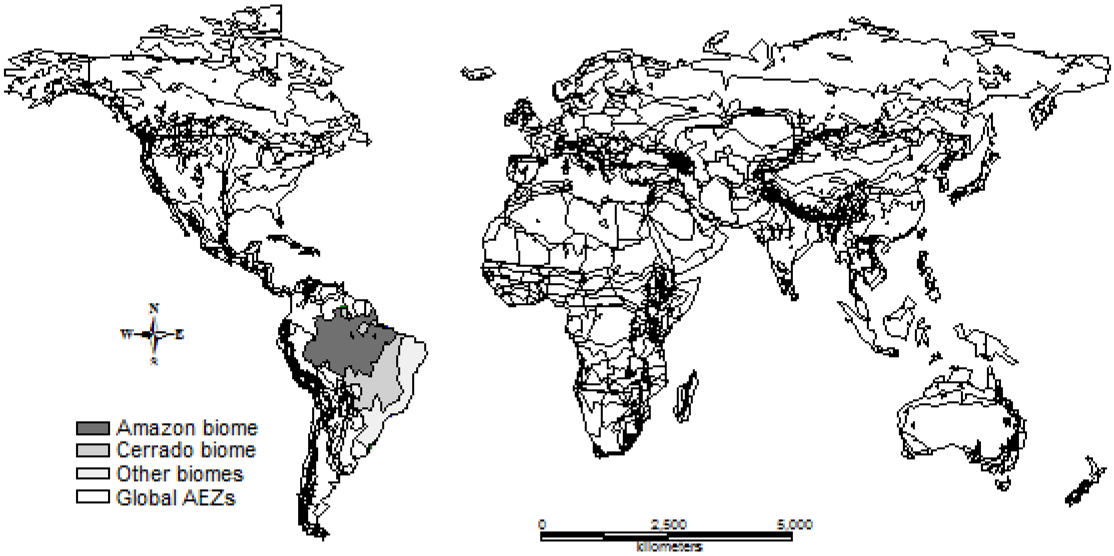

Figure 3.2 - Spatial distribution of the global AEZs and Brazil’s biome-driven AEZs aggregation.

A land use transition matrix was developed inspired by the methodology of Ferreira-Filho and Horridge (2012). This creates the possibility to model land cover changes explicitly and to prevent problems of the land supply curve in combination with a constant elasticity of transformation (CET) standard MAGNET approach to land use, or the CET approach in most other CGE models with land use (WOLTJER, 2013a)[5]. It

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[5] The weakness of the traditional land supply curve is that there is no clear empirical foundation of this curve, and that it doesn’t make explicit where the land expansion is coming from. The weakness of the Constant Elasticity of Transformation (CET) function is that it assumes that if land use is changed from one type to another, it is both the least productive land for the new land use type as well as for the former land use type. In this sense, if we combine an elastic land supply curve (i.e. where increases in agricultural land use do not change the average land price a lot) with the CET function, then very perverse effects may occur. Because the land supply curve is a relationship between average land price and total land use, with an elastic land supply curve the average land price will not change much. When for example as a consequence of a biofuels policy the demand for cropland rises relative to grassland, the price of grassland has to decline in order to keep average land price the same. Because of the lower land

allowed to make explicit in MAGNET that land use transitions are not symmetric, but tend to go from forestland-to-pastureland-to-cropland in the Amazon (BARRETTO et al., 2013; MACEDO et al., 2012). Nevertheless, the MAGNET model land use transitions are not limited to this process and include other land use movements as summarized in Table S1 (Appendix 1) for the whole of Brazil, but which is applied in the model per AEZ region. Especially important is the land transition from natural forest land to deforested land that is considered as land used for cattle in the short run, but over time transfers either in full blown cattle or cropland, or into degraded or abandoned land. This catches in a stylized manner the dynamics of Amazon and Cerrado deforestation, where only part stays in the long term as agricultural land.

Table 3.1 - Synthesis of the regional policies adopted to curb Amazon deforestation and promote biodiversity conservation.

Policy target	Regulatory mark	Policy effect
Protected areas	2003- Presidential Decree*	Mechanism to promote forests conservation and reduce the availability of public lands without destination.
Command and control	2003- Presidential Decree*	Mechanism of law enforcement based on improved surveillance and undercapitalization of the violators.
Rural credit access	2007- Presidential Decree 6.321	Mechanism of law enforcement based on restriction to rural credit access.
Legal Reserves	2012- Forest Code Law 12.651	Mechanism to obligate forests conservation on rural private properties (80%).

*Presidential Decree without number

Land use productivity is also taken into account and it depends on biophysical and technological factors (WOLTJER, 2013b). A baseline land productivity factor is

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price, livestock production may become less extensive when agricultural demand for crops is increased as a consequence of for example a biofuels policy. This is completely counter-intuitive. In this case, the land transition matrix approach solves these problems, because it just models the transitions from different land use types to another, without putting a priori productivity differences on it. The changes in transition are modeled explicitly, so a lot of empirical information can be included in the equations.

derived from FAO projections (ALEXANDRATOS; BRUINSMA, 2012), where based on recent estimates of total factor productivity in agriculture (OECD 2013), factor productivity (including land productivity) has been increased by 1% per year compared with the standard for the period till 2030. Additional to these exogenous changes, MAGNET also allows for substitution in the crop sectors between land and fertilizer, and between capital and labor based on socio-economic drivers. The combination of the exogenous and economic factors turn land use productivity dynamic over time which determines the final land demand projections.

The creation of new PAs policy was implemented in MAGNET as the reduction of land cover changes. In practice, it means that as new PAs are created, land availability decreases, while exploring new parcels of land may be more expensive and therefore reducing the speed of transition from natural land into agricultural land. Rural credit access and command and control actions are treated as mechanisms of law enforcement making land transitions more difficult and therefore reducing the speed of land transitions (ASSUNÇÃO et al., 2012). The size of the effects is based on the econometric studies by Assunção et al. (2012; 2013; 2013b).

The potential effects of new roads paving on Amazon deforestation is also taken into account. It is simulated as a driver of accessibility which reduces transportation costs affecting land rents. In general, it is assumed that paving key stretches of the main transportation routes in the Amazon could lead to an average reduction of 25% to 35% on transportation costs. This reduction has been calculated by several private and public agencies frequently regarding the BR-163, BR-230 and BR-319 highways (CNI, 2013). In this study we assumed an average reduction of 25% on transportation costs simulating the pavement of the 3 aforementioned highways up to 2015 as planned by the Brazilian government (DNIT, 2013) and 35% reduction regarding the implementation of other secondary roads planned up to 2050 depending on scenario assumptions (see section 3.2.3).

All regional drivers described above were calibrated taking into account the land use changes of Cerrado and Amazon for the period 2000-2010 and information contained in Assunção et al. (2012; 2013, 2013b). A model validation on forest loss is performed for the period 2000-2010 as discussed in section 3.3.1. Data on the Amazon PAs network were taken from the Brazilian Ministry of Environment (MMA, 2013), while data of the location and extent of Amazonian built and planed roads are provided by the National Department of Transport and Infrastructure (DNIT, 2013).

3.2.2 Land Allocation

The idea behind this approach was to provide annual maps of potential land cover change patterns based on the suitability or propensity of a given location for agricultural expansion. So, land demand projections were allocated on space based on spatially explicit land use models built on top of the LuccME Framework (AGUIAR et al., 2012). To this purpose a geographical database was also taken for both sub-regions (Amazon and Cerrado) to integrate spatial driving factors assumed to be determinants for the locations of the land use and cover changes.

LuccME is an open-source modeling framework built on top of the TerraME (CARNEIRO et al., 2013), a general programming environment for spatial dynamical modeling. LuccME is also based on the functional structure generally identified in several spatially explicit land use models which address two separately questions: (i) where land-cover changes are likely to take place and (ii) at what rates such changes or land demands are likely to progress over time (VERBURG et al., 2006; DALLA-NORA et al., 2014).

Once land demand comes from MAGNET model it is spatially allocated according to the cell suitability for a given land change transition. This suitability is computed based on the spatial driving factors selected for each region based on empirical evidence and expert knowledge. In summary, LuccME allowed the construction of multi-scale models based on previously defined modules of land demand, potential transition of change and land allocation (Table 3.2 and Table 3.3).

For the Amazon sub-region, model parameters were adapted from LuccME/BRAmazon model. This model and its spatial database were developed, calibrated and validated by Aguiar et al. (2012). A new spatial land use model, LuccME/BRCerrado model along with a new spatial database, was developed for the Cerrado biome as described in detail in the section 3.2.2.1. These models were built sharing the same modeling components and resolution, but calibrated and validated separately to better represent the driving factors most relevant for each sub-region. Also, both models are spatially linked through a common modeling surface along the Amazon-Cerrado transition (Figure S1). This spatial overlay became necessary to ensure a consistent cross-biome land demand allocation based on spatial regression. In addition, the adoption of two or more sub-regions for land allocation is a common procedure on land use modeling and had also been extensively used for the Amazon (SOARES-FILHO et al., 2004; SOARES-FILHO et al., 2006; AGUIAR, 2006; WASSENAAR et al., 2007; NEPSTAD et al., 2008).

We use an allocation procedure based on the original components of the CLUE model (VELDKAMP et al., 1996; VERBUG et al., 1999) implemented by Aguiar et al. (2012). Also, several improvements were introduced such as a potential transition component based on the Spatial Lag technique (AGUIAR et al., 2007; ANSELIN; SMIRNOV, 1996). The original CLUE model relied on Linear Regression to estimate the cell potential for change. This new method accounts for the spatial dependence of the deforestation process which tends to concentrate close to previously cleared areas (ALVES et al., 2002; FERREIRA et al., 2012). This approach allows dynamically update the potential of change considering the deforestation frontier temporal evolution and changes in the spatial drivers at each time step according to the scenarios (for instance, roads paving). The change potential at each time step is given by the regression cover minus the current cell value. In the case of deforestation, the potential is estimated considering the spatial drivers and the amount of deforestation in the neighbor cells. In this thesis, we adopt the same regression coefficients for the whole spatial and temporal extents, assuming the selected set of drivers is robust and simple enough to explain the past and project the future spatial patterns. All coefficients are significant (< 0.01%).

The allocation component is based on the original CLUE continuous allocation procedure described in Verburg et al. (1999). Cells with a positive change potential receive a percentage of the projected annual land demand that must be allocated to the whole area, proportionally to their potential. This version also has some new parameters to control the amount of change in each cell, considering the saturation level in more consolidated areas. In addition, this improvement allow both LuccME/BRAmazon and LuccME/BRCerrado models represent the enforcement of the Forest Code law (BRAZIL, 2012) regarding the percentage of original forest remaining in each cell (LR), as initially proposed in Aguiar (2006).

3.2.2.1 Models parameterization

A spatial database containing land cover maps and potential driving factors of land cover change for each sub-region was taken in order to run the LuccME/BRAmazon and LuccME/BRCerrado models. Such drivers were selected based on the literature regarding Amazon (AGUIAR et al., 2007; ALVES, 2002; BECKER, 2001; MACHADO, 2002; GEIST; LAMBIN, 2002) and Cerrado (DINIZ-FILHO et al., 2009; FERREIRA et al., 2012; JASINSKI et al., 2005; SANO et al., 2010) drivers of land cover change which comprise biophysical, socioeconomic and accessibility spatial drivers of land occupation as synthesized in Table 3.2 and Table 3.3. These spatial driving factors were codified into GIS-variables (Figure S2 and Figure S3) which were included in the exploratory analysis.

Table 3.2 - LuccME/BRAmazon model description.

GENERAL	**Spatial scale**	Extent	Brazilian Amazon Forest (according to PRODES mask)		
		Resolution	Regular cells of 25 x 25 km^2		
	Temporal scale	Extent	2010-2050		
		Resolution	Yearly		
		Calibration	2002-2004 (INPE, 2013)		
		Validation	2004-2010 (INPE, 2013)		
	Land cover classes	Percentage of forest, deforest, no-data (Cerrado, clouds, water) in the cell			
POTENTIAL	*Selected deforestation spatial drivers*	*Variable Description*			*Regression Coefficient*
	W_log_def	Spatial autoregressive coefficient			0.76664980
	constant	Regression Constant			2.24971000
	connMkt_SPNE	Connectivity index via the road network to São Paulo or Recife, proxies of major national markets (AGUIAR at al., 2012)			-0.00000019
	log_distRoads_PAVED	Euclidean distance to the closest paved road (AGUIAR at al., 2012)			-0.10011870
	log_distRoads_UNPAVED	Euclidean distance to the closest unpaved road (AGUIAR at al., 2012)			-0.08295176
	log_distWoodProdPoles	Euclidean distance to the closest timber extraction and processing centre (AGUIAR at al., 2012)			-0.30504930
	settlProject_AGR	Percentage of cell area covered by official agrarian projects for agricultural use (AGUIAR at al., 2012)			0.40322090
	landFertility_HIGH	Percentage of cell area covered by soils of high fertility (AGUIAR at al., 2012)			0.20855270
	protPublicForests_ALL	Percentage of cell area covered by Protected Areas (AGUIAR at al., 2012)			-0.40388840
ALLOCATION	*Main parameters*	*Parameters Description*	*GAM Scenario*	*RAM Scenario*	*GAM+GCE Scenario*
	maxError	Maximum allocation error allowed for each land use	500 km^2	500 km^2	500 km^2
	minValue	Minimum value (percentage) allowed for that land use	0%	0%	0%
	maxValue	Maximum value (percentage) allowed for that land use	20%	90%	20%
	changeLimiarValue	Saturation threshold-St (modify the speed of change in the cell)	50%	50%	50%
	maxChange	Maximum change allowed in a cell in a time step until the St	10%	10%	10%
	maxChangeAbove-St	Maximum change allowed in a cell in a time step after the St	3%	3%	3%
DEMAND	**LuccME component: PreComputedValues**	Uses MAGNET-derived values according to the scenario			

Table 3.3 - LuccME/BRCerrado model description.

GENERAL	**Spatial scale**	Extent	Brazilian Cerrado biome (IBGE, 2004)		
		Resolution	Regular cells of 25 x 25 km^2		
	Temporal scale	Extent	2010-2050		
		Resolution	Yearly		
		Calibration	2002-2008 (PROBIO, 2007; IBAMA, 2009)		
		Validation	2008-2010 (IBAMA, 2011)		
	Land cover classes	Percentage of forest, deforest, no-data (clouds, water) in the cell			
POTENTIAL	*Selected deforestation spatial drivers*	*Variable Description*			*Regression Coefficient*
	W_%_def	Spatial autoregressive coefficient			0.7547938
	Constant	Regression Constant			-0.3024629
	Soil_Fertility_High	Percentage of cell area covered by soils of high fertility (EMBRAPA, 2011)			0.0334022
	Soil_Moisture	Average soil moisture given by the minimum value per cell within three consecutive months (INPE, 2012)			0.6341565
	Altimetry	Average altimetry in each cell (TOPODATA, 2013)			0.0005208
	Urban_Cent_Dist	Euclidean distance to urban centers with population > 250.000 inhabitants (IBGE, 2008)			0.0004122
	Slope	Percentage of flat slope (up to 12%) in each cell (TOPODATA, 2013)			0.3335747
	Log_Dist_Roads	Euclidean distance to the closest paved roads - log10 transformed - (DNIT, 2012)			-0.0370281
	Settl_Projects	Percentage of cell area covered by official agrarian projects (INCRA, 2013)			0.0813517
	Protected_Areas	Percentage of each cell covered by Protected Areas (MMA, 2013)			-0.0851284
ALLOCATION	*Main parameters*	*Parameters description*	*GAM Scenario*	*RAM Scenario*	*GAM+GCE Scenario*
	maxError	Maximum allocation error allowed for each land use	100 km^2	100 km^2	100 km^2
	minValue	Minimum value (percentage) allowed for that land use	0%	0	0
	maxValue	Maximum value (percentage) allowed for that land **use**	90%	30%	30%
	changeLimiarValue	Saturation threshold-St (modify the speed of change in the cell)	50%	50%	50%
	maxChange	Maximum change allowed in a cell in a time step until the St	10%	10%	10%
	maxChangeAbove-St	Maximum change allowed in a cell in a time step after the St	3%	3%	3%
DEMAND	**LuccME component: PreComputedValues**	Uses MAGNET-derived values according to the scenario			

The exploratory analysis aimed to select the most relevant variables regarding the baseline year of each sub-region. Independent variables highly correlated to each other were identified and excluded from the modeling protocol. Initial exploratory regressions were tested using linear regression with stepwise variable selection which excludes some variables depending on its statistical significance. Different sets of variables were tested and selected based on its R square. Spatial Lag regressions were then performed for each resultant set of variables and for each one, low-significance variables were excluded and the resultant set were analyzed. The final set of variables was the one that maximized the R square and at the same time presents high significance for the model as whole.

The final set of deforestation-drivers and coefficients includes seven variables to explain the spatial patterns of land cover in the Brazilian Amazon (connectivity to national markets, distance to paved and unpaved roads, distance to timber extraction and processing centers; presence of agrarian projects, soil fertility and presence of protected areas) (Table 3.2) and eight variables for the Cerrado (soil fertility, soil moisture, altimetry, slope, distance to roads, distance to urban centers, presence of agrarian settlements and protected areas) (Table 3.3). This set of variables is consistent with previous exploratory analyses (AGUIAR et al., 2007; PFAFF, 1999; GEIST; LAMBIN, 2002; DINIZ-FILHO et al., 2009; JASINSKI et al., 2005; SANO et al., 2010) and also modeling exercises (SOARES-FILHO et al., 2006; LAPOLA et al., 2011; FERREIRA et al., 2012) available in the literature regarding both Amazon and Cerrado sub-regions.

Once selected the final set of variables and coefficients the simulations are executed using LuccME/BRAmazon and LuccME/BRCerrado models. Several iterations are performed for each time-step in order to allocate the MAGNET-derived land demand at 25 km^2 resolution based on the spatial-lag regression. Model projections are also used to feedback the MAGNET model regarding forestland availability at each time-step. LuccME/BRCerrado model, in particular, was run for the period 2002-2008 at annual time-steps in order to calibrate and adjust model parameters. The validation of this model was performed for the period 2008-2010 based on multi resolution analysis (COSTANZA, 1989; PONTIUS, 2002) which allowed quantify the pattern errors as discussed in section 3.3.1.

3.2.3 Scenarios

We derived some simple and contrasting pathways in order to explore the interplay between the global demand for food and biofuels along with regional policies. In this sense, a global baseline scenario (based on the most USDA (2012) GDP and population projections till 2030 and IPCC (2013) SPS2 projections till 2050) was run testing different regional land use policies which could affect the Amazon’s suitability for agricultural expansion based on land rents. In practice, it means a global scenario where Brazilian population grows with 19% between 2010 and 2050, and population of the rest of the world grows with 33%. GDP growth in this period equals 185% for Brazil and 183% for the rest of the world. As a consequence, production of crops grows with 110% in Brazil and 109% in the rest of the world. Nevertheless, different land use regulations on national and sub-national levels will affect the supply and demand balance with side effects on other regions.

Leakage effects are simulated in two different ways, regarding land demand and land allocation. In the first case, leakage effects between the Amazon and Cerrado are determined by changes on the relative land rents of different land use types mediated by changes on regional land use policies. In the second case, intra-regional leakage effects are simulated based on Spatial Lag technique for land demand allocation (AGUIAR et al., 2007; 2014) which accounts for the spatial dependence of the deforestation. Having a single region for each Biome allows the exploration of the intraregional leakage effects related to the spatial determinants. A spatial overlay between the cellular spaces of each sub-region was also developed to ensure a consistent land allocation transition over the modeled area. Nevertheless, leakage effects over the remains Brazilian biomes or other countries are not analyzed.

In the first multi-scale scenario called Green-Amazon scenario (GAM), summarized in Table 3.4, Amazon rain-forests protection is simulated through law enforcement. This scenario assumes that new PAs will not be created, but the integral protection of the current ones is guaranteed. Also, the requirement of forests conservation on private properties (80%) is simulated to be fully accomplished. In addition, is assumed that key unpaved roads for Amazon connection to ports and domestic markets such as BR-163, BR-319 and BR-230 highways will be paved up to 2015 (Figure S4). All these highways are currently under paving process in the Amazon (DNIT, 2013) and have implications on transportation costs and land demand allocation.

On the other hand, in the second multi-scale scenario called Red-Amazon (RAM), a set of secondary roads planned to be built until 2050 (DNIT, 2013), along with the previous ones described in the GAM scenario, are simulated to be implemented in the Amazon (Figure S2). All these projects could impose major challenges on land use governance and eventually weaken law enforcement, especially in less assisted areas of the Amazon. This process is simulated by reducing the effectives of private and public areas designated for conservation purposes due to a combination of lower law compliance and growing economic pressure. This implies greater land availability in the Amazon than under the GAM scenario (90%) increasing the region's attractiveness for agricultural expansion.

A third multi-scale scenario, GAM-GCE (Green Amazon and Green Cerrado), explores the conservation of the two biomes. Based on the integral protection of public and private areas required for conservation in each biome, the implications on productivity levels are investigated. Basically, the challenge of biodiversity conservation along with agricultural production is harmonized through artificial productivity gains. The objective of this simulation was to estimate how important land use efficiency would be for conservation purposes. The effects of climate change or major improvements on agronomic techniques are not taken into account in this study. Leakage effects between the two sub-regions still occur and the roads paving schedule is kept the same as presented in the RAM scenario.

Table 3.4 - Regional assumptions on the Green-Amazon and Red-Amazon scenarios.

Policies	GAM	RAM	GAM+GCE
PAs protection	Yes	No	Yes
LRs protection	Yes	No	Yes
New roads (2015)	Yes	Yes	Yes
New roads (2050)	No	Yes	Yes

Finally, the whole modeling protocol was repeated taking into account the expected demand on biofuels consumption due to international biofuel targets - BT (Table 3.5). Once fully implemented, these targets could further press land use transitions in Brazil. It was investigated running our global baseline scenario, plus the expected increase in biofuels demand up to 2050. The idea was to explore how the growing demand for biofuels could increase land cover changes or leakage effects regarding the behavior simulated under GAM and RAM scenarios. The implications of these biofuel targets for Amazon and Cerrado conservation through productivity gains are also analyzed. The roads paving schedule is kept the same as presented in the GAM and RAM scenarios.

Table 3.5 - Biofuel targets assumed by different countries or commercial zones around the world up to 2013.

Countries	Biofuel targets (%)
China	15
Indonesia	10
United States	10
India	10
Canada	03
Russia	10
EU-27	05
Oceania	03
Sea	05

Source: LEI-WUR (2013).

In summary, this modeling exercise simulates six different answers or behaviors at the regional scale against an expected growing demand for agricultural commodities and biofuels in the coming decades. To do so, we take in to account a set of regional land use policies recognized as determinants for the speed of agricultural expansion in Brazil. Of course future agricultural expansion in the Amazon or over the Cerrado is not restricted to these drivers or to the assumptions about law enforcement assumed under the GAM, RAM, GAM+BT or RAM+BT scenarios. Nevertheless, these scenarios aim to explore how connected land use drivers and transitions can be, especially when treated in a mechanistic way.

3.3 Results

3.3.1 Model's performance

MAGNET model presented a reasonable performance regarding Amazon and Cerrado deforestation rates observed in the period 2000-2010. After the modifications discussed in section 3.2.1, MAGNET model projected 8.5% (15.654 km^2) and 5.4% (7.906 km^2) less deforestation for the Amazon and Cerrado respectively, in relation to the amount observed in the period 2000-2010 (Table 3.6). Nevertheless, MAGNET model was able to capture the deforestation slowdown verified in the Amazon since 2005, and almost in the same proportion as in the observed data (4% difference). On the other hand, the scarcity of data availability on Cerrado deforestation prevents a proper calibration of the MAGNET model for this region. As a consequence, MAGNET model was not able to capture the reduction in deforestation observed in the Cerrado from 2005 to 2010. However, the total difference between observed and projected deforestation for this region (5%) was considered satisfactory taking into account the whole period.

Table 3.6 - MAGNET model validation on forest loss for the period 2000-2010.

Period	Observed (km^2)		Projected (km^2)		Change (km^2)		Change (%)	
	Amazon	Cerrado	Amazon	Cerrado	Amazon	Cerrado	Amazon	Cerrado
2000-2004	111210	75466	99390	65858	11820	9608	10.63	12.73
2005-2010	72326	70826	68492	72528	3834	-1702	5.30	2.40
Total	183536	146292	167882	138386	15654	7906	8.53	5.40

LuccME/BRAmazon and LuccME/BRCerrado also presented a reasonable performance on land demand allocation. Both spatial models were validated based on multi resolution analysis (COSTANZA, 1989; PONTIUS, 2002) to quantify the pattern errors where LuccME/BRAmazon reached a spatial adjustment index of 79% (AGUIAR, 2012). LuccME/BRCerrado was validated for the period 2008-2010 and reached a spatial adjustment index of 91% (Figure 3.3). Overall, both models have a tendency to concentrate land demand allocation close to previous cleared areas (reflecting the modifications on LuccME allocation component), but still consistent with the general pattern observed over the whole area.

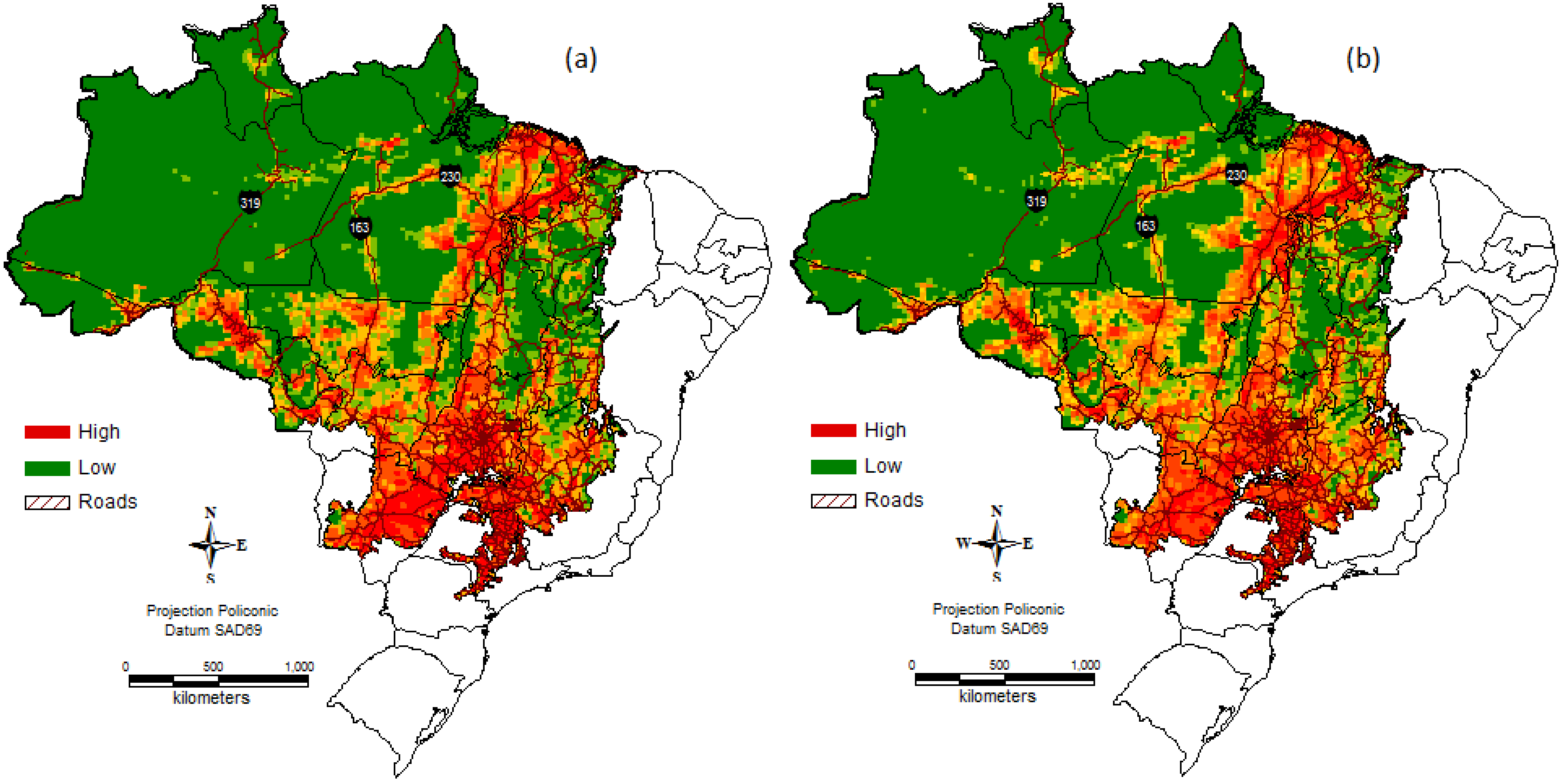

Figure 3.3 - Spatial patterns of deforestation observed (a) and (b) simulated for the Brazilian Amazon and Cerrado up to 2010.

3.3.2 Land demand

Our results unveil that Amazon conservation might not be the end of deforestation in Brazil. Stricter land use policies combined with an efficient PAs network can keep Amazon deforestation rates at residual levels (1.260 km^2/year) totaling 50.415 km^2 from 2010 to 2050 under the Green-Amazon scenario (Table 3.7). Nevertheless, Amazon protection could also press land supply over the Cerrado biome leading to 43% (428.782 km^2) increase on its current deforested area (989.000 km^2). The Cerrado annual deforestation rate could then increase from 7.050 km^2/year (2009-2010 average) (IBAMA, 2011) to 10.720 km^2/year (2010-2050 average) up to 2050 under the same GAM scenario.

Table 3.7 - Projected deforestation rates for the Brazilian Amazon and Cerrado up to 2050 under different scenarios.

Scenario	Biome	Deforestation (km^2)				
		2010-2020	2020-2030	2030-2040	2040-2050	Total
GAM	Amazon	31352	11741	5073	2249	50415
	Cerrado	118846	145005	100851	64080	428782
RAM	Amazon	164463	270832	133903	89802	659000
	Cerrado	85320	71196	57628	47387	261531

On the other hand, an eventual relaxation of current land use policies in the Amazon could slow down the deforestation pressure over the Cerrado and bring the annual deforestation rates to an average of 6.538 km^2/year under the Red-Amazon scenario. It is a deforestation rate close to present values which would lead 26% (261.531 km^2) increase in the Cerrado cleared area from 2010 to 2050. Nevertheless, Amazon deforestation rates could return to higher levels (16.475 km^2/year) and amount 659.000 km^2 at the end of the period. It’s a lower deforestation rate than observed in the period 2000-2004 (22.200 km^2/year), but considerably higher than in the GAM scenario projections. Also, it would represent an increase of 87% over the current Amazon deforested area (752.000 km^2).

To provide both Amazon and Cerrado protection simultaneously no further productivity gains would be necessary up to 2050. Land availability in the Cerrado is high enough to satisfy the extra land demand without land use conflicts under the GAM+GCE scenario. However, if international targets on biofuels consumption would be fully satisfied (GAM+BT scenario), indirect land cover changes can lead 60% (261.498 km^2) increase on Cerrado deforestation regarding the GAM scenario projections at the end of the period (Table 3.8). In this case, to harmonize agricultural commodities plus biofuels demand along with Amazon and Cerrado conservation a 21% increase on average in productivity levels would be necessary until 2050 (Figure 3.4). Amazon and Cerrado deforestation would then be limited to 50.415 km^2 and 574.630 km^2 respectively from 2010 to 2050 (GAM+GCE+BT scenario).

Table 3.8 - Projected deforestation rates for the Brazilian Amazon and Cerrado up to 2050 under different scenarios taking into account biofuel targets.

Scenario	Biome	Deforestation (km^2)				
		2010-2020	2020-2030	2030-2040	2040-2050	Total
GAM+BT	Amazon	31352	11741	5073	2249	50415
	Cerrado	208956	235946	168709	76669	690280
RAM+BT	Amazon	251282	347843	186150	121844	907119
	Cerrado	99006	79559	60246	42478	281289
GAM+GCE	Amazon	31352	11741	5073	2249	50415
	Cerrado	179456	195946	138704	60524	574630

Otherwise, annual deforestation rates in the Cerrado could rise to 17.257 km^2 on average (2010-2050), totaling 690.280 km^2 at the end of the period under the GAM+BT scenario (69.8% increase over the Cerrado cleared area). On the other hand, Amazon deforestation could amount 907.119 km^2 (22.600 km^2 on average) under RAM+BT scenario (37% or 248.119 km^2 higher than RAM scenario). Nevertheless, biofuel targets could press Cerrado deforestation even under the RAM+BT scenario as it is expected 7.5% (19.758 km^2) more deforestation over this region than in comparison with the RAM scenario projections.

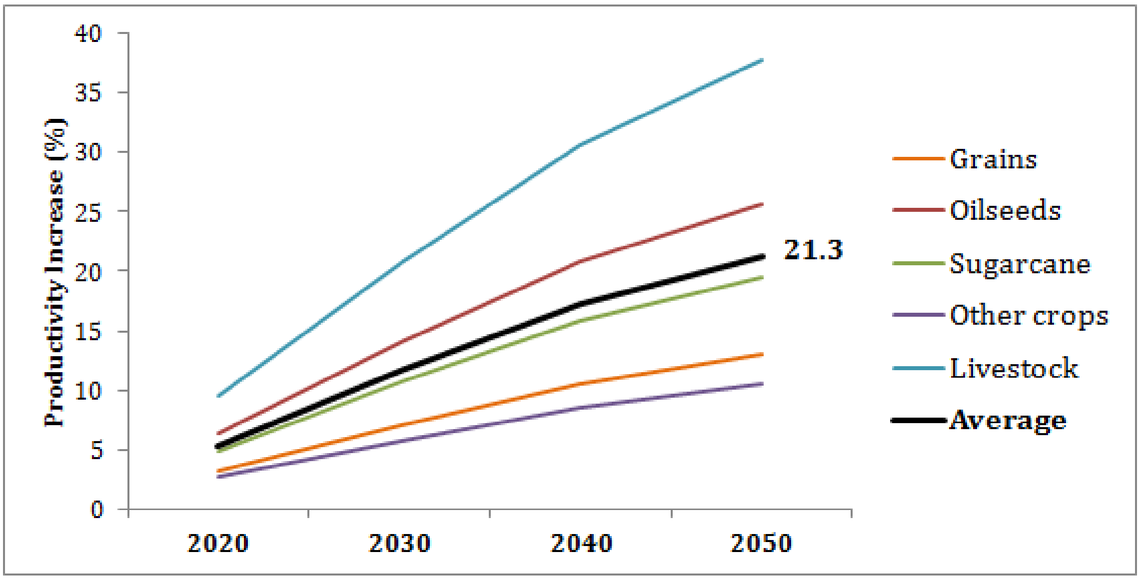

Figure 3.4 - Productivity increases necessary to harmonize food and biofuels supply along with Amazon and Cerrado conservation from 2010 to 2050. An average increase of 21% on productivity levels is projected at the end of the period, but Brazilian agricultural sector present different potentials for land use intensification.

3.3.3 Land allocation

Land demand projections could also lead to contrasting land cover change patters (Figure 3.5). Under the Red-Amazon scenario for instance, Amazon forest loss would be concentrated along the southern and eastern areas of the biome, close to the previously opened areas with a marked expansion trend around the BR-163, BR-230 and BR-319 highways, and to some extent close to the secondary roads projected to be implement throughout the Amazon. Also, there would be expected an extensive fragmentation of the remaining forests located in the central and northern parts of the

Amazon, whilst the Cerrado vegetation areas would remain less perturbed in the northern part of that biome (Figure 3.5a).

Under the Green-Amazon scenario, Amazon deforestation follows the same spatial pattern as in the Red-Amazon scenario, but in this case with less intensity (Figure 3.4). By 2050, Amazon primary forests would remain concentrated in the less accessible regions in the northwest of the biome, and also along some of the less connected existing highways. In contrast, massive land cover changes would be faced throughout the Cerrado biome, especially on the Midwest region and over the emerging agricultural frontier of MAPITOBA (acronym formed by the first letters of the Maranhão, Piauí, Tocantins and Bahia Brazilian states).

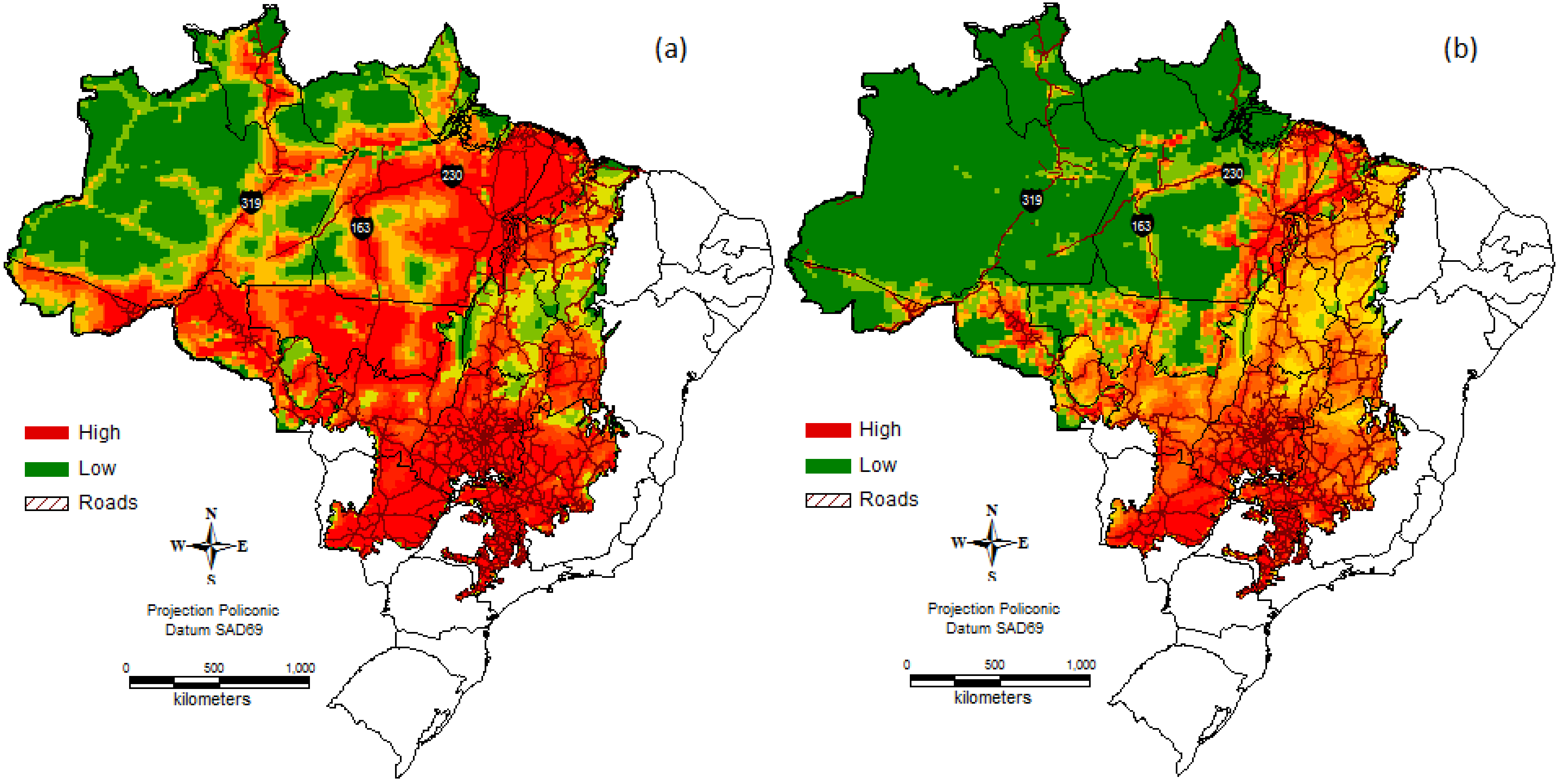

Figure 3.5 - Spatial patterns of land cover change over the Brazilian Amazon and Cerrado under the (a) RAM and (b) GAM scenarios up to 2050.

If land use regulations regarding public and private areas for biodiversity conservation would be fully accomplished along the Amazon and Cerrado biomes (GAM+GCE+BT scenario), natural vegetation would remain concentrated throughout the PAs network and over less accessible areas located in the northern part of the Amazon by the end of the period (Figure 3.5). However, the Cerrado natural vegetation could be widely reduced even under this scenario. Besides the lower requirement for Legal Reserves on private properties, PAs coverage is sparser and more isolated in this biome than in the Brazilian Amazon.

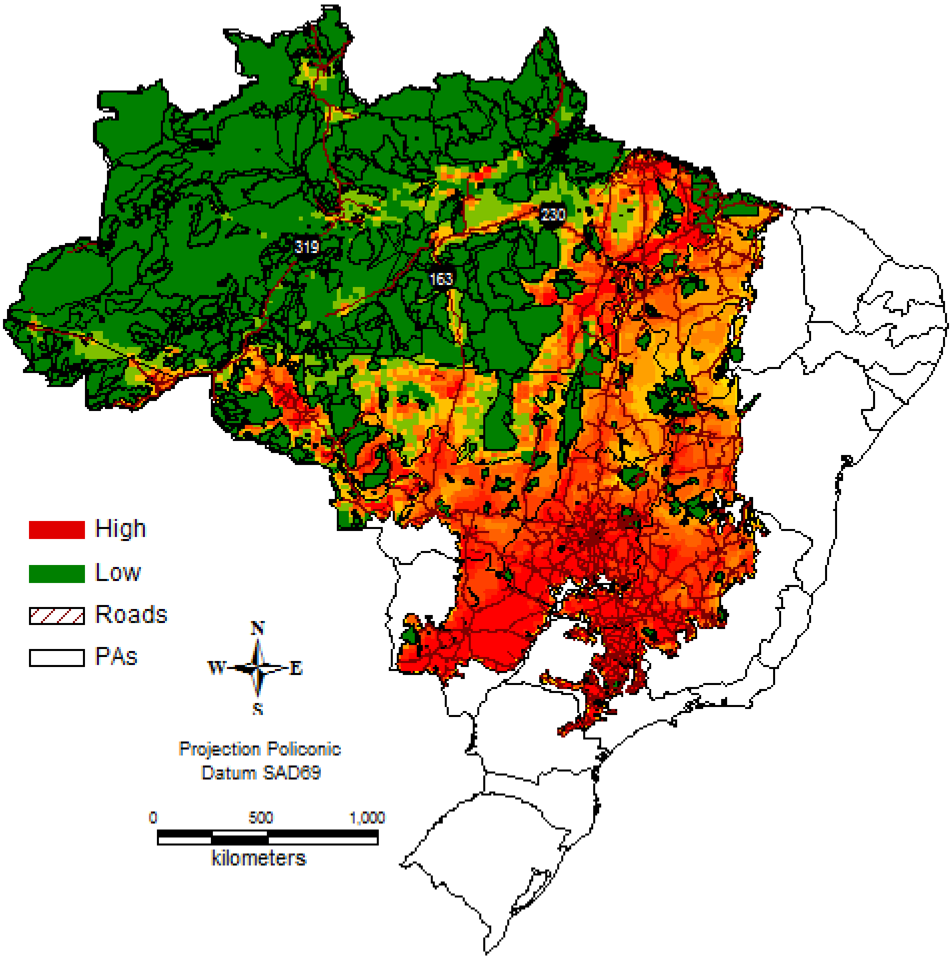

Figure 3.6 - Spatial patterns of land cover change over the Brazilian Amazon and Cerrado under the GAM+GCE+BT scenario up to 2050.

Biofuel targets could strength the deforestation patters observed under the GAM and RAM scenarios (Figure 3.7). Land supply throughout the Cerrado for instance could almost be saturated along the time horizon under the GAM+BT scenario due to extra leakage effects from the Amazon (Figure 3.7b). On the other hand, relaxing land use regulations in the Amazon may further press land cover changes over marginal areas of this biome producing an extreme fragmentation effect under the RAM+BT scenario (Figure 3.7a).

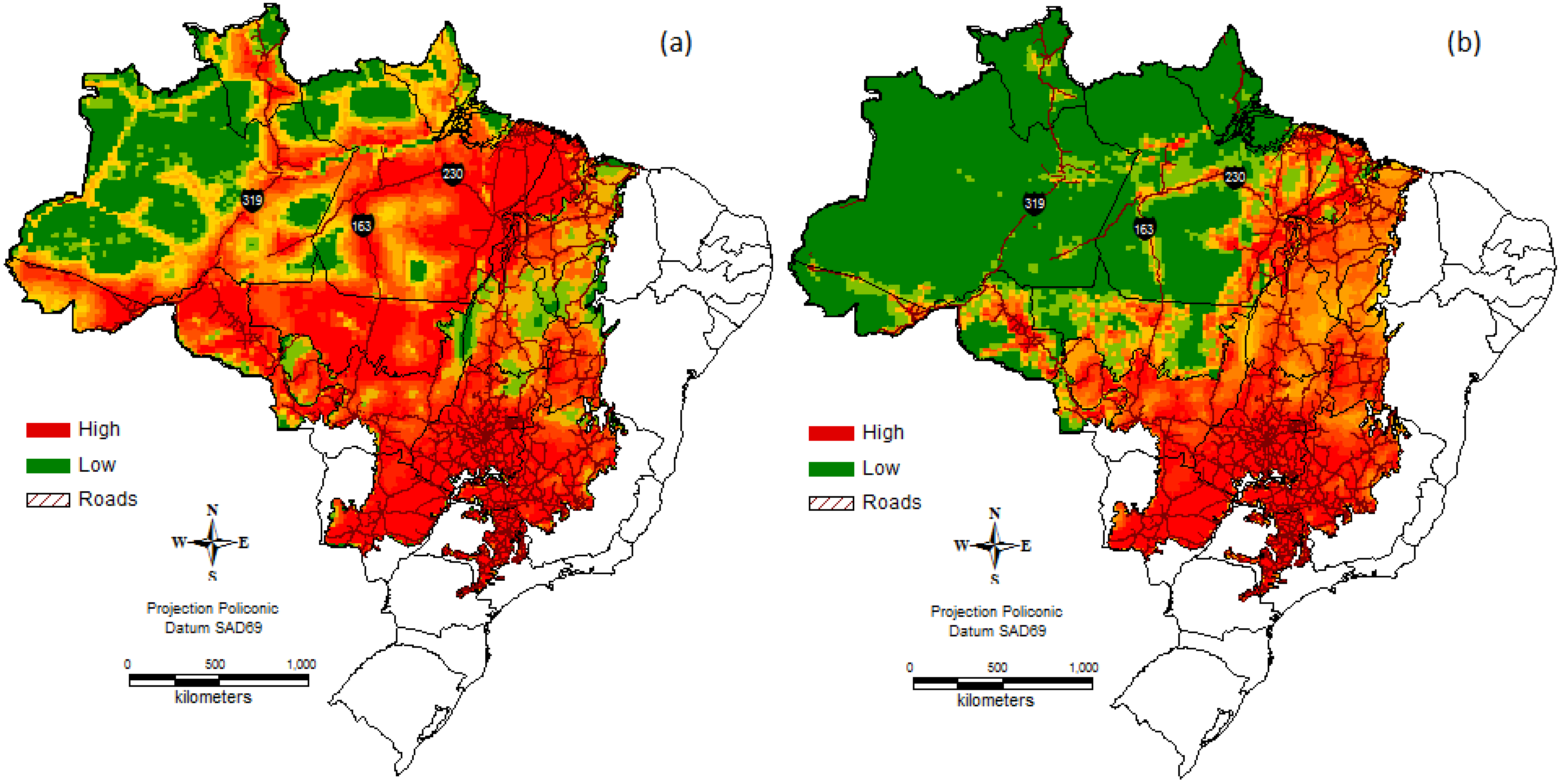

Figure 3.7 - Spatial patterns of land cover change over the Brazilian Amazon and Cerrado under the RAM+BT (a) and GAM+BT (b) scenarios up to 2050.

In general, hotspots of land cover change are also expected to be concentrated in the first half of the time horizon (Figure 3.8). Under the Green-Amazon scenario for instance, 85% of the total forest loss projected to the Amazon and 64% of all deforestation projected to the Cerrado are estimated to occur up to 2030 (Table 3.7). The states of Mato Grosso, Bahia, Piauí, Maranhão and Tocantins show up as the key hotspots of land cover change throughout the Cerrado biome. In this sense, a stronger fragmentation and degradation trend would also be expected over these regions.

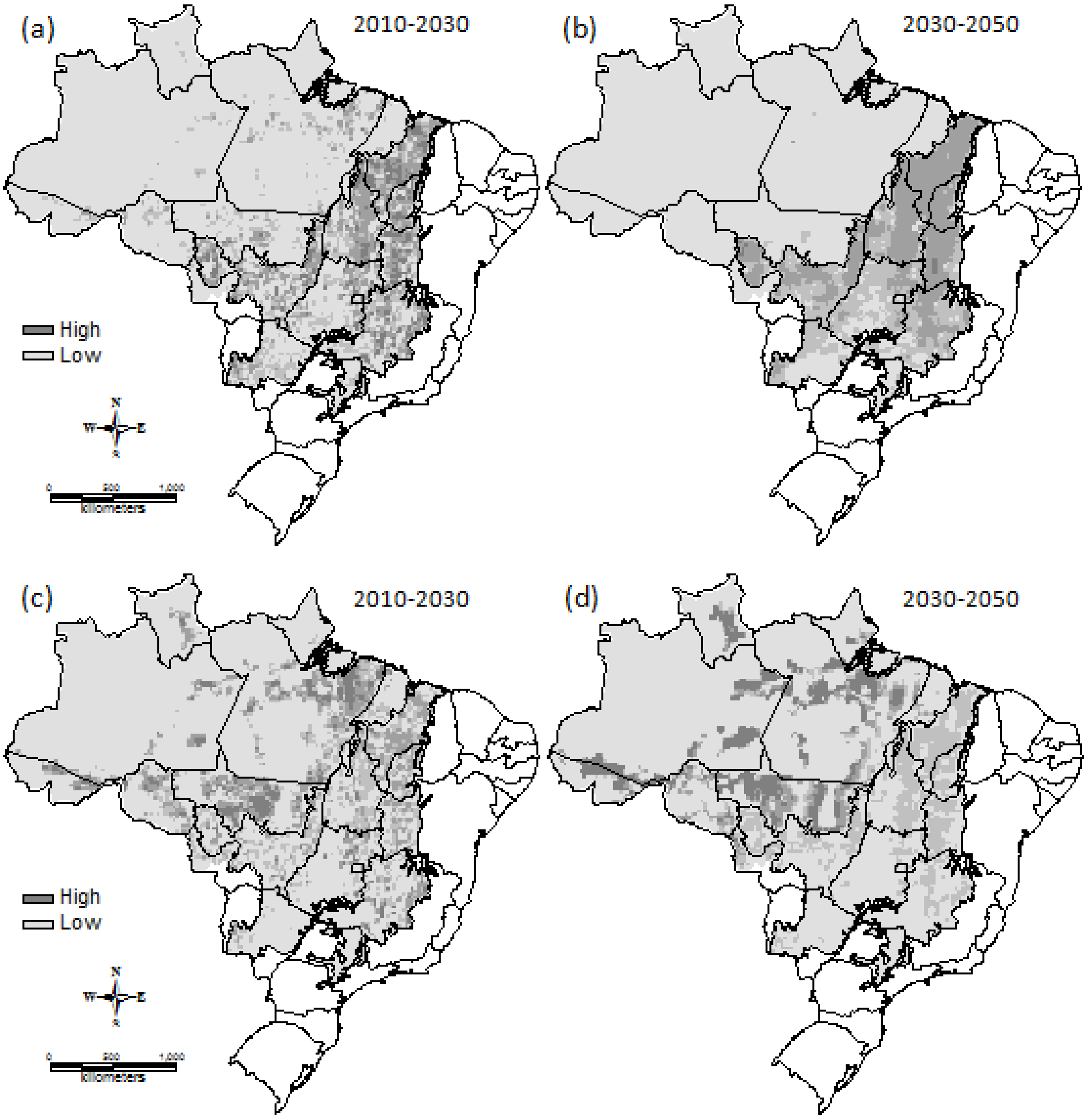

Figure 3.8 - Hotspots of land cover change for the period 2010-2030 and 2030-2050 under the GAM+BT (a, b) and RAM+BT scenarios (c, d). High textural variability is related with major land cover changes (a, c).

From 2030, land cover changes are almost completely focused on the MAPITOBA agricultural frontier under the Green-Amazon scenario as the regions at the south became saturated at this point. Initially, land cover changes are concentrated next to previously cleared areas as in the southeast of the Amazon biome following the spatial dependence of the region's deforestation process (ALVES et al., 2002; FERREIRA et al., 2012). This spatial behavior turns even more intense at the end of the period which raises environmental and political concerns for both biomes as discussed below in the section 3.4.

3.4 Discussion

Unintended effects of land use policies taken to curb Amazon deforestation can lead to strong indirect land cover changes over the Cerrado biome in the coming decades induced by the growing demand for agricultural commodities and biofuels. This line of reasoning in relation to indirect land cover change dynamics in Brazil differs from previous works in two important ways. (i) In this study we make a first attempt to provide empirical evidence about the indirect effects of the soaring Amazon conservation policies over the Cerrado. In general, previous works in this field overlooked this process and explored land demand displacements over the Amazon, due to land use competition (regarding energy-crops expansion for instance) over agriculturally consolidated areas of Brazil (BARONA et al., 2010; LAPOLA et al., 2010; ARIMA et al., 2011; ANDRADE de SÁ et al., 2013). (ii) Also, this work brings a new approach of land use modeling for Brazil linking the world demand for agricultural commodities with local land cover changes based on the integration of global (GDP growth, population growth, market's demand, biofuel targets) and regional forces (land use regulations, distance to roads, presence of protected areas). As discussed by Dalla-Nora et al., 2014, previous modeling efforts were not able to integrate these major forces that shape land use dynamics in the Amazon. In this sense, land demand projections presented in this work are quite contrasting in relation to previous works available in the literature (Figure 3.9).

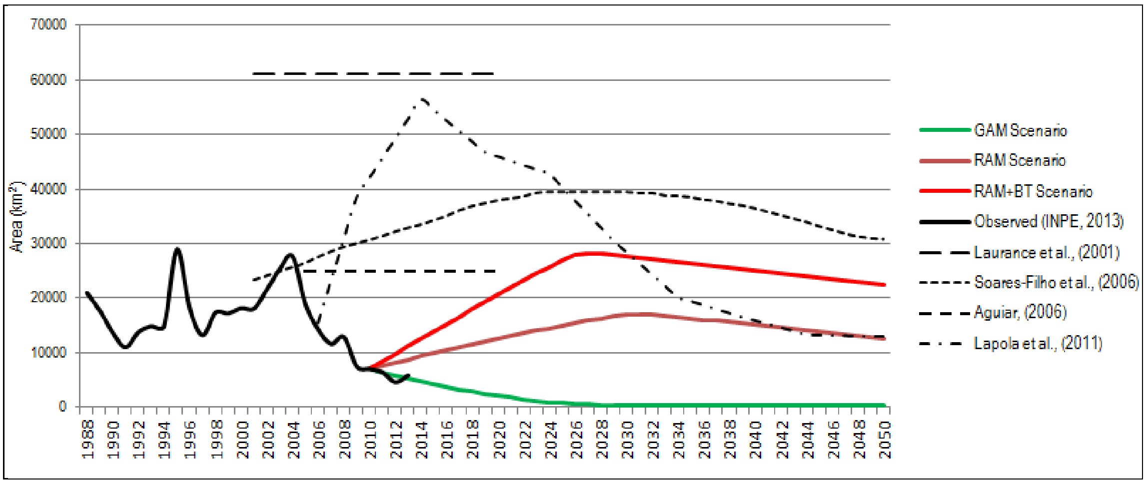

Figure 3.9 - Deforestation rates observed (1988-2013) and projected (2010–2050) for the Brazilian Amazon regarding previous studies.

In general, land demand projections presented in this study are lower than previous ones available in the literature for the Brazilian Amazon. Higher deforestations rates, close to the spikes observed in the past are expected only under RAM+BT scenario. This behavior suggests that even under a scenario of lower law enforcement, economic feedbacks, in this case expressed by changes on land rents, could regulate the speed and magnitude of the land cover changes. In other words, it’s unlikely that Amazon deforestation would progress uninterrupted over time due to a process of economic land use regulation.

Our results provide evidence that harmonized food, fiber and biofuels supply, along with the Brazilian Amazon and Cerrado biome conservation will depend on broader land use policies and land use intensification. In this modeling exercise for instance, we project that an average increase of 21% over the current agricultural and livestock productivity levels would be necessary to reach such conservation and production status. However, meeting such productivity levels may be a challenge in the near future (PIMENTEL et al., 2009), besides, the effects of increasing land productivity in Brazil are very complex (GARRETT et al., 2013; BARRETTO et al., 2013).

It has been suggested in the literature that in agriculturally consolidated areas (southern and southeastern Brazil), land use intensification in the past coincided with either contraction of both cropland and pasture areas, or cropland expansion at the expense of pastures, both cases resulting in farmland stability or contraction. In contrast, in agricultural frontier areas (central and northern Brazil), land use intensification coincided with expansion of agricultural lands (BARRETTO et al., 2013). It means that further productivity gains could generate major incentives for expansion instead of land sparing in the Brazilian agricultural frontier areas.

In general, increasing productivity may generate a reduction in cost and therefore an increase in exports. In our simulation for instance, an increase in land productivity of 10% doubled agricultural exports from Brazil. In this sense, broader land use policies will also be necessary to avoid that improved productivity levels further press cropland expansion over the central and northern Brazil agricultural frontier. In addition, the recovery of degraded, abandoned or underused lands may turn an important strategy to reduce deforestation than only focusing on land use intensification (LAMBIN et al., 2013; LAMBIN; MEYFROIDT, 2011).

Nevertheless, it is worth noting that in this modeling exercise the GAM scenario entails lower amounts of deforestation than the RAM scenario (~479,000 versus 920,000 km^2). In other words, leakage effects are not 100% in terms of area. So, even if there is leakage, the conclusion is that doing something in the Amazon is still better than doing nothing. However, if no policies on improved land use or measures to prevent leakage effects are taken, extensive land cover changes can be faced over the Cerrado once Amazon protection tends to remain a national target, at least in the near future (BRAZIL, 2009).

In this case, the maintenance of Amazon-focused conservation policies in Brazil may endanger large areas of the richest and most extensive savanna in the world (MYERS et al., 2000). As suggested in the GAM+BT scenario, protecting Amazon remaining forests without any other complementary measure to avoid land demand displacements can almost double the cleared area over the Cerrado biome in the coming decades with wide implications on biodiversity loss and carbon emissions. Despite its lower forest coverage and standing biomass, the Cerrado biome plays fundamental ecosystem services as carbon storage (CARVALHO et al., 2010) and as a biodiversity hotspot (MARRIS, 2005). Besides, the functioning of Amazonian ecosystems is tightly linked with the biological integrity of the Cerrado biome (MALHADO et al., 2010).

Ultimately, Amazon-Cerrado land demand displacements also raise concerns about the effectiveness of international initiatives such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation plus sustainable forest management, conservation and enhancement of forest carbon stocks) to promote tropical forests conservation. As evidenced here, indirect land use changes can reverse the eventual benefits of biological and carbon savings intended under such a project in the Brazilian Amazon. The project's focus on forestlands could actually enhance leakage effects over low-biomass ecosystems as the Brazilian Cerrado (MILES; KAPOS, 2008). Besides such initiative obligate applicants to control leakage effects, monitoring systems in this field are very incipient.

In summary, closing the agricultural frontier in the Amazon cannot ensure biodiversity conservation or carbon savings in absence of complementary measures committed with land use efficiency, controlled land use expansion and new economic alternatives. In this sense, recognizing land use systems as open and human-driven systems is a first and central challenge to design more efficient land use polices. Otherwise, managing a transition towards a more sustainable land use can become utopian.

4 FINAL REMARKS

This thesis explored an innovative modeling approach for the Amazon to simulate how the global demand for agricultural commodities and different regional land use policies could affect future deforestation trends inside and outside the Brazilian Amazon. Therefore, a review of previous land use models taken to explore land cover changes in the Amazon was addressed in order to analyze their consistence with the land use dynamics observed in this region. Based on this review, a set of modifications were performed on a global economic model in order to simulate a set of regional land use policies, consistent with the Brazilian Amazon and Cerrado distribution, in combination with global driving forces. Finally, we run a set of contrasting land-cover change scenarios exploring the interaction between land demand for agricultural commodities and biofuels along with regional land use regulations on Brazilian Amazon and Cerrado from 2010 to 2050.

The first working hypothesis was that improved economic and spatial models can better represent the forces that shape land use dynamics in the Amazon regarding previous modeling approaches. The second working hypothesis was that Amazon conservation might not be the end of deforestation in Brazil due to leakage effects on other regions. This final chapter synthesizes the major findings of the whole thesis and discusses how these findings confirm the working hypotheses. In addition, section 4.1 presents some final considerations on the modeling approach proposed in this thesis and point out future research needs related to the thesis' subject. Finally, section 4.2 brings some policy recommendations derived from the main results of this thesis.

4.1 Major findings

Chapter 2 provides evidence that previous modeling approaches were not able to consistently represent the forces that shape land use dynamics in the Amazon. In general they are restricted by either global or regional drives of land cover change. However, Amazon deforestation has been shown to be more complex, involving socioeconomic and political factors acting at multiple scales. Therefore, an alternative modeling approach should be taken to explore cross-scale interactions such as markets demand and land use regulations. In this sense, the integration of a global economic model with a spatially explicit land use model in a stylized manner emerged as a short-term modeling alternative.

Based on this findings MAGNET model was taken to integrate supply and demand factors at both global and regional scales and LuccME/BRAmazon and LuccME/BRCerrado spatial models were used to explore future patterns of land cover change. This modeling framework allowed us to explore a global baseline scenario testing different regimes of land use regulation at the regional scale. Also, the effects of biofuel targets compliance assumed by different countries on local land use transitions were analyzed. A set of multi-scale pathways could then be organized and assessed through deforestation rates and spatial patterns. All theses modeling possibilities, validated for the period 2000-2010, confirmed our first working hypothesis that improved economic and spatial models can better represent the forces that shape land use dynamics in the Amazon regarding previous approaches.

Chapter 3 provides evidence that land use policies taken to curb Amazon deforestation can lead to strong indirect land cover changes over the Cerrado biome in the coming decades. These findings support our second working hypothesis that Amazon conservation might not be the end of deforestation in Brazil due land demand displacements on other regions. If no policies on improved land use, or at least, to prevent leakage effects are taken, massive land cover changes can be faced over the Cerrado in the coming decades and endanger the richest savanna in the world. Biofuels targets compliance can further press land cover changes over this region revealing that productivity gains will be decisive for both Amazon and Cerrado conservation.

These findings also raise concerns about the effectiveness of ongoing international initiatives such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation plus sustainable forest management, conservation and enhancement of forest carbon stocks) to promote tropical forests conservation. The project's focus on forestlands could enhance leakage effects over low-biomass ecosystems as the Brazilian Cerrado and represent a throwback on conservation efforts. The Cerrado biome plays fundamental ecosystem services as carbon storage (CARVALHO et al., 2010) and as a biodiversity hotspot (MARRIS, 2005). Besides, the functioning of Amazonian ecosystems is tightly linked with the biological integrity of the Cerrado biome (MALHADO et al., 2010).

In summary, this thesis provide an alternative approach of land use modeling for Brazil linking the world demand for agricultural commodities with local land cover changes based on the integration of global and regional forces. Also, this thesis explores a different line of indirect land cover change dynamics in Brazil. Overall, previous works in this field explored land demand displacement over the Amazon due to land use transitions regarding energy-crops expansion over agriculturally consolidated areas of the country (BARONA et al., 2010; LAPOLA et al., 2010; ARIMA et al., 2011; ANDRADE DE SÁ et al., 2013). In this sense, this work is also the first one to provide empirical evidence about the indirect effects of Amazon conservation policies over the Cerrado. Finally, the results and modeling advances derived from this thesis can also benefit other modeling teams (Climate Models, Earth System Models) or subsidizing deeper studies regarding impact, adaptation, vulnerability or natural disasters.

4.2 Modeling approach and future research needs

The primary advantage of the modeling approach presented in this thesis is the possibility of representing land use systems as open systems. It means to model land-use systems taking in to account direct and underlying land use drivers acting at both global and regional scales. In addition, this approach allows exploring intra-regional dynamics, mediated by different land use policies, between the Amazon and Cerrado biomes. A number of modeling innovations were necessary which comprise the modification of a global economic general equilibrium model (MAGNET) in order to represent Brazilian sub-regions, consistent with the Brazilian Amazon and Cerrado distribution, and so simulate a set of regional land use policies in combination with global forces. The implementation of a land use transition matrix for these sub-regions (Amazon and Cerrado) also created the possibility to model land cover changes explicitly, preventing the problems of the land supply curve in combination with a constant elasticity of transformation (CET) of the standard MAGNET model. This innovation allowed making explicit in MAGNET that land use transitions are not symmetric, but tending to go from forestland-to-pastureland-to-cropland in the Amazon.

Also, the recent improvements introduced on LuccME Framework, such as a potential transition component based on the Spatial Lag technique implemented by Aguiar (2012), offered the possibility to allocate MAGNET-derived land demand projections taking into account the spatial dependence of the deforestation process, which tends to concentrate close to previously cleared areas (ALVES et al., 2002; FERREIRA et al., 2012). This approach allowed dynamically update the potential of change considering the deforestation frontier temporal evolution and changes in the spatial drivers at each time step according to the scenario assumptions.

Nevertheless, this work is far from exhausting the topic and modeling improvements are still necessary. Future innovations related to this thesis could concentrate in two major aspects. The first one would be the development of a national database to run one single spatial model. Once calibrated and validated such improvement could increase the modeling framework consistency and the capability to analyze leakage effects on other biomes.

The second aspect would be the integration of MAGNET model with a global climatic model. A dynamic exchange of information between these models could permit the investigation of feedback between land cover change and climate change. If precipitation in the Amazon is reduced for instance, the region's suitability can be affected after a critical threshold is crossed and land cover changes could decrease, even under the RAM scenario, and perhaps increase elsewhere.

4.3 Policy recommendations

Our results provide evidence that Brazilian land use policies must be planned having land use systems as open systems connected with remote land use drivers inside and outside the country. Otherwise, region-focused measures run the risk of just displace land demand or deforestation pressure across the country as previously observed in the south and southeast of Brazil (BARRETTO et al., 2013) and also in other tropical countries (LAMBIN; MEYFROIDT, 2011; MEYFROIDT et al., 2013). Broader land use policies will also be necessary to avoid that future productivity gains further press cropland expansion over the central and northern Brazil agricultural frontier. In addition, the recovery of degraded, abandoned or underused lands may turn an important strategy to reduce deforestation than only focusing on land use intensification (LAMBIN et al., 2013; LAMBIN; MEYFROIDT, 2011).

Also, became clear in this work that Cerrado is a highly unprotected Brazilian biome, therefore, under deforestation risk at any scenario. It suggests that new, efficient and biologically representative PAs should be considered as an urgent conservation policy for the Cerrado. This measure is not the solution to guarantee the biological integrity of this biome, but would represent an important strategy to safeguard meaningful pieces of the regional biodiversity at short term.

In this sense, still remains as institutional challenges in Brazil the development of alternative markets or robust incentives for biodiversity conservation (IPEA, 2011; COSTA et al., 2010; ASSUNÇÃO et al., 2013b). Law enforcement by itself cannot ensure a sustainable land use control over the agricultural frontiers. As suggested in the literature, farmers are likely to reduce or not increase their managed acreage only if land becomes a scarce resource (BARRETTO et al., 2013). In this sense, providing new incentives for ecosystem services conservation, beyond carbon sequestration and with national coverage can become an important mechanism for both Amazon and Cerrado deforestation containment. However, political measures following this line of reasoning in Brazil are missing till now.

In summary, closing the agricultural frontier in the Amazon cannot ensure biodiversity conservation or carbon savings in absence of complementary measures committed with land use efficiency, controlled land use expansion and new economic alternatives.

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APPENDIX 1

Supporting Information

Amazon conservation might not be the end of deforestation in Brazil

1. SI Figures

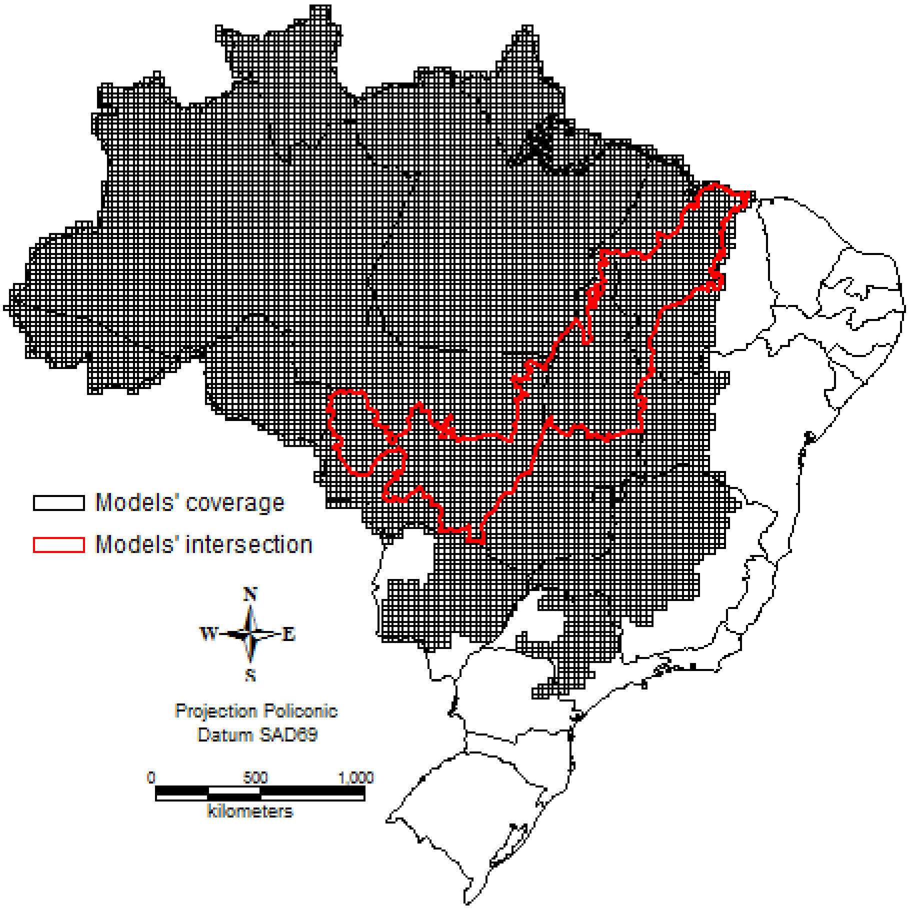

Figure A.1 - Spatial coverage and intersection between the BRAmazon and BRCerrado land use models.

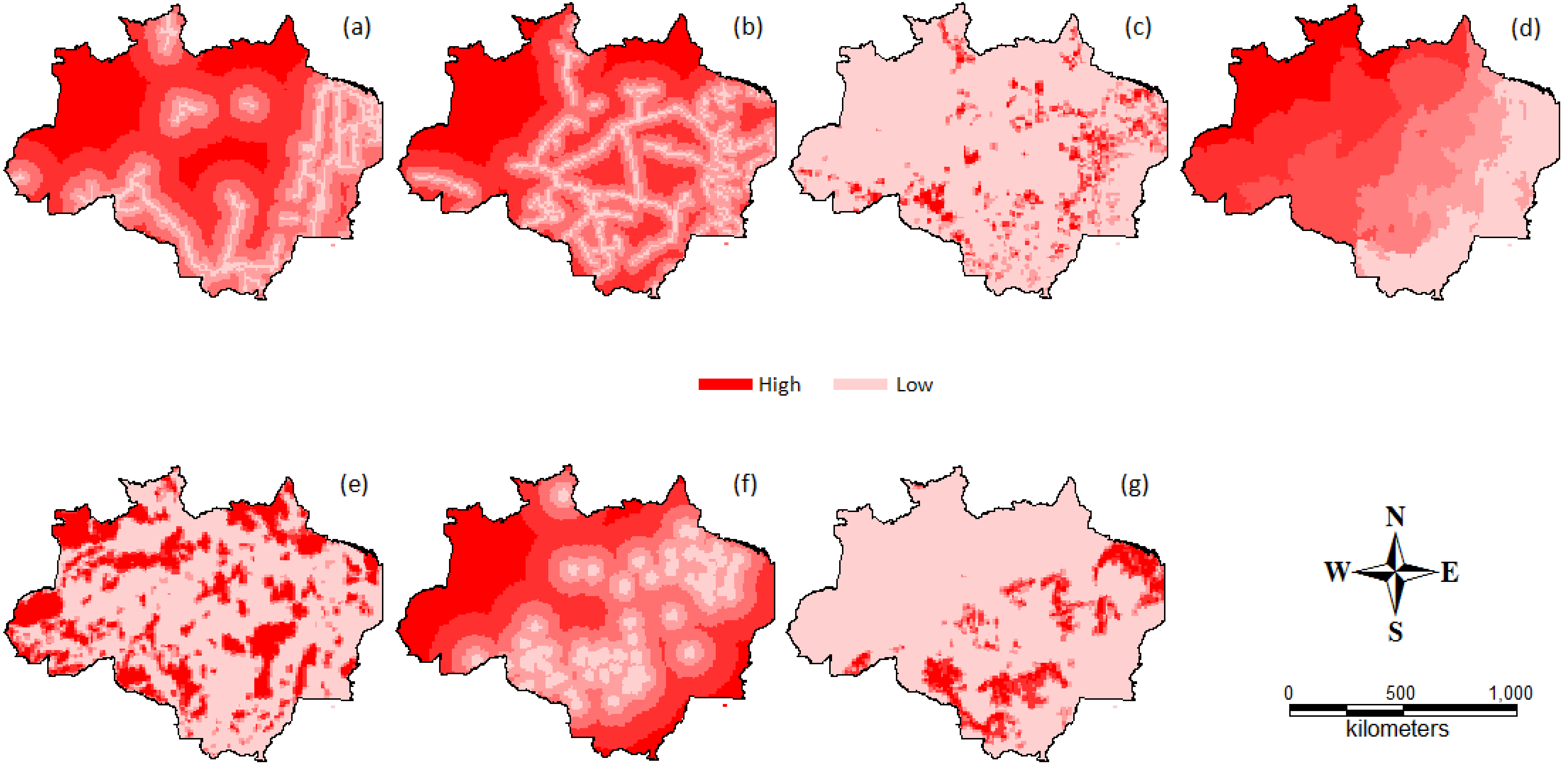

Figure A.2 - Spatial drivers of deforestation selected to run the BRAmazon model: Distance to paved roads (a), Distance to unpaved roads (b), Presence of agrarian settlements (c), Connectivity to national markets (d), Presence of protected areas (e), Distance to wood processing stations (f), Presence of high-fertility soils (g).

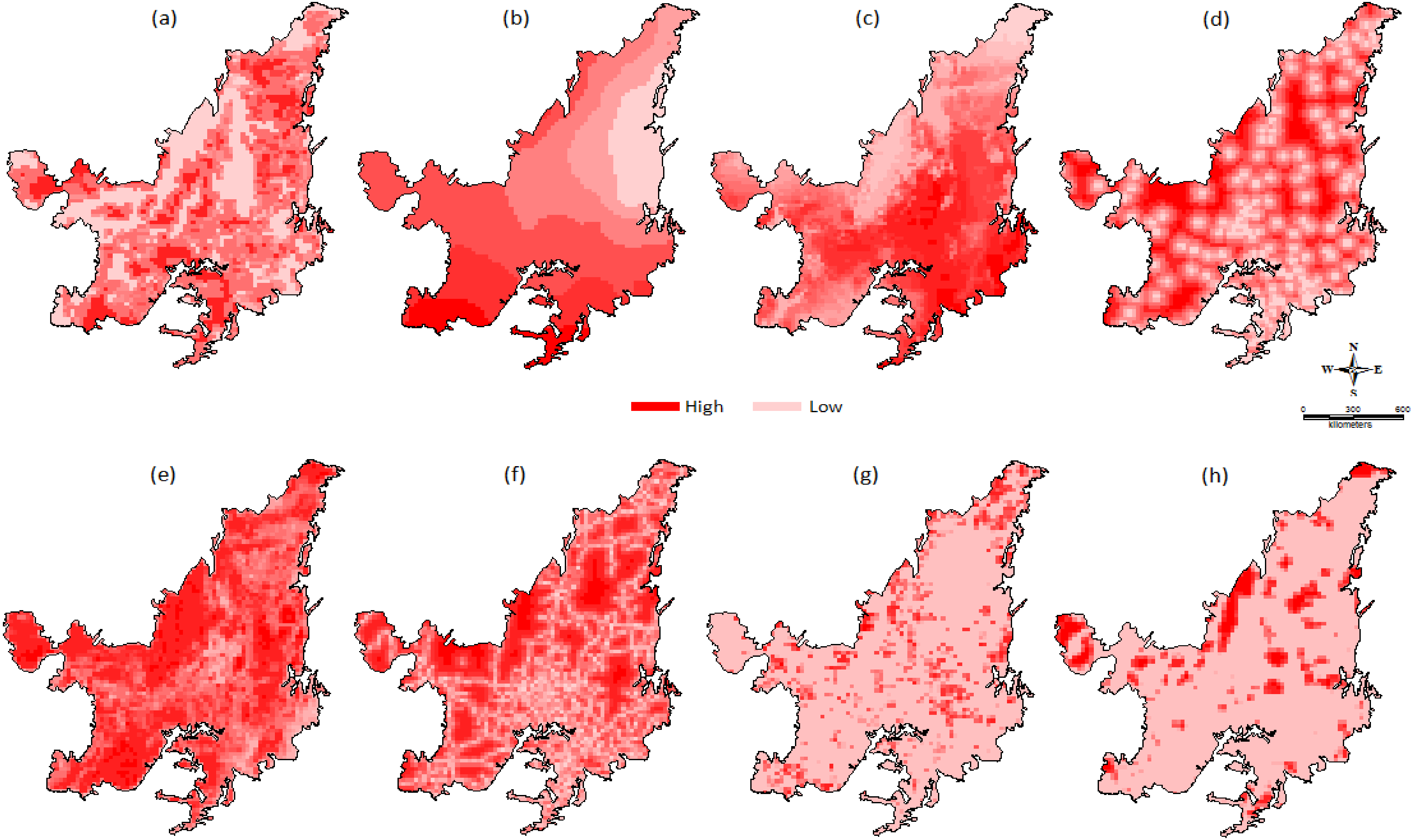

Figure A.3 - Spatial drivers of deforestation selected to run the BRCerrado model: Soil fertility (a), Soil moisture (b), Altimetry (c), Distance to urban centers (d), Slope (e), Distance to roads (f), Presence of agrarian settlements (g) and Protected areas (h).

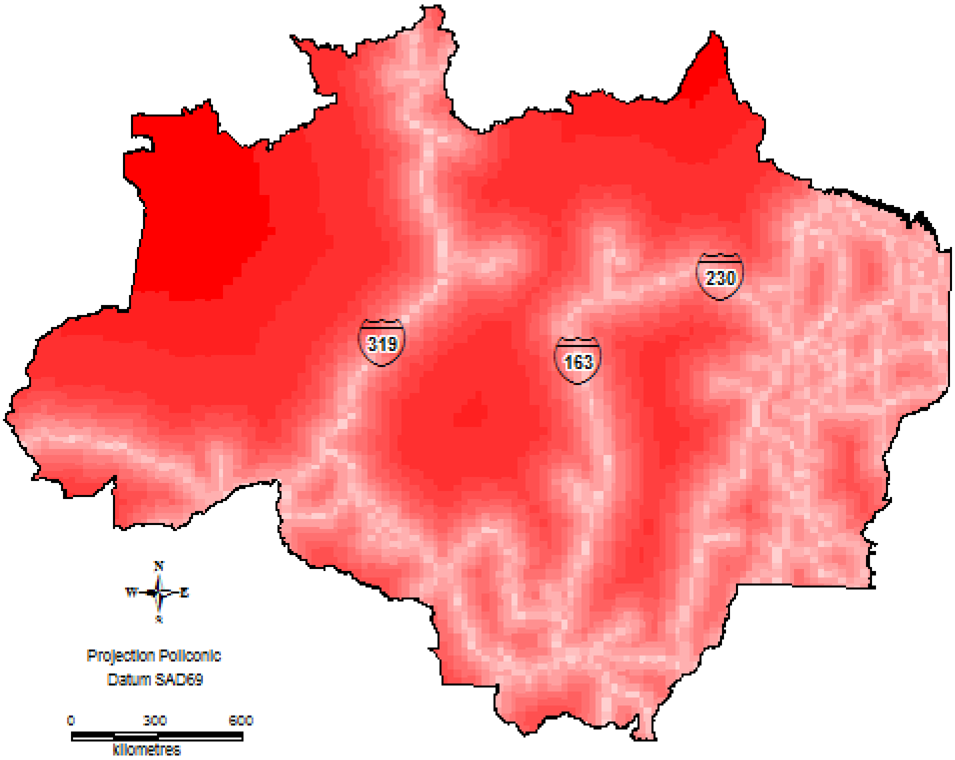

Figure A.4 - Key unpaved roads BR-163 and BR-319 for agricultural expansion in the Amazon simulated to be paved up to 2015 on BRAmazon model (AGUIAR et al., 2012).

1. SI Tables

Table A.1 - MAGNET model land use transition matrix for Brazil.

LANDTRANS	Rice	Wheat	Grain	Oilseeds	Sugar cane	Horticulture	Plant-based fibres	Other crops	Cattle	Milk	Natural forest	Commercial forest	Savannah grassland	Shrubland	Builtup land	Deforested land
Rice	393	274	270	277	285	271	127	272	268	265	3	3	3	3	5	3
Wheat	275	801	407	418	430	410	132	411	411	407	4	4	4	4	8	4
Grain	270	406	10170	2408	2474	1875	130	1134	2351	2327	23	23	23	4	28	22
Oilseeds	280	421	2431	10876	2572	1944	134	1176	2477	2452	25	25	25	5	29	24
Sugar cane	293	440	2543	2618	19578	2033	140	1230	3592	3556	37	37	37	5	30	25
Horticulture	273	409	1880	1930	1983	7407	131	1144	1890	1871	19	19	19	4	28	19
Plant-based fibres	128	132	131	134	138	131	127	132	133	132	1	1	1	1	2	1
Other crops	274	411	1137	1168	1200	1144	131	3711	1146	1134	11	11	11	5	22	11
Cattle	267	443	2452	2742	4213	1996	150	1220	194281	5162	213	213	49	5	30	24
Milk	251	417	2308	2583	3972	1879	142	1149	4857	77492	93	93	43	4	26	20
Natural forest	3	4	22	23	32	18	1	11	0	0	1926435	991	42	4	27	11449
Commercial forest	3	4	22	22	31	18	1	11	201	100	1042	1040328	44	4	28	21
Savannah grassland	7	10	59	59	81	47	3	28	117	117	117	117	116273	11	75	56
Shrubland	3	4	4	4	4	4	1	4	4	4	4	4	4	4140	9	4
Builtup land	2	4	13	13	13	13	1	10	13	13	13	13	13	4	15131	13
Deforested land	2	3	16	16	16	13	1	8	4423	16	16	16	8847	3	20	2392