**University of São Paulo
College of Agriculture “Luiz de Queiroz”**

Agricultural land-use expansion dynamics in Brazil

Alberto Giaroli de Oliveira Pereira Barretto

Thesis presented to obtain the degree of Doctor in
Science. Area: Soils and Plant Nutrition

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2013**

Alberto Giaroli de Oliveira Pereira Barretto
Agronomist

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Prof. Dr. **GERD SPAROVEK**

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RESUMO

A dinâmica da expansão agropecuária no Brasil

O Brasil tem uma importante atuação na agricultura mundial. Nas últimas décadas, a produção agrícola tem aumentado intensamente como resultado da expansão tanto em área quanto em produtividade, levando o Brasil a se tornar um produtor líder mundial de carne bovina, soja, açúcar, frango e café. As dificuldades de renovação de estoques mundiais e o aumento acentuado do consumo, especialmente de grãos tais como milho, soja e trigo resultam em condições favoráveis para as principais regiões agrícolas continuarem aumentando a produção. No entanto, há uma falta de pesquisas com base empírica em grande escala que abordem a complexa dinâmica das mudanças no uso da terra relacionadas ao crescimento agrícola de área e de produtividade. O objetivo deste trabalho é abordar os controversos ou pouco investigados pontos essenciais desta questão central por meio de modelagem espacial e bases de dados de acesso aberto. Em primeiro lugar, a disponibilidade de áreas adequadas para a expansão da lavoura foi estimada por meio de um modelo espacialmente explícito em escala nacional. Em seguida, os efeitos das mudanças de produtividade sobre as mudanças de área foram investigados tanto para pastagem e agricultura através de uma análise espacial retrospectiva de longo prazo que abrangeu o período de 1960 a 2006. Posteriormente, um modelo espacial eficaz utilizando variáveis-chave de levantamento periódico por órgãos oficiais foi desenvolvido para identificar a fronteira agrícola brasileira. Por fim, foi analisada a relação entre desmatamento, expansão da lavoura e expansão da pastagem na região da Amazônia Legal e foram sugeridas evidências para um melhor entendimento da relação entre causa e efeito na mudança do uso da terra. O conjunto de artigos conduziu às seguintes principais conclusões: (i) O Brasil tem uma enorme quantidade de terras cobertas por pastagens (122 milhões de hectares) com condições favoráveis para produção intensiva de culturas agrícolas anuais. (ii) Historicamente, há uma distinção clara na dinâmica de uso da terra entre as áreas agriculturáveis já consolidadas e a fronteira agrícola. Em áreas agrícolas consolidadas, aumentos na produtividade têm sido associados à intensificação de pastagens e à estabilidade ou a diminuição da área agrícola total. Por outro lado, em áreas de fronteira agrícola, o aumento na produtividade tem sido associado com a expansão agrícola. (iii) A análise espacial de transições de uso da terra desde 1960 ilustra a expansão e o movimento gradual da fronteira agrícola em direção ao interior do Brasil. No entanto, também sugere a possível abertura de uma tendência inversa, ou seja, contração agrícola em áreas íngremes do Sudeste dentro do bioma Mata Atlântica, que pode estar de acordo com a teoria da transição florestal (FT). (iv) Na Amazônia Legal, entre 2000 e 2009, crescimento do efetivo bovino, a expansão da agricultura e o desmatamento aconteceram, em geral, de forma simultânea nos municípios, sugerindo a necessidade de modificar a noção generalizada da expansão de áreas cultiváveis em regiões consolidadas como um fator primordial para o desmatamento indireto por meio do deslocamento de pastagens dessas regiões para regiões de fronteira agrícola.

Palavras-chave: Mudança no uso-da-terra; Agricultura; Ambiente; Modelagem espacial; SIG

ABSTRACT

Agricultural land-use expansion dynamics in Brazil

Brazil is one of the most important global agricultural players. In the last decades, agricultural production has increased drastically as a result of expansion in area and productivity growth, which made Brazil a worldwide leading producer of beef, soybean, sugar, ethanol broiler and coffee. The difficulties of world stock renewal and the sharp consumption increase especially of grains such as corn, soybean and wheat result in favorable conditions for agricultural leading regions to continue increasing production. However, there is a lack of evidence-based research at large scale that address complex land-use changes dynamics related to agricultural growth of area and productivity. The purpose of this thesis is to approach controversial or under-investigated key-points of this central issue by using spatial modeling and open access databases. First, the availability of areas suitable for cropland expansion was estimated through a spatially explicit model at national scale. Second, the effects of productivity changes on area changes were investigated both for pasture and cropland by a long-term retrospective spatial analysis that covered the period 1960-2006. Third, a comprehensive and effective spatial model using key variables was developed to identify the Brazilian agricultural frontier. Fourth, the relationship between deforestation, cropland expansion and pasture expansion was analyzed in the Legal Amazon region and evidences for a better understanding of causal-effect relation in land-use change were suggested. The assembly of papers led to the following main findings: (i) Brazil has a huge amount of land covered by pastures (122 million hectares) with suitable biophysical conditions for intensive crop production; (ii) Historically, there is a clear distinction in land-use dynamics between agriculturally consolidated areas and the agricultural frontier. In agriculturally consolidated areas, cropland yield increases have been associated with pasture intensification and stability or contraction in total farmland area. In contrast, in agricultural frontier areas, cropland yield increases have been associated with agricultural expansion; (iii) Spatial examination of land use transitions since 1960 illustrates the expansion and gradual movement of the agricultural frontier towards the inland of Brazil. However, it also suggests the possible initiation of a reversed trend, i.e. agricultural contraction, in steep areas of the Southeast within the Atlantic Forest biome, which might be in line with the Forest Transition theory (FT); (iv) In Legal Amazon during 2000-2009, cattle population growth, cropland expansion and deforestation were in general concurrent at the municipal level, suggesting a need for modifying the widespread notion of cropland expansion in consolidated regions as a prime causal factor of indirect deforestation through displacement of pastures from these regions to frontier regions.

Keywords: Land-use change; Agriculture; Environment; Spatial modeling; GIS

1 INTRODUCTION

1.1 Background

Brazilian agriculture – presently covering about one-third of the Brazilian land area – has expanded substantially during recent decades and is expected to expand further in response to growing demand for food products and biofuel feedstock (BRASIL, 2010a, 2010b; OECD-FAO, 2010; OECD-IEA, 2010). Even though it is expected (and advertised) that most of the future demand will be supplied by intensification of crop and livestock production (BRASIL, 2010a), there is great uncertainty about how much native vegetation will be converted to agriculture in the short and long run..

During the period 1980-2000, 80% of the agricultural expansion in the tropics took place on forested land (GIBBS, RUESCH et al., 2010). Several studies concluded that recent agricultural expansion in Brazil has resulted in substantial loss of natural ecosystems and in negative impacts for biodiversity, soil and water resources (FEARNSIDE, 2001; DA SILVA and BATES, 2002; MORTON, DEFRIES et al., 2006; SAWYER, 2008; BARONA, RAMANKUTTY et al., 2010). According to recent estimations (SPAROVEK, BERNDES et al., 2010; SPAROVEK, BERNDES et al., 2012), historical non-compliance with environmental legislation on private farmlands in Brazil resulted in 87 million hectares (Mha) of agricultural lands in illegal condition. This situation placed Brazilian agribusiness sector, which is responsible for approximately one-quarter of national GDP (CEPEA, 2012), at an uncomfortable crossroad with respect of its future development. It is essential to address environmental issues and at the same time enhance agricultural production to respond to an increasing global demand.

Environmental impacts of *future* expansion have also been subject of researches reporting seemingly contrasting results. Some point to risks of further ecosystem conversion, large greenhouse-gas emissions, biodiversity loss, and resource degradation (CERRI, EASTER et al., 2007; FARGIONE, HILL et al., 2008; NEPSTAD, STICKLER et al., 2008; SCHARLEMANN and LAURANCE, 2008; LAPOLA, SCHALDACH et al., 2010), while others stress that productivity increases and good agronomic practices can reduce agricultural land expansion requirements and mitigate negative impacts (GOLDEMBERG, 2007; NASSAR, RUDORFF et al., 2008; LEITE, LEAL et al., 2009). Reasons for the diverging conclusions include differences in scope and applied methodology, and variation of empirical data used. In Brazil, the primary data required for modeling and quantification are distributed over several sources and institutions, limiting data access and restricting comprehensive

national modeling. However, better data alone are insufficient for improved models and projections of land-use change. They must be matched with an enhanced understanding of the dynamics of changes. There is in general limited knowledge about how cropland expansion affects grazing-based livestock production systems and about land use dynamics in possible agriculture expansion regions such as rangelands and forests-savannas transitional areas (LAMBIN, TURNER et al., 2001; RUDEL, 2007; ANGELSEN, 2010; LAMBIN and MEYFROIDT, 2011).

The purpose of this study is to contribute to this matter by addressing some research questions that directly influence the understanding of the mechanisms of land-use change associated with agricultural expansion in Brazil.

First, it was conducted an effort to improve geospatial databases at national scale focusing on land use information, physical conditions (climate, soil, slope), landscape positions (riparian systems) and political conditions (public protected areas, biomes). The purpose of this effort was to attain a consistent dataset that could be used as input to a spatially explicit model designed to estimate the availability and suitability of lands for agriculture expansion in Brazil, including the framework of environmental legislation. The main results of this work were reported by SPAROVEK, BERNDES et al. (2010), SPAROVEK, BARRETTO et al. (2011), SPAROVEK, BERNDES et al. (2012). The land suitability model which is a component of this principal model named Agricultural Land Use and Expansion Model - Brazil (AgLUE-BR), is reported by **Chapter 2** (Paper I) of the present Thesis.

Second, the review of land-use change science literature led to the conclusion that agricultural intensification and land use zoning are the most common proposed strategies to control negative impacts of agricultural expansion (TURNER, LAMBIN et al., 2007; LAMBIN and MEYFROIDT, 2011). However, a spatial analysis trying to clarify to which extent agricultural intensification could be considered a land saving strategy has not been done yet for Brazil at the national scale. **Chapter 3** (Paper II) focuses this issue by analyzing changes in total farmland area during 1960-2006 and the relationship of changes in yield and stocking rate against changes in cropland and pastures areas in Brazil during 1975-2006. Most of large-scale studies with such scope do not include pasture land in their analysis (see e.g. (EWERS, SCHARLEMANN et al., 2009; RUDEL, SCHNEIDER et al., 2009)). Nevertheless, livestock production remains the world's largest user of land, both directly for grazing and indirectly by consumption of feed crops (NAYLOR, STEINFEID et al., 2005). In Brazil, pasture based livestock production systems occupies an area of approximately 200 Mha with

an average stocking rate of 1.1 animal units.ha⁻¹ (IBGE, 2006). Such huge amount of pastures used at an apparently extensive base is probably the main reserve of land not covered by native vegetation that can be used to allocate global cropland area expansion. Therefore, the understanding of spatial patterns of pasture intensification in Brazil is crucial not only domestically, but also globally. **Chapter 4** (Paper III), in its turn, proposes a methodology to identify the Brazilian Agricultural Frontier in 2006 based on Agrarian Census data and GIS tools. Agricultural Frontier is, by definition, a region where it is expected relatively rapid land use change accompanied by conversion of native vegetation (RICHARDS, 1990; RINDFUSS, ENTWISLE et al., 2007). In that sense, a comprehensive methodology that locates Agricultural Frontier could be a complementary tool for land-use zoning and control, i.e. schemes to allocate land to restricted uses, ensuring that valuable natural ecosystems are not converted (BRIASSOULIS, 2000).

Third, one of the key and controversial mechanisms of land use change is the displacement of one activity by another, inducing a subsequent migration of activities that could cause impacts in another place. So-called “Leakage effect” or “Indirect Land Use Changes (iLUC)” was pointed as a potential problem that could compromise climate direct benefits of using Brazilian biofuels (FARGIONE, HILL et al., 2008; SEARCHINGER, HEIMLICH et al., 2008). Even though iLUC is considered a difficult and controversial issue (MATHEWS and TAN, 2009; PRINS, STEHFEST et al., 2010; GAO, SKUTSCH et al., 2011; NASSAR, HARFUCH et al., 2011), some studies based on Brazilian municipal databases confirmed the causal mechanism of land-use change that occurred in Legal Amazon during the 2000’s, i.e. The expansion of area cultivated with soybeans caused the displacement of cattle ranching activity leading to an increase in deforestation rates (BARONA, RAMANKUTTY et al., 2010; ARIMA, RICHARDS et al., 2011). Using the same municipal database sources, but a different methodology, **Chapter 5** (Paper IV) aims to contribute with this discussion by estimating the extent to which the growth in cropland, pasture areas and deforestation were spatially coincident in the Legal Amazon region during 2000-2009.

1.2 Limitations for answering the research questions

The papers that compose this Thesis have in common the use of spatial modeling to produce results. In addition, the datasets sources were open access secondary databases. The use of models and skip of classical experimentation to answer scientific questions raise the discussion whether or not modeling is science. Models are simplifications of reality.

Moreover, if they combine natural processes and human actions, then they are very unlikely to be verified. Human actions are not predictable and controlling experiments are in most cases inconceivable. So, if a model contains uncertainties that cannot be assured in any absolute sense, why should the results be trusted?

Agriculture operates on the interface between the socioeconomic and natural environment. The complex and urgent issues agriculture is facing, such as climate change, food and energy supply and scarcity of natural resources, cannot be addressed through traditional disciplinary research. Spatially explicit and Integrated Assessment Models appeared in this context as a tool to fulfill the gap left between traditional science and the society needs for evidenced based policies (EWERT, VAN ITTERSUM et al., 2009).

The argument that modeling is the only tool available to address some specific questions does not make model results more trustful or reliable. Even though models contain inherent flaws, AZAR (2011) asserts that by running a model it is possible to have a better view of underlining dynamics and discover fundamental relationships of the studied system. Therefore, the key role of using models should not be the results *per se*, but the insights about reality that may be learned by building and running it. If the use of a model was useful to learn something reasonable about the world, then the model may be trusted. AZAR (2011) also recommends modelers to be critical about two key points. First, clearly address the limitations (structural or parametrical) and simplifications of reality that were done and how they are likely to affect the results. Second, make it clear when/if value-laden assumptions enter the model. The last is often an intricate task because there are assumptions that some argue are value-laden whereas other think are objectively correct and there are typically both unconscious and conscious value-laden assumptions.

The papers presented here aimed to fulfill the basic requirements to enhance the reliability of results. The type of modeling used is in a major extent descriptive, which means that the main objective is to explain how things are like. In all papers, modeling is not a “black-box” but an analytical tool for investigating hidden relationships between variables and to spatially analyze them. The insights learned from the description of past land-use change suggest actions for the present and outline possible future outcomes.

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2 GIS-BASED MULTICRITERIA ASSESSMENT OF CROPLAND SUITABILITY AT THE NATIONAL SCALE IN BRAZIL

Abstract

Approximately one-third of the land in Brazil is used for crop production and/or pasture-based livestock production. Both of these activities are expected to expand. The impact of this expansion depends on several variables, including the extent to which land is suitable for agriculture. We developed a comprehensive model to assess land-suitability for crop production at the national scale. Publicly available climate, soil, and topography data were combined, revised and reviewed to produce a database for processing and modeling. According to the model presented here, 12% (103 Mha) of the Brazilian territory is classified as “Very Suitable”, 35% (294 Mha) as “Suitable”, 35% (294 Mha) as “Marginally Suitable”, and 15% (127 Mha) was classified as “Unsuitable”. The model validity was demonstrated by comparing it to current land-use distribution. Intensive cropping regions matched areas with high suitability for crop production in the model, and restrictive suitability classes were more often associated with low intensive land uses. The model has a satisfactory Relative Operating Characteristics (ROC) statistic of 0.62. The methodology structure was organized as a stepwise exercise, which made it possible to generate and test the suitability model as climate, soil, and topography layers were gradually added. This procedure showed that adding coarse edaphic information could jeopardize model accuracy; on the other hand, a single climate-based model for Brazil probably underestimates areas of native vegetation with good suitability for crop production, i.e., when comparing the first output (climate perspective) to the final output, native vegetation classified as “Very Suitable” increased from 21 Mha to 43 Mha. The results database is open-access, and its design allows its use by those working with agricultural, environmental, and land-use issues. The results may also be useful for supporting models, decisions, and actions aimed at intensifying the use of underutilized agriculture land as an alternative to agricultural expansion.

Keywords: Land use change; Agriculture; Environment; Spatial modeling; GIS

2.1 Introduction

During the period 1980-2000, 80% of the agricultural expansion in the tropics took place on forested land (GIBBS, RUESCH et al., 2010). The Brazilian cropland area increased 19.8 Mha during the period 1975-2006, mostly to support increased production of soybean and sugarcane, which increased from 7.8 to 15.6 Mha, and from 2.6 to 5.6 Mha, respectively (IBGE, 2006). The agriculture expansion is expected to continue during the coming decades due to further growth in food and biofuel demands (BRASIL, 2010; BRASIL, 2010b; OECD-FAO, 2010; OECD-IEA, 2010).

Establishment of policies around the world that stimulate biofuel consumption, and the resulting agriculture expansion to provide biofuel feedstock, causes concerns about risks for undesirable consequences. Especially, effects associated with land use change caused directly

(dLUC) or indirectly (iLUC) by bioenergy projects have been debated (SEARCHINGER, HEIMLICH et al., 2008; NEPSTAD, SOARES et al., 2009; LAPOLA, SCHALDACH et al., 2010). The LUC effects are difficult to quantify with high confidence, especially those associated with iLUC. Attempts to quantify the effects commonly use general or partial equilibrium models (see, e.g. CHUM, FAAIJ et al. (2011) for an overview) of varying scope (e.g., geography and spatial resolution, sectors covered and detail in their characterization), but there are also statistical approaches to detect iLUC (ARIMA, RICHARDS et al., 2011), and approaches that make quantifications based on pre-defined, causal-effect chains (KIM e DALE, 2009; E4TECH, 2010; FRITSCHKE, HENNENBERG et al., 2010). There are many reasons for the large divergence in results – and in conclusions about the effectiveness of biofuels on GHG emissions mitigation (PRINS, STEHFEST et al., 2010; BERNDES, BIRD et al., 2011; KHANNA, CRAGO et al., 2011) – such as assumptions made in models about price elasticity, trade patterns, the use of by-products within the agricultural sector, and agricultural productivity and its development as determined by yield responsiveness, land availability, and land conversion pathways.

Studies available so far commonly do not include a spatially explicit biophysical database (PRINS, STEHFEST et al., 2010; GAO, SKUTSCH et al., 2011). For instance, SEARCHINGER, HEIMLICH et al. (2008) estimated LUC patterns according to the amount and type of land conversion for cultivation in 1990-99, based on the Food and Agricultural Organization Statistical Database. The primary limitation of using highly aggregated data – such as FAO – is that differences in LUC dynamics at sub-national scales cannot be distinguished. LAPOLA, SCHALDACH et al. (2010), on the other hand, included a biophysical database in a large scale LUC analysis for Brazil. However, crop and grassland productivity were estimated by a dynamic global vegetation model driven exclusively by climate variables (BONDEAU, SMITH et al., 2007; LAPOLA, PRIESS et al., 2009). The spatial resolution of the climate-interpolated database used was 0.5 degree latitude/longitude grid cells, but the original data sources suffered from poor coverage in large Brazilian regions. For example, the Amazon Basin, an area of approximately 390 Mha, was represented by 40 climate stations gathering precipitation data and 25 stations gathering temperature data (NEW, HULME et al., 1999). The same climate database is used by FAO/IIASA Agro-ecological Zone (AEZ) methodology (FISCHER, NACHTERGAELE et al., 2012), the main reference for several biophysical models used to assess large-scale potential crop yields, e.g. GTAP-AEZ (HERTEL, LEE et al., 2009) and IMAGE/LEITAP (EICKHOUT, VAN MEIJL

et al., 2009). AEZ methodology is derived from the FAO framework for land evaluation (FAO, 1976) in which land suitability is a core concept.

Land suitability evaluation is based on assessing a set of site-specific physical variables in relation to specified requirements associated with a given agricultural system. Land suitability evaluation may also include consideration of socio-economic variables and can be carried out at different scales depending on the purpose and complexity of approach. A national agricultural suitability assessment is available for more than 40 crops in Brazil, but is based exclusively on agroclimatic zoning (ASSAD and PINTO, 2008; BRASIL, 2011), with results aggregated to the municipality level. Other approaches have been developed for Brazil but these require field surveys and data at a level of detail that is difficult to obtain at the national scale (LEPSCH, JR. et al., 1991; RAMALHO FILHO e BEEK, 1994). A few models are based on digital spatial databases, including soil, climate and topography, which are focused exclusively on a single culture (e.g. sugarcane (BRASIL, 2009; CGEE, 2009), soybean (VERA-DIAZ, KAUFMANN et al., 2008)) and structured and implemented as an integrated software platform for use with land-use allocation and simulation models, e.g. SIMBRASIL (SOARES-FILHO, FERREIRA et al., 2009), which has been applied to the Amazonian region (SOARES, NEPSTAD et al., 2006; NEPSTAD, SOARES-FILHO et al., 2007; NEPSTAD, DANIEL C., STICKLER, CLAUDIA M. et al., 2008; NEPSTAD, SOARES et al., 2009; BOWMAN, SOARES-FILHO et al., 2012) and also at the national scale (GOUVELLO, SOARES-FILHO et al., 2010).

This article presents results from a GIS-based multi-criteria land suitability classification for annual crops in Brazil. The model uses publicly available databases that were reviewed, combined, and adapted for spatial explicit modeling. Model validation was achieved by comparing modeling results with data on current land use distribution.

2.2 Material and methods

This Section is divided into four parts. Section 2.2.1 gives an overview of the land suitability model developed here, defining the main assumptions and summarizing the input databases. The following section (2.2.2) describes how Climate, Soil and Topography data were converted into quality indexes, representing the “suitability” of a certain physical condition for crop production. The third section (2.2.3) explains the stepwise procedure and algorithms adopted to combine Climate, Soil and Topography indexes into a single indicator. Finally, the forth section (2.2.4) describe the method used to evaluate the model performance.

2.2.1 Overview of Land Suitability Model and input dataset

The land suitability evaluation was made as a GIS-based multi-criteria overlay analysis, where land use requirements corresponding to a specific land use system were matched with spatially explicit data on physical conditions (climate, soil and topography) to produce a single indicator designated *High Input Industrial Cropping Agricultural Suitability (HIA-suitability)*. The land use requirements adopted for this study corresponds to those associated with mechanized rain-fed cultivation of the main annual crops in Brazil (soybean, corn, and beans) using high inputs (fertilizers, soil amendments, pesticides) and genetically improved plant varieties. By adopting this approach we covered approximately half of the present cropland area and the expected main focus for the expanding crop cultivation in Brazil, as can be seen next:

- According to the last National Agrarian Census (IBGE, 2006), 78% of Brazilian cropland was cultivated with 4 crops (i.e. soybean (36%), corn (21%), sugarcane (10%), rice (7%) and beans (5%));
- An analysis of the same survey concluded that 80% of Agrarian GDP was generated by industrial agricultural systems based on high inputs and modern technology (FGV-IBRE, 2010);
- Projections forecast a 37% increase in grain production by 2020 (soybean, corn, wheat, rice and beans) (BRASIL, 2010a).

Thus, a large demand for land that meet the *HIA-suitability* criteria in the coming decade is expected and mechanized high-input cultivation might expand on both extensively used agriculture land (e.g. pastures) and on native vegetation by deforestation (legal and/or illegal land clearing).

The original soil-, climate- and topography data were converted into specific quality indexes ranging from 0 (lowest possible quality) to 1 (highest possible quality). These three quality indexes were combined to derive the *HIA-suitability* classes for annual crops. Four different *HIA-suitability* classes were included: 1 = not suitable, 2 = marginally suitable, 3 = suitable, 4 = very suitable.

The data preprocessing for converting the original data to a common format, which was required for producing the different indexes, varied since the original data were available in different formats and scales, or spatial resolution (Table 2.1). When combining and integrating information from a variety of sources it is commonly required that all spatial data have the same spatial resolution, or scale (MALCZEWSKI, 2004); however, due to scarcity

of data at the national scale for Brazil, we adopted a hierarchical approach in which the coarsest resolution data correspond to the lowest weight in the multi-criteria overlay analysis.

Table2.1 - Source and description of model input databases

Dimension	Database name/Provider Institution/Link	Year	Scale or spatial resolution	Format
Soil	Soil Map of Brazil/IBGE/< http://mapas.ibge.gov.br/solos/viewer.htm >	2001	1:5,000,000	Shapefile
Climate	FAOCLIM 2 World-wide Agroclimatic Database/FAO/< http://www.fao.org/nr/climpag/pub/en1102_en.asp >	2001	point	Text
	HIDROWEB Hydrologic Information System/ANA/< http://hidroweb.ana.gov.br >	2005	point	Text
Topography	Brasil em Relevo Digital elevation model of Brazil/EMBRAPA/ http://www.relevobr.cnpm.embrapa.br	2009	90m x 90m	Geotiff

Minor processing of the soil and topography databases was needed since these already had a suitable GIS format and broad spatial coverage. The climate database required significant processing to obtain sufficiently reliable spatial and temporal coverage of the Brazilian territory compatible with high-resolution analysis. Data from 2,676 meteorological stations (Hidroweb/ANA database) that provided only precipitation records were processed through regression analysis and GIS operations and then added to the original FAOCLIM-2 agroclimatic database. The final outcome after removal of duplicate points was a database containing 3,776 meteorological stations. The data processing to obtain temperature data for the stations where only precipitation was recorded aimed at filling gaps in the Amazon basin and central Brazilian regions (both regions very important in land use change assessments), and thus avoiding incomplete climate suitability calculations due to lack of temperature data. Temperature is essential for water balance calculations and thus for the identification of water deficits (a detailed description of the procedures is provided in Appendix A).

2.2.2 Climate, soil and topography quality indexes: rationale and description

As noted by WARKENTIN (1995) suitability for crop production is probably the oldest and among the most frequently used criteria in soil quality evaluation. This is also the case for evaluations of climate, where crop productivity indexes are often used, and for topography where “qualities” such as slope is highly relevant – especially if mechanized cultivation is considered.

The climatic suitability index was derived by combining three commonly considered climatic parameters influencing crop yields i.e., water availability, temperature and radiation (see, e.g., (FAO, 1976; 1983; 1995; 1996; KASSAM e SMITH, 2001; FISCHER,

NACHTERGAELE et al., 2008). Water balance was used as a reference model to compute the difference between the crop water requirement and effective precipitation. Radiation and temperature were both modeled as constraints for photosynthesis and for phenological development using the models described in Table 2.2. The entire analysis was based on a matching procedure considering the specific requirements of soybean, corn and beans. The indexes were calculated for each meteorological station based on multiannual averages. Spatial interpolation of the indexes used Voronoi diagrams as illustrated by Figure A.1.

The soil suitability index was derived by combining data on texture, drainage and soil depth (Table 2.2). A qualitative expert rating of soil map units based on agronomic criteria was made. The IBGE Soil Map of Brazil was used (Table 2.1). Each soil map unit was individually evaluated considering physical and chemical attributes inferred from the definitions of the soil units used in the soil map. The three soil quality indexes were given the same weight (rating within range 0 to 1) and the integrated soil index was calculated as the geometric mean of the individual indexes. The soil evaluation procedure excluded the possibility of major land improvements such as drainage of swamps, reclamation of salinized soils, and irrigation (FAO, 1976; SYS and RIQUIER, 1980). The spatial distribution followed the respective soil map polygons.

The rationale for employing a qualitative expert rating approach to soil suitability assessment lies in the fact that “quality”, interpreted as soil functionality (DORAN, SARRANTONIO et al., 1996; KARLEN, MAUSBACH et al., 1997), depends on complex inter-relations between soil properties and land use requirements. Thus, the translation of measured soil attributes into soil quality indexes requires a large and precise database supporting the modeling of complex soil processes (e.g. nutrient cycling, erosion resistance, water infiltration, biological activity). These types of databases are usually available only for controlled experimental conditions, i.e., for limited areas. Expert rating approaches then represent an option for overcoming the problem of insufficient data when soil suitability assessments are made for larger areas (SYS and RIQUIER, 1980; FISCHER, NACHTERGAELE et al., 2008).

The three quality indexes represent soil features that cannot easily be modified with the current Brazilian crop production technology. The soil texture index represents soil fertility in that the texture influences important factors such as cation-exchange capacity (CEC), base saturation and soil organic matter content. Texture is also one of the most important characteristics with regard to physical soil qualities. It influences water availability, water infiltration, and tillage conditions. The soil drainage index represents the quality of soil

oxygen availability, which is influenced by the depth of ground-water tables and by the soil structure. Finally, the soil depth index is related to limiting conditions for roots development or water percolation.

The topographic suitability index was derived from calculations of surface steepness (slope) using a Digital Elevation Model (DEM) where slope in one specific cell is calculated from topographic data using an algorithm that incorporates the values of the cell's eight neighbors. Slope influences surface run-off and soil erosion, and it has a major influence on the potential for mechanized cultivation. The topographic suitability index was set to represent the degree of restriction for agricultural mechanization. The DEM used (MIRANDA, 2005) is an improved data set of the original product of the Shuttle Radar Topography Mission (FARR, HENSLEY et al., 2000), which has a pixel resolution of 90 x 90 m. Table 2.2 summarizes the indexes and the calculation methodology.

Table 2.2 - Climate, Soil and Topography suitability indexes description

Index name/acronym	Description	Range
Water Index (WI)	Yield reduction estimated from the ratio of actual over potential evapotranspiration (Etr/Eto) during the reproductive phase for the crops considered. The water balance was computed according to THORNTHWAITE and MATHER (1955). The water requirements and matching procedure follow FAO (1992) and DOURADO NETO, SPAROVEK et al. (2004).	0 – 1
Radiation Index (RI)	Yield reduction estimated from the ratio of real over potential carbon dioxide assimilation converted to yield using HEEMST (1986) and DE WIT (1965) models calibrated for Brazilian conditions and annual crops by (DOURADO NETO, FIGUEIREDO JÚNIOR et al., 2004).	0 – 1
Temperature Index (TI)	Reduction in crop productivity estimated based on maximum and minimum annual mean temperatures required for photosynthesis and phenological development of the main annual crops cultivated in Brazil. Thermal requirement thresholds were obtained from the literature and adjusted to a continuous index. See Appendix A for a more detailed account of the approach used.	0 – 1
Climate Mean Index (IMC)	The geometric mean of WI, RI, TI is used as a proxy for the climatic influence on attainable yield for the considered crops	0 – 1
Texture/Fertility Index (FI)	Expert rating based on Brazilian soil map units considering soil nutrient content and possibility for crop nutrition.	0 – 1
Drainage Index (DI)	Expert rating based on information about profile drainage and its effects on the aeration in the root zone for the considered crops.	0 – 1
Root capacity Index (CI)	Expert rating based on information about soil profile depth and permeability.	0 – 1
Soil Mean Index (IMS)	The geometric mean of FI, DI, CI is used as a proxy for the attainable yields as determined by soil qualities	0 – 1
Slope (SLOPE)	Surface (DEM) modeling applying eight neighbors GIS algorithms. The computed slope is directly used for evaluation of agriculture mechanization restrictions according to LEPSCH, JR. et al. (1991) and FAO (1995).	0-100

2.2.3 Stepwise procedure for combination of Climate, Soil and Topography quality indexes

The *HIA-suitability* classes were subsequently derived based on combining the climate, soil and topography indexes in a step-wise procedure. This procedure was divided into four steps where the number of variables was increased for each step. Map calculations on raster files were done pixel-by-pixel (feature dimension) using arithmetic and Boolean operators (map algebra), and a land suitability map was produced for each step. The different steps are described below and also by a complete flowchart in Figure 2.1.

- *Step #1 (Climate)*: Climatic suitability map. The three climate quality indexes computed from the original climate database (1,404 stations) were combined to produce the first map: HIAs-1;
- *Step #2 (Climate plus)*: The climate station database was expanded from 1,404 stations to 3,776 stations based on processing the available data and filling data gaps using regression analysis. The three climate quality indexes computed from the expanded climate database (3,536 stations) were combined to produce the second map: HIAs-2;
- *Step #3 (Climate plus + Soil)*: The three soil quality indexes were combined with the data in the expanded climatic database to produce an edaphic-climatic suitability map: HIAs-3;
- *Step #4 (Climate plus + Soil + Topography)*: The database containing information about computed topographic slope was combined with the database building map HIA-3 to produce a topo-edaphic-climatic suitability map integrating topography, soil and climate information: HIAs-4.

The suitability decreased with each step, by adding restrictions and spatial details. The only situations in which suitability improved by one class were when a “Very Suitable” soil condition overlapped with a “Suitable” or “Marginally Suitable” climate conditions (see Figure 2.1, operation 4). In the adopted logical combination of indexes, climate defined the major suitability level that was regionally detailed by soil information and locally by information about topography.

Figure 2.1 - Flow chart of GIS overlay procedures generating intermediate and final suitability output layers: Diamonds represent input layers; the squares describe value-mapping operations and rounded squares represent output layers

2.2.4 Strategies for model performance evaluation

The model performance evaluation was based on comparison of calculated maps of cropland suitability with a land-use map (e.g. ALCAMO, SCHALDACH et al. (2011) and LAPOLA, SCHALDACH et al. (2010)). For this purpose, a map published in 2007 by the Brazilian government, based on 2002 remote-sensing images (BRASIL, 2007) updated to 2010 using regional surveys (for details see: SPAROVEK, BERNDES et al. (2010)) was used. The uncertainties and potential errors involved during the construction of this data set can be attributed to the classification of land-cover types from remote-sensing data, as well as to the process of merging distinct surveys to a single map. The integration of data from different sources to achieve useful information for land use modeling at a national or continental scale is a common approach adopted due to the limited data availability (for a review see: HEISTERMANN, MULLER et al. (2006)).

The results of overlaying the map of land suitability on the map of land-use were summarized in a contingency table (Table 2.3) and further analyzed in light of the expected tendency to concentrate intensive agriculture (crops) on the areas best suited to such land use. In addition, the proportions of correct (true positives) and incorrect (false positives) were related using the Relative Operating Characteristics (ROC) method, which makes it possible to assess the degree to which the spatial pattern computed by the model is random or not (PONTIUS and SCHNEIDER, 2001).

2.3 Results

The three intermediate maps (HIAs1: “Climate”; HIAs2: “Climate Plus”; HIAs3: “Climate Plus + Soil”) and the final HIA suitability map (HIAs4: “Climate Plus + Soil + Topography”) are presented in Figure 2.2. Equal colors were assigned to the suitability classes in the different maps in Figure 2.2. Water bodies and urban areas are represented by grey color. The set of maps shows the model progression step by step. The results were also aggregated to show the outcome in relation to the five different Brazilian biomes and five large administrative regions (Table 2.3). All the produced maps were matched with a map of current land-use in order to verify spatial distribution of suitability classes and to evaluate the model performance. The results following this procedure are summarized in Table 2.3.

Figure 2.2 - High Input Industrial Cropping Suitability (HIAs) maps computed in four steps: 1°) HIA-1 –climatic suitability map “Climate”, 2°) HIA-2 – expanded climatic suitability map “Climate Plus”, 3°) HIA-3 – Edaphic-climatic suitability map “Climate Plus + Soil”, 4°) HIA-4 – Topo-edaphic-climatic suitability map “Climate Plus + Soil+ Topography”

Table 2.3 - High Input Industrial Cropping Suitability aggregated by land-use, biome and administrative region
(to continue)

	Land suitability class ^a (HIAs1: "Climate")					Land suitability class ^a (HIAs2: "Climate Plus")					Total
	A	B	C	D	E	A	B	C	D	E	
	Mha										
Biome											
Amazon	-	253.0	133.0	2.5	21.5	-	202.4	184.9	1.6	21.0	409.9
Caatinga	0.3	18.5	28.5	33.0	1.0	0.4	17.0	29.9	33.0	1.0	81.3
Savannas	25.4	142.6	31.3	3.1	2.5	36.2	144.6	18.3	3.3	2.5	204.9
Atlantic Forest	47.0	55.9	7.2	2.9	3.9	48.1	52.6	10.1	2.3	3.9	116.9
Pampas	9.6	8.1	-	0.0	2.3	11.8	5.9	-	-	2.3	20.1
Pantanal	1.3	12.8	1.0	-	0.3	1.8	13.2	0.1	-	0.3	15.4
Regions											
Center-West	24.7	125.4	9.6	-	2.0	33.2	126.2	0.4	-	2.0	161.7
Northeast	6.0	44.3	63.2	36.7	2.4	3.7	49.3	59.0	38.3	2.4	152.7
North	-	228.3	124.4	2.5	20.7	-	177.9	177.5	0.2	20.3	375.9
Southeast	25.3	67.0	-	0.1	2.8	31.3	60.8	0.1	0.1	2.8	95.2
South	27.5	25.9	3.8	2.2	3.5	30.2	21.5	6.3	1.6	3.5	63.0
Land use^b											
Crop	21.4	34.4	1.2	0.3	-	24.3	31.3	1.6	0.2	-	57.4
Pasture	37.6	120.8	41.5	11.1	-	43.8	118.1	37.0	12.0	-	211.0
Forestry	2.5	3.6	0.5	0.1	-	2.7	3.3	0.6	0.1	-	6.6
Native Vegetation	21.4	331.0	155.8	28.4	0.5	26.9	282.0	201.7	26.5	0.0	537.1
Rivers/Water Body	-	-	-	-	27.9	-	-	-	-	27.9	27.9
Other	0.7	1.2	2.0	1.7	3.1	0.7	1.0	2.5	1.4	3.0	8.6
Total	83.6	490.9	201.0	41.5	31.5	98.4	435.7	243.4	40.2	31.0	848.6

^aLand Suitability Classes: A= Very suitable, B=Suitable, C=Marginally suitable, D= Unsuitable, E=Not evaluated

^bThe main source of land use information is the Probio Project (Brasil, 2007), which was updated to year 2010 using regional surveys as detailed in SPAROVEK, BERNDES et al. (2010)

Table 2.3 - High Input Industrial Cropping Suitability aggregated by land-use, biome and administrative region
(conclusion)

	Land suitability class ^a (HIAs3: "Climate Plus + Soil")					Land suitability class ^a (HIAs4: "Climate Plus + Soil + Topography")					Total
	A	B	C	D	E	A	B	C	D	E	
	Mha										
Biome											
Amazon	51.5	145.4	187.2	4.8	21.1	36.8	136.6	185.5	29.9	21.1	409.9
Caatinga	2.0	18.8	23.0	36.5	1.0	1.5	16.3	21.7	40.9	1.0	81.3
Savannas	49.0	84.5	62.7	6.1	2.5	34.1	86.0	63.3	19.0	2.5	204.9
Atlantic Forest	55.8	43.6	11.1	2.6	3.9	19.3	39.3	17.7	36.8	3.9	116.9
Pampas	9.6	6.3	1.8	-	2.3	7.5	7.6	2.1	0.5	2.3	20.1
Pantanal	3.9	8.0	3.2	-	0.3	3.8	7.9	3.3	0.2	0.3	15.4
Regions											
Center-West	59.7	70.3	29.7	-	2.0	49.3	72.8	30.7	6.9	2.0	161.7
Northeast	8.6	40.7	56.3	44.7	2.4	4.4	36.3	53.7	55.9	2.4	152.7
North	31.9	133.3	186.9	3.4	20.4	19.6	123.6	185.2	27.2	20.4	375.9
Southeast	44.8	39.9	7.6	0.1	2.8	15.7	38.3	13.7	24.6	2.8	95.2
South	26.8	22.4	8.5	1.8	3.5	14.1	22.6	10.2	12.6	3.5	63.0
Land use^b											
Crop	28.1	24.7	4.3	0.2	-	18.0	28.4	6.2	4.8	-	57.4
Pasture	67.3	83.5	46.9	13.3	-	39.1	84.6	51.4	35.8	-	211.0
Forestry	2.5	3.2	0.9	0.1	-	1.5	3.2	1.1	0.8	-	6.6
Native Vegetation	73.3	194.2	234.8	34.7	0.1	43.8	176.6	232.7	83.8	0.1	537.1
Rivers/Water Body	-	-	-	-	27.9	-	-	-	-	27.9	27.9
Other	0.7	1.0	2.2	1.6	3.1	0.5	0.8	2.1	2.2	3.1	8.6
Total	171.8	306.6	289.0	50.0	31.2	103.0	293.6	293.5	127.3	31.2	848.6

^aLand Suitability Classes: A= Very suitable, B=Suitable, C=Marginally suitable, D= Unsuitable, E=Not evaluated

^bThe main source of land use information is the Probio Project (Brasil, 2007), which was updated to year 2010 using regional surveys as detailed in SPAROVEK, BERNDES et al. (2010)

2.4 Discussion

2.4.1 Model performance evaluation: Comparison of High Input Industrial Cropping Suitability Maps with the current land-use

The results are consistent with the “Agricultural Adjustment” theory (MATHER and NEEDLE, 1998; RUDEL, SCHNEIDER et al., 2010) noting the tendency to concentrate intensive agriculture (crops) on the areas best suited to such land use.

Overlaying the calculated suitability maps on the land-use map, made it possible to relate proportions of true positive and false positive using the Relative Operating Characteristics (ROC) method. The resulting curves are shown in Figure 3.3. The performance measure of ROC is the area under the curve. If it turns out that all the most suitable areas computed by the model are, in fact, current cropland, then the area under the curve will be 1.0. If, however, the suitability values were randomly distributed among cropland and non-cropland, then the value of ROC would be 0.5 and would follow the 1:1 line (PONTIUS and SCHNEIDER, 2001)”

Figure 3.3 - Relative operating characteristic (ROC) curves for comparison the calculated cropland suitability maps to land use pattern for the base year 2007. The 1:1 line represents the sensitivity and false-positive values achieved by random distribution of cropland. (a) HIA1: “Climate”, (b) HIA2: “Climate Plus”, (c) HIA3: “Climate Plus + Soil”, (d) HIA4: “Climate Plus + Soil + Topography”

In our analysis (Figure 3.2), the area under the curve ranged from 0.53 to 0.81, depending on the modeling step. The best ROC was obtained using the suitability model based only on the expanded climate database (ROC = 0.81), which is similar to that obtained by Lapola et al. (2010) for crops in Brazil using a climate-based suitability model (ROC = 0.87). The addition of edaphic information apparently increased the randomness of land suitability assessment, i.e. both cropland and other land use areas were classified as highly suitable for crops. The ROC for the final suitability map, after addition of topographic information, was 0.62, a better score than a random result, but not significantly.

The results of ROC method suggest three likely interpretations: (i) the attempt to reach more precision by adding multiple layers (soil, topography) did not improve at the aggregated level the accuracy of the analysis, so, for large-scale assessments in which only regional characterization is needed, a climate-based suitability model would be an optimal solution; (ii) the addition of soil and topography layers made it possible to downscale the analysis and revealed alternative regions with good suitability for crop production that are not currently under such use and at the same time revealed cropland that are currently located in marginally conditions, which increased the proportion of false positives and decreased the ROC statistics; (iii) a possible optimal solution for a suitability model using the available data for Brazil could be the single combination of climate and topography layers. This last solution was not tested here. The next section expands the discussion of which conclusions could be drawn from the stepwise inclusion of climate, soil and topography layers.

2.4.2 Discussion of the validity of the stepwise exercise

The aggregated data in Table 2.3 represent the spatial distribution shown in the maps (Figure 2). The stepwise inclusion of soil and topographic data resulted in higher resolution in land suitability classes and reductions in the total extent of suitable land. The area classified as either “Suitable” or “Very Suitable” decreased from 68% (575 Mha) to 47% (397 Mha) and the area classified as “Unsuitable” increased from 5% (42 Mha) to 15% (127 Mha) when soil and topography data were added to produce the HIAs-4 map.

The production of the expanded, higher-resolution, climate database allowed more precise boundaries in the North region, in the entire Amazon biome, in the transition from the Amazon forests biome to Savannas, in high altitude zones located in the South region, and in transitions between the Atlantic Forest biome and the Savannas. The higher resolution also made it possible to detect disparate climate information and to confine outlier measurements

to small areas (e.g. in the Center of Brazil, a large region classified as marginally suitable in step #1 because of a single climate station data was then converted to suitable in step #2).

The inclusion of soil information resulted in more regional restrictions and increased variability of suitability classes. The Center region of Brazil, which was almost entirely classified as belonging to one suitability class in the previous steps, was split in several suitability classes and large continuous areas of high suitability within Amazon biome arose. In addition, physical constraints in the Pantanal biome were detected and large areas in the North of the Savanna biome were classified as marginally suitable. No significant changes occurred in the extreme North and Northeast regions, where strong climate related restrictions were detected already in step #1. Wider areas along the coastline were classified as very suitable due to the occurrence of fertile and well-drained soils, which probably was at cause of the low ROC statistic discussed in the previous section.

The inclusion of topographic information brought the assessment to a 90m x 90m spatial resolution. Local constraints for agricultural mechanization were identified for the whole of Brazil except for the Amazon basin and the Pantanal biome, where natural vegetation or wetlands influence radar elevation detection (ROSSETTI and VALERIANO, 2007; VALERIANO and ABDON, 2007) and, as a consequence, slopes cannot be precisely determined. The importance of topography information was highest along the coastline, where unsuitable steep areas could be clearly identified, e.g. class D in the Atlantic Forest increased from 3 to 37 Mha as a result of including topographic information. In this case, considering topographic constraints not only changed suitability locally, but also regionally.

As observed by MALCZEWSKI (2004), the main problem related to land-use suitability analysis based on multi-criteria overlay mapping and modeling is that there is no commonly-accepted method for assigning the weights of relative importance to the criterion maps. Therefore, different methods may produce different results. The stepwise exercise as presented here was a helpful tool to calibrate the weights of climate, soil and topography in the suitability assessment as it allowed for tracking the model performance and explicitly showed the global and regional effects of each one of these themes on the results.

2.5 Overall conclusions and discussion

According to the model presented here, 12% (103 Mha) of the land in Brazil is classified as “Very Suitable”, 35% (294 Mha) as “Suitable”, 35% (294 Mha) as “Marginally Suitable”, and 15% (127 Mha) was classified as “Unsuitable” for crops. Overlaying the model results on the map of actual land use shows that intensive cropping regions matches areas with high suitability for crop production, and restrictive suitability classes were more often associated with low-intensive land uses. The results are consistent with the “Agricultural Adjustment” theory (MATHER and NEEDLE, 1998; RUDEL, SCHNEIDER et al., 2010) noting the tendency to concentrate intensive agriculture (crops) on the areas best suited to such land use. This was also confirmed by satisfactory ROC statistics, suggesting that the model can be used for suitability analysis for annual crops in Brazil.

The stepwise exercise made it possible to generate and test the suitability model as climate, soil and topography layers were gradually added. This procedure showed the relative importance of each layer in determining the land suitability for mechanized, high-input, rain-fed cultivation of the main annual crops, suggesting three main conclusions.

First, a single climate-based suitability model could be considered a robust strategy for suitability assessment, especially in regions with scarcity of soil and topographic data. The addition of coarse edaphic information, as done here using a soil map at scale 1:5,000,000, should be carefully examined due to the risk of decreasing the model accuracy.

Second, the attempt to downscale the analysis by adding multiple layers (soil and topography) revealed regions with good suitability for crop production that are currently under native vegetation and revealed cropland located in marginally suitable areas. The area under native vegetation that is highly suitable for crop production doubled comparing the first output (climate perspective) to the final output, increasing from 21 Mha to 43 Mha and cropland in marginal conditions increased from 2 Mha to 11 Mha. Thus, significantly different perspectives of land occupation patterns are obtained by adding the soil and topography layers.

Third, throughout the stepwise procedure, the area of pasture classified as “Very Suitable” for crop production was equal or greater than 40 Mha. Such area is about four times larger than the estimated cropland expansion for the next 10 years (i.e. Brazilian government estimated 9.6 Mha of cropland expansion by 2020 (BRASIL, 2010a) and a recent study estimated 12 Mha by 2022 (FIESP-ICONE, 2012)). Thus, from the perspective of land suitability there seems to be little need for expanding croplands into areas with prevalence of

native vegetation, at least when considering the 2020 time horizon. However, there are large areas with native vegetation that could also be successfully used for crop production. Studies suggest that conservation of these areas may be endangered if the current development pathways are maintained (SOARES, NEPSTAD et al., 2006; MARTINELLI, NAYLOR et al., 2010; METZGER, LEWINSOHN et al., 2010; SPAROVEK, BERNDES et al., 2010). Effective nature protection requires that legal and other instruments be further developed to favor productivity improvements and land consolidation within existing agriculture areas. The land suitability assessment and associated databases presented in this paper can support further land-use modeling and assessment as well as policy discussions.

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3 AGRICULTURAL INTENSIFICATION IN BRAZIL AND ITS EFFECTS ON LAND USE PATTERNS: AN ANALYSIS OF 1975-2006 PERIOD

Abstract

Does agricultural intensification reduce the area used for agricultural production in Brazil? Census and other data for time periods 1975-1996 and 1996-2006 were processed and analyzed using GIS and statistical tools to investigate whether and if so, how, changes in yield and stocking rate coincide with changes in cropland and pasture area. Complementary medium-resolution data on total farmland area changes were used in a spatially explicit assessment of the land use transitions that occurred in Brazil during 1960-2006. The analyses show that in agriculturally consolidated areas (mainly southern and southeastern Brazil), land use intensification (both on cropland and pastures) 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, land use intensification coincided with expansion of agricultural lands. These observations provide support for the thesis that (i) technological improvements create incentives for expansion in frontier areas and (ii) farmers are likely to reduce their managed acreage only if land becomes a scarce resource. The spatially explicit examination of land use transitions since 1960 reveals an expansion and gradual movement of the agricultural frontier toward the interior (center-western Cerrado) of Brazil. It also indicates a possible initiation of a reversed trend in line with the forest transition theory, i.e., agricultural contraction and recurring forests in marginally suitable areas in southeastern Brazil, mainly within the Atlantic Forest biome.

Keywords: Land-sparing; Land-use change; Agricultural yield; Cropland; Pasture

3.1 Introduction

The conversion of natural ecosystems to anthropogenic landscapes is perhaps the most evident human alteration of the Earth. This conversion has caused negative impacts but has also supported global population growth by providing food and other biomass-based products. Understanding and managing land use change (LUC) is a central challenge for global sustainability (LAMBIN and MEYFROIDT, 2011). Under existing land use regimes, population growth and societal development seems to induce further land conversion (DEFRIES, RUDEL et al., 2010). This prompts investigations into how an expanding human population can “...feed itself better without losing most of what still remains of wild nature”? (BALMFORD, GREEN et al., 2005)

The intensification of agricultural production to increase commodity output per unit of area has the potential to reduce LUC pressure. Research, development, and technology transfer initiatives associated with the “Green Revolution” brought a strong growth in agricultural productivity and contributed to the decline of the proportion of hungry people

from about 60% in 1960 to 17% in 2000 (BORLAUG, 2007). As an illustration of the land saving implications, a study estimated that agriculture intensification has helped avoiding LUC emissions corresponding to about 160 gigatons of carbon (GtC) since 1961 by avoiding the cropland expansion at 1,514 Mha (more than a double of global cropland area) that would have been required if yield levels had stayed at the 1961's level (BURNEY, DAVIS et al., 2010).

The hypothesis that agricultural intensification spares land (the *land sparing hypothesis*) has been challenged in studies reporting that land use intensification is infrequently associated with a decrease in cropland (BALMFORD, GREEN et al., 2005; EWERS, SCHARLEMANN et al., 2009; RUDEL, SCHNEIDER et al., 2009). Technological improvements and productivity gains potentially also make the agricultural activity more profitable and thus more attractive, resulting in a rebound effect. As a consequence, intensification might lead to an increase in total agricultural land rather than a reduction (LAMBIN and MEYFROIDT, 2011). However, it is unclear whether the observed rebound effect mainly reflects land use re-allocation at the regional level or in fact is a global phenomenon, i.e., that intensification results in a faster rather than slower agricultural land expansion at the global scale. The explanation behind a global rebound effect would be that the development driving intensification also results in cheaper production, which would lead to higher demand for food products. Analyses of productivity and land use development associated with the ten main crops during the period 1970-2005 indicate that the rebound effect is indeed a factor at the global scale (RUDEL, SCHNEIDER et al., 2009). Other studies indicate that the phenomenon is more likely to occur in situations where the intensification involves cash crops with relatively elastic demand, as observed for soybeans in Brazil (FEARNSIDE, 2005; NEPSTAD, SOARES et al., 2009).

The Brazilian government has projected that crop production will grow on average 2.7% per year during the period 2010-2019 (BRASIL, 2010a). Milk and beef production are expected to grow 1.9% and 2.1% per year, respectively, during the same period (BRASIL, 2010a). The rate of land use intensification will determine the need for additional agricultural land to support this growth, especially in the livestock (beef cattle) sector, which is mostly based on grazing on pastures presently covering roughly 200 million hectares (Mha) of land. However, given the complex relationship between yield increases and land use it is evident that careful investigation is required before any conclusions can be drawn about future land

use in Brazil, because land use consequences of intensification will depend on which agricultural activities intensify, and where.

Studies carried out at the regional scale in Brazil have related intensification of crop production to an increase of fire outbreaks and direct conversion of natural ecosystems (MORTON, DEFRIES et al., 2006; MORTON, DEFRIES et al., 2008). Other more recent studies also carried out at the regional scale suggest that cropland intensification and expansion during the 2000s displaced cattle ranching to the frontier region causing deforestation (BARONA, RAMANKUTTY et al., 2010; ARIMA, RICHARDS et al., 2011). BOWMAN, SOARES-FILHO et al. (2012) suggest that if cattle ranching intensification proves profitable, it will increase rather than decrease the land demand for cattle production in Brazil. On the other hand, MARTHA-JUNIOR et al. (2012) isolated the individual factors of beef production growth in Brazil and found a land-saving effect at 525 million hectares in the time period 1950–2006, due to productivity gains.

This paper reports results from a study of agricultural land use in Brazil during the period 1975-2006, including both pasture based livestock production and crop cultivation. The aim was to investigate the validity of the land sparing hypothesis in the Brazilian context. One specific aim was to investigate correlations between agricultural intensification and land use in different areas of Brazil. A spatially explicit assessment of the relation between yields and land demand was done at the municipality level. In addition, data on changes in total farmland area were used to assess land use transitions that occurred in Brazil during the period 1960-2006.

3.2 Materials and methods

The correlation between cropland area changes and yield changes was assessed in the manner of EWERS, SCHARLEMANN et al. (2009), along with the correlation between pasture area changes and stocking rate changes and the cross-correlation between changes in crop and pasture yields and areas. The assessment was done for the entire national territory divided into 3,659 areas for the period 1975-1996 and into 4,267 areas for the period 1996-2006. The years 1975, 1996, and 2006 were selected for the analysis because pasture area data were available from the National Agrarian Census Surveys for these years. Changes in total farmland area were calculated for the same periods and also for the period 1960-1975.

Six land-use classes were included in the “farmland” category: “perennial crops”, “annual crops”, “native pastures (rangeland)”, “cultivated pastures”, “forestry plantations”

and “idle lands (fallow fields)”. Lands classified in the Agrarian Census Surveys as “unexploitable” or “degraded” (e.g., wetlands, hillsides, water bodies, salinized, desertified soils, or gullies) were not included in the farmland category. A summary of aggregated data alongside the five Brazilian administrative regions is available in the Supporting Information (APPENDIX B.S1).

The analyses used tabular public database data provided by the Brazilian Institute of Geography and Statistics (IBGE) and the Institute for Applied Economic Research (IPEA), a federal public foundation linked to the Strategic Affairs Secretariat of the Presidency. Data from the public government database IPEADATA (IPEA, 2011) was collected and processed at the level of geographically consistent units designated Minimum Comparable Areas (MCA), which here correspond to municipalities since these can be compared over long time periods in Brazil. The data come from the most extensive and comparable surveys available for the years of study and the analyses were made at the most detailed geographical units possible (average area of 2,327 km² and 1,995 km² for the first (1975-1996) and second time period (1996-2006), respectively). The spatial distributions of MCAs for the periods 1975-1996 and 1996-2006 are illustrated in Figure 3.1. Data on deforestation/reforestation were not included in the analysis. None of the sources include land-use data derived from remote sensing. Spatially explicit information on land use was not available at the MCA scale for the time period analyzed. The spatial component in this study was obtained by combining tabular data and displaying the results as maps. The approach is judged to be the best possible for outlining LUC patterns related to intensification of pasture and crop production considering the aim of covering a relatively long time period.

The seven most important crops in Brazil (soybeans, corn, sugarcane, beans, cassava, rice, and wheat) were included in the analysis. The cultivation of these crops occupied 82% of the cropland area in Brazil in year 2006 (IBGE, 2006). Crop biomass production was converted from mass to gross energy (GE) equivalent, based on data in WIRSENIUS (2000). Crop yields were calculated for all MCAs for the years 1975, 1996, and 2006 as the annual biomass production (in GE) divided by the total area (ha) under a given crop. Similarly, stocking rates on pastures were calculated for each MCA in 1975, 1996, and 2006 as the total number of animal units (AU) divided by the area of pasture (ha). Bovine, equine, goat, and sheep were included.

Changes over time were obtained by combining the 1975, 1996, and 2006 values to produce the dimensionless quantities $\log_2 [\text{value}_{1996}/\text{value}_{1975}]$ and

$\log_2[\text{value}_{2006}/\text{value}_{1996}]$. Ordinary least square regression models were fitted with change in cropland or pasture area as the dependent variables and change in yield or stocking rate as the independent variables. A two-tailed statistical test was performed over the regression slope (β_2) coefficient ($y = \beta_1 + \beta_2 x_2 + u$) to check the null hypothesis $H_0: \beta_2 = 0$ against $H_a: \beta_2 \neq 0$ at significance level $\alpha = 0.05$. P-values greater than 0.05 did not reject the null hypothesis that the regression parameter was 0 at significance level of 0.05. In addition to considering the entire dataset, regressions were also made for the five Brazilian administrative regions. The approach allows capturing how productivity and area have changed in each MCA, and it also makes it possible to present geographically explicit information on these changes for Brazil as a whole. While providing information about the correlation between land productivity and area changes, the approach does not clarify whether area expansion/contraction arises as a consequence of land productivity change or due to other factors that drive changes in both area and land productivity. The regional results are available in the Supporting Information (Appendix B.S2) together with aggregated data for production and area used for pastures and for cultivation of the seven crops included in the study (Appendix B.S1).

Maps display the results of the regression analysis for crops (aggregated) and pastures for the periods 1975-1996 and 1996-2006. Maps also display changes in total farmland area computed at the MCA level as $\log_2[\text{value}_{1960}/\text{value}_{1975}]$, $\log_2[\text{value}_{1996}/\text{value}_{1975}]$ and $\log_2[\text{value}_{2006}/\text{value}_{1996}]$.

GIS tools were used to link the tabular dataset obtained from IPEADATA to a corresponding vector object. The vectors used in each period were generated from the Brazilian municipality boundaries (Figure 3.1), which had their polygons dissolved, based on a relational key provided by IBGE to reach the MCAs for each period. The linking of tabular datasets to vector GIS objects allowed not only the display of the regression analysis results, but also the combination of pasture and crop layers for a more comprehensive spatial analysis.

Figure 3.1 - Boundaries of Minimum Comparable Areas (MCAs) in Brazil for 1970s-1990s (right panel) and 1990s-2000s (left panel)

3.3 Results

Section 3.3.1 presents the results of the regression analysis. Tendencies regarding the correlation between productivity changes and area changes are indicated in Figures 3.2 and 3.3 showing the cropland area change vs. yield change and the pasture area change vs. stocking rate change for the time periods 1975-1996 and 1996-2005. Each dot in the diagrams corresponds to one MCA unit (Figure 3.1) meaning that the number of dots is equal to the number of MCAs with existing data on area and yield. Crops with extensive distribution over Brazil, such as corn and beans, are thus represented by more dots than crops that are geographically concentrated, such as soybeans. The calculated mean yield and area changes are also shown in the diagrams. The number of MCAs included in each regression and the statistical parameters are available in the Supporting Information (Appendix B.S3).

In Section 3.3.2, three types of maps present the results of the spatially explicit analysis. The first type (Figure 3.4a-b, 3.4d-e) associates colors with the quadrants in the diagrams “Pastures” and “Crops” in Figures 2 and 3 as follows: Red (+,+); Green (+,-); Yellow (-,-); and Blue (-,+). The second type of map (Figure 3.4c, 3.4f) was obtained by combining “Pastures” and “Crops” maps for each of the two periods. These maps display only the MCAs where an increase in yield and in stocking rate occurred, i.e., the areas where agricultural intensification is associated with expansion/contraction of croplands or pastures or both.

Finally, in Section 3.3.3, a third type of map displays the changes in farmland area (the sum of cropland, pastures, and fallow land) for 1960-1975, 1975-1996, and 1996-2006.

3.3.1 Correlation between changes in area and yield/stocking rate in the MCA units data set

For the aggregate group of crops, no statistically significant correlation was found between yield and cropland area in any of the periods (Figures 3.2b and 3.3b). The regression coefficient β_2 was close to 0 for both cases, and the statistical test confirmed the null hypothesis $\beta_2=0$ ($P=0.645$, $P=0.232$; respectively for the 1st and 2nd period). The regression analysis for individual crops showed a positive significant relation ($\beta_2>0$, $P<0.05$) for all crops in the 2nd period, but only for sugarcane ($\beta_2=0.66$, $P=0.000$) and soybean ($\beta_2=1.50$, $P=0.000$) in the 1st period. Greater positive coefficients in the 2nd period were found for sugarcane ($\beta_2=0.40$, $P=0.000$), soybean ($\beta_2=0.25$, $P=0.005$) and rice ($\beta_2=0.50$, $P=0.000$). Neutral regression β_2 coefficients were found for cassava and corn in the 1st period, and negative regression coefficients were found for rice ($\beta_2=-0.26$, $P=0.000$) and beans ($\beta_2=0.23$, $P=0.000$) in the 1st period.

The analysis indicates that for sugarcane and soybeans an increase in yield has historically correlated with an increase in cultivated area. The same observation is valid for the seven most important crops in Brazil when only the 2nd period (1996-2006) is considered. This result does not contradict the land sparing hypothesis since total crop output has increased: the cropland areas could have grown more in the absence of yield increases.

For pasture, a negative and statistically significant correlation was found between area and stocking rate, both for the 1st period ($\beta_2=-0.62$, $P=0.000$) and the 2nd period ($\beta_2=-0.66$, $P=0.000$), see Figures 3.2a and 3.3a. In other words, pasture intensification has historically correlated with a reduction in pasture area.

Figure 3.2 - Cropland area change vs. yield change and pasture area change vs. stocking rate change: period 1975-1996. Each dot corresponds to one municipality, or MCA

Figure 3.3 - Cropland area change vs. yield change and pasture area change vs. stocking rate change: period 1996-2006. Each dot corresponds to one municipality, or MCA

3.3.2 Spatially explicit display of the correlation between change in area and change in yield/stocking rate in the MCA units data set

Results are available at a higher level of geographical detail for the 2nd period (Figures 3.4d-f) compared with the 1st period (Figures 3.4a-c) because of the larger number of MCAs analysed for the 2nd period, especially in the north and central-west regions. In the 1st period, MCAs in the north region were very large, which masked a likely geographic variation in yield and land use dynamics in northern Brazil.

Generally, similar yield and land use dynamics were detected for the 1st and 2nd periods when a large part of Brazil, but especially the center-southern part, experienced crop yield increases coinciding with cropland expansion (“red” in Figures 3.4a and 3.4d). In the 2nd period a border line in the north and northeast (states of Maranhão and Tocantins) emphasizes the emerging crop production region MAPITO¹ (Figure 3.4d). Apart from a cluster localized in a hilly part of the southeast, reduction in cropland area coinciding with crop intensification (“green”) was sparse and not significant in extent, confirming the general trends detected by the regression analysis (Figures 3.2 and 3.3). Compared to the 1st period, the areas with decreasing crop yields in the 2nd period were smaller in the northeast and north but still remained in remote areas of the Amazon or in the semi-arid region of the northeast where smallholder agriculture prevails (“blue” or “yellow” in Figures 3.4a and 3.4d).

For pasture, yield and land use dynamics were also similar in the 1st and the 2nd period (Figures 3.4e and 3.4b). The predominant development within the agriculturally consolidated regions located in center-southern Brazil was that pasture area decreases coincided with stocking rate increases (“green”). This pattern was concentrated to a main cluster in the southeast during the 1st period but was present also in the center-west and the north during the 2nd period. Increases in stocking rate coinciding with pasture expansion (“red”) was the most common development in the north and center-west in the 1st period, but appeared only in the southeastern border of the Amazon biome in the 2nd period. Decreasing stocking rate coincided with pasture expansion during both periods in the semi-arid inland region of the northeast and along the main rivers in Amazon, where pastures cover a relatively small area. Decreasing stocking rate only coincided with decreasing pasture area in a very steep region of southeastern Brazil where small-scale dairy cattle production was predominant.

¹ MAPITO is an acronym formed from the first letters of the three Brazilian states names Maranhão, Piauí and Tocantins.

Finally, the colored areas in Figure 3.4c (1st period) and Figure 3.4f (2nd period) show where both crop production and pasture production intensified. The two shades of green represent locations where increasing stocking rate coincided with pasture area contraction while crop yield increases coincided with either cropland expansion (light green) or contraction (darker green). Red and orange colors represent locations where increasing stocking rates coincided with pasture expansion while crop yield increases coincided with either cropland expansion (red) or contraction (orange).

Thus, over the last 30 years many municipalities in consolidated agricultural regions have experienced expanding and intensified crop cultivation coinciding with intensified animal grazing on decreasing pasture areas (light green in Figures 3.4c and 3.4f). Concentrated in the 1st period to mostly southern and southeastern Brazil, this pattern was more widespread in the 2nd period appearing in center-western regions associated with the cropland expansion boom in the late 1990's and early 2000's. Municipalities in consolidated agricultural regions have also experienced that land use intensification has coincided with a reduction in both cropland and pasture areas (darker green areas). During the 1st period, this pattern was concentrated to the periphery of the main cities in the south and southeast of Brazil such as Porto Alegre, São Paulo, Rio de Janeiro and Belo Horizonte, and might be associated with a migration from rural areas into urban areas. In the 2nd period, this dynamic was spatially more extensive, covering large areas of the southeast and also some areas in the northeast. Figures 3.4c and 3.4f show an agricultural frontier region called the "Deforestation Arc" in the southeastern border of the Amazon, where intensified land use has coincided with area expansion.

Figure 3.4 - Spatial display showing the four possible combinations of cropland area change and yield change, and pasture area change and stocking rate change, for time periods 1975-1996 (panels a, b) and 1996-2006 (panels d, e). Colors were associated to the quadrants of the graphs “Pastures” (Figures 3.2a, 3.3a) and “Crops” (Figures 3.2b, 3.3b). Panels (c) and (f) show area changes in MCAs where both crop production and pasture production intensified.

3.3.3 Spatially explicit display of changes in farmland area in the MCAs units data set for periods 1960-1975, 1975-1996 and 1996-2006

Figure 3.5 shows the geographical patterns of agricultural LUC, i.e., changes in the sum of cropland and pastures, during the periods 1960-1975, 1975-1996, and 1996-2006. During the 1960s and early 1970s (Figure 3.5a), farmland stability was predominant in the southeast (states of São Paulo and Minas Gerais) while most other regions experienced expansion. The total farmland area increased by 56 Mha in the period, with 51% of the expansion occurring in the center-western region (Table S1.1).

Between 1975 and 1996 (Figure 3.5b), farmland contraction could be observed in southeastern and northeastern Brazil. In the southeast, this contraction was more common near metropolitan areas (São Paulo, Rio de Janeiro, Belo Horizonte) and in steep regions with prevalence of smallholder agriculture and dominance of the Atlantic Forest biome. In the northeast, farmland contraction took place both in the inland semi-arid region and in the traditional sugarcane production region located in the narrow coastal plain between the Atlantic Ocean and the dry inland. At the same time, farmland expansion remained the dominant pattern in the center-west (+4Mha) and the north (+20Mha).

During the period 1996-2006, total farmland area in Brazil was roughly stable (2 Mha decrease, see Table S1.1). However, the spatial analysis reveals (Figure 3.5c) that there was significant LUC during the period, with farmland contraction/stability in agriculturally consolidated regions (south and southeast: in total 11 Mha reduction in farmland area), which was counterbalanced by an expansion of 9Mha in the agricultural frontier (center-west, north, northeast).

Figure 3.5 - Changes in total farmland computed at the resolution given by the MCAs as $\log_2$ [value1960/value1975] (panel a), $\log_2$ [value1996/value1975] (panel b) and $\log_2$ [value2006/value1996] (panel c). Farmland includes cropland, pastures, forestry plantations and idle lands. Native vegetation, degraded (e.g., salinized, desertified soils) and unexploitable lands (e.g. wetlands, water bodies, hillsides) were not included in the farmland category. Green colors represent areas where the farmland area was stable; cold colors (blue/purple) represent areas experiencing farmland contraction and warm colors (yellow/red) represent areas experiencing farmland expansion

3.4 Discussion

3.4.1 Drivers of changes in yield and area

According to the economic theory on land use (VON THUNEN, 1826), land is allocated to the use that gives the best rent. Therefore, if a change in land use practice (or increase in prices for the agriculture products) leads to an increased profitability of a certain land use, then this land use can be expected to expand at the expense of less profitable land uses. In that sense, adoption of land-saving technologies (intensification), which normally are associated with costs, are only likely to take place where land is a scarce production factor making land opportunity costs sufficiently high (ANGELSEN and KAIMOWITZ, 1999; KAIMOWITZ and ANGELSEN, 2008; ANGELSEN, 2010). The findings reported above provide some support for this theory:

(i) in consolidated agricultural areas, where land availability is a constraining factor and land rents are higher, the common pattern observed was land use intensification (both on cropland and pastures) coinciding with cropland and pasture contraction, or with cropland expansion at the expense of pastures, resulting in farmland stability or in farmland contraction. Such farmland contraction in consolidated areas could be explained by non-profitability of agricultural activities on marginally suitable lands or by high land opportunity costs in close proximity to urban centers inducing out-migration of agricultural activities;

(ii) in agricultural frontier areas, where land is an abundant inexpensive resource, land use intensified but this intensification coincided with expansion of agricultural lands. The methodology used did not allow for establishing whether technological improvements (i.e., yield or stocking rate increase) in this case moderated agriculture area expansion or instead induced increased expansion by making the agriculture more economically competitive (liming, fertilization, adoption of no tillage systems, development of soybean-bacteria symbiosis, cultivation of exotic grasses and genetically modified crops are examples of technological improvements that made it possible to cultivate marginally suitable soils of the Cerrado and Amazon, inducing strong agricultural expansion in Brazil since the 1970's (LANDERS, 1999; FEARNSIDE, 2001; KAIMOWITZ and SMITH, 2001)). Possible re-allocations between cropland and pasture production are also masked at the municipality level when both cropland and pasture expand;

(iii) cropland contraction also occurred in remote areas, on marginal quality lands, and for crops mainly used for local or domestic consumption (staple crops). In semi-arid, poorly

developed areas in northeastern Brazil (likely having low land rents), the observed farmland contraction might be explained by non-profitability of agricultural activities and out-migration.

When comparing the total farmland area in 1960 and 2006, the same spatial land use pattern is detected, where farmland stability or contraction dominates in consolidated agricultural regions while farmland expansion dominates in frontier regions.

The results prompt two principal questions: (i) What are the linkages between the land use dynamics in consolidated agricultural regions and in agricultural frontier areas? (ii) What caused the observed cases of farmland contraction – are they examples of intensification sparing land for nature or are they due to other factors driving a reversal in land-use trends for a given territory, e.g., socio-economic transformations toward increased industrialization and urbanization, or environmental legislation?

3.4.2 Linkages between agriculturally consolidated regions and frontier areas

Agriculturally consolidated regions and frontier regions are distinctly different areas. Agricultural frontier regions are characterized by in-migration where arriving farmers might also introduce land management practices that differ from already established practices. LUC in frontier regions is commonly highly dynamic and involves exploitation of multiple natural resources, including the removal of native vegetation (deforestation) (FEARNSIDE, 2005; 2007; RINDFUSS, ENTWISLE et al., 2007; NEPSTAD, SOARES et al., 2009). As agricultural frontiers move on, land use in previous frontier regions gradually becomes more similar to land use in consolidated agricultural regions.

In addition to consolidated agricultural regions growing via the processes taking place in frontier regions, studies have proposed other relations that connect the consolidated agricultural regions with the agricultural frontiers. The link between production growth in consolidated regions and expansion of the agricultural frontier in Brazil has been discussed extensively as an example of indirect LUC (iLUC) associated with biofuel expansion (LAPOLA, SCHALDACH et al., 2010; BERNDES, AHLGREN et al., 2012). The hypothesis is that the planting of biofuel crops on pastures or croplands in consolidated agricultural regions induces increased expansion of agricultural land in frontier regions to compensate for the lost food production capacity.

Our analysis revealed that areas of cropland expansion and contraction commonly occur within short distances of each other (Figures 3.4a and 3.4d), while pasture area dynamics have a different spatial pattern of regional clusters with opposed expansion/contraction dynamics (see Figures 3.4b and 3.4e). A possible interpretation is that crop cultivation has a shorter-range migration dynamic, also observed by SPAROVEK, BARRETTO et al. (2009), while pasture dynamics might be associated with migration over longer distances. This is reasonable considering that livestock production can be established in areas with fairly limited infrastructure, while crop production depends on a more developed and complex set of services and infrastructure. This observation provides support for the hypothesis that iLUC occurs in Brazil. However, previous research suggests that the existence of roads, and the desire to engage in land speculation and/or secure tenure rights are equally important factors for land conversion in agricultural frontiers as the expected profitability of crop or livestock production (MARGULIS, 2004; KAIMOWITZ and ANGELSEN, 2008). Brazil has at least 123 Mha of land with no tenure rights; this land is concentrated in the Amazon and the center-west where most of the agricultural expansion has been taking place in the last decades (BRASIL, 2010b). In 2009, the Brazilian government started a massive program to secure land tenure rights in Legal Amazon (Terra Legal Program (BRASIL, 2012)). The effectiveness of this kind of policy in reducing pressure on forest might have been underestimated.

It will likely be difficult to evaluate the effectiveness of measures intending to address LUC impacts in frontier regions based on regulating agricultural land use in distant consolidated agricultural regions (e.g., by using iLUC factors to discourage cultivation of certain biofuel crops). However, analysis of Brazilian historical data at the municipal level during 1975-2006 indicated that: (i) in consolidated agricultural regions, land use intensification resulted in farmland stability or contraction and (ii) in agricultural frontier areas, land use intensification coincided with agricultural expansion. Therefore, intensification *per se* may not be the silver bullet for addressing impacts associated with the land conversion pressure of Brazilian agriculture such as LUC emissions and biodiversity losses. If intensification in consolidated agricultural regions induces cropland expansion onto pastures, this might induce migration of livestock production to frontier regions. Furthermore, intensification in frontier regions may itself induce agriculture expansion by making the agriculture more competitive.

Thus, in order to effectively address frontier LUC, measures to stimulate agriculture intensification will likely need to be combined with locally developed policies and actions in the most important frontier regions, e.g., based on a compliance regime and market exclusion, which have been reported effective in lowering deforestation rates and promoting sustainable development in Legal Amazon frontiers (RUDORFF, ADAMI et al., 2011; BRANNSTROM, RAUSCH et al., 2012; NEVES, 2012).

3.4.3 Farmland contraction in Brazil

A long-term pattern of farmland contraction associated with intensification was found for both crop and livestock production in the agriculturally consolidated region. In addition, aggregation of census data (Table S1.1.) reveals that the total Brazilian farmland has been roughly stable during the last two decades while agriculture output has increased considerably; during the period 1990-2010 Brazilian production increased on average 7.2%/y for soybean, 3.5%/y for corn, 5.2%/y for sugarcane, 5.6%/y for milk and 6.7%/y for beef (IBGE, 2010b; CONAB, 2012). This implies that intensification has spared considerable land areas for nature, but as noted above this intensification might also have contributed to higher growth rate in agriculture production by making Brazilian agriculture more economically competitive.

In some regions, forest ecosystem recovery can be observed after long periods of agricultural land use. This is in line with the Forest Transition (FT) theory proposing that a period of net forest area loss can be followed by a period of net gain (MATHER, 1992; MATHER and NEEDLE, 1998). Observations in line with this theory have been reported for parts of the Amazon (PERZ and SKOLE, 2003), and the Atlantic Forest (BAPTISTA and RUDEL, 2006). Results reported in this article indicate substantial farmland contraction in steep areas within the Atlantic Forest biome located in the southeast of Brazil, but not in the Amazon.

The tendency of farmland contraction in the Atlantic Forest Biome was strongest during the period 1975-1996, which was the same period covered by BAPTISTA and RUDEL (2006) although their study focused mainly on the south of Brazil. Farmland contraction was also observed in semi-arid areas of northeastern Brazil during the recent 30 years, indicating the same process of reversal to natural conditions, although in this case not to rainforest.

WALKER (2012) and PFAFF and WALKER (2010) point to misinterpretation of observed regional forest reversal as a general country-wide process and reinforce the need to consider regional interdependence in FT processes. Specifically, WALKER (2012) modeled aggregated Atlantic Forest and Amazon biomes and concluded that the Atlantic forest is recovering less quickly than Amazonian forests are lost. Thus, FT takes place in certain regions but for Brazil as a whole there is still a net loss in forest area. The results reported in this article indicate that land-sparing has likely occurred in consolidated agricultural regions in the last 30 years, which includes not only the Amazon and Atlantic Forest biomes covering 63% of entire territory, but also Cerrado, Caatinga, Pantanal and Pampas biomes. Modeling to investigate Brazilian forest transition needs to encompass the entire nation and consider a wider context including also other important biomes. More research is needed to clarify the importance of different causes behind such transitions in Brazil, which include agricultural intensification, socio-economic transformations, and environmental legislation.

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4 THE BRAZILIAN AGRICULTURAL FRONTIER IN 2006: SPATIAL DESCRIPTION, IMPLICATIONS FOR NATURAL CONSERVANCY AND AGRICULTURAL PRODUCTION

Abstract

Agricultural production in Brazil has been constantly increasing in the last decades, and this tendency is expected to continue in the short and long-run due to an increasing global demand for food and biofuels. Such growth in production is a consequence of both technological improvements and expansion of the agricultural area over natural ecosystems. The purpose of this study is to develop a comprehensive and robust spatial model to identify the Brazilian Agricultural Frontier. Furthermore, the Frontier was compared to no-Frontier regions in relation to economic, land-use and environmental indicators. Approximately one-fifth of Brazilian territory was identified as belonging to the Frontier, mainly concentrated in the North and Center-west regions, shaping two vectors of agricultural expansion, one towards Amazon Biome and the other towards preserved areas of Savannas Biome. The Frontier region had 55% of deforestation (2000 to 2009), 72% of livestock growth (1995 to 2006) and 19% of cropland growth (1995 to 2006). However, only 5% of gross production value from agribusiness was attributed to the Frontier region in 2006. The strong differences in land use and efficiency between Frontier and agriculturally consolidated areas suggest rethinking the dependence relation that might exist between them as well as the nature conservation strategies.

Keywords: Land-use; GIS; Modeling; Agricultural expansion

4.1 Introduction

Brazil is an important country in the global food system and also in the area of bioenergy. In the last decades, agricultural production has increased drastically as a result of expansion in area and productivity growth, which made Brazil a worldwide leading producer of beef, soybean, sugar, ethanol, broiler and coffee (BRASIL, 2010a). The difficulties of world stock renewal and the sharp consumption increase, especially of grains such as corn, soybean and wheat, are favorable conditions to countries such as Brazil to continue increasing agricultural production (BRASIL, 2011). It is uncertain however, how much of production growth will be accounted to an improvement in technologies through intensification, and how much will depend on expansion of agricultural lands over native vegetation.

During 1980-2000, 80% of the agricultural expansion in the tropics took place on forested land (GIBBS, RUESCH et al., 2010). In Brazil, the long history of non-compliance with environmental legislation, involving extensive deforestation, has placed a large part of agricultural areas in an illegitimate situation (SPAROVEK, BERNDES et al., 2010;

SPAROVEK, BERNDES et al., 2012). It is regular knowledge that most of the conversion from native vegetation to agricultural land-uses takes place in a geographic region called Agricultural Frontier. The Frontier is considered the “front or leading edge associated with people moving into a geographic area, bringing with them land management practices that differ from the land management schemes already in place. It is a process that, by definition, involves relatively rapid land-use change” (RINDFUSS, ENTWISLE et al., 2007, p 740). The prevalence of native vegetation conversion in the Frontier was already observed for Brazil by several studies (FEARNSIDE, 2005; 2007; NEPSTAD, SOARES et al., 2009), which makes this special region a hot-spot for actions aiming the reduction of deforestation and mitigation of negative impacts of agricultural expansion. However, a methodology to pinpoint the Agricultural Frontier in Brazil has not been developed yet.

The purpose of this paper is to present a spatially explicit model to locate the Brazilian Agricultural Frontier, using as input information only periodically surveyed open access databases. The model operates at the Brazilian Census Sectors scale (9,806 polygons) and its reference base year is 2006. Furthermore, the area classified as the Agricultural Frontier Region was compared to the area classified as the Brazilian no-Frontier Region in order to investigate the state and dynamics of environment, land-use, and local economy of the Brazilian Agricultural Frontier.

4.2 Methods

This Section is divided into four parts. Section 4.2.1 reviews basic concepts and definitions of Frontier. The following section (4.2.2) describes databases sources and variables used in the model. The third section (4.2.3) explains the decision rule used for identification of the Census Sectors with frontier dynamic. Finally, the forth section (4.2.4) gives the methodological details for comparison of the Frontier Region to Brazilian no-Frontier Region in relation of environment, land use and economic indicators.

4.2.1 Basic concepts

Frontier is considered a dynamic and irregular zone of division between the settled and the unsettled parts of a country. The process involves an initial penetration to an unsettled area followed by the creation of secondary and tertiary frontier zones (RICHARDS, 1990). In a great extent, the Frontier separates a region with higher degree of preserved native vegetation from a region where native vegetation is a scarcer resource. Insofar as frontier

moves forward there is a tendency to concentrate intensive agriculture (crops) on the area best suited for such land-use (MATHER and NEEDLE, 1998; RUDEL, SCHNEIDER et al., 2010) in a process called “Agricultural Adjustment”.

The analysis of land-use patterns and their changes in the microeconomic theorization tradition is mostly based on von Thünen’s model concept, which states that land is allocated to the use that gives the highest rent. ANGELSEN (2010) defined agricultural rent as: $r^a = p^a y^a - w^a l^a - q^a k^a - v^a d^a$. Agricultural production per hectare (yield) is given (y^a). The produce is sold in a central market at a given price (p^a). The labor (l^a) and capital (k^a) required per hectare are fixed, with input prices being the wage (w^a) and annual costs of capital (q^a). The fixed wage assumption implies that labor can move freely in and out of agriculture. Transport costs are the product of costs per kilometer (v^a) and distance from the center (d^a). From the land rent approach, the frontier is where agricultural expansion is not profitable anymore and agricultural land rent is, as a consequence, very low.

From that framework and from the previous definitions, it will be assumed hereafter that the “Brazilian Agricultural Frontier” (BAF) is located where:

- a. There has been recent agriculture expansion (crop and/or livestock)
- b. There are abundant natural resources, represented by native vegetation (natural forest)
- c. The distance from markets is relatively high
- d. The opportunity cost of production is low (low land rent)

In the following sections, it is explained how a spatial database was organized and proxy variables computed to capture the above listed points for spatial location of the Brazilian Agricultural Frontier in 2006, as well as to detail some specific features of the frontier expansion process.

4.2.2 Database preparation

4.2.2.1 Sources

The reference year of 2006 was adopted for BAF calculation due to availability of Brazilian Agrarian Census Data. The Agrarian Census is the most extensive assessment of rural areas in Brazil, being performed in intervals of 5 or 10 years (the last two conducted in 1996 and 2006, covering an average of 37% of Brazilian total area). The primary data is generated by interviews with landowners and further aggregated to a sub-municipality level of 9,876 census sectors.

The census performed every 10 years is not adequate for time series computation. Time series are essential for the identification of trends in land-use changes. Therefore, the robust and comprehensive Agrarian Census data were combined with Municipality databases generated at annual basis during 2001-2006.

The exogenous variable of the Brazilian road network was used as complementary information for model evaluation. Native vegetation surveyed through remote sensing entered the model as an indicator of environmental conservation. The sources used as well as the main characteristics of each data survey are listed in Table 4.1.

Table 4.1 - Surveys used as information sources in this study and their general characteristics

Source original name	Institution/ reference	Data collection method	Scale	Data aggregation	Time basis	Focus
Censo Agropecuário 2006	Brazilian Institute of Geography and Statistics (IBGE, 2006)	Interview with landowners	National	9876 Census Sectors	Decennial	Entire Rural Life
Produção da Pecuária Municipal (PPM)	Brazilian Institute of Geography and Statistics (IBGE, 2010c)	Reports delivered by a local agent	National	5565 Municipalities	Annual	Livestock Production
Produção Agrícola Municipal (PAM)	Brazilian Institute of Geography and Statistics (IBGE, 2010c)	Reports delivered by a local agent	National	5565 Municipalities	Annual	Crop Production
Projeto de Monitoramento do Desflorestamento na Amazônia Legal (PRODES)	Brazilian National Institute for Space Research (INPE, 2010)	Remote sensing land use classification	Regional (Legal Amazon)	760 Municipalities	Annual	Deforestation
Plano Nacional de Logística e Transporte (PNLT)	Ministry of Transport (MT) (BRASIL, 2010b)	Remote sensing	National	-	2010	Network of roads
Projeto de conservação e utilização sustentável da diversidade biológica Brasileira - PROBIO	Ministry of Environment (MMA) (BRASIL, 2007)	Remote sensing	National	-	2002	Native vegetation

4.2.3 Computing Proxy-Variables

As posed above in section 4.2.1, the Agricultural Frontiers are places undergoing relatively rapid transformation in land-use and land management practices. In addition, the Agricultural Frontier is expected to be far away from the markets, have low land rent and abundance of natural resources, in this case, forests. We computed proxy variables to capture these characteristic as follows:

- a. Recent agriculture expansion (crop and/or livestock). Proxy variables:
 - Mean annual growth of annual crops harvested area (ha.y^{-1}). Calculated by linear regression using the minimum squares method.
 - Mean annual growth rate of annual crops harvested area ($\%. \text{y}^{-1}$). Calculated by log-linear regression using the minimum square method.
 - Mean annual growth of bovine population (heads.y^{-1}). Calculated by linear regression using the minimum squares method.
 - Mean annual growth rate of bovine population ($\%. \text{y}^{-1}$). Calculated by log-linear regression using the minimum square method.
- b. Abundant natural resources (native vegetation). Proxy variable:
 - Share of farmland covered by native vegetation (%).
- c. Distance from markets
 - Mean distance from roads (km). Computed by GIS tools using the Brazilian net of paved roads (BRASIL, 2010b).
- d. Opportunity cost of production (land rent)
 - Value of the agriculture production per hectare ($\text{R}\$. \text{ha}^{-1}$). Sum of gross value of all production of a farm, including animal production, vegetal production and agroindustry.

In addition to the above mentioned variables, we also included in the analysis indicators of pasture productivity (stocking rate) and indicators of the type of production system (small holders, family based production and industrial farming). We divided the variables into three groups, with three different purposes. The objective of the first group was to identify the Agriculture Frontier Region. As a prerequisite of the model, a variable used for the Frontier identification must be periodically surveyed by Brazilian Institute of Geography and Statistics (IBGE), which is the main provider of data and information in the country, so

the methodology could be replicated both for the past and future. The second group of variables was used to test if the Frontier was identified properly, and the purpose of the third group was to describe the region in relation to environment, land-use and economy. Table 4.2 describes in detail these three groups of variables computed:

Table 4.2 - Proxy variables selected for the assessment

Proxy variable	Description	Dimension	Period	Source
<i>Group 1: Variables used to locate the agriculture frontier (periodical public surveys)</i>				
Cinc	Mean annual growth of crops harvested area	ha.y ⁻¹	2001-2006	PAM/IBGE
Ctx	Mean annual growth rate of crops harvested area	%. y ⁻¹	2001-2006	PAM/IBGE
AUinc	Mean annual growth of livestock population*	AU.y ⁻¹	2001-2006	PPM/IBGE
AUtx	Mean annual growth rate of livestock population*	%. y ⁻¹	2001-2006	PPM/IBGE
NV_farm	Share of farmland covered by native vegetation	%	2006	CA/IBGE
<i>Group 2: Variables used to verify the assessment</i>				
RdDist	Mean Distance from Roads	km	2006	PNLT/MT
PV	Agricultural production value per hectare of farmland	R\$.ha ⁻¹	2006	CA/IBGE
<i>Group 3: Variables used to general characterization</i>				
StRate	Pasture stocking rate*	AU.ha ⁻¹	2006	CA/IBGE
SmH_Num	Proportion of number of small-holder farmers	%	2006	CA/IBGE
SmH_PV	Proportion of total agricultural production value that comes from small-holders farms	%	2006	CA/IBGE
Area	Mean farm area	Ha	2006	CA/IBGE
NV_tot	Share of total area covered by native vegetation	%	2002	PROBIO/MMA
Dinc	Mean annual growth of deforested area	km ² .y ⁻¹	2001-2006	PRODES/INPE
Dtx	Mean annual growth rate of deforested area	%. y ⁻¹	2001-2006	PRODES/INPE
PV_Past	Animal production value per hectare of pasture	R\$.ha ⁻¹	2006	CA/IBGE
PV_Crop	Crop production value per hectare of cropland	R\$.ha ⁻¹	2006	CA/IBGE

* For calculation of Animal Units (AU), the livestock population of bovine, goat, sheep and buffalo were considered. For each category, a proper factor to convert number of animals to AU was used, assuming that an adult female bovine is equivalent to 1 AU.

4.2.4 Identification of the Agricultural Frontier Region

The variables of Group 1 listed in Table 4.2 were used in a selection procedure for separating census sectors where there was a significant expansion of crops or pasture in the period 2001-2006 together with the presence of significant areas of native vegetation in

farmland. Therefore, Census Sectors were considered as belonging to the Agriculture Frontier Region in 2006 if the two criteria below were met:

First Criterion: Recent agriculture expansion, given as:

- a. Mean annual growth of crop harvested area (Cinc) AND Mean annual growth rate of crop harvested area (Ctx) above the percentile 90 of the Brazilian distribution
- OR
- b. Mean annual growth of livestock population (AUinc) AND Mean annual growth rate of livestock population (AUtx) above the percentile 90 of the Brazilian distribution

Rationale: Brazil experienced during 1996-2006 an overall increase of approximately 16 million Animal Units and 10 million hectares of crops (IBGE, 2010c). Expansion was a regular tendency of the entire country. Our objective was to select the most important Census Sectors of that expansion by ranking all of them and selecting the top of the list, instead of adopting a threshold value that could include a large number of sectors. The combination of “*annual growth rate (%.yr⁻¹)*” with “*annual growth (ha.yr⁻¹ or heads.yr⁻¹)*” was used to avoid either the inclusion of high rates associated with low amounts (no spatial relevance) or high amounts with low rates (no dynamic relevance).

Second Criterion: Abundance of natural resources (native vegetation) in farmland, given as:

- a. Share of farmland covered by native vegetation (NV_farm) between 25 to 50%, identifying the LOW-FRONTIER
- b. Share of farmland covered by native vegetation (NV_farm) between 50 to 75%, identifying the UP-FRONTIER
- c. Share of farmland covered by native vegetation (NV_farm) greater than 75%, identifying the EDGE-FRONTIER

Rationale: The use of a native vegetation gradient to separate three types of Frontier regions was an attempt to include flexibility in the data analysis, that could led to a more complete characterization of the Agriculture Frontier Region. The decision rule to separate the Census Sectors is described in Figure 4.1:

```

IF
[ ((AUtx_percentile >= 0.90 AND AUinc_percentile >= 0.90) OR (Ctx_percentile >=
0.90 AND Cinc_percentile >= 0.90)) AND NV_FARM >= 25 AND NV_farm < 50]
THEN Census Sector == LOWFRONTIER

ELSE IF
[ ((AUtx_percentile >= 0.90 AND AUinc_percentile >= 0.90) OR (Ctx_percentile >=
0.90 AND Cinc_percentile >= 0.90)) AND NV_FARM >= 50 AND NV_FARM < 75]
THEN Census Sector == UPFRONTIER

ELSE IF
[ ((AUtx_percentile >= 0.90 AND AUinc_percentile >= 0.90) OR (Ctx_percentile >=
0.90 AND Cinc_percentile >= 0.90)) AND NV_FARM >= 75]
THEN Census Sector == EDGEFRONTIER

ELSE Census Sector == noFRONTIER
END IF

```

Figure 4.1 - Script used to identify the Brazilian Agricultural Frontier (BAF) and to divide it into three classes, according to the amount of native vegetation preserved in farmland

4.2.4.1 Identification of the region beyond the Agricultural Frontier.

According to the concept of Frontier, this hypothetical zone could be seen as a dynamic borderline between a region more preserved in terms of native vegetation and a region where this resource is scarcer due to intense conversion to other land-uses. Therefore, when identifying the Frontier it is also important to separate the regions that are beyond the Frontier from regions that had already experienced a process of intense conversion of native vegetation. For that purpose, the percentage of total native vegetation surveyed by remote sensing (BRASIL, 2007) was used. The threshold value adopted was 50% according to the script shown in Figure 4.2.

```

IF
Census Sector == noFRONTIER AND NV_tot >= 50
THEN Census Sector == noFRONTIER_HighNV

ELSE IF
Census Sector == noFRONTIER AND NV_tot < 50
THEN Census Sector == noFRONTIER_LowNV
END IF

```

Figure 4.2 - Script used to separate regions beyond and behind the frontier according to the amount of total native vegetation preserved

4.2.4.2 Frontier and No-Frontier Regions classified according to suitability for agricultural production

According to the “Agricultural Adjustment” theory, after the inclusion of the Frontier to the agriculturally consolidated region, it is expected that intensive agriculture concentrates in areas with more favorable biophysical conditions, while less intensive uses, such as cattle ranching or natural conservation, are allocated to marginally suitable areas. The Frontier and no-Frontier regions identified here were overlayed on a large scale suitability map for intensive crop production (see: Chapter 2). The purpose was to spatially locate the areas at the Frontier and the areas ahead of the Frontier with high suitability for intensive agricultural production and distinguish them from those with low suitability. The same procedure was applied in the agriculturally consolidated area and the final result was a classification of Brazilian Census Sectors in 6 different classes: (i) Frontier - high suitability, (ii) Frontier - low suitability, (iii) no Frontier, with high native vegetation coverage, and high suitability, (iv) no-Frontier, with high native vegetation coverage and low suitability, (v) no-Frontier, with low native vegetation coverage and high suitability, (vi) no-Frontier, with high native vegetation coverage and high suitability. The threshold to be considered low or high suitability was 3 in a scale from 0 = “Unsuitable” and 4 = “Very suitable” as shown in Figure 4.3.

Figure 4.3 - Intensive cropping suitability information used to classify frontier and no frontier regions according to average suitability

4.3 Results

4.3.1 Outcome of the selection and geographical grouping of Census Sectors

The selection procedure outcome is shown in Figure 4.3. 323 Census Sectors (3.3% of 9,893 Brazilian Census Sectors) were selected as belonging to the Agriculture Frontier Region. This region is concentrated to a fairly small number of the Brazilian Census Sectors, but the area is relatively high, including 19% of the Brazilian territory. As expected, the Frontier was located mainly in the North and Center-West Region, in the states of Pará and Mato Grosso. Apart from this main region, we also located an Agricultural Frontier in the borderline of the North and Northeast regions, in the states of Maranhão, Piauí and Tocantins.

The Low-Frontier, characterized by 25-50% of native vegetation (NV) in farmland, included 236 census sectors, the Up-Frontier (50-75% of NV) included 71 census sectors and the Edge-Frontier (>75% of NV) included 16 census sectors. The share of area was respectively for Low-Frontier, Up-Frontier and Edge-Frontier: 49%, 40% and 11%. As shown

in Figure 4.4., the three Frontier Regions shaped a geographical core-periphery gradient, in which the core is the Low-Frontier and the periphery is the Up-Frontier and the Edge-Frontier.

The regions not classified as “Frontier”, were divided into two classes according to the remaining amount of native vegetation. 6541 census sectors (29% of Brazilian territory) were classified as areas with poor native vegetation cover. These areas are located in the Center and South of Brazil and along the coastline and are consistent with the agriculturally consolidated region. On the other hand, 52% of the entire Brazilian territory was classified as no-Frontier with considerable native vegetation cover. Such area is concentrated mainly in the North and Northeast regions, ahead of Frontier zones.

Figure 4.3 - The geographical distribution of the Agriculture Frontier Region separated in three classes: Low-Frontier, Up-Frontier and Edge-Frontier

4.3.2 Model verification by exogenous variables

According to our assumptions, the Agricultural Frontier is a region characterized by an intense agricultural expansion, high availability of native vegetation, high distance from markets and a low land rent. We located the Agriculture Frontier using as criteria the agricultural expansion and the availability of native vegetation. In order to check the reliability of our model, we used the spatial distribution of exogenous variables representing the distance from markets and the land rent.

As a proxy of distance from markets we computed the mean distance to paved roads for each one of the 9,893 Census Sectors. The histogram shown by Figure 4.5 represents the distribution of this variable for all Brazilian Census Sectors. We plotted as reference lines the average values calculated for Brazil and for the three classes of Agricultural Frontier Regions. As expected, the average values for Frontier Regions are higher than the Brazilian mean value. The results also show that the mean distance to roads increases from the Low-Frontier

to the Edge-Frontier, indicating that the model was effective in selecting Census Sectors located in relatively remote areas, which is a main characteristic of the Agricultural Frontier.

Figure 4.5 - Histogram of Brazilian distribution of proxy variable Mean Distance to Roads and reference lines with the average values for Brazil and Frontier Regions

In a second verification we selected the “Agricultural Production Value per hectare” as a proxy variable to represent land rent (opportunity cost). The Production Value is the sum of the gross value of all products generated by a farm in one year. We considered that the higher the land rent the higher would be the “Production Value per hectare”. Similarly, the higher the cost of opportunity (labor and capital) the higher would be the “Production Value per hectare. Agriculture Frontier is characterized by the use of labor/capital-*saving* production systems because most remote farmers face severe labor/capital constraints. Therefore, we expected that the Agriculture Frontier would be related to relatively low “Production value per hectare”.

The histogram shown by Figure 4.6 represents the distribution of variable “Production value per hectare” for all Brazilian Census Sectors. We plotted as reference lines the average values calculated for Brazil and for the three classes of Agriculture Frontier Regions. As it was expected, the Agriculture Frontier Region average was lower than the Brazilian average. In addition, the “Production Value per hectare” decreases from the Low-Frontier to the Edge-

Frontier. These results are in accordance to the theoretical expectancy and evidence the effectiveness of our model to locate the Agriculture Frontier Region.

Figure 4.6 - Histogram of Brazilian distribution of proxy-variable Production Value per hectare and reference lines with the average values for Brazil and Frontier Regions

4.3.3 Comparison of average values of proxy variables between Frontier and no Frontier regions

Average values for the 15 proxy variables listed in Table 4.2 are shown in Table 4.3 for the following regions: Brazil (entire territory), No-Frontier, Frontier (all three classes), Low-Frontier, Up-Frontier and Edge-Frontier. The Frontier Region was compared to the no-Frontier Region using a *t-test* for independent samples. Mean values significantly differ at the $p < 0.05$ level were preceded by an asterisk in Table 4.3.

Table 4.3 - Average values of proxy variables for Brazil, No-Frontier Region and Frontier Region

Region	Census Sectors	Cinc	Ctx	AUinc	AUtx	NV_farm
	n	ha.yr ⁻¹	%.y ⁻¹	AU.yr ⁻¹	%.y ⁻¹	%
FRONTIER	323	*3156	*18.8	*14486	*11.9	*44
Edge-Frontier	16	3600	13.9	10950	16.3	81
Low-Frontier	236	2597	18.7	15273	11.8	36
Up-Frontier	71	4913	20.3	12669	11.1	60
No FRONTIER	9570	*423	*2.3	*840	*1.9	*21
High NV	3029	361	2.9	1209	2.5	30
Low NV (consolidated)	6541	452	2.1	670	1.6	16
Brazil	9893	512	2.9	1286	2.2	21
Region	NV_tot		RdDist	PV	PV Past	PV Crop
	%		km	R\$.ha ⁻¹	R\$.ha ⁻¹	R\$.ha ⁻¹
FRONTIER	*63		*22	*196	*171	*1232
Edge-Frontier	86		51	81	142	1186
Low-Frontier	57		19	222	181	1265
Up-Frontier	75		26	137	143	1132
No FRONTIER	*36		*7	*912	*853	*1956
High NV	77		11	543	496	1596
Low NV (consolidated)	17		5	1084	1021	2121
Brazil	36		7	888	830	1931
Region	StRate	SmH Num	SmH PV	Area	^a Dinc	^a Dtx
	AU.ha ⁻¹	%	%	ha	km ² .yr ⁻¹	%.y ⁻¹
FRONTIER	0.73	79	*44	*304	*145	*6.6
Edge-Frontier	0.77	88	69	262	99	6.4
Low-Frontier	0.73	79	43	252	146	5.5
Up-Frontier	0.70	79	43	487	155	9.3
No FRONTIER	0.76	78	*51	*88	*24	*3.2
High NV	0.61	81	58	106	25	4.5
Low NV (consolidated)	0.84	77	48	80	23	1.6
Brazil	0.76	78	51	95	52	4.0

*Significant difference at a p<0.05 level (t-test for independent samples)

^aData available only for Census Sectors within Legal Amazon Region

Table 4.4 - (auxiliary) Proxy variables description

Proxy variable	Description	Source
Cinc	Mean annual growth of crops harvested area	PAM/IBGE
Ctx	Mean annual growth rate of crops harvested area	PAM/IBGE
AUinc	Mean annual growth of livestock population	PPM/IBGE
AUtx	Mean annual growth rate of livestock population	PPM/IBGE
NV_farm	Share of farmland covered by native vegetation	CA/IBGE
NV_tot	Share of Census Sector covered by native vegetation	PROBIO/MMA
RdDist	Mean Distance from Roads	PNLT/MT
PV	Agricultural production value per hectare of farmland	CA/IBGE
StRate	Pasture stocking rate	CA/IBGE
SmH_Num	Proportion of number of small-holders farms	CA/IBGE
SmH_PV	Proportion of total agricultural production value that comes from small holders	CA/IBGE
Area	Mean farm area	CA/IBGE
Dinc	Mean annual growth of deforested area	PRODES/INPE
Dtx	Mean annual growth rate of deforested area	PRODES/INPE
PV_Past	Animal production value per hectare of pasture	CA/IBGE
PV_Crop	Crop production value per hectare of cropland	CA/IBGE

In comparison to the no-Frontier Region, the Brazilian Agricultural Frontier (BAF) was characterized by higher farm size. The mean farm area was 304 ha in the Frontier compared to an average farm area of 88 ha in the no-Frontier. According to the data, this difference cannot be attributed to more presence of large scale farmers in the Frontier because the proportion of number of farms and production value of small-holders were almost the same in both regions. The presence of larger farms in the Frontier is probably a regular characteristic of the entire North and Center-west region where the Frontier is located. However, the analysis of the three classes of Frontier shows that the farms tend to be smaller in the Edge-Frontier and the importance of small-holder agriculture greater when compared to the Up-Frontier and Low-Frontier.

Deforestation rates were two times higher in the Frontier Region and the production value generated both by animal and crop production was significantly lower when compared to the no-Frontier Region. Despite the production value per hectare of pasture being almost five times higher in the no-Frontier Region, the stocking rate was the same in all regions. In other words, the same amount of animals per hectare resulted in a higher annual production in the no-Frontier, showing higher production system efficiency of no-Frontier Region. This “efficiency” was relatively greater in the Low-Frontier when compared to the Up-Frontier and Edge-Frontier regions. In addition, when comparing the Frontier region to the no-Frontier located in agriculturally consolidated areas (Low NV), the differences in efficiency increase.

The production value per hectare in agriculturally consolidated regions is twice bigger for crops and almost ten times bigger for livestock production, than the average values of the Frontier Region.

4.3.4 Additional information for characterization of the Frontier and no-Frontier Regions

Indicators of land-use (e.g. Pasture, Cropland, Farmland), economy (e.g. Agricultural gross production value), and environment (e.g. Native vegetation, Public protected areas) were computed both to the Frontier and no Frontier regions and the proportions of each indicator were displayed by Figure 4.7.

Figure 4.7 - Indicators of land use, economy and environment for Frontier and no Frontier regions

The Frontier Region corresponds to 19% of Brazilian entire territory. This region also holds 16% of *Farmland*, 15% of *Livestock Production value*, 14% of *Pastures*, 22% of *Native vegetation*, and 20% of *Public Protected Areas*. These percentages are of the same order of magnitude of the Frontier Region *Total area* (19%). On the other hand, deviations from what would be proportional to the size of Frontier Region were observed both upward and downward. While the Frontier Region accounted only with 6% of number of *Farms*, 4% of

Crop Production Value, 6% of *Livestock Production Value*, it was the region where 55% of *Deforestation* from 2000 to 2009 took place, as well as 72% of *Livestock population growth* from 1995 to 2006.

The no-Frontier with poor vegetation cover (consolidated region) is 29% of Brazilian territory but responds for 76% of *Gross Agricultural Production Value*. On the other hand, two thirds of total Brazilian native vegetation coverage is concentrated in the no-Frontier Region ahead of the Frontier (no-Frontier-HNV).

4.3.5 Frontier and no-Frontier regions vs suitability for intensive agricultural production

In this section it was used a different classification of Frontier and no-Frontier regions, using as a complementary parameter the suitability for intensive agriculture, as detailed in methodological section 4.2.4.2. The geographical outcome of the classification is displayed in Figure 4.8. In addition, the proxy variables listed in Table 4.2 (section 4.2.3.2) are shown in Table 4.5 for the classes of Frontier and no-Frontier regions generated after the inclusion of suitability information into the analysis.

The Frontier region with high suitability for intensive agriculture is almost half the size of the Frontier with low suitability but have almost the same size of total farmland. Both regions generate the same total production value, which does not support the idea that better biophysical conditions result in higher yields. This tendency is also confirmed by indicators of productivity in Table 4.5 such as “Production Value per hectare (*PV*)”, “Production Value per hectare of pasture (*PV Past*)” and “Production Value per hectare of cropland (*PV Crop*)”. This same pattern was also observed for consolidated region. The Consolidated region with high suitability generated 41% of total Brazilian agricultural production value in 28% of total Farmland, while the consolidated region with low suitability generated 35% of Production Value in 23% of Farmland.

The classification of consolidated region according to suitability conditions resulted in an approximately fifth-fifth area division. The half with better suitability is concentrated in the center of Brazil where most of the corporative agricultural production takes place, while the other half with lower suitability is distributed over the territory, mainly in steep landscapes or in the inland semi-arid region of northeast as shown by Figure 4.8 in grey colors. The number of small-holders and the production value generated by small-holders are significantly greater in the consolidated region with low suitability for intensive cropping (see: Table 4.5,

variables “small-holders number (SmH_Num)” and small-holders production value (SmH_PV”). Concentration of small-holders in areas with low suitability is perceptible not only in the consolidated region but also in the Frontier and no-Frontier regions with high native vegetation cover.

Figure 4.8 - Spatial display of Frontier and no-Frontier regions classified according to land suitability for intensive agriculture (top panel) and indicators of land utilization (bottom panel). The colors of the map legend match the colors of the stacked bar chart

Table 4.5 - Average values of proxy variables for Brazil, No-Frontier Region and Frontier Region classified by considering suitability for intensive agriculture. Variables definitions can be accessed in auxiliary Table 4.4

Region	Census Sectors	Cinc	Ctx	AUinc	AUtx	NV_farm
	N	ha.yr ⁻¹	%.y ⁻¹	AU.yr ⁻¹	%.y ⁻¹	%
Frontier – High Suitability	126	4832	18.6	16628	13.4	43
Frontier – Low Suitability	197	2084	19.0	13117	10.9	44
no Frontier (High NV) - High Suitability	341	1191	6.1	2282	2.0	25
no Frontier (High NV) – Low Suitability	2688	255	2.4	1073	2.5	31
Consolidated – High Suitability	2385	982	4.5	407	-0.3	12
Consolidated – Low Suitability	4156	148	0.7	820	2.7	18
Brazil	9893	512	2.9	1286	2.2	21

Region	NV_tot	RdDist	PV	PV Past	PV Crop
	%	km	R\$.ha ⁻¹	R\$.ha ⁻¹	R\$.ha ⁻¹
Frontier – High Suitability	55	25	156	158	1038
Frontier – Low Suitability	67	21	222	179	1355
no Frontier (High NV) - High Suitability	75	13	431	306	1533
no Frontier (High NV) – Low Suitability	77	11	557	520	1604
Consolidated – High Suitability	13	5	1172	1037	2066
Consolidated – Low Suitability	20	5	1033	1011	2153
Brazil	36	7	888	830	1931

Region	StRate	SmH Num	SmH PV	Area	Dinc ^a	Dtx ^a
	AU.ha ⁻¹	%	%	ha	km ² .yr ⁻¹	%.y ⁻¹
Frontier – High Suitability	0.81	75	36	458	161	7.2
Frontier – Low Suitability	0.67	82	50	206	131	6.1
no Frontier (High NV) - High Suitability	0.68	76	45	172	50	4.4
no Frontier (High NV) – Low Suitability	0.60	82	60	98	22	4.5
Consolidated – High Suitability	1.00	69	32	135	28	1.6
Consolidated – Low Suitability	0.74	81	56	49	19	1.6
Brazil	0.76	78	51	95	52	4.0

^aData available only for Census Sectors within Legal Amazon Region

4.4 Discussion

4.4.1 Land-use dynamics of Frontier and no-Frontier regions

By locating the Brazilian Agricultural Frontier and using public available databases, it was possible to describe the Frontier and differentiate it from the agriculturally consolidated areas and from the regions that are spatially beyond the Frontier. The Frontier is almost 20% of Brazilian total area and concentrates most of deforestation and livestock growth as well as a significant percentage of cropland growth. In other words, when looking at aggregated data of Brazil, there is indeed a spatial overlap between expansion of agriculture and deforestation, which corroborates positive statistical correlations between them assessed by several studies (BARONA, RAMANKUTTY et al., 2010; ARIMA, RICHARDS et al., 2011). Furthermore, as already pointed by previous studies, the Frontier Region in Brazil is bordering the Amazon forest as well as areas of Savannas biome wealth of native vegetation (FEARNSIDE, 2001; FEARNSIDE, 2005; WALKER, DEFRIES et al., 2009). Therefore, it is plausible the assertion that an increase of Brazilian agricultural production could eventually cause an expansion in area and represent a menace for natural ecosystems (FARGIONE, HILL et al., 2008; LAPOLA, SCHALDACH et al., 2010).

However, data analyzed here, showed that the Frontier region is significantly less efficient on the use of production factors, contributing to approximately only 5% of total production value from agriculture. Moreover, this small share does not change even considering different sectors (i.e. livestock, crop) or different production systems (i.e. small-holders, no-small-holders). Our analysis showed that generation of agricultural production value in Brazil is not linked to the Frontier region, which means that a very little share of agribusiness wealth depends on the Frontier land-use change dynamic. Several implications both for conservation strategies and for agribusiness sector could be drawn from this context.

First, regions with different land-use dynamics should have different conservation strategies. It is known that, in Brazilian agricultural expansion areas, there is low level of compliance to environmental legislation in private lands (SPAROVEK, BERNDES et al., 2010). On the other hand, there is a broad consensus in the literature that protected areas such as Parks or Indian Reservations are effective in preventing land clearing and should remain a central component of conservation strategies (BRUNER, GULLISON et al., 2001; DEFRIES, HANSEN et al., 2005; WALKER, MOORE et al., 2009). These conditions suggest that in the Frontier region and neighboring areas, the conservation of natural ecosystems is more likely

to be effective if focused on creation of Protected Areas rather than on increase restrictiveness of environmental legislation applied to private lands.

Second, the Frontier Region is a burden for Brazilian Agribusiness. Even though the economic contribution of Frontier region for agricultural total production is very low, the Frontier as a business is still profitable, particularly if it is considered extensive cattle ranching and land speculation (MARGULIS, 2004). In addition, the profitability of what we could call the “Frontier Business” is expected to continue in a long-term time horizon (SOARES, NEPSTAD et al., 2006; BOWMAN, SOARES-FILHO et al., 2012). There is not a clear borderline separating the “Frontier Business” to the “Agribusiness”, but, as exemplified here through a simple spatial model, such differentiation is reasonable and a regionalization is possible. The enhancement of differences between Frontier and no-Frontier places the Agribusiness in a better position to take control of Frontier dynamic and curb deforestation. First, because the Agribusiness image is the most affected by the high deforestation rates in Frontier Region. Second, because both “Frontier Business” and “Agribusiness” have the same final products/markets. Third, because in Brazil there are several sectorial organizations such as UNICA (Brazilian Sugarcane Industry Association) for sugarcane, ABIOVE (Brazilian Association of Vegetable Oil Industries) for soybean, ABIEC (Brazilian Association of Beef Industry) for beef with power enough to establish market quality standards and to adopt certification schemes. Since 2006, the two main associations of soybean sector (ABIOVE and ANEC) and their respective member companies have pledged not to trade soy originated after that date in deforested areas within the Amazon Biome. So far, this program has been considered a successful example of market based strategy to control deforestation (BRANNSTROM, RAUSCH et al., 2012).

4.4.2 The role of small-holder agriculture in the “Agricultural Adjustment”

The classification of Brazilian census sectors considering the suitability for intensive agriculture and further analysis of Agrarian Census database resulted in small differences in productivity between areas with good and moderate biophysical conditions. Such pattern is the same both in the Brazilian consolidated area and in the Frontier region. Therefore, differently to what would be expected according to the “Agricultural Adjustment” theory

(MATHER and NEEDLE, 1998; RUDEL, SCHNEIDER et al., 2010), intensive agriculture in Brazil (i.e. more agricultural outputs per area of land input) was not concentrated on the areas best suited for such land-use. In addition, it was observed that the main difference between areas with high suitability and low suitability is that the small-holder agriculture is more important in regions with low suitability not only in terms of number of farms, but also in terms of total production. Therefore, to some extent, small-holder agriculture compensates lower land suitability through a more efficient use of production factors. Previous studies based on Brazilian Agrarian Census database stated that even though the share of total production value that comes from small-holder agriculture is relatively small (23%), it uses only 18% of farmland in Brazil (FGV-IBRE, 2010; SPAROVEK, BARRETTO et al., 2011), thus representing a greater efficiency than the no-small-holder category that concentrates 82% of farmland producing 77% of total value generated by agricultural sector.

The data discussed here corroborates the concept that expansion in remote areas depends on low land rent in which low labor costs is an important component. Therefore, immigration of land-less farmers attracted by the economic opportunities, as well as further displacement of small-holders to marginal lands, is a determinant factor for the well-function of Frontier expansion as already discussed by previous studies (MATSON and VITOUSEK, 2006; LAMBIN and MEYFROIDT, 2011). In the previous section (4.4.1.) it was suggested that the “Agribusiness Sector” probably is best placed to control the “Frontier Business” and curb deforestation, on the other hand, how and to what extent the small-holder agriculture may be affected by stopping the Frontier progression is not yet clear. A better understanding of such process is matter for further research. The mitigation of potential social impacts is, nevertheless, a role that governmental policies could successfully play.

4.5 Conclusions

- Using information of cropland and livestock growth from periodically surveyed public databases it was possible to develop an effective methodology for geographical location of Brazilian Agricultural Frontier. Adding to the methodology an indicator of environmental preservation, made it possible to differentiate three classes of Frontier regions (i.e. Low-Frontier, Up-Frontier and Edge-Frontier), as well as to differentiate the region spatially beyond the Frontier from the agriculturally consolidated area. This classification was important not only to indicate the geographical direction of agricultural expansion, but also to show patterns of land utilization.

- The Agricultural Frontier summed up 19% of Brazilian entire territory and is formed by two main vectors of expansion, the most extensive is in the North and Center-west regions within Amazon Biome, and a secondary vector is in transitional areas between Amazon and Savannas biomes of Northeast region.
- The majority of Brazilian deforestation (55%) and Livestock population growth (72%), as well as great share of cropland expansion (19%) take place in the region identified as the Agricultural Frontier. At same time, this region contributes to less than 5% of gross value of agricultural production in Brazil. These characteristics make this region special not only for conservation strategies but also for the sustainable development of Brazilian agricultural sector.

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5 AGRICULTURAL LAND USE CHANGES AND DEFORESTATION IN THE BRAZILIAN AMAZON DURING 2000-2009: MODIFYING THE NOTION OF CROPLAND EXPANSION AS THE PRIME INDIRECT DRIVER OF DEFORESTATION

Abstract

Governments are increasingly promoting biofuels. The crop allocation to biofuels production and the resulting changes in land use have raised concerns about ecosystem impacts as well as doubts about the climate benefits of biofuels. One of the most disputed impacts of cropland expansion in Brazil (mainly related to soybean and sugarcane expansion) is the potential displacement of cattle ranching towards the Amazon deforestation frontier. This study estimates the extent to which the growth in cropland and pasture areas and deforestation were spatially correlated at municipality level in the Legal Amazon region during 2000-2009. We first identified those municipalities in the Legal Amazon which exhibited the largest growth of either, a) cropland acreage, b) pasture acreage, or c) deforestation rates during the time period. We then compared the rates of cropland and pasture expansion and deforestation in the three geographical regions formed by the 'expansion' municipalities with the municipalities adjacent to these regions. The results corroborate the well-known spatial separation of cropland expansion dominating in the agriculturally consolidated regions (mainly in the South) and pasture expansion dominating in the deforestation regions. However, the results also show that at municipal level, deforestation rates were substantial (on average 3.5 percent year⁻¹) in cropland expansion municipalities, with no statistically significant evidence of higher deforestation rates in areas adjacent to cropland 'expansion' regions. Furthermore, although cattle herd growth rates were significantly higher in deforestation areas, they were also substantial (2.5 percent year⁻¹) in cropland 'expansion' areas. These results suggest a need for modifying the widespread notion of cropland expansion in consolidated regions as the prime causal factor of indirect deforestation through displacement of pastures from these regions to frontier regions. Given the likely existence of several concomitant, but relatively independent, causal factors behind deforestation this notion is overly simplistic.

Keywords: Deforestation; Agricultural expansion; iLUC; Amazon; Soybean; Pasture

5.1 Introduction

Together with USA, Brazil has world-leading technology for ethanol production in the world and is well positioned to meet an increasing global demand (GOLDEMBERG, 2007). Some studies have shown that Brazil has biophysical conditions to increase sugarcane production substantially (CGEE, 2008; BRASIL, 2009; LEITE, LEAL et al., 2009). The Brazilian Government Energy Plan (BRASIL, 2012) aims at providing the infrastructure needed to support an increase of 2.5 times the current ethanol production by 2020. In addition, in 2002 Brazil launched a national program for promoting the production of biodiesel based

mainly on soybean oil, which in 2005 resulted in a mandatory blend of 5% of biodiesel in conventional diesel (BRASIL, 2005). The increasing demand for ethanol and the emerging biodiesel market have contributed to the fast expansion of cropland in Brazil– between 1990 and 2009, Brazilian sugarcane area grew from 4 million ha (Mha) to 9 Mha and soybean from 12 Mha to 22 Mha (IBGE, 2010c). Roughly half the harvested sugarcane is presently used for ethanol and 27% of produced soybean oil is used for biodiesel (BRASIL, 2010; BRASIL, 2012).

The connection between biofuel expansion and land use change (LUC) has caused concern and studies have pointed to a range of undesirable impacts (for an overview, see BERNDES, AHLGREN et al. (2012)). For the case of Brazil, the link between production growth in consolidated regions and expansion of the agricultural frontier has been discussed as an example of indirect LUC (iLUC) associated with biofuel expansion (SPAROVEK, BARRETTO et al., 2009; LAPOLA, SCHALDACH et al., 2010). The hypothesis is that the planting of biofuel crops on pastures or croplands in consolidated agricultural regions induces increased expansion of agricultural land in frontier regions to compensate for the lost food production capacity. The risks of extensive iLUC has also been pointed out as a possible consequence of enforcing compliance with environmental legislation in consolidated agricultural regions: pristine unprotected areas risk conversion to agriculture lands to maintain production capacity as current agricultural areas are reconverted to natural vegetation to meet legal reserve requirements (SPAROVEK, BERNDES et al., 2010; SPAROVEK, BERNDES, et al., 2012).

Studies of LUC emissions of greenhouse gases (GHG) associated with biofuels report widely different results and especially the inclusion of iLUC adds greatly to the uncertainty in quantifications of LUC effects (KHANNA, CRAGO et al., 2011; BERNDES, AHLGREN et al., 2012; DJOMO and CEULEMANS, 2012). Limitations in methodology and data makes quantification of iLUC emissions and identification of causal mechanisms behind iLUC highly contentious issues (MATHEWS and TAN, 2009; PRINS, STEHFEST et al., 2010; GAO, SKUTSCH et al., 2011; NASSAR, HARFUCH et al., 2011). Most of the attempts to quantify iLUC have used general or partial equilibrium models (see, e.g. CHUM, FAAIJ et al. (2011) for an overview) of varying scope (e.g., geography and spatial resolution, sectors covered and detail in their characterization), but there have also been approaches based on pre-defined, causal-effect chains (KIM and DALE, 2009; E4TECH, 2010; FRITSCHÉ,

HENNENBERG et al., 2010) and statistical analysis (BARONA, RAMANKUTTY et al. (2010), ARIMA, RICHARDS et al. (2011)).

This paper aims at contributing to the understanding of land use and LUC in the Legal Amazon Region (LAR). First, challenges of linking distant agriculture activities in the Legal Amazon - and especially the use of statistical analyses to identify causal chains and to quantify iLUC associated with specific agriculture activities - are discussed. Results from own analyses of LUC in LAR are then presented. Based on this, options for addressing LUC in the Legal Amazon are discussed. A concluding section summarizes the observations and presents conclusions.

5.2 Causes of deforestation and land use change in the Legal Amazon

Several studies on deforestation have suggested the existence of causal links between land use activities in spatially separated, distant regions. For instance, explorative modeling indicates that indirect land use change (iLUC), especially those pushing the rangeland frontier into the Amazonian forests, could offset the greenhouse gas (GHG) savings from biofuels by causing high GHG emissions (LAPOLA et al. 2009). In an analysis of the statistical correlation between soybean expansion and deforestation in the Legal Amazon, BARONA, RAMANKUTTY et al. (2010) suggested that the “increase in soybean occurred in regions previously used for pasture, which may have displaced pastures further north, causing indirect deforestation there” (p. 8). On the same topic and using similar methodology, ARIMA, RICHARDS et al. (2011) went even further and claimed to have quantified a causal link between soybean expansion and deforestation in the Legal Amazon, stating that “a 10% reduction of soy in old pasture areas would have decreased deforestation by as much as 40%” (p. 1).

In both these studies, the perceived causality is characterized as a ‘displacement’ effect, i.e. that the expansion of one land use activity (here soybean) in one region has the effect that the previous land use activity (here pasture) moves out and reconstitutes in another region (here in deforestation frontier areas). However, although perhaps convincing due to its simplicity, it is not evident what the concrete mechanism of displacement is, and whether it is an accurate description of the true causal mechanisms involved in the observed land use change process. One concrete mechanism of displacement might be that pasture land owners in the soybean ‘expansion’ regions sell land at profits, and reinvest this capital in beef production in deforestation regions. If this is the main mechanism involved in the land use

change process, then displacement would seem to be an accurate description. However, it is also possible that the concomitant growth in soybean production and deforestation is not causally linked, but instead driven by separate, relatively independent causal factors. Obviously, studies that examine the statistical correlation between land use activities in spatially separated regions, such as ARIMA, RICHARDS et al. (2011), BARONA, RAMANKUTTY et al. (2010), as well as this paper, cannot prove the existence, let alone quantify the magnitude, of any these before mentioned factors, since the methodology deals only with correlation, not causation.

For understanding and validating the mechanisms of (indirect) deforestation, a consistent theoretical framework is of importance. ANGELSEN (2010) distinguished between three levels of causes of deforestation: i) the deforestation ‘agents’ (individuals, households, companies) and their activities ii) the ‘immediate’ causes, i.e. external factors that influence the agent’s choices, such as markets, (de-facto) regulations, technology, and biophysical conditions, and iii) the ‘underlying’ causes, i.e. factors that in turn influence the immediate causes, such as national and international macroeconomics and policies. It is not the purpose of this section to describe each of these levels in detail; here we just want to stress and illustrate the difference between agents and immediate causes, since this distinction is crucial for discerning ‘displacement’ factors from other factors.

In the ‘agent’ category we can group some of the factors of a displacement nature, for example: land use agents (e.g. land owners or agricultural producers) accrue capital from profits in one region which they invest in (expanding) agricultural production in another region. In this category we can also place the phenomena of deforestation as a means of establishing property rights to the land, i.e. that agents deforest not with the main purpose of making profits from producing agricultural goods (or selling timber), but on speculation that this will strengthen their land title claims (ANGELSEN, 2010). Importantly, since this land-acquisition deforestation is not mainly linked to generating profit from produce, the influence of short-term market conditions on this behavior is minor.

In the ‘immediate’-causes category, among the most important factors are the scale of demand and prices of inputs and outputs. These factors determine the scale of supply and how producer agents choose to allocate the production factors land and inputs (fertilizer, labor, machinery, etc.). Another important factor is roads and other infrastructure, which determine the spatial extent where producing agents obtain an agricultural land rent above zero. In

relation to infrastructure, one possible causal link of ‘displacement’ nature between consolidated agricultural areas and frontier areas can be mentioned: High and increasing profitability in consolidated areas creates incentives to infrastructure improvements, which reduces transportation costs not only to the consolidated areas, but also to the frontier. This raises profitability in frontier areas and also extends the area where the agricultural land rent is positive deeper into the hitherto unexploited areas.

Returning to the issue of soybean expansion and its possible causal effect on pasture expansion in the deforestation frontier in the Amazon, another confounding factor in statistical analyses of correlation between these land use activities is that the scale of demand and supply for agricultural produce has increased significantly during the examined time periods. During 2000-2010, global supply of pasture-based produce, ruminant meat and milk, increased by on average 1.2 and 2.2 percent year⁻¹, respectively, whereas global soybean supply grew by about 5 percent year⁻¹ (FAOSTAT, 2012). In Brazil in 2000-2010, beef and milk supply increased by on average 6.1 and 5.7 percent year⁻¹, respectively, with the total cattle herd growing by 2 percent year⁻¹ (IBGE, 2010c; b). The growth trend in soybean was somewhat higher, increasing by on average 5 percent year⁻¹. The observed correlation between soybean and pasture expansion in the Amazon during this time period may, therefore, partly be due to the existence of two concomitant, but not causally linked, trends driven by growing regional and global scales of demand and supply.

5.3 Mapping and analyzing land use change in the Amazon

5.3.1 Overview

The Legal Amazon (Figure 5.1), is a socio-geographical region of Brazil that comprises 760 municipalities covering in total 503 Mha (60% of the Brazilian territory). The region includes entire the Brazilian Amazon biome and one third of the Brazilian Savannah (*Cerrado*) biome. The main land cover is native vegetation (77%), followed by pasture (16%) and agricultural crops (2%) (BRASIL, 2007). The Legal Amazon is relevant not only because the presence of the Amazonian rain forest, but also because during the period 2000-2009, 28% of the Brazilian cropland expansion and 76% of the cattle herd increase took place in this region (IBGE, 2010c).

Figure 5.1 - Location of Legal Amazon Region (LAR) within Brazil

5.3.2 Methodology and data

Land use and LUC in the Legal Amazon was analyzed using the same methodology as SPAROVEK, BARRETTO et al. (2009). More specifically, we identified the municipalities in the Legal Amazon that had the largest LUC dynamics in terms of cropland expansion, pasture expansion, and/or deforestation during the period 2000-2009, and then (i) compared LUC in these municipalities with LUC in their neighboring municipalities; and (ii) investigated to what extent the three LUC processes coincided at municipality level. The selected time period 2000-2009 was the longest time period possible since annual deforestation data is not available before year 2000 (INPE, 2010).

The spatial separation into ‘expansion’ and ‘adjacent’ regions is motivated by the hypothesis that iLUC might be more likely to occur in the periphery of an ‘expansion’ region, i.e. if a region experiences a large increase in cattle production or cropland area, the indirect effects of these changes might be greatest in neighboring, rather than distant, regions. The hypothesis of likely dominance of local spillover effects (“leakage”) following changes in

land-use has support in studies quantifying the effects of public protected areas on conservation and economy of the surrounding areas (BRUNER, GULLISON et al., 2001; ARMSWORTH, DAILY et al., 2006; MCDONALD, YUAN-FARRELL et al., 2007).

The methodology of this study consisted of three steps:

1) Calculation of proxy variables to characterize land use proportions and dynamics at municipality level. Three land-use types were studied: cropland (arable land), pasture and deforestation.

2) Identification of municipalities in the Legal Amazon that during 2000-2009 experienced significant growth of cropland, pastures or deforestation. For each land-use type, these ‘expansion’ municipalities were grouped, after which the municipalities neighboring to these were identified as ‘adjacent’. Hence, the outcome of this exercise was three ‘expansion’ regions (i.e. cropland ‘expansion’, pasture ‘expansion’ and deforestation ‘expansion’) paired with three ‘adjacent’ regions.

3) Statistical analysis of the mean values of the proxy variables for ‘expansion’ and ‘adjacent’ regions. (a) t-test for independent samples to compare ‘expansion’ vs ‘adjacent’ regions; (b) ANOVA to compare all three ‘expansion’ regions.

Each of the methodological steps above is described in more detail in the following sections.

5.3.2.1 Calculation of proxy variables

For each land-use type (deforestation, pasture and cropland), we calculated proxy variables to characterize land use proportions and dynamics (see Table 5.1). The variables were calculated at municipality level, using data from Brazilian Institute of Geography and Statistics (IBGE, 2010c) and from the Brazilian National Institute for Space Research (INPE, 2010). Municipalities that had their boundaries changed during 2000-2009 and data sequences with more than one missing value were removed from the analysis. These filters removed 49 (6%) municipalities out of a total of 761 in the Legal Amazon.

The major data issue that had to be dealt with was the insufficient data about land use. The most extensive agricultural land use in Brazil is pasture (native and planted), which covers roughly 20% of the Brazilian territory. Despite its magnitude, pasture coverage is not surveyed at an annual basis. The available information for pastures comes from the National Agrarian Census, with intervals of 5 or 10 years (the last two were conducted in 1996 and

2006, and covered an average of 37% of Brazilian total area), and from a national remote sensing survey executed only in 2002 (BRASIL, 2007). Similar data flaws apply also to forestry (eucalyptus and pines plantations) and native vegetation. Therefore, the total cattle herd size in the municipality was used as a proxy variable for pasture areas for the years in between the censuses. Cattle herd size is annually surveyed by IBGE based on expert opinions.

The combination of several surveys is usually adopted to compensate the lack of land use data. In this study, for instance, we combined i) agrarian census surveys, in which the primary data comes from interviews with landowners, ii) municipalities surveys, in which the data comes from municipality reports delivered by a local agents (IBGE, 2010a), and iii) remote sensing surveys conducted by research institutions. Merging data sources of diverging nature carries the risk of introducing (additional) inaccuracies to the combined data set. To minimize this risk for each land use type (i.e. native vegetation, pasture and crops) only one single source of information was used.

Table 5.1 - Definition, rationale and data sources of proxy variables used in the analysis. All variables refer to municipality level

Proxy variable	Land Use Represented	Description	Rationale	Unit	Primary source
C_{inc}	Cropland	Mean annual growth of annual crops harvested area. Calculated by linear regression using the least squares method.	Size of land use change	ha.y ⁻¹	PAM/IBGE
C_{tx}	Cropland	Mean annual growth rate of annual crops harvested area. Calculated by log-linear regression using the minimum square method.	Intensity of land use change	%. y ⁻¹	PAM/IBGE
C_{mean}	Cropland	Average of 2000-2009 annual crops area	Local and regional importance over the period.	ha	PAM/IBGE
P_{inc}	Pasture	Mean annual growth of cattle herd. Calculated by linear regression using the minimum squares method.	Size of cattle herd change	heads.y ⁻¹	PPM/IBGE
P_{tx}	Pasture	Mean annual growth rate of cattle herd. Calculated by log-linear regression using the minimum square method.	Intensity of cattle herd change	%. y ⁻¹	PPM/IBGE
P_{mean}	Pasture	Average of 2000-2009 cattle herd	Local regional importance over the period.	heads	PPM/IBGE
D_{inc}	Deforestation	Mean annual growth of deforested area. Calculated by linear regression using the minimum squares method.	Size of deforestation change	ha.y ⁻¹	PRODES/INPE
D_{tx}	Deforestation	Mean annual growth rate of deforested area. Calculated by log-linear regression using the minimum square method.	Intensity of deforestation change	%. y ⁻¹	PRODES/INPE

5.3.2.2 Grouping of municipalities into ‘expansion’ and ‘adjacent’ regions

The proxy variables mean annual growth of cropland, cattle herd and deforestation (i.e. C_{inc} , P_{inc} and D_{inc} , respectively) were used to identify the municipalities that experienced the highest rates of cropland and pasture expansion and deforestation between 2000 and 2009. To be included in an ‘expansion region’, the municipality required to be above the percentile 90 of the distribution of the before mentioned variables. This means that out of the total of 761 municipalities of the Legal Amazon, around 70 were selected for each ‘expansion’ region. With these ‘expansion’ municipalities grouped together, the municipalities

neighboring to these were identified as ‘adjacent’. These adjacent municipalities hence formed the ‘adjacent regions’. Table 5.2 summarizes the criteria used and the resulting group counts.

Other GIS-based studies similarly identified an area surrounding the area under study for the purpose of making comparisons (for a discussion see (MAS, 2005)). This approach is motivated by that potentially important factors not explicitly analyzed (e.g., climate, local socio-economy, policies) are likely more similar in areas close to each than when areas are far away from each other (TOBLER, 1970), hence there is less risk that differences in non-considered factors dominate over the ones analyzed.

Table 5.2 -Selection criteria and number of municipalities in ‘expansion’ and ‘adjacent’ regions

‘expansion’ regions	Variable used to select the ‘expansion’ municipalities	Threshold value (minimum value) for ‘expansion’ municipality (percentile 90)	Number of municipalities included in the ‘expansion’ region	Number of adjacent municipalities
Cropland	Mean annual growth of annual crops harvested area (C_{inc})	1,434 ($ha.y^{-1}$)	74	136
Pasture	Mean annual growth of cattle herd (P_{inc})	12,473 ($heads.y^{-1}$)	70	137
Deforestation	Mean annual growth of deforested area (D_{inc})	8,275 ($ha.y^{-1}$)	61	135

5.3.2.3 Statistical analysis of proxy variables in ‘expansion’ and ‘adjacent’ regions

The mean values for the calculated proxy variables listed in Table 5.1 were analyzed using two types of statistical tests to compare means as described below and shown in Figure 5.2:

- ‘Expansion’ regions compared to each of its region of ‘adjacent’ municipalities using a *t-test* for independent samples. The homogeneity of variances between groups was tested using Levene’s Test for Equality of Variance. In the cases where variances between groups were significantly heterogeneous, the *t-test* for "Unequal" variances was used.
- ‘Expansion’ regions compared with each other using one-way analysis of variance (ANOVA) followed by a *post-hoc* test to determine which specific region differed from each other. When the data met the assumption of homogeneity of variances, the

Tukey's (HSD) *post-hoc* test was used. If the data did not meet the homogeneity of variances assumption then the Games Howell *post-hoc* test was used.

Figure 2 - Schematic representation of which statistical test was performed to compare means of proxy variables: (a) *t*-test for independent samples, and (b) one-way analysis of variance (ANOVA)

The *t*-test is a commonly used method to quantify the statistical significance of a difference between two data samples' mean values (here, 'expansion' and 'adjacent' groups). The *p*-value obtained from a *t*-test represents the probability of error in rejecting the null hypothesis (i.e., no difference between the samples exists). However, when comparing groups like this, their variances should be relatively similar and Levene's test checks for this. The ANOVA test may be considered as being a generalization of the *t*-test when more than two groups (here, three 'expansion' regions) need to be compared.

Before running the statistical tests, the distributions of all variables were graphically inspected for normality and outliers using histograms. When non-normal (skewed or kurtotic) distributions were detected the data was log transformed. All statistical tests were run both on the original data set (i.e. outliers kept, original distribution) as well as on the manipulated data set (i.e. outliers removed, distribution transformed). However, in both cases the statistical analysis led to approximately the same significance values and the same conclusions. The results presented here are those based on the original, non-manipulated data set. Both the *t*-test for independent samples and ANOVA are considered robust against the normality and equality of variance assumptions when the sample sizes are relatively large ($n > 40$) (BONEAU, 1960). In this study, the samples were all above 60, which supports the validity of the statistical tests.

5.3.3 Presentation and discussion of results

5.3.3.1 Grouping of municipalities into ‘expansion’ and ‘adjacent’ regions

By choosing the top 10% municipalities in deforestation, cropland or pasture expansion, respectively, about 70 out of 760 municipalities were selected as belonging to one or several of the ‘expansion’ groups. These municipalities accounted for about 85% of cropland expansion, 53% of cattle herd increase and 50% of deforestation that occurred in the Legal Amazon during the studied period 2000–2009 (see bold numbers in Table 5.3). Hence, the ‘expansion’ groups may be considered as representative for each of the three land use dynamics. Note that the values of increase presented in Table 5.3 do not refer to net increase. The calculated increments considered only the municipalities that presented a positive change (i.e., value 2009 > value 2000).

Table 5.3 - Aggregated proxy variable data for municipalities identified as ‘expansion’ or ‘adjacent’ regions, or none of these. Percentages refer to fraction within each ‘expansion’ category

		Municipalities	Cattle herd increase 2000-2009		Cropland area increase 2000-2009		Deforestation 2000-2009	
Computed regions		Count	heads x 10 ⁶	%	ha x 10 ⁶	%	ha x 10 ⁶	%
Pasture	‘expansion’	70	14.6	53	0.2	4	8.5	42
	‘adjacent’	137	5.4	20	1.4	30	4.8	24
	Others	553	7.4	27	3.1	66	7.0	34
Cropland	‘expansion’	74	2.1	8	4.0	85	2.9	14
	‘adjacent’	136	6.2	23	0.3	6	3.4	17
	Others	550	19.0	70	0.5	10	14.0	69
Deforestation	‘expansion’	61	9.8	36	0.9	19	10.1	50
	‘adjacent’	135	6.0	22	1.8	38	5.1	25
	Others	564	11.6	42	2.0	42	5.1	25
Entire Legal Amazon		760	27.4		4.7		20.3	

The spatial outcome of the geographical grouping (Figure 5.3) reveals a pattern with clusters of ‘expansion’ regions, which in the case of cropland is more compact than for deforestation and pasture (cattle herd). The patterns in Figure 5.3 corroborate the well-known spatial separation of cropland expansion concentrated in the agriculturally consolidated regions, mainly in the South of the Legal Amazon, and pasture expansion dominating in the deforestation regions in the agricultural frontier zone. Thus as previous studies have shown (ALVES, MORTON et al., 2009; ESPINDOLA, AGUIAR et al., 2011), in the first decade of 2000, cropland expansion was concentrated to the agriculturally consolidated zone in the

South of the Legal Amazon while pasture expansion and deforestation mainly occurred in the agricultural frontier zone.

Figure 5.4 shows the overlap of different ‘expansion’ regions. One quarter (14 Mha) of Cropland ‘expansion’ region coincided to deforestation region (Figure 5.4c). There was also an overlap of pasture ‘expansion’ and deforestation regions, broadly aligned with the area in the Legal Amazon often referred to as the ‘arc of deforestation’ (Figure 5.4d). The size of this overlap area represents 15% of the Legal Amazon (78 Mha).

Figure 5.3 - Geographical outcome of municipality grouping: a) cropland ‘expansion’ and ‘adjacent’ regions, b) pasture ‘expansion’ and ‘adjacent’ regions and c) deforestation ‘expansion’ and ‘adjacent’ regions

Figure 5.4 - Municipalities that were included in two or more 'expansion' regions: a) Overlap between all three 'expansion' regions, b) Overlap between Pasture and Cropland 'expansion' regions, c) Overlap between Deforestation and Cropland 'expansion' regions, d) Overlap between Deforestation and pasture 'expansion' regions

5.3.3.2 Statistical analysis of proxy variables in ‘expansion’ and ‘adjacent’ regions

The mean values of proxy variables calculated for the cropland, pasture and deforestation ‘expansion’ regions and respectively adjacent municipalities are presented in Table 5.4.

Table 5.4 - Estimated numbers and statistical significance of the mean values of the proxy variables characterizing ‘expansion’ and ‘adjacent’ regions. ‘Expansion’ groups with homogeneous means are displayed with the same letter (for alpha = 0.05, ANOVA *post hoc* Tukey HSD test)

Proxy variable	Unit	Regions	Comparison of ‘expansion’ regions using ANOVA	Mean value	Significance (t-test) of ‘expansion’ vs ‘adjacent’ mean values	
Average of 2000-2009 annual crops area C_{mean}	ha	Cropland	<i>expansion</i>	a	90,795	.000
			<i>adjacent</i>		8,370	
		Pasture	<i>expansion</i>	b	10,261	.086
			<i>adjacent</i>		18,356	
		Deforestation	<i>expansion</i>	b	19,879	.468
			<i>adjacent</i>		28,849	
Mean annual growth rate of annual crops harvested area C_{tx}	% .y ⁻¹	Cropland	<i>expansion</i>	a	15.8	.000
			<i>adjacent</i>		4.0	
		Pasture	<i>expansion</i>	b	-1.6	.061
			<i>adjacent</i>		1.3	
		Deforestation	<i>expansion</i>	b	2.2	.938
			<i>adjacent</i>		2.3	
Average of 2000-2009 cattle herd P_{mean}	Heads	Cropland	<i>expansion</i>	a	136,317	.619
			<i>adjacent</i>		126,036	
		Pasture	<i>expansion</i>	b	314,882	.000
			<i>adjacent</i>		130,200	
		Deforestation	<i>expansion</i>	c	228,370	.000
			<i>adjacent</i>		103,617	
Mean annual growth rate of cattle herd P_{tx}	% . y ⁻¹	Cropland	<i>expansion</i>	a	2.5	.003
			<i>adjacent</i>		4.6	
		Pasture	<i>expansion</i>	b	12.0	.000
			<i>adjacent</i>		5.0	
		Deforestation	<i>expansion</i>	b	9.6	.031
			<i>adjacent</i>		6.6	
Mean annual growth rate of deforested area. D_{tx}	% . y ⁻¹	Cropland	<i>expansion</i>	a	3.5	.301
			<i>adjacent</i>		2.8	
		Pasture	<i>expansion</i>	a	4.9	.001
			<i>adjacent</i>		3.1	
		Deforestation	<i>expansion</i>	b	12.2	.006
			<i>adjacent</i>		6.7	

As expected, the mean values for cropland acreage and cropland acreage increase were significantly higher in the cropland ‘expansion’ region than in the ‘adjacent’ region. These high mean values also differed from the deforestation and pasture ‘expansion’ regions as revealed by the ANOVA test (Table 5.4). The distinctness of the cropland ‘expansion’ municipalities in terms of variables representing ‘crops’ confirms the effectiveness in singling out the municipalities in which crop production is a core land-use dynamic.

For deforestation, the differences between the cropland ‘expansion’ region and its ‘adjacent’ region were not statistically significant. The difference in average deforestation rate in the cropland ‘expansion’ municipalities (3.5 percent year-1) and the pasture ‘expansion’ municipalities (4.9 percent year-1) was not statistically significant. Thus, at the municipal level, cropland expansion and cattle herd growth seems to be more or less equally associated with deforestation.

Both the average cattle herd size and growth rate were substantial in the cropland ‘expansion’ municipalities, but still smaller than in the pasture ‘expansion’ and deforestation regions. For the cattle herd size, there was no statistical difference between the cropland ‘expansion’ and its ‘adjacent’ region, but the cattle herd *growth rate* was indeed statistically higher in the ‘adjacent’ region (4.6 percent year-1 compared to 2.5 percent year-1). Thus, cattle production is significant in both cropland ‘expansion’ municipalities and their ‘adjacent’ municipalities, but it appears that cropland expansion holds back the expansion of cattle production in the municipality, possibly thereby inducing higher growth in the ‘adjacent’ regions, which have lower cropland expansion rates.

Naturally, given the overlap of deforestation and pasture ‘expansion’ regions, the deforestation region experienced higher cattle herd growth than its ‘adjacent’ region and the average cattle herd size was twice as large. Likewise, the pasture ‘expansion’ region had higher deforestation rates than its ‘adjacent’ region. Also, there are no statistically significant differences between the deforestation and pasture ‘expansion’ regions concerning cattle herd size growth and cropland area and growth.

5.3.3.3 Patterns of agricultural expansion and deforestation at municipality levels

The spatially explicit analysis revealed patterns that would not be easily observed if only standard statistical analysis were applied. The selection and mapping of municipalities

with intense land-use change revealed *per se* (i) the spatial coincidence of deforestation and pasture ‘expansion’ regions, and (ii) the concentration of cropland expansion to a few compact clusters in the south and southeast of the Legal Amazon. The latter pattern supports the notion of crop production as an activity that replaces other land uses in consolidated agriculture areas where both infrastructure and biophysical factors are favorable for crop production. The spatial separation of municipalities into ‘expansion’ and ‘adjacent’ with subsequent comparison of mean values revealed that also the municipalities with the highest cropland expansion rates had large and increasing cattle herds, resulting in an average herd size no statistically different from that in neighboring municipalities. Furthermore, deforestation rates were equally large in the cropland ‘expansion’ region as in neighboring municipalities and similar as in the region with the greatest pasture expansion.

The interdependence between deforestation and pasture expansion in the Legal Amazon has been supported by various studies using remote-sensing techniques (ESPINDOLA, AGUIAR et al., 2011; LEITE, COSTA et al., 2011; YOSHIKAWA and SANGA-NGOIE, 2011), and also economic modeling (MARGULIS, 2004; NEPSTAD, SOARES et al., 2009; BOWMAN, SOARES-FILHO et al., 2012). Moreover, the effect of crop production driving up land rents and forming clusters replacing less profitable activities (i.e. extensive cattle ranching) in consolidated areas, is in line with the economic theory on land use (VON THUNEN, 1826) that land is allocated to the use that gives the best rent.

Previous studies have pointed to the richness of land-use changes in the Legal Amazon. MORTON, DEFRIES et al. (2006) estimated that 2.3 and 1.1 Mha of native vegetation in Mato Grosso state was converted directly to pastures (53% of total conversion) and croplands (23%), respectively, during 2001-2004. During the same period, 0.4 Mha of forest was converted to fallow land and 0.6 Mha of pasture land was converted to cropland. MACEDO, DEFRIES et al. (2012) estimated that 22% soybean production increase in MatoGrosso in the late 2000s was due to intensification. ARVOR, MARGARETH et al. (2012) showed that crop intensification by double cropping systems evolved rapidly in the Legal Amazon 2000-2007 and direct conversion of forests to cropland had a minor role in the deforestation in this period.

The municipal level results - simultaneous high growth rates of deforestation, cropland area and cattle herd size - can be explained by several rearrangements or LUC patterns within the municipalities, including the conversion of native vegetation to either pastures or to cropland, cropland establishment on pastures, intensification of cattle production, cattle and

crop rotation, transition from fallow lands to native vegetation, use of less productive croplands for cattle grazing. It should be kept in mind that the 760 municipalities in the Legal Amazon are large: the average size is 659,000 ha, or 759,000 ha if considering only the 382 municipalities characterized as either ‘expansion’ or ‘adjacent’ municipality in the analysis presented above. Thus, several LUC pathways can occur simultaneously in the same municipality, even if one is predominant. Deeper insights into LUC dynamics in the Legal Amazon - including iLUC - therefore require analyses using sub-municipality scale databases/statistics or spatially explicit methodologies based on remote-sensing mapping, encompassing not only one single state (such as many of the studies cited above) but the entire region.

5.4 Conclusions

In the first decade of 2000, both cropland area and deforestation grew rapidly in the Legal Amazon and there was a correlation between cropland expansion, occurring mainly in the consolidated agriculture region in the south of the Legal Amazon, and growth of cattle herds and deforestation in the agricultural frontier zone. At the same time, cattle herds also grew substantially (although less) in the municipalities dominated by cropland expansion and there was no statistically significant evidence that deforestation rates were lower in cropland expansion municipalities than in the adjacent municipalities.

Statistical analyses of the correlation between cropland expansion and deforestation are confounded by the fact that regional and global demand for major agricultural produce (e.g. beef, soybean, sugarcane) grew considerably during the examined time period. The observed correlation between cropland and pasture expansion in the Amazon during the time period may therefore, to a large extent, be due to the existence of two concomitant, but not causally linked, trends driven by growing regional and global demand. In addition, it is also possible that speculative land-acquisition deforestation, which is relatively unaffected by short-term agricultural market trends, has been a major factor behind deforestation.

Given the complexity of agriculture land use in the Legal Amazon with possible existence of several concomitant, but relatively independent, causal factors of deforestation, it is not possible to quantify to what extent cropland expansion in the consolidated agriculture region has induced deforestation in the frontier. Following on that, it will likely be difficult to evaluate the effectiveness of measures intending to address LUC impacts in frontier regions

based on regulating agricultural land use in distant consolidated agricultural regions (e.g., using iLUC factors to discourage cultivation of certain biofuel crops, or investing in yield-enhancing technologies to reduce the land demand).

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APPENDICES

APPENDIX A

The APPENDIX A is divided into 2 sections:

- A.S1 - Climate database improvements
- A.S2 – Temperature Index (TI) calculation

A.S1 Climate database improvements

Brazil does not have a particular national climate database with enough spatial and temporal coverage for land suitability assessments that requires monthly: Temperature (max, min, mean), Precipitation (total) and Radiation information. As a result, the database used in this article was combined from different sources, adding national and regional data. Moreover, 8 linear regression equations reviewed from the literature were applied regionally to a national precipitation database of 2,676 stations in order to provide temperature information based on Latitude, Longitude, and Altitude. This procedure increased the number of climate data points and filled important geographic gaps, as illustrated by Figure A.2. To be included, a station had to have a minimum of 10 years data observations. Table A.1 summarizes the climate database improvements, Figure A.1 references geographically the equations used, Table A.2 list the equations for each region.

Table A.1 - Sources of climate information, variables used and improvements made

Original Source	Scale (Spatial/Temporal)	Stations	Variables ^a	Improvements
FAOCLIM 2 World-wide Agroclimatic Database/FAO/ < http://www.fao.org/nr/climpag/pub/en1102_en.asp >	National/Monthly data (1961-1990)	1,402	P, T	No improvements
HIDROWEB Hydrologic Information System/ANA/< http://hidroweb.ana.gov.br >	National/Daily (1985-present)	2,676	P	Filter of duplicate points, and inconsistent data, Linear regressions
Atlas Solarimétrico do Brasil (TIBA, FRAIDENRAICH et al., 2000)	National/Monthly (1977-1997)	132	R	Digitalization and Spatial interpolation

^aP = Precipitation, T=Temperature, R=Radiation

Zone	Stations	Num. Years	Min Lat	Max Lat	Min Long	Max Long	Reference
Z1	36	50	28	34	48	58	(FERREIRA, BURIOL et al., 1971)
Z2	15	30	25	28	47.67	54.8	(FERREIRA, BURIOL et al., 1974)
Z3	57	>10	20	25	48	61	(OLIVEIRA-NETO, REIS et al., 2002)
Z4	57	>10	15	20	48	60	(OLIVEIRA-NETO, REIS et al., 2002)
Z5	50	>10	15	25	42	48	(COELHO, SEDIYAMA et al., 1973)
Z6	39	30	15	23.25	38	42	(FEITOZA, SCARDUA et al., 1979)
Z7	74	>10	0.5	15	34	46	(MEDEIROS, CECÍLIO et al., 2005)
Z8	15	>10	5.33	15	46	74	(FERREIRA, VALLADARES et al., 2006)

Figure A.1 - References for linear regressions used to estimate monthly and annual mean air temperatures

Table A.2 - Equations used to estimate monthly and annual mean air temperatures for zones 1 to 8
(to continue)

	Zone 1	Zone 2
	(lat/long (minutes), alt (meters))	(lat/long (minutes), alt (meters))
Jan	$y=44.11-0.010443*\text{lat}-0.006673*\text{alt}$	$y=14.23+0.003549*\text{long}-0.005266*\text{alt}$
Feb	$y=42.46-0.009752*\text{lat}-0.006492*\text{alt}$	$y=17.24+0.002449*\text{long}-0.0052*\text{alt}$
Mar	$y=41.8-0.010305*\text{lat}-0.006062*\text{alt}$	$y=24.28-0.000205*\text{long}-0.005278*\text{alt}$
Apr	$y=34.8-0.008464*\text{lat}-0.00497*\text{alt}$	$y=33.93-0.005234*\text{long}-0.005234*\text{alt}$
May	$y=31.85-0.00854*\text{lat}-0.004462*\text{alt}$	$y=34.38-0.005368*\text{long}-0.005379*\text{alt}$
Jun	$y=34.32-0.011195*\text{lat}-0.004066*\text{alt}$	$y=29.49-0.00427*\text{long}-0.005322*\text{alt}$
Jul	$y=32.65-0.010495*\text{lat}-0.003864*\text{alt}$	$y=32.04-0.005482*\text{long}-0.004816*\text{alt}$
Aug	$y=40.29-0.014063*\text{lat}-0.004248*\text{alt}$	$y=22.78-0.002088*\text{long}-0.004338*\text{alt}$
Sep	$y=45.06-0.015784*\text{lat}-0.004725*\text{alt}$	$y=14.94+0.001034*\text{long}-0.004449*\text{alt}$
Oct	$y=47.06-0.015651*\text{lat}-0.005501*\text{alt}$	$y=11.29+0.004708*\text{long}-0.004708*\text{alt}$
Nov	$y=48.52-0.014888*\text{lat}-0.006176*\text{alt}$	$y=5.69+0.005342*\text{long}-0.004799*\text{alt}$
Dec	$y=46.16-0.012304*\text{lat}-0.006311*\text{alt}$	$y=6.7+0.005644*\text{long}-0.005057*\text{alt}$
Annual	$y=40.46-0.011661*\text{lat}-0.005246*\text{alt}$	$y=20.6-0.000087*\text{long}-0.004989*\text{alt}$

Table A.2 - Equations used to estimate monthly and annual mean air temperatures for zones 1 to 8

(to continue)

	Zone 3 (lat/long (degrees), alt (meters), tx (binary variable =1 see: OLIVEIRA-NETO, REIS et al. (2002))	Zone 4 (lat/long (degree), alt (meters))
Jan	$y=26.506461-0.000005*alt^2-1.265956*(tx)$	$y=26.506461-0.000005*alt^2$
Feb	$y=26.506461-0.000005*alt^2-1.265956*(tx)$	$y=26.506461-0.000005*alt^2$
Mar	$y=26.506461-0.000005*alt^2-1.265956*(tx)$	$y=26.506461-0.000005*alt^2$
Apr	$y=34.664048-0.513316*lat-0.000005*alt^2$	$y=34.664048-0.513316*lat-0.000005*alt^2$
May	$y=36.156325-0.644805*lat-0.005172*alt$	$y=36.156325-0.644805*lat-0.005172*alt$
Jun	$y=33.822532-0.680707*lat-0.000004*alt^2$	$y=33.822532-0.680707*lat-0.000004*alt^2$
Jul	$y=33.822532-0.680707*lat-0.000004*alt^2$	$y=33.822532-0.680707*lat-0.000004*alt^2$
Aug	$y=38.260611-0.871328*lat+0.003221*alt-0.000006*alt^2+0.7222*(tx)$	$y=38.260611-0.871328*lat+0.003221*alt-0.000006*alt^2$
Sep	$y=41.940204-0.908572*lat-0.004171*alt+1.044569*(tx)$	$y=41.940204-0.908572*lat-0.004171*alt$
Oct	$y=38.074965-0.652347*lat-0.000005*alt^2+0.057348*(tx)$	$y=38.074965-0.652347*lat-0.000005*alt^2$
Nov	$y=26.811993-0.000005*alt^2-2.289133*(tx)$	$y=26.811993-0.000005*alt^2$
Dec	$y=19.902931+0.126868*long-0.000005*alt^2-1.509252*(tx)$	$y=19.902931+0.126868*long-0.000005*alt^2$
Annual	$y=33.479962-0.473747*lat-0.000005*alt^2$	$y=33.479962-0.473747*lat-0.000005*alt^2$

Table A.2 - Equations used to estimate monthly and annual mean air temperatures for zones 1 to 8

(to continue)

	Zone 5 (lat/long (degrees), alt (meters))	Zone 6 (lat/long (minutes), alt (meters))
Jan	$y=25.4922-0.186151*lat+0.112997*long-0.00560437*alt$	$y=27.4163-0.0018177*lat+0.00054168*long-0.0058556*alt$
Feb	$y=26.5073-0.18557*lat+0.0914547*long-0.0055381*alt$	$y=27.5197-0.0006285*lat-0.00005155*long-0.0059595*alt$
Mar	$y=24.5729-0.262232*lat+0.156385*long-0.00544252*alt$	$y=28.224-0.00173932*lat-0.00006055*long-0.00589032*alt$
Apr	$y=23.8086-0.46015*lat+0.221168*long-0.00509255*alt$	$y=28.371-0.00347634*lat-0.00000128*long-0.00579838*alt$
May	$y=22.8704-0.552452*lat+0.22967*long-0.0046566*alt$	$y=28.9292-0.00309112*lat-0.00124306*long-0.00574797*alt$
Jun	$y=22.6165-0.63349*lat+0.218271*long-0.00480673*alt$	$y=25.3831-0.00353616*lat-0.00012449*long-0.00598387*alt$
Jul	$y=19.1005-0.641427*lat+0.320528*long-0.00509414*alt$	$y=23.3989-0.00335117*lat+0.000376175*long-0.00617636*alt$
Aug	$y=12.5133-0.628241*lat+0.493722*long-0.0049308*alt$	$y=19.1678-0.00332503*lat+0.002464*long-0.00623187*alt$
Sep	$y=15.1033-0.688942*lat+0.510375*long-0.00513752*alt$	$y=22.6133-0.00567717*lat+0.0028432*long-0.00592896*alt$
Oct	$y=18.8003-0.624257*lat+0.431918*long-0.00550874*alt$	$y=26.4312-0.00845717*lat+0.00322588*long-0.00590571*alt$
Nov	$y=19.9533-0.392559*lat+0.307999*long-0.00544291*alt$	$y=27.5998-0.00787031*lat+0.00277384*long-0.00600977*alt$
Dec	$y=22.8347-0.247034*lat+0.184212*long-0.00546014$	$y=27.0979-0.00482634*lat+0.00177331*long-0.00599963*alt$
Annual	$y=21.1083-0.46368*lat+0.278922*long-0.00522254*alt$	$y=26.3272-0.00399483*lat+0.00092305*long-0.0059453*alt$

Table A.2 - Equations used to estimate monthly and annual mean air temperatures for zones 1 to 8

(conclusion)

	Zone 7 (lat/long (degrees), alt (meters))	Zone 8 (lat/long (degrees), alt (meters))
Jan	$y = -25.9924 - 0.00513 * \text{lat}^2 - 2.67684 * \text{long} - 0.03354 * \text{long}^2 - 0.000006 * \text{alt}^2$	$y = 26.3565 + 0.0489 * \text{lat} - 0.0004 * \text{long} - 0.0064 * \text{alt}$
Feb	$y = 26.34049 - 0.000006 * \text{alt}^2$	$y = 22.9491 + 0.0081 * \text{lat} - 0.0534 * \text{long} - 0.0055 * \text{alt}$
Mar	$y = 26.32828 - 0.000006 * \text{alt}^2$	$y = 24.2764 - 0.0462 * \text{lat} - 0.0308 * \text{long} - 0.006 * \text{alt}$
Apr	$y = 33.81864 + 2.04365 * \text{lat} - 0.00392 * \text{long}^2 - 0.00589 * \text{alt} + 0.04897 * \text{lat} * \text{long}$	$y = 26.6495 - 0.0437 * \text{lat} + 0.0082 * \text{long} - 0.0063 * \text{alt}$
May	$y = 24.51485 - 0.03856 * \text{lat} - 0.0062 * \text{alt} + 0.01487 * \text{lat} * \text{long}$	$y = 25.9785 - 0.0934 * \text{lat} - 0.0034 * \text{long} - 0.0065 * \text{alt}$
Jun	$y = 24.46099 - 0.0391 * \text{lat}^2 - 0.00673 * \text{alt} + 0.01339 * \text{lat} * \text{long}$	$y = 25.679 - 0.0203 * \text{lat} - 0.0126 * \text{long} - 0.0071 * \text{alt}$
Jul	$y = 27.7085 + 1.4875 * \text{lat} - 0.0064 * \text{alt} + 0.02993 * \text{lat} * \text{long}$	$y = 24.9309 - 0.0087 * \text{lat} - 0.0271 * \text{long} - 0.0073 * \text{alt}$
Aug	$y = 36.16463 + 4.08316 * \text{lat} - 0.00459 * \text{long}^2 + 0.00017 * \text{alt} * \text{lat} + 0.09392 * \text{lat} * \text{long}$	$y = 21.1802 + 0.004 * \text{lat} - 0.1115 * \text{long} - 0.0059 * \text{alt}$
Sep	$y = 40.52614 + 4.83384 * \text{lat} - 0.00667 * \text{long}^2 - 0.00696 * \text{alt} + 0.11274 * \text{lat} * \text{long}$	$y = 22.4018 - 0.0368 * \text{lat} - 0.0915 * \text{long} - 0.0077 * \text{alt}$
Oct	$y = -54.51334 - 0.01407 * \text{lat}^2 - 3.87154 * \text{long} - 0.04503 * \text{long}^2 - 0.000006 * \text{alt}^2$	$y = 21.9537 + 0.0913 * \text{lat} - 0.1114 * \text{long} - 0.0069 * \text{alt}$
Nov	$y = -68.59439 - 0.01385 * \text{lat}^2 - 4.68628 * \text{long} - 0.05634 * \text{long}^2 - 0.000006 * \text{alt}^2$	$y = 22.4456 + 0.0856 * \text{lat} - 0.0942 * \text{long} - 0.0055 * \text{alt}$
Dec	$y = -50.90658 - 0.00996 * \text{lat}^2 - 3.86843 * \text{long} - 0.04736 * \text{long}^2 - 0.000006 * \text{alt}^2$	$y = 25.029 + 0.1328 * \text{lat} - 0.0414 * \text{long} - 0.0061 * \text{alt}$
Annual	$y = 32.45762 + 1.87032 * \text{lat} - 0.00297 * \text{long}^2 - 0.000006 * \text{alt}^2 + 0.04181 * \text{lat} * \text{long}$

Figure A.2 - Spatial distribution of FAOCLIM 2 Agroclimatic database, HIDROWEB/ANA precipitation database and the combined database after the regression analysis and removal of duplicate points. Panels (a) and (b) show Voronoi diagrams generated from the climate station's geographic coordinates and used for spatial interpolation of climate data.

A.S2 Temperature Index (TI) calculation

In addition to the water and radiation constraints on crop development, measured respectively by Radiation Index (RI) and Water Index (WI), climate suitability analysis also included an index that intended to estimate temperature constraint on plant growth. The rationale behind the Temperature Index (TI) is that: each crop has an optimal temperature range for carbon accumulation as a result of photosynthesis and respiration balance; below or above that range, plant development can be restricted.

Specialized literature was reviewed to collect annual mean temperature ranges for the main crops cultivated in Brazil. Then, an exponential trend line was used to match the reviewed data and Boolean operators to trim the curve above and below maximum and minimum temperatures. References and the applied equation are summarized on Table B.1.

Table B.1 - Temperature Index (TI) model and parameters references

Crop	Unsuitable	Suitable	Unsuitable	Reference
Beans	$Ta^a < 18^{\circ}\text{C}$	$Ta = 21^{\circ}\text{C}$	$Ta > 30^{\circ}\text{C}$	(CAMARGO, PINTO et al., 1980)
Soybean	$Ta < 10^{\circ}\text{C}$	$22^{\circ}\text{C} < Ta < 33^{\circ}\text{C}$	$Ta > 35^{\circ}\text{C}$	(CAMARGO, PINTO et al., 1980)
Rice	-	$20^{\circ}\text{C} < Ta < 25^{\circ}\text{C}$	-	(CAMARGO, PINTO et al., 1980)
Corn	$Ta < 15.5^{\circ}\text{C}$	$25^{\circ}\text{C} < Ta < 30^{\circ}\text{C}$	$Ta > 35^{\circ}\text{C}$	(FANCELLI e DOURADO NETO, 2000)
TI (%)	if $(Ta < 14)$ value = 0.1 else if $(Ta \leq 29)$ value = $(- (1.5858 * Ta^2) + (68.187 * Ta) - (633.58))$ else value = 0.1 end if			

^aTa = Annual mean temperature

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APPENDIX B

The APPENDIX B is divided into 3 sections:

- B.S1 - A summary of aggregate land use, crop production and livestock census data from 1960 to 2006 along the five Brazilian administrative boundaries.
- B.S2 – Cropland area change vs. yield change and pasture area change vs. stocking rate change from 1975 to 1996 and 1996 to 2005 along the five Brazilian administrative boundaries.
- B.S3 – Regression analysis summary output

B.S1 - A summary of aggregate land use, crop production and livestock census data from 1960 to 2006 along the five Brazilian administrative boundaries.

Table B.S1.1 - Aggregate land use census data from 1960 to 2006 along the five Brazilian administrative boundaries

	Perennial crops	Annual crops*	Native pastures	Cultivated pastures	Forestry plantations	Farmland (subtotal) †	Native vegetation	Total‡
	Mha							
1960								
North	0.1	0.4	7.8	0.3	0.1	8.7	19.1	32.8
Northeast	2.3	6.4	18.0	4.0	0.6	31.3	14.8	62.9
Southeast	3.2	6.5	28.6	9.5	0.7	48.5	7.0	65.9
South	1.9	6.2	16.9	1.4	0.5	26.9	6.6	38.6
Centerwest	0.2	1.1	31.3	4.8	0.2	37.4	8.1	50.6
Brazil	7.6	20.7	102.5	19.9	2.1	152.8	55.6	250.8
1970								
North	0.1	0.5	3.8	0.6	0.0	5.1	13.9	23.2
Northeast	4.0	6.3	22.1	5.8	0.1	38.3	16.4	74.3
Southeast	2.2	7.4	34.1	10.6	0.9	55.2	6.7	69.5
South	1.6	9.5	18.0	3.6	0.6	33.2	5.7	45.5
Centerwest	0.1	2.3	46.4	9.1	0.0	57.9	13.6	81.7
Brazil	8.0	26.0	124.4	29.7	1.7	189.8	56.2	294.1
1975								
North	0.2	1.0	3.7	1.6	0.1	6.6	21.5	32.6
Northeast	4.0	7.1	23.8	6.8	0.0	41.7	17.5	78.7
Southeast	2.6	7.8	35.7	11.6	1.6	59.3	6.5	72.5
South	1.4	11.6	16.7	4.4	0.9	35.1	5.0	46.2
Centerwest	0.2	4.2	46.0	15.3	0.2	65.9	17.4	94.0
Brazil	8.4	31.6	126.0	39.7	2.9	208.5	67.9	323.9
1996								
North	0.7	1.2	9.6	14.8	0.3	26.6	25.5	58.4
Northeast	2.6	7.7	20.0	12.1	0.4	42.8	19.4	78.3
Southeast	3.3	7.3	17.3	20.5	2.5	50.9	7.7	64.1
South	0.6	11.7	13.7	7.0	1.9	34.9	5.3	44.4
Centerwest	0.2	6.3	17.4	45.3	0.3	69.7	31.0	108.5
Brazil	7.5	34.3	78.0	99.7	5.4	224.9	88.9	353.6
2006								
North	1.9	2.3	5.9	20.6	0.3	31.0	22.0	54.8
Northeast	3.5	11.7	16.0	14.5	0.4	46.1	25.4	75.6
Southeast	4.0	9.1	10.9	16.7	1.5	42.3	9.6	54.2
South	1.5	13.6	10.8	4.8	2.0	32.7	6.7	41.5
Centerwest	0.7	11.5	13.7	44.8	0.3	71.0	30.2	103.8
Brazil	11.6	48.2	57.3	101.4	4.5	223.1	94.0	329.9

Source: Brazilian Institute of Geography and Statistics, Agrarian Census. Available at:

<<http://www.sidraibge.gov.br>>

* Category "annual crops" includes idle lands; † farmland considered as the sum of previous categories; ‡ Total area includes degraded and unexploitable land, such as wetlands, water bodies or salinized areas

Table - B.S1.2 Area and production of soybeans, corn, sugarcane, beans, rice, and cassava in 1975, 1996 and 2006 along the five Brazilian administrative boundaries, aggregate data

	Soybean			Corn			Sugarcane			Beans			Rice			Cassava			Wheat		
	ha	t	t.ha ⁻¹	ha	t	t.ha ⁻¹	ha	t	t.ha ⁻¹	ha	t	t.ha ⁻¹	ha	t	t.ha ⁻¹	ha	t	t.ha ⁻¹	ha	t	t.ha ⁻¹
1975																					
North	80	96	1.2	115,640	125,290	1.1	25,070	675,957	27.0	25,894	19,548	0.8	234,687	272,109	1.2	149,667	1,784,143	11.9	-	-	-
Northeast	19	34	1.8	2,199,385	1,512,045	0.7	812,851	37,306,666	45.9	1,681,239	868,469	0.5	865,791	1,125,279	1.3	1,055,120	11,917,629	11.3	-	-	-
Southeast	224,498	366,745	1.6	3,107,268	4,918,325	1.6	1,189,330	57,228,041	48.1	840,478	481,119	0.6	1,430,262	1,641,624	1.1	290,747	4,087,416	14.1	28,758	34,864	1.2
South	3,244,582	4,451,908	1.4	3,944,456	6,743,680	1.7	147,305	5,650,369	38.4	1,066,245	742,317	0.7	995,457	2,317,382	2.3	526,495	7,410,600	14.1	1,786,454	1,983,520	1.1
Centerwest	145,879	192,831	1.3	556,719	886,427	1.6	34,633	1,540,632	44.5	201,596	120,580	0.6	1,268,635	1,803,733	1.4	81,072	1,318,767	16.3	24,179	12,954	0.5
Brazil	3,615,058	5,011,614	1.4	9,923,468	14,185,767	1.4	2,209,189	102,401,665	46.4	3,815,452	2,232,033	0.6	4,794,832	7,160,127	1.5	2,103,101	26,518,555	12.6	1,839,391	2,031,338	1.1
1996																					
North	24,617	47,271	1.9	610,882	948,781	1.6	14,131	724,865	51.3	233,644	145,395	0.6	604,516	1,125,430	1.9	389,948	5,425,464	13.9	-	-	-
Northeast	571,085	1,255,571	2.2	3,053,294	2,437,783	0.8	1,246,516	60,658,799	48.7	2,653,943	1,028,799	0.4	1,225,922	1,732,323	1.4	1,043,081	10,946,619	10.5	-	-	-
Southeast	1,130,655	2,385,166	2.1	2,829,571	8,069,674	2.9	2,728,496	201,051,837	73.7	811,159	620,254	0.8	526,793	990,563	1.9	145,018	2,339,447	16.1	26,902	49,489	1.8
South	5,416,792	11,986,519	2.2	5,638,962	18,575,039	3.3	291,429	21,687,348	74.4	1,098,978	963,222	0.9	1,242,294	5,954,577	4.8	295,785	5,519,011	18.7	942,503	1,457,089	1.5
Centerwest	4,531,856	10,008,110	2.2	1,813,611	6,235,674	3.4	278,490	19,576,648	70.3	208,679	188,498	0.9	774,013	1,423,171	1.8	72,331	1,192,418	16.5	25,329	27,293	1.1
Brazil	11,675,005	25,682,637	2.2	13,946,320	36,266,951	2.6	4,559,062	303,699,497	66.6	5,006,403	2,946,168	0.6	4,373,538	11,226,064	2.6	1,946,163	25,422,959	13.1	994,734	1,533,871	1.5
2006																					
North	504,238	1,252,818	2.5	546,499	1,101,404	2.0	20,957	1,286,641	61.4	173,488	125,734	0.7	464,045	968,937	2.1	489,360	7,304,624	14.9	-	-	-
Northeast	1,359,445	3,175,006	2.3	2,706,623	3,110,361	1.1	1,104,746	62,221,370	56.3	2,170,855	1,038,110	0.5	715,317	1,112,214	1.6	883,114	9,610,381	10.9	-	-	-
Southeast	1,664,113	4,107,259	2.5	2,326,621	9,641,679	4.1	4,144,955	332,733,858	80.3	627,919	797,274	1.3	116,333	277,793	2.4	136,138	2,490,505	18.3	61,844	161,241	2.6
South	7,870,070	17,173,211	2.2	4,498,732	18,411,586	4.1	482,429	35,719,055	74.0	835,841	1,097,703	1.3	1,225,300	7,951,977	6.5	290,636	5,718,424	19.7	1,393,937	2,137,042	1.5
Centerwest	9,739,109	24,555,481	2.5	2,379,970	9,802,044	4.1	584,013	44,330,117	75.9	215,872	384,485	1.8	405,666	1,062,215	2.6	90,159	1,419,354	15.7	62,217	118,321	1.9
Brazil	21,136,975	50,263,775	2.4	12,458,445	42,067,074	3.4	6,337,100	476,291,041	75.2	4,023,975	3,443,306	0.9	2,926,661	11,373,136	3.9	1,889,407	26,543,288	14.0	1,517,998	2,416,604	1.6

Source: Institute for Applied Economic Research. Available at: <<http://www.ipeadata.gov.br>>

Table B.S1.3 - Pasture area and livestock population in 1975, 1996, and 2006 along the five Brazilian administrative boundaries

	Bovine	Equine	<i>Equus asinus</i>	<i>Equus mulus</i>	Sheep	Goat	Buffalo	Animal Units	Pasture	Stocking Rate
	heads				AU				ha	AU.ha ⁻¹
1975										
North	2,129,609	131,485	3,103	20,406	72,479	28,264	80,770	2,406,747	5,281,440	0.46
Northeast	18,041,417	1,342,653	1,184,248	617,054	5,353,867	6,172,419	21,521	23,648,568	30,624,044	0.77
Southeast	35,236,666	1,297,958	23,402	505,825	257,312	160,852	29,904	37,310,174	47,276,785	0.79
South	21,516,021	1,211,133	2,606	170,544	11,644,561	278,830	17,932	25,425,821	21,159,758	1.20
Centerwest	24,750,040	757,235	15,295	105,860	158,340	69,063	58,950	25,814,479	61,310,221	0.42
Brazil	101,673,753	4,740,464	1,228,654	1,419,689	17,486,559	6,709,428	209,077	114,605,789	165,652,250	0.69
1996										
North	17,276,621	506,904	31,911	129,407	323,636	83,957	498,484	18,625,384	24,386,621	0.76
Northeast	22,841,728	1,368,012	1,021,384	531,375	6,717,980	6,176,457	80,997	28,567,284	32,076,339	0.89
Southeast	35,953,897	1,551,653	35,266	221,114	434,054	120,754	61,545	38,095,756	37,777,049	1.01
South	26,219,533	1,114,556	5,420	68,119	5,858,833	151,296	136,391	28,871,140	20,696,549	1.39
Centerwest	50,766,496	1,024,572	11,815	127,253	620,052	58,182	57,505	52,231,496	62,763,912	0.83
Brazil	153,058,275	5,565,697	1,105,796	1,077,268	13,954,555	6,590,646	834,922	166,391,060	177,700,472	0.94
2006										
North	31,336,290	651,820	23,460	141,094	481,462	139,748	600,559	33,002,703	26,524,174	1.24
Northeast	25,326,270	1,172,853	596,189	354,184	7,790,624	6,470,893	78,349	30,505,269	30,539,604	1.00
Southeast	34,059,932	1,123,981	22,309	125,731	794,387	159,463	79,219	35,722,262	27,561,143	1.30
South	23,364,051	754,686	6,076	27,502	4,182,359	261,559	88,646	25,214,078	15,610,729	1.62
Centerwest	57,526,794	838,492	6,678	102,018	918,672	75,945	38,346	58,798,935	58,518,216	1.00
Brazil	171,613,337	4,541,832	654,712	750,529	14,167,504	7,107,608	885,119	183,243,247	158,753,866	1.15

Source: Institute for Applied Economic Research, available at: <<http://www.ipeadata.gov.br>>

B.S2 Cropland area change vs. yield change and pasture area change vs. stocking rate change from 1975 to 1996 and from 1996 to 2005 along the five Brazilian administrative boundaries (North, Northeast, Centerwest, Southeast and South).

Figure B.S2.1 - North region, 1975 to 1996: Cropland area change vs. yield change and pasture area change vs. stocking rate change

Figure B.S2.2 - Northeast region, 1975 to 1996: Cropland area change vs. yield change and pasture area change vs. stocking rate change

Figure B.S2.3 - Centerwest region, 1975 to 1996: Cropland area change vs. yield change and pasture area change vs. stocking rate change

Figure B.S2.4 - Southeast region, 1975 to 1996: Cropland area change vs. yield change and pasture area change vs. stocking rate change

Figure B.S2.5 - South region, 1975 to 1996: Cropland area change vs. yield change and pasture area change vs. stocking rate change

Figure B.S2.6 - North region, 1996 to 2006: Cropland area change vs. yield change and pasture area change vs. stocking rate change

Figure B.S2.7 - Northeast region, 1996 to 2006: Cropland area change vs. yield change and pasture area change vs. stocking rate change

Figure B.S2.8 - Centerwest region, 1996 to 2006: Cropland area change vs. yield change and pasture area change vs. stocking rate change

Figure B.S2.9 - Southeast region, 1996 to 2006: Cropland area change vs. yield change and pasture area change vs. stocking rate change

Figure B.S2.10 - South region, 1996 to 2006: Cropland area change vs. yield change and pasture area change vs. stocking rate change

B.S3 Regression analysis summary output

Table B.S3.1 - Regression analysis of area change vs. yield change and the pasture area change vs. stocking rate change for Brazil during the periods from 1975 to 1996 and from 1996 to 2006

Period 1975-1996	Number of MCAs included	% of total MCAs	$\beta 1$	$\beta 2$	t Stat*	P-value	R-Square
Pasture	3577	98	0.135	-0.617	-47.542	0.000	0.384
Crops	3629	99	-0.007	0.010	0.460	0.645	0.000
Sugarcane	2180	60	-0.151	0.663	9.357	0.000	0.039
Soybean	505	14	0.102	1.490	5.717	0.000	0.061
Corn	3409	93	-0.105	-0.032	-0.935	0.350	0.000
Wheat	350	10	-0.067	0.082	0.362	0.718	0.000
Cassava	2873	79	-0.803	0.046	1.010	0.312	0.000
Rice	2701	74	-1.430	-0.263	-5.016	0.000	0.009
Beans	3182	87	-0.045	-0.226	-5.736	0.000	0.010
Period 1996-2006							
Pasture	4211	99	-0.023	-0.661	-70.006	0.000	0.538
Crops	4178	98	-0.129	-0.029	-1.196	0.232	0.000
Sugarcane	2456	58	0.198	0.404	5.724	0.000	0.013
Soybean	999	23	1.189	0.255	1.985	0.047	0.004
Corn	3983	93	-0.405	0.155	5.663	0.000	0.008
Wheat	502	12	0.484	0.407	3.526	0.000	0.024
Cassava	3357	79	-0.215	0.271	4.231	0.000	0.005
Beans	3627	85	-0.675	0.167	4.930	0.000	0.007
Rice	2568	60	-1.637	0.505	9.763	0.000	0.036