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IMPACTS OF LAND USE AND LAND COVER CHANGES ON SOIL NITROGEN BALANCE IN THE BRAZILIAN CERRADO REGION

Luciene Gomes

Doctorate Thesis of the Graduate Course in Earth System Science, guided by Drs. Jean Pierre Henry Balbaud Ometto, Maria Cristina Forti, and Elói Lennon Dalla Nora, approved in September 06, 2017.

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E-mail: pubtc@inpe.br

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Ciência do Sistema Terrestre

Dr. Peter Mann de Toledo

Presidente / INPE / São José dos Campos - SP

Dr. Jean Pierre Henry Balbaud Ometto

Orientador(a) / INPE / São José dos Campos - SP

Dra. Maria Cristina Forti

Orientador(a) / INPE / São José dos Campos - SP

Dr. Elói Lennon Dalla Nora

Orientador(a) / TerraSAT / Rio Grande do Sul - RS

Dra. Rita Marcia da Silva Pinto

Convidado(a) / CEMADEN / São José dos Campos - SP

Dra. Klécia Gili Massi

Convidado(a) / UNESP / São José dos Campos - SP

Este trabalho foi aprovado por:

( ) maioria simples

(✓) unanimidade

São José dos Campos, 06 de setembro de 2017

(In Portuguese)

Dedico esta tese a meus amados pais, Silvio e Ivete, que me ensinaram a amar o aprendizado.

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ABSTRACT

How has agricultural extensification and intensification affected nitrogen cycle in the Brazilian Cerrado? How will it affect nitrogen cycle in the future? Nitrogen is an essential element to food production. Little nitrogen indicates low crop productivity and soil degradation, while too much of it indicates environmental pollution that is detrimental to environmental health, economic prosperity, and food security. First, we conducted a spatial assessment of soil nitrogen balance in the Brazilian Cerrado based on land use dynamics in the years 2000, 2010, and 2012. Second, in order to explore trajectories of agricultural expansion and estimate soil nitrogen balance for the year 2050, we developed a spatially explicit modelling approach capable of representing land use change and soil nitrogen balance for the Cerrado. The trajectories were examined: Sustainability (A); Middle of the road (B); and Fragmentation (C). First results show a movement toward soil nitrogen depletion. In 2000 the balance shows a slight nitrogen accumulation (0.07 TgN) to a condition of nitrogen depletion (-0.37 TgN) in 2012. Such results suggests that agricultural practices in the Cerrado region have been mining soil nitrogen, potentially affecting soil sustainability. Silviculture, annual crops (e.g soybeans and maize), and pasture were found to be the main drivers of nitrogen depletion. Second results show negative soil nitrogen balance in all trajectories: -0.94 TgN (A), -3.19 TgN (B), and -1.69 TgN (C). Only in the sustainability scenario (A), where natural vegetation was maintained and better agricultural production practices were applied, soil nitrogen was less affected. Silviculture and pasture continued to be the main drivers of soil nitrogen depletion in all trajectories. Unless an effective government program of sustainable land management is implemented, areas of inefficient nitrogen management will expand, compromising agricultural production and ecosystems services.

Keywords: Soil nitrogen balance. Agri-environmental indicator. Land use change modelling. Agricultural intensification. Agricultural extensification. Brazilian Cerrado. Matopiba

IMPACTOS DAS MUDANÇAS DE USO E COBERTURA DA TERRA NO BALANÇO DE NITROGÊNIO DO SOLO EM REGIÕES DO CERRADO BRASILEIRO

RESUMO

Como a extensificação e a intensificação agrícola têm afetado o ciclo do nitrogênio no Cerrado brasileiro? Como isso afetará o ciclo do nitrogênio no futuro? O nitrogênio é um elemento essencial para a produção de alimentos. Pouco nitrogênio indica baixa produtividade e degradação do solo, enquanto seu excesso indica poluição ambiental que é prejudicial para a saúde ambiental, prosperidade econômica e segurança alimentar. Na primeira etapa deste estudo, nós realizamos uma avaliação espaço-temporal do balanço de nitrogênio no solo com base na dinâmica do uso da terra nos anos 2000, 2010 e 2012 para o Cerrado brasileiro. Na segunda etapa, nós desenvolvemos uma abordagem de modelagem espacialmente explícita capaz de representar mudanças de uso da terra e mudanças no balanço de nitrogênio no solo. As trajetórias examinadas foram: sustentabilidade (A); meio do caminho (B); e fragmentação e caos (C). Os primeiros resultados mostram um movimento em direção à depleção de nitrogênio no solo. Em 2000 o balanço mostra um leve acúmulo de nitrogênio no solo (0,07 TgN) para uma condição de depleção em 2012 (-0,37 TgN). Estes resultados sugerem que as práticas agrícolas na região do Cerrado têm minerado o nitrogênio do solo, potencialmente afetando a sustentabilidade do solo. Silvicultura, culturas anuais (por exemplo, soja e milho) e pastagens têm sido os principais condutores da depleção de nitrogênio do solo. Os segundos resultados mostram que os balanços de nitrogênio no solo foram negativos em todas as trajetórias: -0,94 TgN (A), -3,19 TgN (B), and -1,69 TgN (C). Somente no cenário sustentabilidade (A), onde a vegetação natural foi mantida e melhores práticas de produção agrícola foram aplicadas, o nitrogênio do solo foi menos afetado. Silvicultura e pastagens continuaram a ser os principais condutores da depleção de nitrogênio no solo em todas as trajetórias. A menos que um programa governamental eficaz de manejo sustentável da terra seja implementado, áreas de ineficiente gerenciamento de nitrogênio irão se expandir, comprometendo a produção agrícola e os serviços ecossistêmicos.

Palavras-chave: Balanço de nitrogênio no solo. Indicador agro-ambiental. Modelagem das mudanças de uso da terra. Intensificação agrícola. Extensificação agrícola. Cerrado brasileiro. Matopiba.

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CHAPTER 1 - GENERAL INTRODUCTION, THESIS OUTLINE, HYPHOTESIS, RESEARCH QUESTIONS AND STUDY AREA

1.1 INTRODUCTION

At present, multiple challenges are posed to many countries in the search for sustainable agriculture development (UNITED NATIONS, 2013). The central question is how to provide food and biofuels to a growing population that will reach 9 billion in 2050, without straining ecosystems (FAO, 2009). Nearly all of this population growth will occur in developing countries (FAO, 2009). Thus, in meeting future demand for agricultural products, they will face growing pressure on finite and already scarce agricultural resources, such as land, soil, water, and nutrient elements (EU NITROGEN EXPERT PANEL, 2015; FAO, 2009).

Brazil has become a hotspot of agricultural production. Currently in second place as global supplier of food and agricultural products, the country is poised to take the leadership when responding to additional global demand (OECD/FAO, 2015). Such good performance has been credited to production expansion into the Brazilian savanna (Cerrado) (RADA, 2013). The Cerrado is responsible for 70% of Brazilian agricultural production (WICKRAMASINGHE, 2012), which accounts for 95% of the total cotton, 54% of soybeans, 55% of beef, and 43% of the sugarcane produced in Brazil (IBGE, 2010a). It also plays an important role in bioenergy production from sugarcane and eucalyptus planted forests (LEITE et al., 2009; BALCOMBE & RAPSOMANILIS, 2008). However, in striving to meet the higher demand for agricultural products, the Cerrado has lost 46% (95 Mha) of its native vegetation cover (BRASIL, 2015). Of the remaining natural vegetation, 88.4% is suitable for growing soybeans, and 68.7% for sugarcane, crops whose demand is predicted to rise markedly in the coming decades (STRASSBURG et al., 2017).

A sustainable landscape management foresees that agricultural activities and environmental conservation are in harmony with the provision of ecosystem services (SAYER et al., 2013). The increase in agricultural production and productivity observed in the Cerrado should take into account the status of land use (BINDRABAN et al., 2000). Ideally, indicators on the status of land use should integrate several components of the landscape. Nitrogen flow and its management are seen as an integrative indicator of production efficiency and environmental risks, or benefits. Nitrogen excess indicates potential environmental problems such as eutrophication of freshwater and estuarine ecosystems, groundwater contamination, soil degradation and air pollution. A deficit indicates decline in soil fertility and poses a risk to the sustainability of agriculture (ZHANG et al., 2015; GALLOWAY et al., 2008). Thus, nitrogen is a useful indicator of progress toward a sustainable landscape when limits associated with its excess and insufficiency are known (EU NITROGEN EXPERT PANEL, 2015; KANTER et al., 2016).

It is possible to investigate how sustainable agricultural systems in the Brazilian Cerrado are by using nitrogen as an integrative indicator of the land use status and environment risks or benefits. Furthermore, this line of research allows us to explore future pathways, pottentially enhancing agricultural production and land yield, and using natural resources in a sustainable way. Quite a few studies have focused on how agriculture has affected biodiversity (STRASSBURG et al., 2017; RATTER et al., 1997; MYERS et al., 2000), water resources (COSTA et al., 2003; FERREIRA et al., 2011), and carbon emissions (BUSTAMANTE & FERREIRA, 2010). However, there is a scientific gap on the role of agricultural extensification and intensification on nitrogen cycle in the Cerrado biome. The construction of a spatially explicit soil nitrogen balance for agricultural sector will make it possible to identify the large imbalances between nitrogen inputs and outputs at local and regional scales, as well as the opportunities for policy intervention and resource optimization.

This thesis is divided in 5 chapters. **Chapter 1** includes objective, hypothesis, research questions, main results, and study area. **Chapter 2** presents estimates of annual soil loss rates for the Brazilian Cerrado in the years 2000, 2010, and 2012. Such estimates were used in Chapter 3 and 4 to estimate nitrogen outputs by erosion processes (OUT_{ero}). **Chapter 3** includes the results of spatially explicity soil nitrogen balance performed in 2000, 2010, and 2012. **Chapter 4** presents trajectories of land use and soil nitrogen balance for the year 2050 and **Chapter 5** presents conclusion and recommendations.

1.2 OBJECTIVE

The main objective of this study was to perform spatio-temporal soil nitrogen balances for the Brazilian Cerrado based on land use dynamics in the years 2000, 2010, and 2012. In addition, we aimed to explore trajectories of land use change and soil nitrogen balance for the year 2050 using techniques of dynamic spatial modeling.

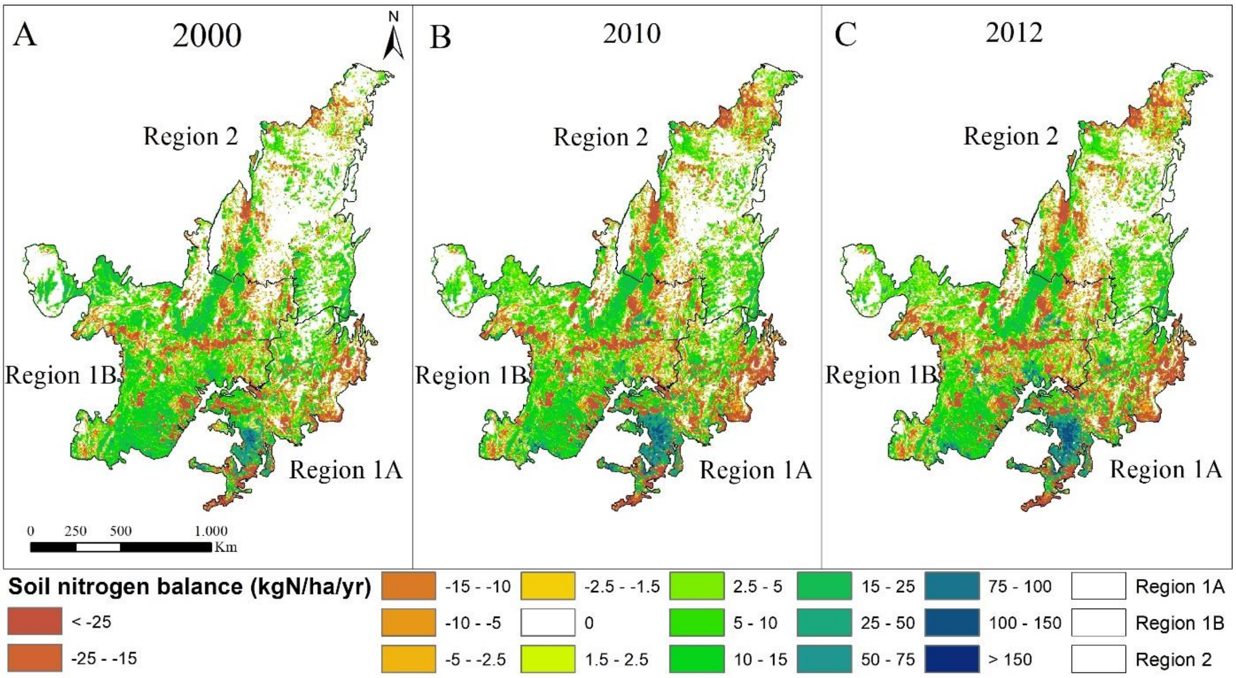
The working hypothesis is that agricultural expansion and intensification in the Brazilian Cerrado may not be significantly affecting the nitrogen balance in that region at the moment, but may become a disruptive force in the future.

1.3 RESEARCH QUESTIONS

1. How has agricultural intensification and extensification affected nitrogen cycle in the Brazilian Cerrado?

In Chapter 3, we conducted a spatial assessment of nitrogen fluxes in agricultural regions of the Brazilian Cerrado. Little nitrogen indicates low crop productivity and soil degradation, while too much of it indicates environmental pollution. Results show increasingly negative soil nitrogen balances in the Brazilian Cerrado. In 2000 the balance shows a slight nitrogen accumulation (0.07 TgN) to a condition of nitrogen depletion (-0.37 TgN) in 2012. These number suggest that agricultural practices in the Cerrado are mining soil nitrogen, affecting soil sustainability. Silviculture, annual crops, and pasture are the most important drivers of soil nitrogen depletion, with harvested products and erosion as main nitrogen outputs. Figure 1.1 shows spatio-temporal variation of soil nitrogen balances.

Figure 1.1 - Espatially explicit soil nitrogen balance for Brazilian Cerrado in the years 2000, 2010 and 2012.

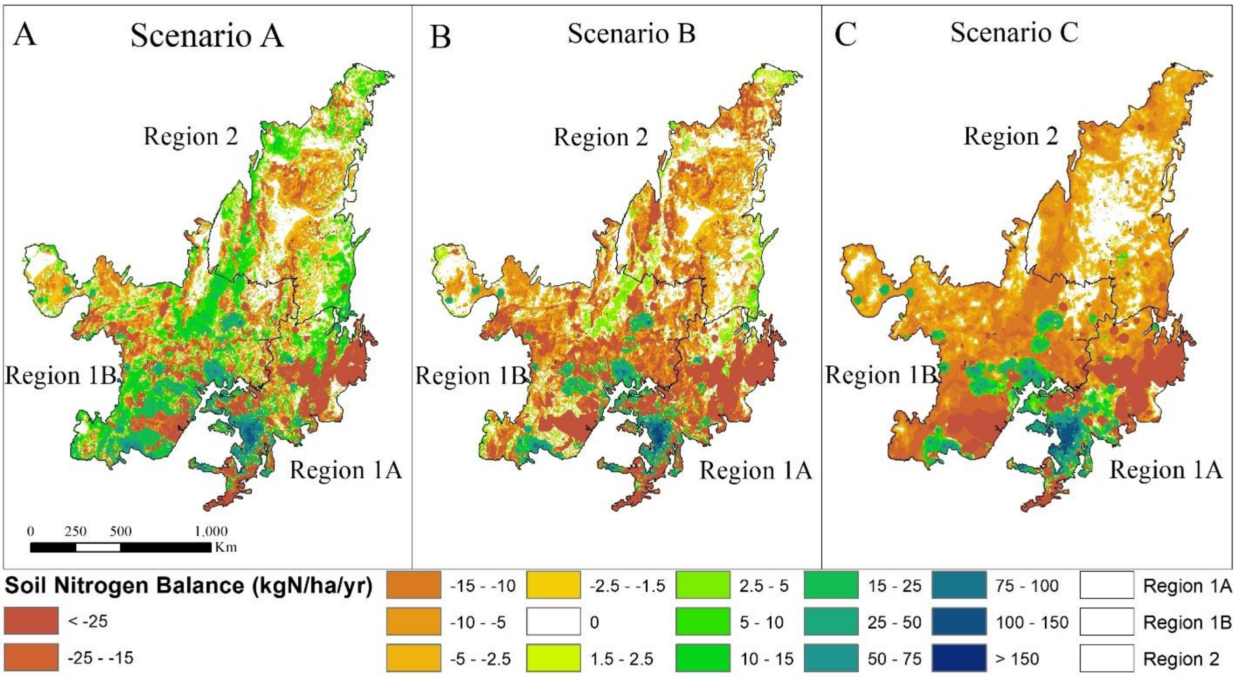


Source: author's production.

2. How will agricultural extensification and intensification affect future nitrogen cycle in the Brazilian Cerrado?

In Chapter 4, we explored three trajectories of agricultural expansion and soil nitrogen balance for 2050 in the Brazilian Cerrado: Sustainability (A); Middle of the road (B); and Fragmentation (C). Results show negative soil nitrogen balance in all trajectories: -0.94 TgN (A), -3.19 TgN (B), and -1.69 TgN (C). Only in the sustainability scenario (A), where natural vegetation was maintained and better agricultural practices were applied, soil nitrogen was less affected. Silviculture and pasture are the drivers of soil nitrogen depletion, with harvested products and erosion as main nitrogen outputs. Figure 1.2 shows the spatially explicit soil nitrogen balance for the A, B, and C trajectories.

Figure 1.2 - Spatially explicit soil nitrogen balance simulated for the Brazilian Cerrado in the year 2050. (A) Sustainability scenario (A); (B) Middle of the road scenario (B); and (C) Fragmentation scenario (C).



Source: author's production.

1.4 STUDY AREA

The Cerrado encompasses approximately 2 million km^2 of the Brazilian Central Plateau (24% of the country`s total area), and it is in transition with the Amazon Rainforest, Caatinga, Pantanal and Atlantic Forest (SANO et al., 2008). It supplies nearly 70% of the water that flows north to the Araguaia-Tocantins basin, south-southeast to the Paraná basin, and northeast to the São Francisco basin, the three largest hydrographic basins in South America (FELFILI & SILVA JUNIOR, 2005; LAHSEN et al. 2016). The Cerrado is considered one of the richest and most diverse savanna in the world (LEWINSOHN & PRADO, 2005), it is one of the 35 global biodiversity hotspots (MYERS et al. 2000; MITTERMEIER et al., 2005) due to the high level of endemism and rapid habitat loss caused by fire regimes and agricultural expansion (BUSTAMANTE et al. 2012).

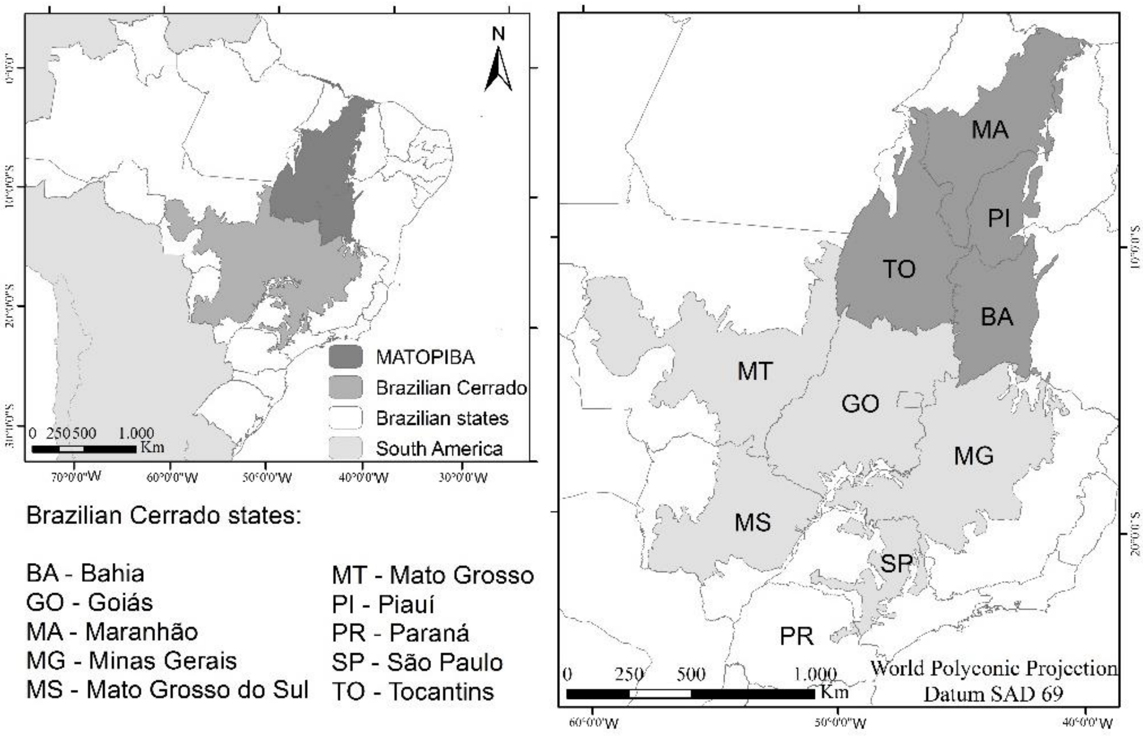
Main vegetation types in the Cerrado are grassland (*campo limpo*), grassland with scattered trees (*campo sujo*), savanna (*cerrado*, strict sense), and woodland (*cerradão*) (EITEN, 1972). In terms of diversity, the biome houses 12,000 species of angiosperms (MENDONÇA et al., 2008) and is highly diverse in leguminous species (MEDINA, 1993), many of them endemic to the region (SPRENT, 2009). These leguminous species are highly nodulated and show evidence of effective nodules fixing nitrogen biologically (SPRENT, 2009). The fauna is also rich, with about 159 species of mammals (23 endemic), 837 species of birds (29 endemic), 180 reptile species (20 endemic) and 113 amphibian species (32 endemic) (MYERS et al. 2000).

The climate is characterized by distinctly wet and dry seasons of relatively equal duration, with annual precipitation ranging from 800 to 1.800mm. Almost all of it (>90%) falls during the rainy season, between October and April (EITEN, 1972). The average annual temperature varies from 20 to 26°C (BUSTAMANTE et al., 2012). Soil types are predominantly Ferralsols (~41%), Arenosols (~15%), Acrisols (~12%), and Plinthosols (~10%) (SANTOS et al., 2011), all of which are highly weathered with low organic matter and nutrient contents, especially nitrogen and phosphorus (MEDINA et al., 1993). The availability of soil nutrients varies over the vegetation types. In general, it tends to be higher in woodlands than in grasslands. High levels of oxides and aluminum hydroxides are also present in all soil types. They can be acidic, deep and very well drained (SANO et al., 2008). The relief is mostly flat with gentle hill areas (VALERIANO, 2009).

Fire is a factor of paramount ecological importance in natural vegetation regions. It influences the cycle of nutrients and affects the dynamics of vegetation, mainly the herbaceous/woody biomass ratio (COUTINHO, 2002; MIRANDA et al., 2002; NARDOTO et al., 2003; BUSTAMANTE et al. 2012). As fire frequency increases, herbaceous/woody biomass ratio tends to increase, and vegetation physiognomy changes to a more open form. Simultaneously, the release and availability of nutrients is enhanced (COUTINHO, 2002; MIRANDA et al., 2002). Paleontological studies indicate the occurrence of burnings in the region before the presence of man (SALGADO-LABOURIAU et al., 1994). In general, the Cerrado is characterized by for four factors: 1) periods of low water availability; 2) highly weathered soils with low nutrient availability; 3) soil that are high in oxides and aluminum hydroxides; and 4) high frequency of fires in natural vegetation regions (MEDINA, 1993; COUTINHO, 2002; BUSTAMANTE et al., 2004).

Since the 1970’s, Brazilian governmental programs have incouraged the occupation and economic development of the country’s central region, leading to the intensification of land use change in the Cerrado (FERREIRA et al., 2013). Consequently, until 2013, 46% (95 Mha) of the biome’s native vegetation cover had been deforested and turned into pasture and mechanized agriculture areas (BRASIL, 2015). As a result, Cerrado's present-day condition are nothing short of tragic. By some estimates, only 20% of the region remains undisturbed and a mere 8% is preserved in protected areas. To make matters worse, the biome that suffers the most anthropic pressure in Brazil (ICMBIO, 2017; STRASSBURG et al., 2017; SILVA & BATES, 2002) is now home to the newest Brazilian agricultural frontier, named MATOPIBA (Acronym from the first two letters of Maranhão (MA), Tocantins (TO), Piauí (PI) and Bahia (BA) states). This most recent frontier has been characterized by rapid changes in land-cover and land-use for agricultural expansion (DIAS et al., 2016). During the 2005-2014 period, for example, the area used for soy crops in MATOPIBA increased by 86%, as the increase at the national level was of 29% (CONAB, 2016; LAHSEN et al., 2016). Figure 1.3 shows the political division of the Brazilian Cerrado (States) and its newest agricultural frontier, the MATOPIBA.

Figure 1.3 Location of the study area. Brazilian Cerrado encompasses totally or partially the states of Bahia (BA), Goiás (GO), Maranhão (MA), Minas Gerais (MG), Mato Grosso do Sul (MS), Mato Grosso (MT), Piauí (PI), Paraná (PR), São Paulo (SP) and Tocantins (TO).



Source: Author's production.

CHAPTER 2 - ESTIMATES OF ANNUAL SOIL LOSS RATES IN THE BRAZILIAN CERRADO

2.1 INTRODUCTION[1]

Soil erosion is a serious environmental problem that has adversely affected food production throughout the world by reduction of land productivity and water availability (PIMENTEL et al., 1987). Erosion is a natural geomorphic process that results from topsoil removal by wind and water (GARES et al., 1994), and can be influenced by several factors such as climate variables, slope steepness, soil physical parameters, vegetation and land use patterns (PIMENTEL et al., 1995). Moreover, erosion processes may be intensified by human intervention through inappropriate land use and land cover changes. Severe soil erosion has occurred in the world's major agricultural regions and worsened with growing agricultural activities in forest fringe areas (PIMENTEL et al., 1987). Agricultural extensification and intensification that did not take into account the bearing capacity of soils have accelerated the erosion processes in some tropical regions (GRECCHI et al., 2014). World food projections have pointed out that these areas are particularly important in the global agricultural scenario as potential sites of farmland expansion that will ensure food security to an additional 2.3 billion people by 2050 (RADA, 2013; TILMAN et al., 2011; ALEXANDRATOS & BRUINSMA, 2012). Nonetheless, many of these regions have been classified as hotspots of land degradation due to water erosion (SCHERR & YADAV, 1996).

Brazil has become the second-largest exporter of agricultural products in the world, particularly due to production expansion into soils of its tropical savanna, known as *Cerrado* (RADA, 2013). Between 2009 and 2010, the Cerrado accounted for 70% of Brazil's food production (WICKRAMASINGHE et al., 2012) growing 95% of its cotton, 54% of soybeans, 55% of meat and 43% of its sugarcane (IBGE, 2010a). It is the country's most important agricultural region and has been considered one of the world's great breadbaskets (THE ECONOMIST, 2010). However, due to landscape fragility and

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[1] This chapter is an adapted version of the paper:
GOMES, L.; SIMOES, S.J.C.; FORTI, M.C.; OMETTO, J.P.H.B.; DALLA-NORA, E.L. Using geotechnology to estimate annual soil loss rate in the Brazilian Cerrado. **Journal of Geographic Information System**, v.9, p. 420-439, 2017.

climatic characteristics, the Cerrado is highly susceptible to water erosion (MACEDO, 1994). Agricultural expansion may be leading to severe arable land erosion, and causing different environmental problems and loss of biodiversity (SCHERR & YADAV, 1996). Therefore, if Brazil is to contribute 40% of the global food demand by 2050 (OECD/FAO, 2015), it is imperative that soil erosion in the Cerrado receives close attention.

Quantitative soil erosion data and its spatial distribution are essential to a successful erosion assessment in a fragile landscape. From these data, it is possible to design and implement an appropriate erosion control and conservation measures that will have a great impact on soil loss reduction and water conservation (SHI et al., 2014). There are different methods to assess quantitative soil erosion (MERRITT et al., 2003). Universal Soil Loss Equation (USLE) (WISCHMEIER & SMITH, 1978) and Revised Universal Soil Loss Equation (RUSLE) (RENARD et al., 1997) are the most frequently applied. Their advantages are simplicity, effectiveness of the equations, and success in predicting long term average annual soil loss with acceptable accuracy (ZHANG et al., 2013).

USLE and RUSLE models were originally used for local conservation planning. Their factors were usually calculated from field measurements (WISCHMEIER & SMITH, 1978). Due to limitations in terms of cost, representativeness, and reliability of the results data, soil loss quantification based on erosion plots cannot provide the spatial deistribution of soil erosion in large and difficult access areas, as are several areas in Brazil (LU et al., 2004; OLIVEIRA et al., 2011). However, when assessment of soil erosion is integrated with a Geographical Information System (GIS) environment, it is possible to estimate soil erosion and its spatial distribution with reasonable time, cost, as well as with improved accuracy in large areas (LU et al., 2004). This integration has been widely used, especially in developing countries, such as Brazil, India, and Turkey (LU et al., 2004; OLIVEIRA et al., 2011; BESKOW et al., 2009; PARVEEN et al., 2012; ERDOGAN et al., 2007). Thus, the main objective of this study is to estimate the spatial distribution of annual soil loss rate using the RUSLE model integrated into a GIS. Also, we aim to investigate how farmland and silviculture are related to soil loss in the most important agriculture region in the country. Most frequently, studies estimate annual soil loss rate in small regions (BESKOW et al., 2009; FARINASSO et al., 2006; TRABAQUINI et al., 2012). Here, we present a spatial distribution of annual soil loss rate for the entire Brazilian Cerrado. Reference years were 2000, 2010, and 2012.

2.2 MATERIAL AND METHODS

Data acquisition and processing

All input data for the RUSLE model were stored, analyzed, and visualized within the ArcGIS® environment (version 10.3). The GIS database was georeferenced using World Polyconic projection and SAD 69 (South American Datum 1969). The full database (vector and raster formats) includes the following:

1) Erosivity Map (approximated scale of 1:5,000,000) obtained from (OLIVEIRA et al., 2012);

2) Soil Map from EMBRAPA (Brazilian Agriculture Research Corporation) at the scale of 1:5,000,000 (SANTOS et al., 2011);

3) Digital Elevation Model (DEM) generated from TOPODATA database provided by INPE (Brazilian Institute for Space Research) with spatial resolution of 30m from SRTM data produced originally by NASA originally (VALERIANO et al., 2008);

4) 2000, 2010, and 2012 Land Use and Cover Maps produced by IBGE (Brazilian Institute for Geography and Statistics) at the scale of 1:5,000,000 (IBGE, 2015). This map has fourteen different land use and land cover units, which were reclassified in order to represent the classes of interest that follows:

a) *Agriculture class* - agriculture areas, mosaic of agricultural areas with remaining forest, mosaic of forest vegetation with agricultural areas, and mosaic of grassland with agricultural areas;

b) *Pasture* - planted and managed pastureland (e.g. cattle-ranching);

c) *Silviculture* - planted and managed forests with exotic species (e.g. eucalyptus, pines);

d) *Natural vegetation* - natural vegetation (e.g. forest vegetation, grassland, wetland);

e) *Others* - artificial areas (e.g. urbanized zones, road systems, non-agricultural systems), continental water bodies, coastal water bodies, and uncovered lands (e.g. rocks outcrops and sand dunes).

In order to separate agricultural areas from forest vegetation and grassland, the *Agriculture* unit was split into three classes: annual (grains), semi-perennial (sugarcane), and perennial (coffee and citrus). For that purpose, the *Agriculture* unit was multiplied by spatially explicit data of grains (CONAB, 2011a), sugarcane (RUDORFF et al., 2010), coffee and citrus (MOREIRA et al., 2010). As a result, it was obtained *Annual*, *Semi-perennial* and *Perennial* agricultural units were obtained, as residues were reclassified as *Natural vegetation*. The resulting map comprises seven land-use units: *Pasture*, *Natural vegetation*, *Silviculture*, *Annual crops, Semi perennial crops*, *Perennial crops* and *Others*.

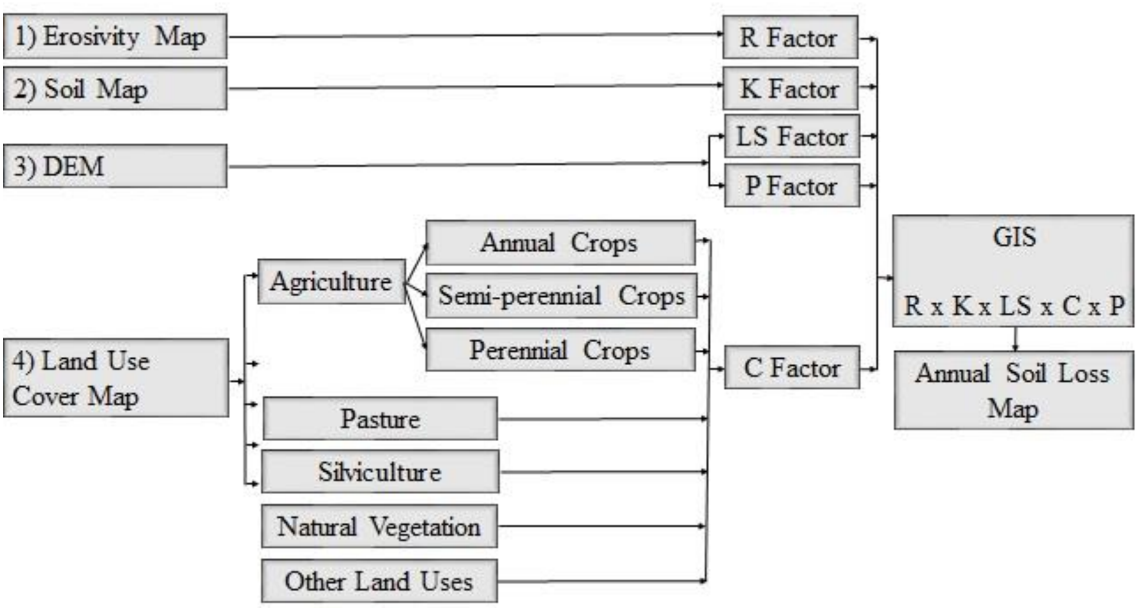
RUSLE model

Estimations of soil loss and its spatial distribution were obtained using the RUSLE model integrated into a GIS. RUSLE is an empirical mathematical model developed from USLE to estimate soil erosion water (RENARD et al., 1997). As it predecessor, it cannot estimate sediment deposition on the slope (ZHANG et al., 1995). And is only able to reach an estimate of the average annual soil loss caused by rill and interril erosion (KINNEL, 2010). These estimates signal the intensity of the erosion processes. The model is a product of five factors, according to Equation 1:

$$A = R \times K \times LS \times C \times P \qquad 2.1$$

where A is the annual average soil loss per unit of area ($t.ha^{-1}.yr^{-1}$), R is the rainfall-runoff erosivity factor ($MJ.mm.ha^{-1}.h^{-1}.yr^{-1}$), k is the soil erodibility factor ($t.h.MJ^{-1}.mm^{-1}$), LS is the slope length and slope steepness factor (dimensionless), C is the crop management factor (dimensionless), and P is the erosion control practice factor (dimensionless). Integrated into a GIS, soil erosion loss was calculated on a cell-by-cell basis in order to recognize the spatial patterns of soil loss. Thus, each factor was calculated taking grid cells of 94 m x 94 m as reference and, an uniform spatial analysis environment for GIS modeling was established (BESKOW et al., 2009). Spatial distribution of soil erosion loss was produced by multiplying all factor layers and creating a final map. The methodological approach followed in RUSLE is detailed in the simplified flowchart depicted in Figure 2.1.

Figure 2.1 Flowchart of the methodology applied to estimate averaged rate of soil loss and its spatial distribution for the Brazilian Cerrado using the RUSLE model integrated into a GIS.

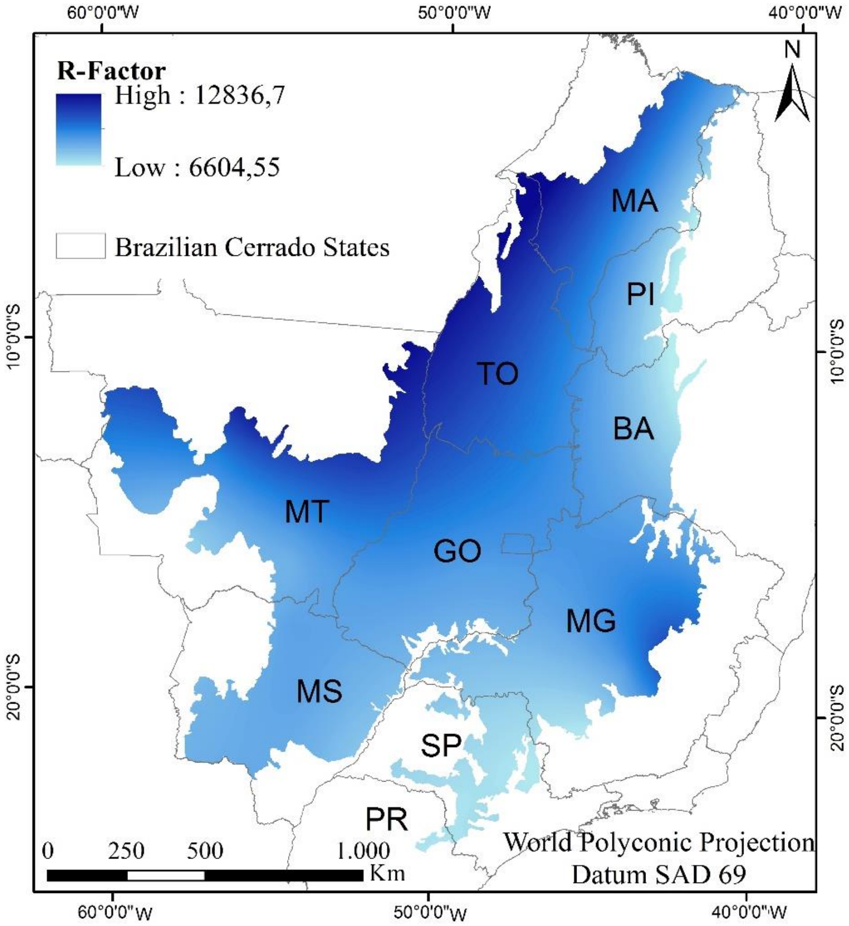


Source: Author's production.

Rainfall-Runoff erosivity factor (R)

The erosivity factor (R) represents the erosive power of precipitation on a given soil, regolith or other weathered material. Precipitation is the driving force of erosion and has direct effects on different phases of erosional processes including the detachment of soils particles, the breakdown of aggregates and the transport of eroded material by runoff. The R-factor is the kinetic energy of raindrops that fall onto the ground and is affected by rainfall intensity and raindrop size (WISCHMEIER & SMITH, 1978). Figure 2.2 shows rainfall-runoff erosivity factor map.

Figure 2.2 Rainfall-runoff erosivity fator (R) map of the study area. Brazilian Cerrado states are: Bahia (BA), Goiás (GO), Maranhão (MA), Minas Gerais (MG), Mato Grosso do Sul (MS), Mato Grosso (MT), Piauí (PI), Paraná (PR), São Paulo (SP) and Tocantins (TO).



Source: adapted from Oliveira et al. (2012).

Erodibility factor (K)

The soil erodibility factor (K) is a property that depends upon two factors; the first of them is the infiltration capacity to resist detachment and avoid its transportation by rainfall and the second is the runoff process (WISCHMEIER & MANNERING, 1969). Therefore, K values reflect the rate of soil loss per rainfall-runnoff erosivity (R) for a specific soil (RENARD et al., 1997). The K-factor varies from zero to one, where *zero* refers to soils with little susceptibility to water erosion and *one* refers to soils highly susceptible (FARHAN & NAWAISEH, 2015). The K-factor map was based on soil map and erodibility values published from several studies conducted in different areas of Brazil for the same soil types. K values for each soil type of the Brazilian Cerrado are shown in Table 2.1.

Table 2.1. Soil classification in the Brazilian Cerrado and soil erodibility (K) values and their respective sources.

No.	Brazilian Classification	FAO (1974) Classification	Area (%)	K ($t.h.MJ^{-1}.mm^{-1}$)	Source
1	Latosol	Ferralsols	40.61	0.010 – 0.028	Demarchi & Zimback, (2014); Farinasso et al. (2006); Mannigel et al. (2002); Cabral et al. (2005)
2	Quartzarenic Neosols	Arenosols	14.38	0.046 – 0.056	Farinasso et al. (2006); Castro et al. (2011)
3	Argisols	Acrisols	11.90	0.031 – 0.055	Farinasso et al. (2006); Demarchi & Zimback, (2014); Castro et al. (2011)
4	Plinthosols	Plintosols	10.21	0.012 – 0.055	Cabral et al. (2005); Farinasso et al. (2006)
5	Cambisols	Cambisols	9.37	0.036 – 0.043	Silva et al. (2009); Farinasso et al. (2006); Mannigel et al. (2002)
6	Litholic Neosols	Leptosols	8.03	0.036 – 0.050	Farinasso et al. (2006); Cabral et al. (2005)
7	Gleysols	Gleysols	1.63	0.001	Cabral et al. (2005)
8	Planosols	Haplics	0.80	0.057	Farinasso et al. (2006)
9	Regolithic Neosols	Regosols	0.61	0.050	Cabral et al. (2005)
10	Chernosols	Chernozems	0.58	0.030	Silva & Alvares (2005)
11	Fluvic Neosols	Fluvisols	0.56	0.046	Cabral et al. (2005)
12	Luvisols	Luvisols	0.40	0.150	Mannigel et al. (2002)
13	Nitosols	Nitisols	0.27	0.011	Farinasso et al. (2006)
14	Vertisols	Vertisols	0.08	0.040	Ahmad & Mermut (1996)
15	Organosols	Histosols	0.01	0.061	Silva & Alvares (2005)
16	Others[a]	Others	0.56	-	-

Topographic factor (LS)

The topographic factor represents the influence of the relief on the erosion process (RENARD et al., 1997). The LS-factor depends on slope steepness (S) and slope length (L), assuming slopes show uniform profiles. In general, soil erosion increases with slope steepness when runoff flow velocity is higher. It also increases with slope length when runoff in downslope accumulates (WISCHMEIER & SMITH, 1978; FARHAN & NAWAISEH, 2015). Maximum slope length is seldom longer than 600 ft or shorter than 15-20 ft (BROOKS et al., 2003). Both were obtained from the Digital Elevation Model (DEM) by applying different approaches and methods (DESMET & GROVERS, 1996; BESKOW et al., 2009). This study was based on Desmet and Grovers (1996), where the L-factor was calculated from the upslope contributing area of each cell, as show in Equation 2:

$$Li,j = \frac{\left[(Ai,j{-}in + D^2)^{m+1} - (Ai,j{-}in)^{m+1}\right]}{\left[D^{m+2} \times xi,j^{m} \times (22{,}13)^{m}\right]} \qquad 2.2$$

where $L_{i,j}$ is the slope length factor for the grid cell with coordinates ($_{i,j}$); $A_{i,j\text{-}in}$ is the contributing area at the inlet of the grid cell with coordinates ($_{i,j}$) (m^2); D is the grid cell size (m); m is a dimensionless exponent that depends on slope steepness (S); $x_{i,j}$ is flow direction value for the grid cell with coordinate ($_{i,j}$). The exponent m was calculated according to [17], where S < 1%, m = 0.2; 1% ≤ S ≤ 3%, m = 0.3; 3% < S ≤ 5%, m = 0.4; e S > 5%, m = 0.5.

The *S factor* was calculated based on (MCCOOL et al., 1987), as shown in Equations 3 and 4:

$$S = 10.8 \times \sin\theta + 0.03 \; for \; slopes < 9\% \qquad 2.3$$

$$S = 16.8 \times \sin\theta - 0.50 \; for \; slopes \geq 9\% \qquad 2.4$$

where θ is the slope angle (°). Slope steepness was divided into six categories based on (RAMALHO FILHO & BEEK, 1995) as shown in Table 2.2.

Table 2.2 Slope steepness categories for the Brazilian Cerrado.

Categories (%)	Relief Classification	Area (%)
0 – 3	Flat Reliefs	89.98
3 – 8	Gentle Hillslope	8.88
8 – 13	Moderate to Gentle Hillslope	0.99
13 – 20	Strongly Undulating Relief	0.14
20 – 45	Mountain with Steep Hillslope	0.01
45 – 100	Ridge Escarpments	0.00

Source: adapted from Ramalho & Filho (1995).

Cover and management factor (C)

The cover and management factor (C) integrates several factors that affect erosion, including vegetative cover, plant litter, soil surface and land management (WISCHMEIER & SMITH, 1978; RENARD et al., 1997). It is the most important factor in RUSLE, after topography, since it represents the conditions that can be easily changed to reduce overland flow and soil erosion (BESKOW et al., 2009; FARHAN & NAWAISEH, 2015]. Even though it is treated as an independent variable in the equation, the C factor depends upon others. It varies from nearly zero, in case there is good erosion protection, to one, when protection is poor (GASNARI & RAMESH, 2016). As mentioned before, this work took into account seven land use classes in the Brazilian Cerrado: *Pasture*, *Natural vegetation*, *Silviculture*, *Annual crops*, *Semi perennial crops*, *Perennial crops* and *Others*. The C-factor values that were extracted from literature and percentage of each land use area are presented in Table 2.3.

Table 2.3 Values of the cover management factor (C) for each land use cover class in the Brazilian Cerrado.

No.	Land use	Area (%) 2000	Area (%) 2010	Area (%) 2012	C	Source
1	Pasture	36.79	41.20	40.76	0.05	Galdino (2012); Peron & Evangelista (2003)
2	Natural Vegetation	55.36	47.84	47.31	0.01	Oliveira et al. (2015)
3	Silviculture	0.80	0.92	0.91	0.12	Silva et al. (2014); Silva et al. (2016)
4	Annual crops	4,75	6.73	7.34	0.08	Bertol et al. (2001); Bertol (2002)
5	Semi-perennial crops	0.88	1.72	2.05	0.31	Weill (1999)
6	Perennial crops	0.32	0.43	0.47	0.11	Prochnow et al. (2005)
7	Others	1.09	1.16	1.16	0.00	-

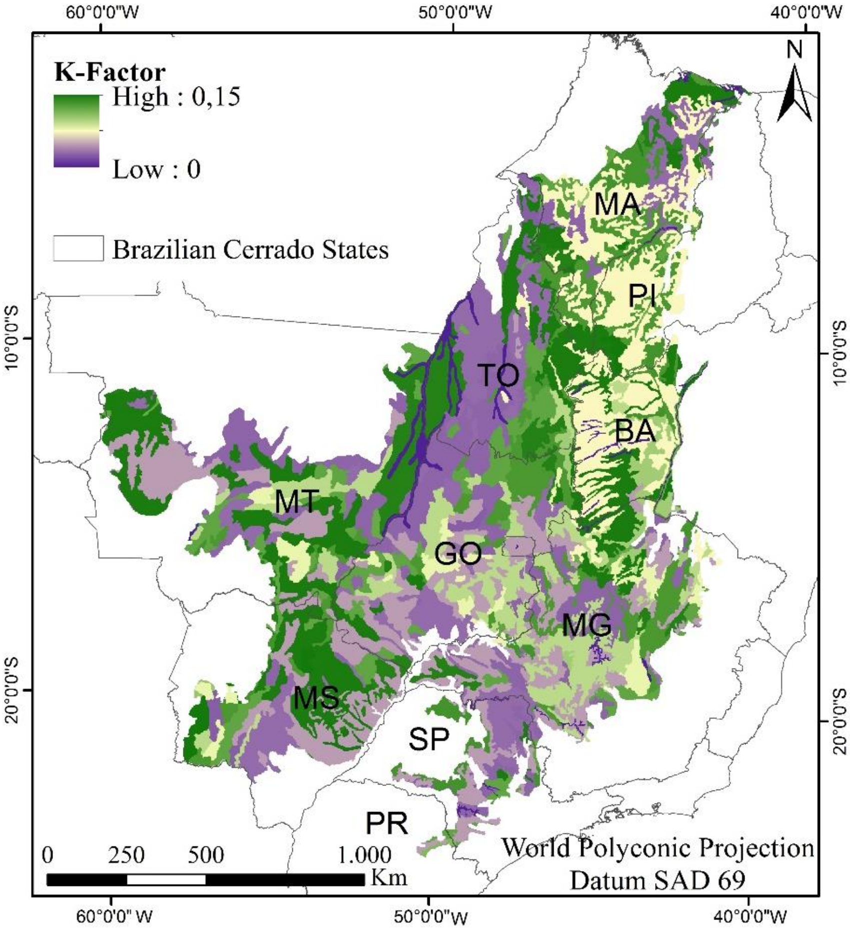
Supporting practice factor (P)

The erosion control practice (P) reffers the relationship between soil loss with a specific support practice and the corresponding loss with up-downslope cultivation (PANDEY et al., 2007). The P-factor varies according to soil conservation practices, therefore having a strong influence on soil loss (BESKOW et al., 2009). Practices characterized by *P* include strip-cropping and terraces, and are not applied to most forested regions. Since the soil conservation practices for each system are not known for the whole of the Brazilian Cerrado, where about 880,000 km^2 are occupied by farmlands, P-factor values were determined as in Oliveira et al., 2007, where they are calculated based on slope angle (α). Thus, the values found for *P* were 0.6 for $0 \leq \alpha \leq 5\%$, $0.69947 - 0.08991\ \alpha + 0.01184\ \alpha^2 - 0.00035\ \alpha^3$ for $5\ \% < \alpha \leq 20\ \%$ and 1.0 for $\alpha > 20\ \%$.

2.3 RESULTS AND DISCUSSION

The spatial distribution of all RUSLE's factors (K, C, LS and P) is shown in Figure 2.3, 2.4, 2.5 and 2.6, respectively. The different soil types produced a large spatial variability (Figure 2.3), with a higher than 0.03 $t.h.MJ^{-1}.mm^{-1}$ (Table 2.1) K-factor in 56.35% of total area. These results indicate that over half of the soils in the Cerrado are very susceptible to water erosion (BESKOW et al., 2009). Arenosols, Acrisols, Plintosols, Cambisols and Leptosols are soils with higher potential for erosion, given their large amount of particles (sand and silt) that are easily detached and carried away. One the other hand, soils with low susceptibility to water erosion account for 43.09% of the total area. These are the Ferralsols, Gleysols, Chernosols and Nitisols, whose lower erodibility is credited to higher relative content of clay and organic matter. In spite of large spatial variability show by the K-factor, it is possible to observe where the areas most susceptible to erosion are concentrated, comprising the states of Maranhão (MA), Piauí (PI), Bahia (BA) and part of Tocantins (TO) (Figure 2.3). The soil fragility to erosion in these parts of the Cerrado shows how important effective land management practices are. This is a crucial point, since the largest changes in land-use and land-cover in Brazil have been occurring precisely in the MATOPIBA region, where there is a predominance of soils that are prone to higher erosion rates.

Figure 2.3 Soil erodibility factor (K) map of the study area. Brazilian Cerrado states are: Bahia (BA), Goiás (GO), Maranhão (MA), Minas Gerais (MG), Mato Grosso do Sul (MS), Mato Grosso (MT), Piauí (PI), Paraná (PR), São Paulo (SP) and Tocantins (TO).



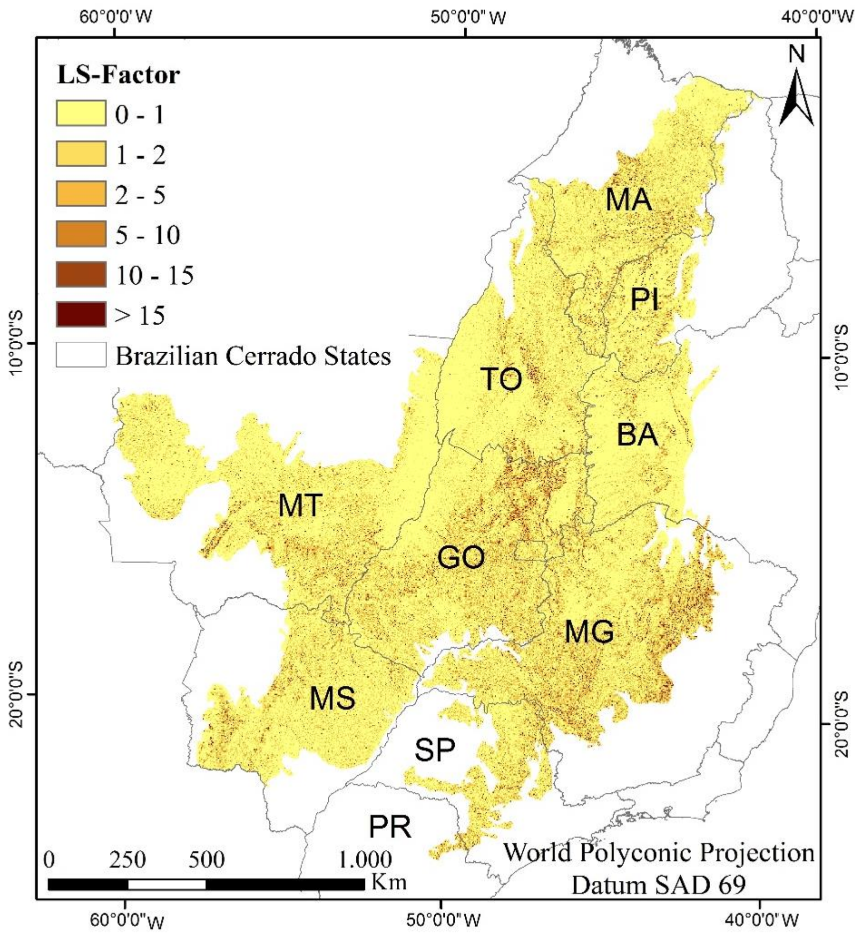
Source: Author’s production.

The LS-factor is very important in RUSLE since topography affects runoff characteristics and sediment transport (PANDEY et al., 2007). Table 2.4 shows the area distribution of each LS-factor intervals. About 93% of total Cerrado area presents LS values above 5, which refers to *moderate vulnerability to water erosion* (BESKOW et al., 2009), while only 2.69% of its total area presents LS-factors greater than 10, indicating *high vulnerability to water erosion* (BESKOW et al., 2009). Figure 2.4 shows spatial distribution of LS-factors; the highest values are concentrated in regions with undulating and strongly undulating topography, where runoff flow velocities are higher, especially in Goiás (GO), Minas Gerais (MG), and Mato Grosso (MT) states.

Table 2.4 Categories of the topographic factor (LS) for the Brazilian Cerrado.

No.	Categories	Area (%)
1	0 – 1	69.73
2	1 – 2	13.14
3	2 – 5	10.49
4	5 – 10	3.95
5	10 – 15	1.21
6	>15	1.48

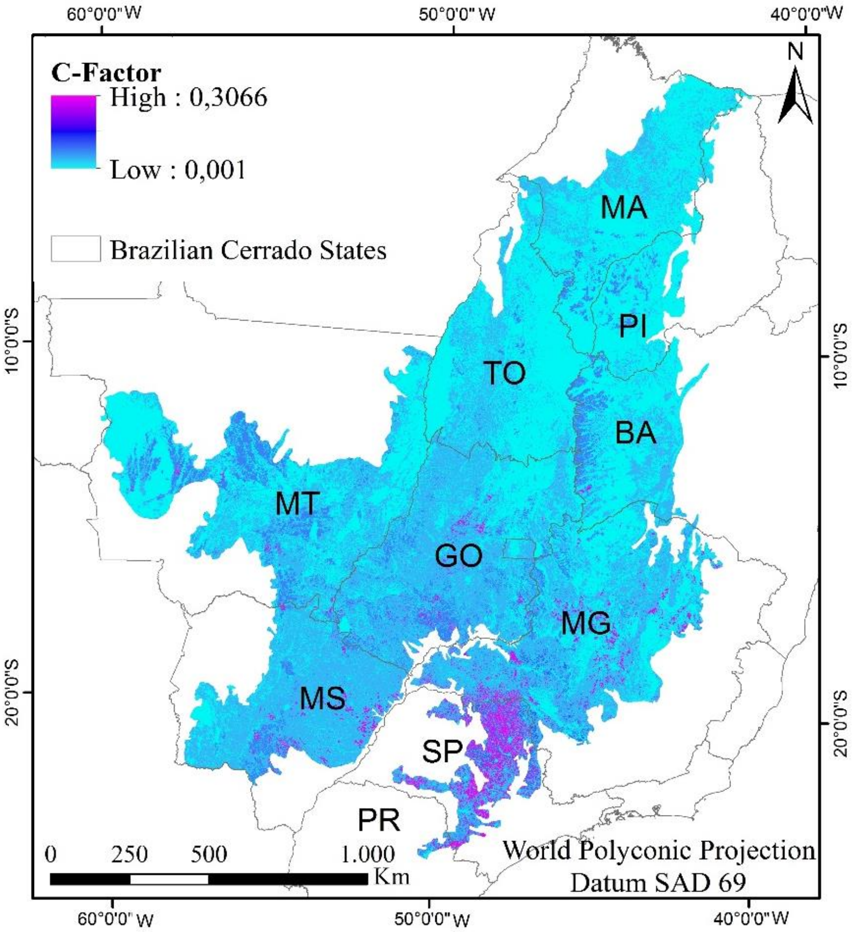
Figure 2.4 Soil topographic factor (LS) map of the study area. Brazilian Cerrado states are: Bahia (BA), Goiás (GO), Maranhão (MA), Minas Gerais (MG), Mato Grosso do Sul (MS), Mato Grosso (MT), Piauí (PI), Paraná (PR), São Paulo (SP) and Tocantins (TO).



Source: Author’s production.

The C-factor corresponding to *Crop/Vegetation and Management Factor* ranged from 0 (zero) to 0.3066 (Figure 2.5). As mentioned before, values closer to zero are indicative of very well protected soils; in contrast, values closer to one indicate very poor protection (DESMET & GROVERS, 1996). The highest C-factor values (~0.30) for the Brazilian Cerrado were associated with semi-perennial crops. These systems are located mostly in the states of São Paulo (SP), Minas Gerais (MG), Mato Grosso do Sul (MS) and Goiás (GO) (Figure 2.5). Areas with C-factors of 0.10 are also found in Minas Gerais, Mato Grosso do Sul, and São Paulo states, occupied by silviculture and perennial crops. In general, conventional tillage, with plowing and disking, is adopted in most agricultural systems in Brazil, facilitating erosion processes (IBGE, 2006). Annual crops have a lower C-factor value (0.08) because over 50% of their area is managed by conservation tillage practices, which significantly decrease soil losses (FREITAS & LANDRES, 2014). With regard to pasture, it was estimated, from experimental data, C-factor values of 0.061 and 0.007 for highly degraded and not degraded pastures, respectively (GALDINO, 2012). Assuming that approximately 80% of Cerrado's pasture has already endured some degree of degradation (PERON & EVANGELISTA, 2003), we adopted a C-factor value of 0.05 for all pasture area. Vast areas with C-factors between 0.08 and 0.05 are visible in all states covered by the Cerrado (Figure 2.5). Natural vegetation has the lowest C-factor values, indicating very good soil protection; most of these lands are in the MATOPIBA region, North of Cerrado biome.

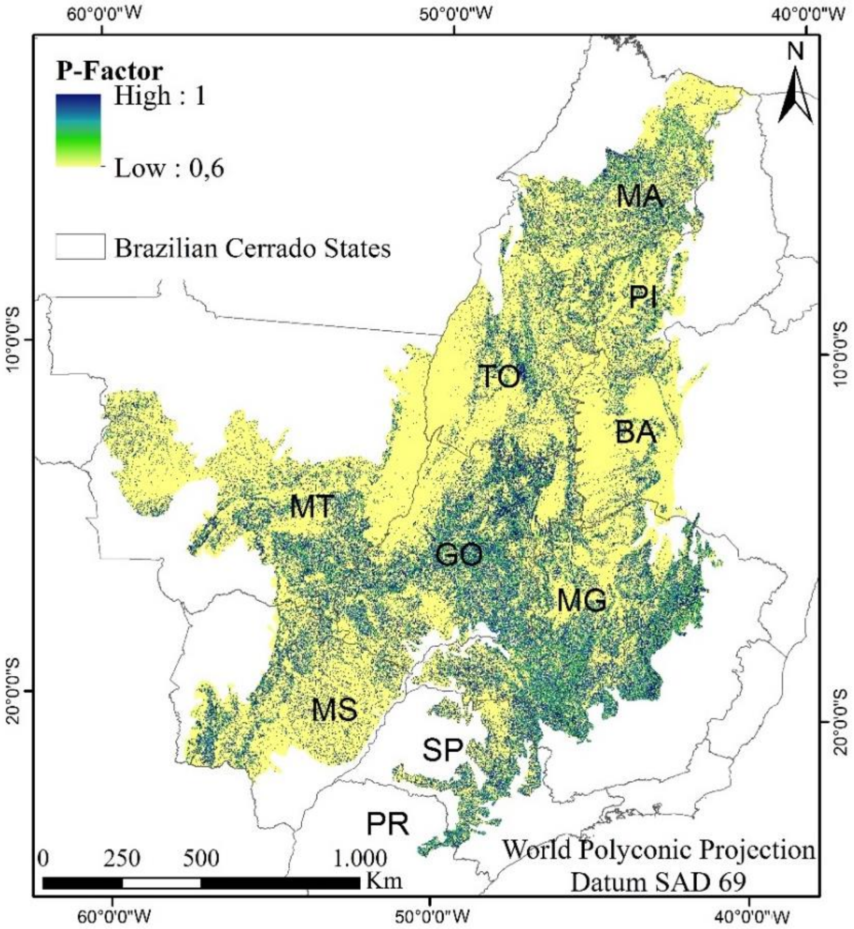
Figure 2.5 Soil cover and management factor (C) map of the study area. Brazilian Cerrado states are: Bahia (BA), Goiás (GO), Maranhão (MA), Minas Gerais (MG), Mato Grosso do Sul (MS), Mato Grosso (MT), Piauí (PI), Paraná (PR), São Paulo (SP) and Tocantins (TO).



Source: author’s production.

The P-factor varies according to soil conservation practices. In this study, P-factors were based on slope values to define conservation practices and varied from 0.6 to 1 (Figure 2.6). Values closer to 0.6 indicate more efficient conservation practices, and those closer to 1 indicates less appropriate conservation practices. In general, P-factor values were closer to 1 in most steep areas (undulating and strongly undulating relief).

Figure 2.6 Soil supporting practice factor (P) map of the study area. Brazilian Cerrado states are: Bahia (BA), Goiás (GO), Maranhão (MA), Minas Gerais (MG), Mato Grosso do Sul (MS), Mato Grosso (MT), Piauí (PI), Paraná (PR), São Paulo (SP) and Tocantins (TO).



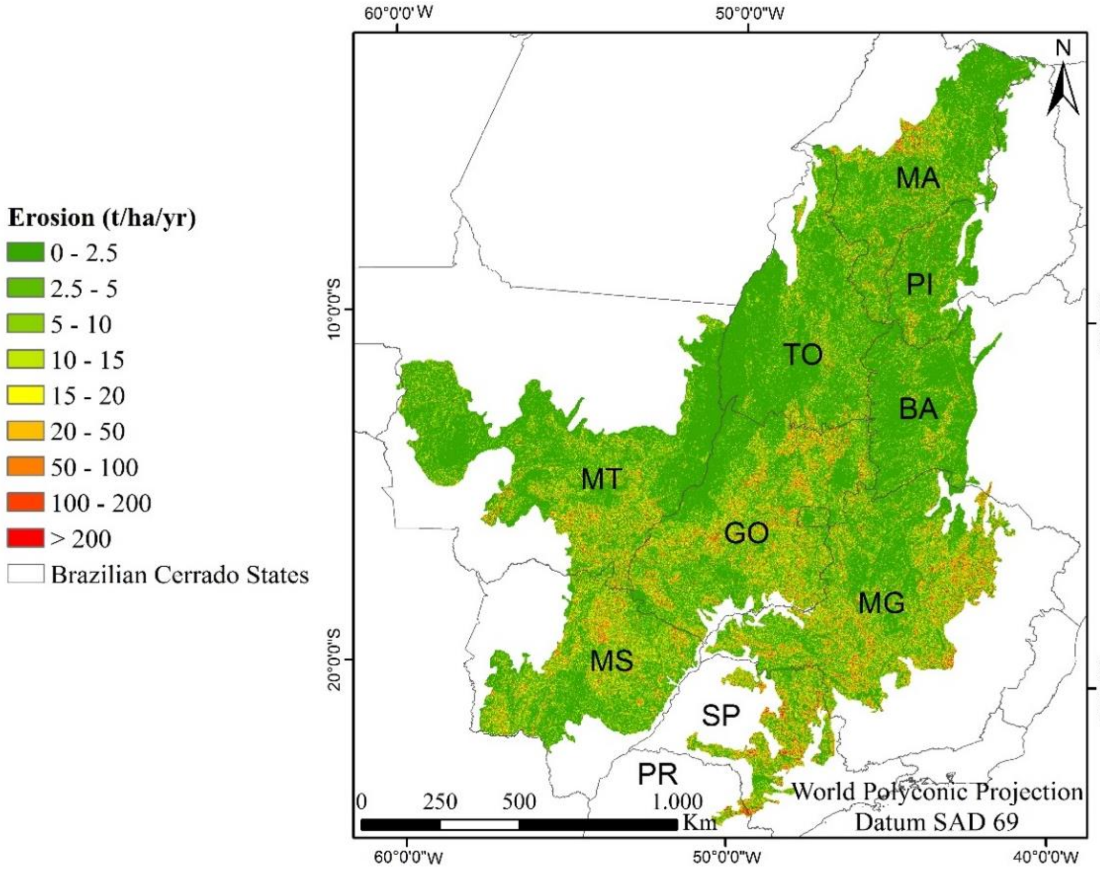
Source: Author's production.

The Revised Universal Soil Loss Equation was originally used for estimating average annual soil loss based on sample plot data (WISCHMEIER & SMITH, 1978; LU et al., 2004). With a integration of RUSLE and GIS, soil loss rates were quantified in a spatially explicit approach. Also, interpretative maps, as well as a final map of average annual soil loss, were produced based on 2000, 2010 and 2012 land-use maps for the Brazilian Cerrado. The use of GIS made it possible to manage and analyse data from different formats, qualities, projections and spatial resolutions. However, uncertainties regarding data sources may compromise soil erosion estimates. Combined with low resolution dataset, such uncertainties make it difficult to get better erosion estimates. A 94 m-resolution was used to calculate all RUSLE factors. It is, therefore, possible that the values of these parameters were underestimated. Unfortunately, whereas better resolutions are preferable and available for smaller areas in Brazil, data of higher resolution are scarces for large areas.

In summary, this study provides a potential estimate of soil loss in the Brazilian Cerrado based on the combination of RUSLE and GIS. Its results can provide support to establish an environmental conservation plan where crop farms and silviculture operations may become active agents of soil erosion.

In general, the average estimated rates of soil loss for the Cerrado were 10.4 $t.ha^{-1}.yr^{-1}$ (2000), 11.6 $t.ha^{-1}.yr^{-1}$ (2010), and 12.0 $t.ha^{-1}.yr^{-1}$ (2012), which may be considered moderate (FAO, 1967; PANDEY et al. 2007). The values estimated in our analyses are consistent with those observed by TRABAQUINI et al. (2012), who found an average rate of soil loss of 12.5 $t.ha^{-1}.yr^{-1}$ for a watershed with different land uses (crops, pasture, and natural vegetation) within of the Cerrado region. Figure 2.7 shows the Map of Average Soil Loss, taking 2010 as the reference year, which identifies the areas most vulnerable to high rates of soil erosion, which occur mainly in São Paulo (SP), Minas Gerais (MG), Goiás (GO), Mato Grosso do Sul (MS) and Mato Grosso (MT) states. As expected, the areas with very high annual soil loss (>50 $t.ha^{-1}.yr^{-1}$) are concentrated in regions with steep slopes and where pasture, crops, and silviculture are predominant.

Figure 2.7 Map of average soil loss in 2010 of the study area. Brazilian Cerrado states are: Bahia (BA), Goiás (GO), Maranhão (MA), Minas Gerais (MG), Mato Grosso do Sul (MS), Mato Grosso (MT), Piauí (PI), Paraná (PR), São Paulo (SP) and Tocantins (TO).



Source: Author's production.

Table 2.5 shows the spatial distribution of different erosion classes. *Soils with reduced erosion loss* cover large areas and are found in most of the Cerrado (80%). They are especially associated with the natural vegetation that provides good soil protection, and low LS-factor (69.73%) related to flat and gently undulating relief. Respectively, 16% and 4% of the Cerrado area is considered to be in *moderate soil loss zones* and *high soil loss zones*, the latter where steeper slopes occur. In addition, a significant soil loss associated with farm and silviculture land is observed. The most critical land use and land cover units are silviculture, semi-perennial and perennial crops, that combined with the practice of conventional tillage caused soils to suffer high losses. In quantitative terms, the average soil loss rates were 33.9 $t.ha^{-1}.yr^{-1}$ (2000), 35.3 $t.ha^{-1}.yr^{-1}$ (2010), 38.3 $t.ha^{-1}.yr^{-1}$ (2012) for silviculture, 43.8 $t.ha^{-1}.yr^{-1}$ (2000), 40.0 $t.ha^{-1}.yr^{-1}$ (2010), and 43.1 $t.ha^{-1}.yr^{-1}$ (2012) for semi perennial crops, and 29.4 $t.ha^{-1}.yr^{-1}$ (2000), 28.1 $t.ha^{-1}.yr^{-1}$ (2010), and 31.4 $t.ha^{-1}.yr^{-1}$ (2012) for perennial crops. The lowest values were obtained for annual crops with 11.2 $t.ha^{-1}.yr^{-1}$ (2000), 11.1 $t.ha^{-1}.yr^{-1}$ (2010), 11.5 $t.ha^{-1}.yr^{-1}$ (2012), mainly due to no tillage practices, followed by pasture with 14.2 $t.ha^{-1}.yr^{-1}$ (2000), 14.6 $t.ha^{-1}.yr^{-1}$ (2010), and 14.9 $t.ha^{-1}.yr^{-1}$ (2012).

Table 2.5 Interval of soil losses estimated for the Brazilian Cerrado, according to FAO (1967).

Soil loss zone	Soil loss interval ($t.ha^{-1}.yr^{-1}$)	Area (%) em 2000	Area (%) em 2010	Area (%) em 2012
Low	0 – 2.5	55.89	52.89	52.40
	2.5 – 5	14.44	14.99	15.03
	5 – 10	11.65	12.24	12.36
Moderate	10 – 15	5.09	5.47	5.53
	15 – 20	3.02	3.25	3.31
	20 – 50	6.26	6.92	7.02
High	50 – 100	2.23	2.55	2.59
	100 – 200	0.92	1.09	1.12
Very high	≥200	0.50	0.61	0.64

These results can guide regional planning for soil conservation and environmental management, as well as aid in the selection of control practices that are better suited to each land use system. With the exception of annual crop areas, all farm areas and silviculture lands showed average soil loss ranging from moderate to high. Moreover, agricultural expansion at expense of natural vegetation and agricultural intensification toward fragile soils significantly contribute to greater soil erosion loss over time, given that a large part of the Cerrado is highly susceptive to it. This is most prominent in the North region corresponding to MATOPIBA, where deforestation rates have been very high and soils are very much sandy with considerable erosion potential (MMA, 2011).

2.4 CONCLUSIONS

The methodology applied for estimating annual soil loss and its spatial distribution (RUSLE integrated into GIS framework) in the Brazilian Cerrado, showed good precision. It was possible to identify the areas most susceptible areas to water erosion, which is important provide support to define recovery and conservation plans where agriculture and silviculture may become agents of soil erosion. Even though the results obtained were good, a spatial resolution of 94 meters can underestimate soil loss particularly in areas where gully erosions are dominant.

The average estimated rate of soil loss was low with 10.4 $t.ha^{-1}.yr^{-1}$ (2000), 11.6 $t.ha^{-1}.yr^{-1}$ (2010), and 12.0 $t.ha^{-1}.yr^{-1}$ (2012), for the total Cerrado area. Areas most vulnerable to erosion are mainly where steeper slope areas combine with pasture, crops, and silviculture land uses. A large part of the total Cerrado area (80%) is under low soil loss, while 16%, and 4% are under moderate, and high soil loss, respectively.

The results showed that, with the exception of annual crops and pasture that showed low average soil loss, all farms and silviculture areas are under moderate soil loss. Good crop management practices, such as no-tillage, terrace and green fertilizers, in fragile soils regions, and the maintenance of the litter layer on the soil cover, are important factors that may hinder soil loss processes in the Brazilian Cerrado and help maintain and improve land productivity, therefore ensuring that national and international food demands are met.

CHAPTER 3 - AGRICULTURAL INTENSIFICATION AND EXTENSIFICATION AS CAUSES OF SOIL NITROGEN MINING IN BRAZIL

3.1 INTRODUCTION

Land-cover change is the major driver of global environmental change (TURNER II et al., 2007) and land use expansion upon natural ecosystems is the most important form of land-based change. Such conversion has supported global population growth by providing food, fiber, and other benefits (LAMBIN & MEYFROIDT, 2011). Negative impacts can, though, be identified. In tropical regions new agricultural lands have mainly established at the expense of forest, savannah, and steppes (LAMBIN et al., 2003), raising concerns about biodiversity loss, increases in greenhouse gas emissions and the exhaustion of environmental services. Action towards a sustainable landscape management, harmonizing food production and environmental conservation, might address the intensification of agriculture (LAMBIN & MEYFROIDT, 2011; TILMAN et al., 2011).

Agricultural intensification aims to enhance yields of existing crops. In general, this is accomplished by using more fertilizers, irrigation, chemical products for pests and weed control, mechanization, and genetically improved cultivars. That should reduce, at local and regional scales, the pressure over natural ecosystems (FOLEY et al., 2011). Although the scientific literature discusses whether agricultural intensification effectively spares natural lands (BALMFORD et al., 2005; MATSON & VITOUSEK, 2006; RUDEL et al., 2009; LAMBIN & MEYFROIDT, 2011; BARRETO *et al*., 2013; STRASSBURG et al., 2014; LAPOLA et al., 2010), productivity gains are expected to meet the global food demand for the coming decades (TILMAN et al., 2011; FOLEY et al., 2011). The question is how to allocate the increasing demand for food production - by area expansion or intensification? Either way, tropical regions are natural candidates. Most of the projected growth in global population is expected to happen in those regions, because of their climate – a basic requirements for increasing productivity per area per year – and due to the availability of arable lands (ALEXANDRATOS & BRUINSMA, 2012; TILMAN et al., 2011; LAMBIN & MEYFROIDT, 2011).

Agriculture in Brazil has been historically known for driving anthropogenic use of land over natural vegetation. However, in the recent years, Brazilian agriculture has also strengthened productivity through intensification (DIAS et al., 2013; OECD/FAO, 2015), improving its ‘tropical agriculture’ substantially and becoming the second largest agricultural exporter in the world (OECD/FAO, 2015). The increase in agricultural productivity in Brazil has occurred mainly due to two reasons. The first of them is the expansion of croplands over degraded pasture areas, which happened on agriculturally consolidated regions (BARRETO et al., 2013; DIAS et al., 2016). Additionally, productivity has rised due to the increased investments in agricultural technologies and practices, such as improvement of crop cultivars (e.g., soybean varieties more efficient on biological nitrogen fixation in tropical conditions), no-tillage systems, liming, and the large use of fertilizers, speciallly nitrogen and phosphorus (OECD/FAO, 2015). Notably, the increase in agriculture productivity and production in Brazil is projected to contribute with 40% of global food by 2050 (OECD/FAO, 2015).

The Cerrado savanna, a biome with a total area of 206 Mha, is currently responsible for 70% of the country’s food production (WICKRAMASINGHE, 2012) and 44% of its area used as agricultural land, at the expense of natural vegetation (LAHSEN et al., 2016). Between 2009 and 2010, the Cerrado accounted for 95% of the cotton, 54% of soybeans, 55% of beef, 43% of sugarcane, and 41% of the milk produced in Brazil (LAHSEN et al., 2016; IBGE, 2010a). Besides, this biome plays an important role in bioenergy production, through ethanol and biomass from sugarcane and eucalyptus planted forests (LEITE et al., 2009, BALCOMBE & RAPSOMANIKIS, 2008). Due to its high production capacity, the Cerrado has been pointed out one of the world’s greatest breadbasket (THE ECONOMIST, 2010).

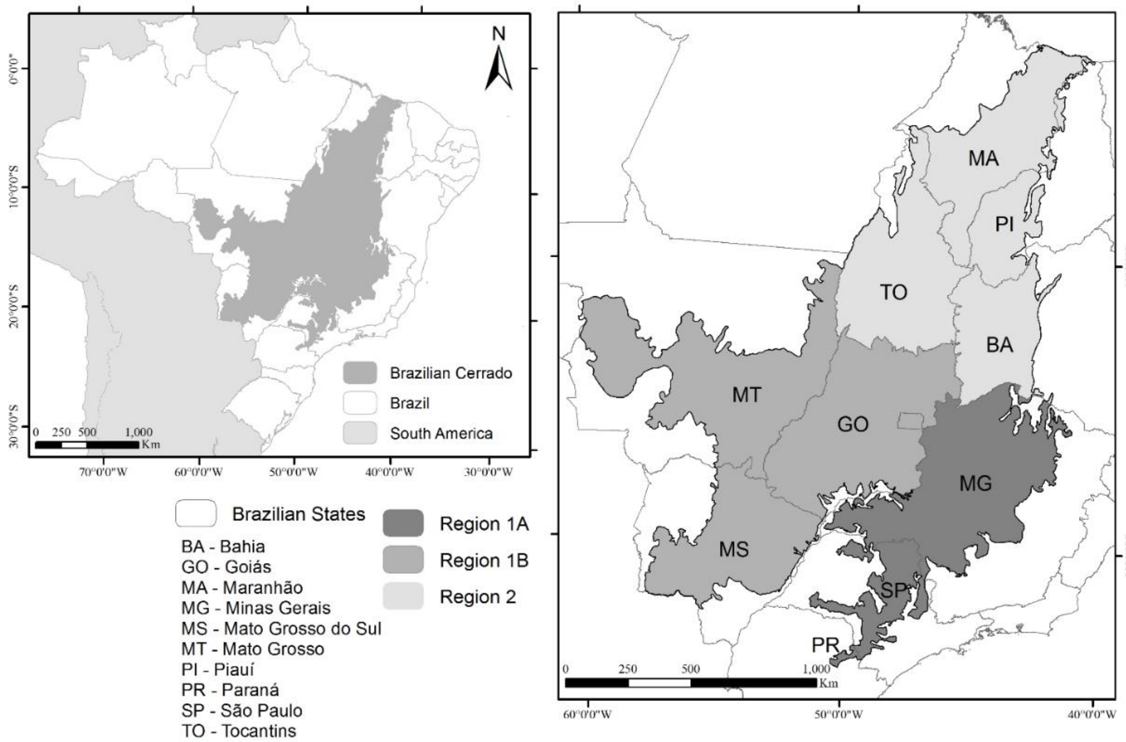
Sustainable landscape management foresees that land-based activities and environmental conservation and ecosystem services are in harmony. Ideally, land use status indicators should integrate various components of the landscape. Nitrogen flow and its management are seen as an integrative indicator of production efficiency and environmental risks, or benefits (SUTTON et al., 2014). The Cerrado is a hotspot of agricultural production and the processes of intensification and extensification are historically related to the expansion and consolidation of this activity in the region. Nitrogen is one of the most important agriculture yield-enhancing factor, an essential element in securing food production (SUTTON et al., 2014). However, many environmental issues can arise due to nitrogen unbalance. Low levels of nitrogen can bring down crop productivity and induce soil degradation, while an excessive amount of it can lead to environmental pollution such as eutrophication of freshwater and estuarine ecosystems, groundwater contamination, soil degradation and air pollution. Therefore, unbalanced nitrogen can negatively impact human health, economic prosperity, and food security (ZHANG et al., 2015; GALLOWAY et al., 2003; GALLOWAY et al., 2008; CLARK et al., 2008; AUSTIN et al., 2013).

Previous studies have focused on how agriculture has affected biodiversity (RATTER et al., 1997; MYERS et al., 2000), water resources (COSTA et al., 2003; FERREIRA et al., 2011), and carbon emissions (BUSTAMANTE & FERREIRA, 2010). However, there is a scientific gap on the influence of agricultural intensification and extensification over nitrogen cycle in the Cerrado. Moreover, only a few studies made use of a spatially explicit database to estimate nitrogen flows in agricultural lands at regional scale (LESSCHEN et al., 2007; LASSALETA et al., 2012). More frequently, studies regard a country or a whole region homoniously (FILOSO et al., 2006; MARTINELLI et al., 2012). Here, we present a spatially explicit assessment of nitrogen flows in agricultural regions of the Brazilian Cerrado, where the processes of intensification and extensification are identified. To achieve that, we produced spatio-temporal nitrogen balances for 2000, 2010, and 2012. The balances include the main nitrogen inputs and outputs covering a significant part of the nitrogen cycle and its possible imbalances. Ultimately, this study aims to inform the discussion on alternative pathways to improve agricultural policy and the sustainable development of agriculture in Brazil.

3.2 MATERIALS AND METHODS

To conduct this study, we divided the Brazilian Cerrado into two agricultural regions according to land-use dynamics: *Region 1*, encompasses regions with consolidated agriculture (PR, SP, MG, MS, MT and GO) and *Region 2* – encompasses the agricultural frontier region (MA, TO, PI and BA) with the largest areas of natural vegetation. As nitrogen inputs and outputs are directly related to land-use types, the *Region 1* was divided into two parts: *Region 1A* with the largest areas of semi perennial, perennial, and silviculture lands (PR, SP, MG); and *Region 1B* with has the largest areas of annual crops and pasture lands (MS, MT, GO) (Figure 3.1).

Figure 3.1 Brazilian Cerrado biome totally or partially encompasses the states of Maranhão (MA), Piauí (PI), Tocantins (TO), Bahia (BA), Mato Grosso (MT), Goiás (GO) Minas Gerais (MG), Mato Grosso do Sul (MS), São Paulo (SP) and Paraná (PR).The biome was divided into agriculturally consolidated regions (Region 1Aand 1B) and the agricultural frontier region (Region 2).

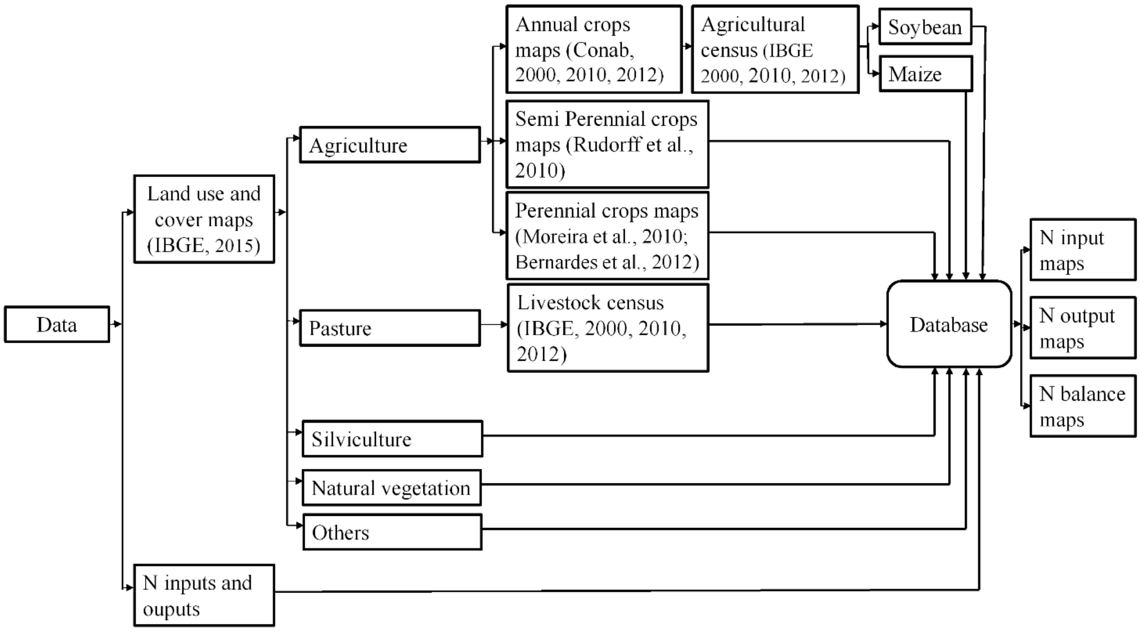


Source: Author’s production.

Land-use database

The spatio-temporal nitrogen balance in the Brazilian Cerrado was computed based on the integration of different land use and cover spatially explicit data, nitrogen data, and data from agriculture and livestock census. Annual crops considered were soybean and maize, semi perennial crops (sugarcane), perennial crops (coffee and citrus), pasture, and silviculture. All data were compiled in a GIS (Geographic Information System) environment and organized in a Geographic Database, as shown in Figure 3.2 flowchart.

Figure 3.2 Flowchart of the mapping protocol used for the production of the spatio-temporal soil nitrogen balance for the Brazilian Cerrado in the years 2000, 2010, and 2012.



Source: Author's production.

This study used, the land use and cover maps were produced by the Brazilian Institute for Geography and Statistics (IBGE, 2015). They include 14 different land-use and land-cover classes considering the years of 2000, 2010, and 2012. All three original maps were reclassified to emphasize the classes of interest:

1) *Agriculture*: agricultural areas, mosaic of agricultural areas with remaining forest, mosaic of forest vegetation with agricultural areas, and mosaic of grassland with agricultural areas;

2) *Pasture*: planted and managed pastureland (e.g. cattle-ranching);

3) *Silviculture*: planted and managed forests with exotic species (e.g. eucalyptus, pinus);

4) *Natural vegetation*: natural vegetation (e.g. forest vegetation, grassland, wetland);

5) *Others*: urbanized zones, road systems, non-agricultural systems, continental water bodies, coastal water bodies, and uncovered lands (e.g. rocky outcrops and sand dunes);

In order to separate agricultural areas from forest vegetation and grassland, the *Agriculture* class divided into three sub-classes: annual (grains), semi perennial (sugarcane), and perennial (coffee and citrus). For this purpose, we multiplied *Agriculture* class by spatially explicit data on grains (CONAB, 2001, 2011a, 2013a), sugarcane (RUDORFF *et al*., 2010), coffee (BERNARDES *et al*., 2012; MOREIRA *et al*., 2010; CONAB, 2011b, 2013b) and citrus (MOREIRA *et al*., 2010) production. As a result, it *Annual*, *Semi perennial* and *Perennial* agricultural classes were obtained, whereas residues were reclassified as *Natural vegetation*. Finally, all three maps (2000, 2010, and 2012) ended up with seven classes: *Pasture*, *Natural vegetation*, *Silviculture*, *Annual crops*, *Semi perennial crops*, *Perennial crops* and *Others*.

The land use and cover maps (for 2000, 2010 and 2012) were decomposed into a regular grid of 5km x 5km. After that, the percentages of each class were computed for each grid (85,382 grids in total). As the *Annual Crops* class does not discriminate soybeans and maize distribution, the data for soybean and maize areas were obtained from the Municipality-based Agricultural Census (IBGE, 2000a, 2010a, 2012a). These data were converted from polygon-based information into grid cells of 5km x 5km, as in Espindola *et al*. (2012). The computation assumed that soybean and maize were uniformly distributed over the *Annual Crops* class. That way, we found the proportion of soybean and maize in each grid. Municipality-based Livestock Census data provided the number of cattle heads (IBGE, 2000b, 2010b, 2012b), while the agricultural censuses from 1996 and 2006 provided the farm areas (IBGE, 1996, 2006). In addition, the ratios obtained from of those data were used to calculate the bovine stocking rates (head.ha^{-1}) for *Pasture* class for the same period.

In order to learn about land-cover dynamics in the Brazilian Cerrado, we calculated the areas of land-cover classes that underwent transition from one land-cover type to another between 2000 and 2012. For that, we built a transition matrix obtained by calculating the areas that underwent a transition from a land-cover class i to another class j in a given region (Müller-Hansen *et al*., 2016). The transition matrix of one region $T(t)$ is an $n \times n$ matrix with elements $Tij\ (t),\ i, j \in \{1, \ldots, n\}$, where n corresponds to the number of land-cover classes. The transition matrix depends upon time and indicates that the transition rates generally are not constant over time, which means that the system is not stationary (MÜLLER-HANSEN *et al*., 2016). However, for ease of notation, we omitted the time dependence effect. We estimated Ti,j from land use and cover maps containing all seven (n) classes. Then, in a GIS environment, we combined the information contained in the two land cover maps from 2000 and 2012 into a data set and obtained the areas of land-cover classes that underwent transition.

Nitrogen database

Soil nitrogen balance – We used the soil nitrogen balance for the land-use systems in the Brazilian Cerrado found in the literature (LIU *et al.*, 2010, STOORVOGEL & SMALING, 1998; SMALING *et al.*, 1993). For the analyses we assumed that the soil nitrogen balance is the difference between total nitrogen inputs (IN) and outputs (OUT) on agricultural lands; where IN is divided into four factors and OUT is divided into five factors as shown in Eqs 1 and 2. This approach does not take into account the amount of nitrogen stored in the soil. Soil cover considered were pasturelands, annual crops, semi perennial crops, perennial crops, and silviculture. A nitrogen positive balance, or surplus, indicates that inputs that are in excess in agricultural lands, while negative balance indicates excess outputs or nitrogen soil depletion.

$$IN = IN_{fer} + IN_{man} + IN_{dep} + IN_{fix} \qquad 3.1$$

$$OUT = OUT_{crop/prod} + OUT_{res/man} + OUT_{lea} + OUT_{gas} + OUT_{ero} \qquad 3.2$$

Where, for nitrogen:

IN and OUT - total input and output; IN_{fer}: mineral fertilizer input; IN_{man}: manure input in crops and silviculture (in pasture IN_{man} is not considered an input because it is an internal process); IN_{dep}: wet and dry atmospheric deposition; IN_{fix}: biological fixation.

$OUT_{crop/prod}$: output from crops, harvested wood and animal products; $OUT_{res/man}$: output from crops, wood residues and manure exported from pasture; OUT_{lea}: output from leaching; OUT_{gas}: output from gaseous losses; and OUT_{ero}: output from erosion.

All nitrogen inputs and outputs are expressed in kilograms per hectare per year ($kgN.ha^{-1}.yr^{-1}$). Table 3.1 presents the average and standard deviation values of nitrogen inputs and outputs used when calculating of soil nitrogen balance. All values were obtained from literature. OUT_{ero}, was presented separately in item "Nitrogen Outputs". In general, nitrogen inputs and outputs vary in space and time under Brazilian field conditions due to a diversity of landscape physical elements, soil chemicals variety, and climate. However, in this study, a generalization was necessary for establishing soil nitrogen balance due to the large dimension of the study area (206 Mha) and the annual nature of most of the nitrogen input and output data.

Crops productivity was based on Municipality-based Agricultural Productivity (IBGE 2000c, IBGE 2010c, IBGE 2012c). Silviculture productivity were based on Annual Statistical Reports (ABRAF, 2006; ABRAF, 2013) of Silviculture Science and Research Institute (IPEF). For silviculture productivity were considered independent producers (small and medium producers) and large producers, that one associated to ABRAF (Brazilian Association of Planted Forest Producers). At the beginning of the year 2000 about 22% of planted forest was from independent producers and 79% from large producers (ABRAF, 2006). In general, independent producers have lower productivity gains. In 2000, silviculture productivity was about 20-25 $m^3.ha^{-1}.yr^{-1}$ for independent producers, while for large producer it was 32 $m^3.ha^{-1}.yr^{-1}$. Between 2010 and 2012, about 60% of planted forest was from independent producers with productivity of 25 $m^3.ha^{-1}.yr^{-1}$, whereas 40% of forest planted was from large producers with productivity of 40 $m^3.ha^{-1}.yr^{-1}$ (MCTIC, 2017; ABRAF, 2013). The Table 3.1 also presents the productivity used in this study for crops and silviculture.

Table 3.1 Average rates and standard deviation of nitrogen inputs and nitrogen output fluxes (kgN.ha^{-1}.yr^{-1}) for crops, pasture, and silviculture in the Brazilian Cerrado.

Input	**Land use**	**Agrosystem**	**Productivity (Mg.$ha^{-1}yr^{-1}$ or head. $ha^{-1}yr^{-1}$)**	**Average rate and standard deviation[1] (kgN.$ha^{-1}yr^{-1}$)**	**Reference**
IN1: Mineral Fertilizer	Annual crop	Soybean	2.5 (2000)	0	Mendes et al. (2007); Crispino et al. (2001)
			2.9 (2010)		
			2.9 (2012)		
		Maize	2.7 (2000)	55 (7.1)[1]	Coelho and França 1995
			4.3 (2010)	112.5 (30.7)	Alves et al. (2006); Cruvinel et al. (2011); Ribeiro et al. (1999); Mar et al 2003
			5.1 (2012)		
	Semi perennial crop	Sugarcane	59.6 (2000)	70 (14.1)	Vitti et al (2002); Rosseto and Dias (2005)
			74.1 (2010)	102.5 (26.3)	Vitti et al. (2007); Vitti et al. (2002); Cantarella et al. (2008); Silva et al 2017
			69.9 (2012)		
	Perennial crop	Coffee	1.2 (2000)	273.3 (7.1)	Mesquita et al. (2016); Boaretto et al. (2007); Fenilli et al. (2008); Cantarella et al. (1992); Cantarella and Quaggio (1996)
			1.0 (2010)		
			1.0 (2012)		
		Citrus	18.9 (2000)	200.0	
			16.9 (2010)		
			17.8 (2012)		
	Silviculture	Silviculture	25.0 (2006)	78.0 (17.4)	Laclau et al. (2010); Barreto et al. (2008); Pulito et al. (2015)
			31.4 (2010)	125.0 (27.8)	
			31.4 (2012)		
	Pasture	Pasture	-	0	Santos et al. (2002); Boddey et al. (2004); Cruvinel et al. (2011)
IN2: Organic inputs / Manure from indigenous cattle grazing outside the farm	Semi perennial crop	Sugarcane	59.6 (2000)	83.0 (19.2)	Paredes et al. (2014); Oliveira et al. (2013); Canisares et al. (2017); Carmo et al. (2013)
			74.1 (2010)	103.3 (23.9)	
			69.9 (2012)		

Table 3.1 Average rates and standad deviation of nitrogen inputs and nitrogen output fluxes (kgN.ha^{-1}.yr^{-1}) for crops, pasture, and silviculture in the Brazilian Cerrado (continuated).

Input	**Land use**	**Agrosystem**	**Productivity (Mg.ha^{-1}yr^{-1} or head. ha^{-1}yr^{-1})**	**Average rate and standard deviation[1] (kgN.ha^{-1}yr^{-1})**	**Reference**
IN3: Wet and dry deposition	All	All	-	5.5	Vet et al. (2013)
IN4: Biological N fixation	Annual crop	Soybean	2.5 (2000)	174.8 (12.0)	Boddey et al. (1984); Filoso et al. (2006); Alves et al. (2006); Alves et al. (2003)
			2.9 (2010)		
			2.9 (2012)		
		Maize	-	-	-
	Semi perennial crop	Sugarcane	59.6 (2000)	48.8 (12.4)	Oliveira et al. (1994); Martinelli et al. (2008)
			74.1 (2010)		
			69.9 (2012)		
	Perennial crop	Coffee and citrus	-	-	
	Silviculture	Silviculture	-	-	
	Pasture	Pasture	-	25.0 (14.1)	Filoso et al. (2006); Boddey and Victoria (1986)

Table 3.1 Average rates and standad deviation of nitrogen inputs and nitrogen output fluxes ($kgN.ha^{-1}.yr^{-1}$) for crops, pasture, and silviculture in the Brazilian Cerrado (continuated).

Output	Land use	Agrosystem	Productivity ($Mg.ha^{-1}yr^{-1}$ head. $ha^{-1}yr^{-1}$)	Average rate and standard deviation[1] ($kgN.ha^{-1}yr^{-1}$)	Reference
OUT1: Harvested Crop Parts / Animal Products	Annual crop	Soybean	2.5 (2000)	147.7 (18.5)[1]	Alves et al. (2006); Hungria et al. (2003); Borkert et al. (1994)
			2.9 (2010)	171.3 (21.5)	
			2.9 (2012)		
		Maize	2.7 (2000)	44.3 (7.7)	Alves et al. (2006); Coelho et al. (2003)
			4.3 (2010)	83.6 (14.5)	
			5.1 (2012)		
	Semi perennial crop	Sugarcane	59.6 (2000)	46.1 (9.4)	Shultz et al. (2015); Coelho et al. (2003); Vitti et al. (2002)
			74.1 (2010)	56.9 (11.6)	
			69.9 (2012)		
	Perennial crop	Coffee	1.2 (2000)	146.4	Fenilli et al. (2008); Boaretto et al. (2007); Boaretto et al. (2013)
			1.0 (2010)		
			1.0 (2012)		
		Citrus	18.9 (2000)	50.7 (11.2)	
			16.9 (2010)		
			17.8 (2012)		
	Silviculture	Silviculture	25.0 (2006)	221.7 (84.3)	Barreto et al. (2012)
			31.4 (2010)	354.7 (134.6)	
			31.4 (2012)		
	Pasture	Pasture	0.42 (2000)	4,7	Boddey et al. (2004)
			0.52 (2010)	5,82	
			0.54 (2012)	6,05	
OUT2: Removed Crops Residues / Manure leaving the farm	All	All	-	0	Smaling et al. (2008)

Table 3.1 Average rates and standad deviation of nitrogen inputs and nitrogen output fluxes (kgN.ha^{-1}.yr^{-1}) for crops, pasture, and silviculture in the Brazilian Cerrado (continuated).

Output	Land use	Agrosystem	Productivity (Mg.ha^{-1}yr^{-1} head. ha^{-1}yr^{-1})	Average rate and standard deviation[1] (kgN.ha^{-1}yr^{-1})	Reference
OUT3: Leaching	Annual crop	Soybean	2.5 (2000)	0	Hungria et al. (2006)
			2.9 (2010)		
			2.9 (2012)		
		Maize	2.7 (2000)	16.0 (5.2)	Wilcke & Lilienfen (2005); Coelho et al. (2003); Alves et al. (2006)
			4.3 (2010)		
			5.1 (2012)		
	Semi perennial crop	Sugarcane	59.6 (2000)	4.6 (0.1)	Trivelin et al. (2002); Oliveira et al. (2002); Oliveira et al. (2000)
			74.1 (2010)		
			69.9 (2012)		
	Perennial crop	Coffee	1.2 (2000)	7.8 (4.5)	Bortolloto et al. (2012); Fenilli et al. (2008); Cantarella et al. (2003)
			1.0 (2010)		
			1.0 (2012)		
		Citrus	18.9 (2000)	36.0 (1.4)	
			16.9 (2010)		
			17.8 (2012)		
	Silviculture	Silviculture	25.0 (2006)	0	Laclau et al. (2010)
			31.4 (2010)		
			31.4 (2012)		
	Pasture	Pasture	0.42 (2000)	0	Costa (2006)
			0.52 (2010)		
			0.54 (2012)		

Table 3.1 Average rates and standad deviation of nitrogen inputs and nitrogen output fluxes ($kgN.ha^{-1}.yr^{-1}$) for crops, pasture, and silviculture in the Brazilian Cerrado (continuated).

Output	Land use	Agrosystem	Productivity ($Mg.ha^{-1}yr^{-1}$ head. $ha^{-1}yr^{-1}$)	Average rate and standard deviation[1] ($kgN.ha^{-1}yr^{-1}$)	Reference
OUT4: Gaseous losses	Annual crop	Soybean	2.5 (2000)	0	Hungria et al. (2006)
			2.9 (2010)		
			2.9 (2012)		
		Maize	2.7 (2000)	18.0 (9.0)	Alves et al. (2006); Zavaschi et al. (2014)
			4.3 (2010)		
			5.1 (2012)		
	Semi perennial crop	Sugarcane	59.6 (2000)	4.4 (4.4)	Silva et al. (2017); Carmo et al. (2013)
			74.1 (2010)		
			69.9 (2012)		
	Perennial crop	Coffee	1.2 (2000)	3.5 (1.0)	Fenilli et al. (2008); Dominghetti et al. (2016); Boaretto et al. (2013); Cantarella et al. (2003)
			1.0 (2010)		
			1.0 (2012)		
		Citrus	18.9 (2000)	26.6 (4.9)	
			16.9 (2010)		
			17.8 (2012)		
	Silviculture	Silviculture	25.0 (2006)	0	Laclau et al. (2010)
			31.4 (2010)		
			31.4 (2012)		
	Pasture	Pasture	0.42 (2000)	2,37	Boddey et al. (2004); Lessa et al. (2014)
			0.52 (2010)	2,94	
			0.54 (2012)	3,05	

Nitrogen Inputs – IN_{fer} for pasture was set at zero because nitrogen fertilizer addition is unusual (SANTOS et al. 2002; BODDEY et al., 2004) (Table 3.1). In silviculture, IN_{fer} was based on the average rate of nitrogen fertilizer to eucalyptus with full-rotation. The full-rotation eucalyptus considered showed a pattern ranging for a minimum of five years and a maximum of thirteen years (BARRETO et al., 2008). IN_{man} was considered only in semi perennial crops because application of organic manure, such as vinasse and filter cake, from sugar-ethanol industry is a common practice in Brazil. IN_{man} was set a zero for other crops and silviculture. IN_{dep} was based on modeled estimates of total wet and dry nitrogen (NO_y + NH_4) deposition from Vet et al. (2013). Vet et al. (2013) estimates nitrogen deposition based on data collected for two periods of 3 years: 2000 to 2002 and 2005 to 2007.

Nitrogen Outputs- $OUT_{crop/prod}$ for silviculture was based on the rate of nitrogen from harvested eucalyptus with the same rotation pattern as above (BARRETO et al., 2012) (see Table 3.1). In pasture areas, $OUT_{crop/prod}$ was estimated by multiplying the livestock density by the rate of accumulated nitrogen in live weight of animal. For the Brazilian Cerrado, the livestock density was calculated by multiplying the number of cattle heads from the Municipality-based Livestock Census of 2000, 2010, and 2012 (IBGE, 2000b, 2010b, 2012b) by the farm areas from the Agricultural Census of 1996 and 2006 (IBGE, 1996, 2006). Livestock density was 0.42, 0.52, 0.54 head.ha^{-1} in 2000, 2010, and 2012, respectively. The rate of accumulated nitrogen in live weigh of animal was obtained (2.8 kgN.ha^{-1}.yr^{-1}) from Boddey et al. (2004). The adopted value refers to the nitrogen accumulated in the 4 years of animal development (slaughter age). The resulting values for 2000, 2010, and 2012 are shown in Table 3.1.

$OUT_{res/man}$ was set at zero for crops and silviculture, because we assumed that residue removal is not a common practice, and for pasture, because it is not common to collect manure in the Brazilian Cerrado. OUT_{lea} was set at zero for pasture because nitrogen fertilizer application is not usual and leaching from manure is negligible (BODDEY et al., 2004). According to Laclau et al. (2010), leaching in silviculture is insignificant. For pasture, OUT_{gas} was estimated by multiplying livestock density (0.42, 0.52, and 0.54 for 2000, 2010, and 2012, respectively) by average animal nitrogen excretion rates (dung and urine) (36 kgN.ha^{-1}.yr^{-1}) (BODDEY et al., 2004). The result was then multiplied by the nitrogen emission rate from excreta (15.7%) (LESSA et al., 2014). Values obtained for the years 2000, 2010, and 2012 are displayed in Table 3.1.

OUT_{ero} was calculated by multiplying the soil erosion, presented in Chapter 2 for the years 2000, 2010, and 2012, by total nitrogen in soil (OLIVEIRA, 1999).

All nitrogen inputs and outputs were decomposed into a regular grid of 5km x 5km. Then, they were multiplied by land use percentage in each grid for 2000, 2010, and 2012. Finally, we calculated the difference between IN and OUT for agriculture and silviculture lands was calculated, resulting in soil nitrogen balances for the years 2000, 2010, and 2012.

The soil nitrogen balances and nitrogen flows were calculated at the regional scale for both agricultural consolidated regions (*1A* and *1B*) and the agriculture frontier (*Region 2*). The results we obtained are in $TgN.yr^{-1}$. Also, nalyses at a local scale also were performed to show spatial variation in the soil nitrogen balances and nitrogen flow rates. The obtained results are in $kgN.ha^{-1}.yr^{-1}$.

3.3 RESULTS

Farmland area took over natural vegetation in the Cerrado region (Table 3.2). During the studied period,such transition is primarily related to the expansion of pasturelands (82,047.79 km^2), annual crops (53,367.14 km^2), semi-perennial crops (24,275.97 km^2), perennial crops (3,059.52 km^2) and silviculture (2,253.08 km^2). Accordingly, the natural vegetation area was reduced by 166,244.55 km^2. The small difference between farmland expansion and natural vegetation reduction (1,241.05 km^2) was due to expansion of artificial areas, such as urbanized zones and no-agricultural systems. In pasturelands, livestock density increased from 0.42 in 2000 to 0.54 $head.ha^{-1}$ in 2012.

Table 3.2 Areas, in km^2 of natural vegetation, pasture, agricultural crops, and silviculture in the Brazilian Cerrado for the defined agricultural regions in 2000, 2010, and 2012.

Year	Natural Vegetation		Pasture		Annual		Semi Perennial		Perennial		Silviculture	
	km^2	(%)[a]	km^2	(%)[a]	km^2	(%)[a]	km^2	(%)[a]	km^2	(%)[a]	km^2	(%)[a]
Region 1[a]												
2000	164,628	7.98	195,679	9.49	20,178	0.98	15,925	0.77	6,555	0.32	12,881	0.62
2010	138,890	6.73	201,830	9.78	23,177	1.12	28,178	1.37	8,666	0.42	15,046	0.73
2012	137,764	6.68	198,171	9.61	23,781	1.15	31,808	1.54	9,396	0.46	14,969	0.73
Region 1B												
2000	402,640	19.5	433,375	21.0	65,209	3.16	2,277	0.11	0.08	0.00	3,381	0.16
2010	339,225	16.4	467,947	22.7	87,964	4.26	7,320	0.35	16.31	0.00	3,755	0.18
2012	333,617	16.2	459,975	22.3	98,304	4.77	10,670	0.52	84.49	0.00	3,601	0.17
Region 2												
2000	574,642	27.9	130,050	6.30	12,686	0.61	0.00	0.00	0.00	0.00	271	0.01
2010	508,510	24.7	180,479	8.75	27,672	1.34	0.00	0.00	0.00	0.00	229	0.01
2012	504,284	24.4	183,007	8.87	29,355	1.42	0.00	0.00	0.00	0.00	216	0.01
Total												
2000	1,141,910	55.4	759,106	36.80	98,074	4.75	18,202	0.88	6,555	0.32	16,534	0.80
2010	986,626	47.8	850,257	41.21	138,813	6.73	35,498	1.72	8,682	0.42	19,031	0.92
2012	975,666	47.3	841,153	40.77	151,441	7.34	42,478	2.06	9,481	0.46	18,787	0.91

[a]Value relative to the Brazilian Cerrado total area (2,063,727.5 km^2).

Between 2000 and 2012, pastureland expansion took place mainly over natural vegetation (Table 3.3), but this class was also the main source of land to all crops and silviculture expansion. Annual, semi perennial and perennial crops, along with silviculture, expanded vigorously over pasturelands. The transition matrix also reveals a land-use competition process where bidirectional transitions are observed between annual, semi perennial and perennial crops. This process is observed among silviculture, pastureland and natural vegetation as well as.

Table 3.3 Transition matrix in the period 2000-2012 for the Brazilian Cerrado. Values in area (km^2).

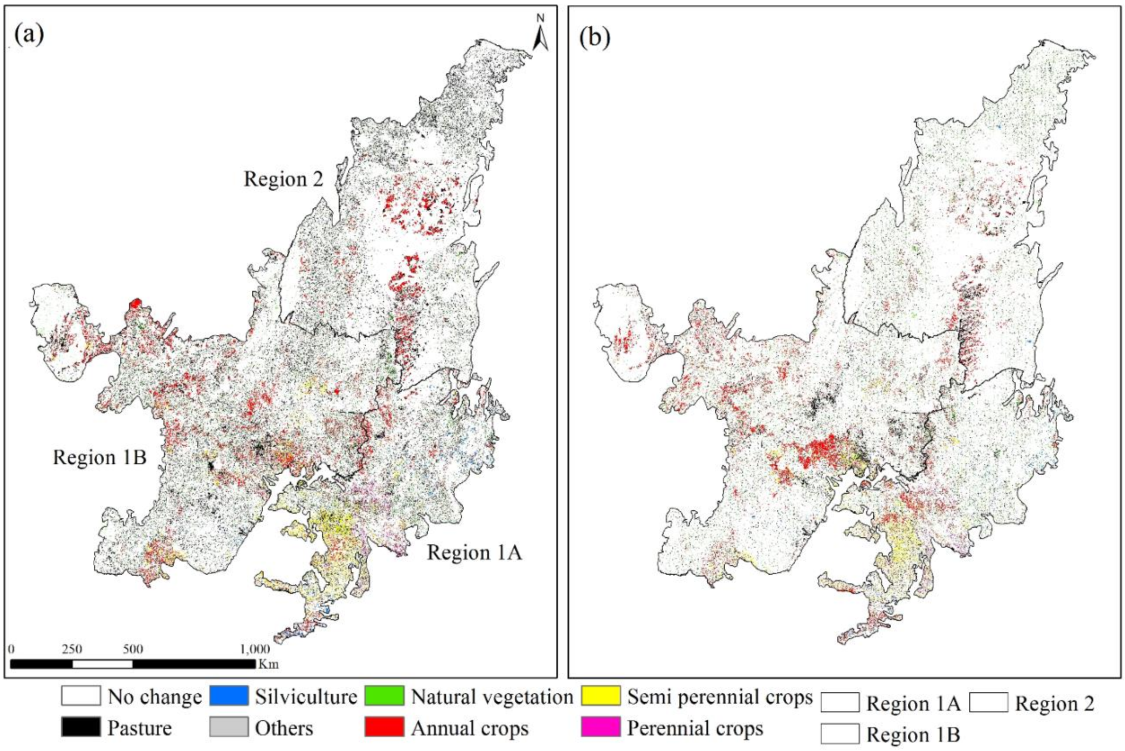
		"To" 2012							
		Pasture	Natural Vegetation	Annual	Semi Perennial	Perennial	Silviculture	Others	Total 2000
"From" 2000	Pasture	639,632	22,658	69,662	17,574	3,609	4,655	1,396	759,189
	Natural Vegetation	165,352	946,126	25,523	1,054	492	1,737	2,203	1,142,491
	Annual	29,712	5,986	53,909	7,689	303	168	301	98,071
	Semi Perennial	1,725	105	877	15,348	47	47	51	18,202
	Perennial	711	83	298	436	4,985	19	19	6,555
	Silviculture	3,255	271	554	210	75	12,140	26	16,534
	Others	853	1,015	603	163	100	18	19,927	22,682
	Total 2012	841,245	976,247	151,429	42,478	9,614	18,788	23,925	2,063,727

At the intraregional scale, land use dynamics showed that total area of pasture, crops and silviculture in both *Region 1A* and *Region 1B* increased by 10.71% and 13.56% in 2000 and 2012, respectively. In *Region 2* this growth was even more expressive reaching 48.65% (Table 3.2). These results indicate that *Regions 1A* and *1B* are agriculturally consolidated, which can be attributed to the largest natural-anthropic conversions that occurred before 2000, and the bidirectional transitions between uses that have recently become more significant. *Region 2* may be considered an agricultural frontier because its transitions are essentially unidirectional. Natural vegetation has been converted into agriculture and pasture, and little or no competition is observed between different uses. These results indicate a spatially heterogeneous process of intensification, directly linked to the availability of natural areas for conversion.

In *Regions 1A* and *1B,* pasture has been historically predominant (Table 3.2). However, pasture had only a subtle increase in the period from 2000 to 2010 (6.47%) when main changes were associated to agricultural annual (e.g. soybean) and semi perennial (sugarcane) expansion of 95.02% and 30.16%, respectively (see also Figure 3.3). This process became more intense in recent years, from 2010-2012, when pasture and silviculture were reduced by 1.74% and 1.23%, respectively.

In *Region 2*, natural vegetation prevails (Table 3.2). However, it suffered a strong reduction (11.51%) between 2000 and 2010, mostly due to pasture and annual crops expansion, which increased significantly by 38.78% and 118.13%, respectively (see also Figure 3.3). The expansion continued over the next two years (2010-2012) although not through land-use competition. Pasture and annual crops expansion occurred over natural vegetation by means of agricultural extensification coupled with high speed of farmland expansion.

Figure 3.3 Changes in land-use hot spots in the 2000-2010 (a) and 2010-2012 (b) periods.



Source: Author’s production.

Spatio-temporal soil nitrogen balance

In the study area, input and output values represent N flows in different classes of land use (see Table 3.4). N flows are presented for agricultural regions as shown in Table 3.5. These results are described in the next sections.

Table 3.4 Nitrogen flows, in $TgN.yr^{-1}$, in the Brazilian Cerrado for years 2000, 2010, and 2012.

Years	Nitrogen Flows ($TgN.yr^{-1}$) IN					OUT						Balance
	IN_{fer}	IN_{man}	IN_{dep}	IN_{fix}	TIN	$OUT_{crop/prod}$	OUT_{res}	OUT_{lea}	OUT_{gas}	OUT_{ero}	TOUT	
Pasture												
2000	0	0	0.45	2.05	2.50	0.39	0	0	0.20	1.80	2.38	0.12
2010	0	0	0.50	2.28	2.78	0.53	0	0	0.26	2.26	3.06	-0.28
2012	0	0	0.50	2.26	2.75	0.55	0	0	0.28	2.31	3.14	-0.38
Annual crops												
2000	0.15	0	0.04	0.86	1.05	0.85	0	0.04	0.05	0.11	1.05	0.00
2010	0.43	0	0.06	1.37	1.86	1.66	0	0.06	0.07	0.19	1.98	-0.12
2012	0.53	0	0.07	1.40	2.00	1.77	0	0.08	0.08	0.23	2.16	-0.16
Semi perenial crops												
2000	0.13	0.15	0.01	0.09	0.38	0.08	0	0.01	0.01	0.08	0.18	0.20
2010	0.36	0.37	0.02	0.17	0.92	0.20	0	0.02	0.02	0.15	0.38	0.54
2012	0.43	0.44	0.02	0.21	1.10	0.24	0	0.02	0.02	0.19	0.46	0.64
Perennial crops												
2000	0.18	0	0.00	0	0.18	0.10	0	0.01	0.00	0.02	0.12	0.06
2010	0.24	0	0.00	0	0.24	0.13	0	0.01	0.00	0.03	0.17	0.07
2012	0.26	0	0.01	0	0.27	0.14	0	0.01	0.00	0.04	0.19	0.08
Silviculture												
2000	0.14	0	0.01	0	0.15	0.39	0	0	0	0.06	0.46	-0.31
2010	0.26	0	0.01	0	0.27	0.73	0	0	0	0.08	0.81	-0.55
2012	0.25	0	0.01	0	0.26	0.72	0	0	0	0.09	0.81	-0.54
Total												
2000	0.59	0.15	0.52	3.00	4.26	1.81	0	0.06	0.26	2.07	4.19	0.07
2010	1.28	0.37	0.60	3.82	6.07	3.24	0	0.08	0.35	2.72	6.40	-0.33
2012	1.48	0.44	0.61	3.87	6.39	3.42	0	0.10	0.39	2.85	6.76	-0.37

Table 3.5 Regional Breakdown of Brazilian Cerrado nitrogen flows ($TgN.yr^{-1}$).

Year	Nitrogen Flow ($TgN.yr^{-1}$) IN					OUT						Balance
	IN_{fer}	IN_{man}	IN_{dep}	IN_{fix}	TIN	$OUT_{crop/prod}$	OUT_{res}	OUT_{lea}	OUT_{gas}	OUT_{ero}	TOUT	
Region 1[a]												
2000	0.45	0.13	0.15	0.75	1.47	0.72	0	0.03	0.08	0.81	1.64	-0.17
2010	0.83	0.29	0.16	0.85	2.12	1.22	0	0.03	0.10	1.01	2.36	-0.24
2012	0.89	0.33	0.16	0.88	2.25	1.28	0	0.04	0.10	1.07	2.49	-0.24
Region 1B												
2000	0.12	0.02	0.28	1.81	2.23	0.92	0	0.02	0.14	0.96	2.04	0.19
2010	0.35	0.08	0.32	2.26	3.01	1.61	0	0.04	0.18	1.20	3.03	-0.02
2012	0.48	0.11	0.32	2.27	3.18	1.71	0	0.05	0.21	1.27	3.24	-0.06
Region 2												
2000	0.02	0	0.08	0.45	0.56	0.16	0	0.01	0.04	0.29	0.51	0.05
2010	0.10	0	0.12	0.71	0.94	0.41	0	0.01	0.07	0.50	1.00	-0.06
2012	0.11	0	0.12	0.72	0.95	0.43	0	0.02	0.08	0.51	1.03	-0.08

Nitrogen inputs

Total nitrogen input (TIN) increased significantly from 4.26 to 6.39 Tg in a period of twelve years (2000-2012), as can be seen in Table 3.4. The 50% gain was the result of an increase in all components. Biofixation (IN_{fix}) was responsible for the largest input, accounting for 70.42% (2000), 62.93% (2010), and 60.56% (2012) of all nitrogen inputs. It was followed by IN_{fer}, which accounted for 13.85% (2000), 21.09% (2010), and 23.16% (2012) of it. Nitrogen input from IN_{dep} contributed with 12.24% (2000), 9.89% (2010), and 9.55% (2012). The contribution of IN_{man} was only 3.52% (2000), 6.10% (2010), and 6.89% (2012).

Nitrogen inputs intraregional dynamic

At the regional scale, the highest nitrogen inputs occurred in agriculturally consolidated regions: *Region 1B* followed by *Region 1A* (Table 3.5). The largest nitrogen inputs occurred in *Region 1B* via IN_{fix}. In contrast, in *Region 1A* occurred the largest nitrogen occurred inputs via IN_{fer}. *Region 2* had the smallest nitrogen inputs of the Cerrado.

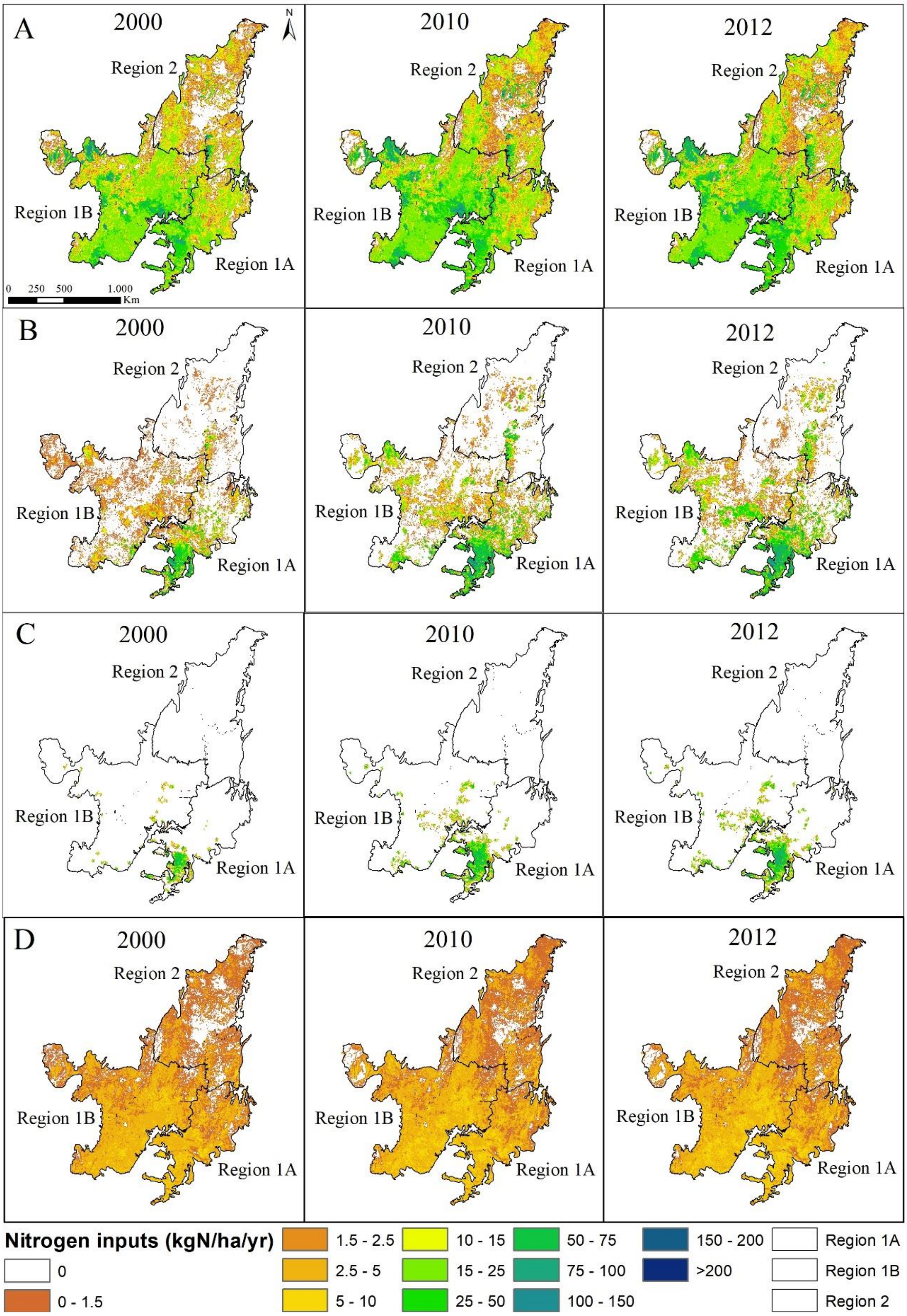
The highest nitrogen inputs take place in *Region 1B* (Table 3.5) because the largest pastureland and annual crops area of the Cerrado are within this region (Table 3.2), and have the largest nitrogen inputs by IN_{fix} (Table 3.5). Additionally, *Region 1B* showed high IN_{fer} values, primarily due its areas of annual crops. This region presented an increase of 42.60% in the total IN (TIN, Table 3.5) between 2000 and 2012 mostly due to rise in IN_{fix} (20.26%) and IN_{fer} (300%), which reflects the expansion of pasture and annual crops in the period.

Region 1A had the second largest nitrogen inputs (Table 3.5) because it holds the largest area of semi perennial crops, perennial crops, and silviculture (Table 3.2). Accordingly, *Region 1A* had the highest nitrogen inputs via IN_{fer} (Table 3.5) and, due to its semi perennial crops and areas of pasture, showed high levels of IN_{fix}. Between 2000 and 2012, total IN (TIN, Table 3.5) increased by 53.06%, mostly due to a rise in IN_{fix} (17.33%) and IN_{fer} (97.78%) resulting directly from crops and silviculture expansion.

Region 2 showed the biome´s highest percentage of total IN increase (TIN, Table 3.5) owing to IN_{fix}, which is responsible for most of the nitrogen inputs. Total IN increased by 69.64% between 2000 and 2012, mainly due to an increase in IN_{fix} (60%) and IN_{fer} (450%) that resulted from the expansion of pasture and annual crops.

Figures 3.4A to 3.4D depict the N-input variation ($kg.ha^{-1}.yr^{-1}$) at the local scale. The highest IN_{fix} rates (75-100 $kg.ha^{-1}.yr^{-1}$) was observed in *Region 1B* and *Region 1A*, mostly related the areas of annual crops. The highest IN_{fer} (50-100 $kg.ha^{-1}.yr^{-1}$) rates were observed in *Region 1A* where there are intensely fertilized areas of semi perennial crops, perennial crops, and silviculture. IN_{man} (25-75 $kg.ha^{-1}.yr^{-1}$) was intense in *Region 1A*, also due to semi perennial crops. IN_{dep} was higher (2.5 - 5 $kg.ha^{-1}.yr^{-1}$) in *Region 1B* and *Region 1A*. The time sequence, depicted in Figures 3.4a to 3.4c shows intensification of the N-input for all regions.

Figure 3.4 Nitrogen inputs (kg.ha^{-1}.yr^{-1}) maps in 2000, 2010, and 2012. (A) Biofixation-inputs; (B) Fertilizer-inputs; (C) Manure-inputs; (D) Atmospheric deposition inputs.



Source: Author's production.

Outputs nitrogen

Total nitrogen output (TOUT) was larger than total nitrogen input (TIN) from 2000 (Total, Table 3.4), indicating occurrence of soil nitrogen mining. Total nitrogen output increased from 4.19 TgN to 6.76 TgN in that period. The 2.57 TgN output change is attributed to the increase of 1.61 TgN from harvested crops and animal products ($OUT_{crop/prod}$), 0.78 TgN from erosion (OUT_{ero}), 0.13 TgN from gaseous losses (OUT_{gas}) and 0.04 TgN from leaching (OUT_{lea}). Nitrogen output from $OUT_{crop/prod}$ was the largest output, accounting for 43.20% (2000), 50.63% (2010), and 50.59% (2012), followed by OUT_{ero}, with 49.40% (2000), 42.50% (2010), and 42.16% (2012). The nitrogen outputs from OUT_{gas} contributed with 6.21% (2000), 5.47% (2010), and 5.77% (2012), while OUT_{lea} outputs contributed with 1.43% (2000), 1.25% (2010), and 1.48% (2012).

Nitrogen outputs intraregional dynamic

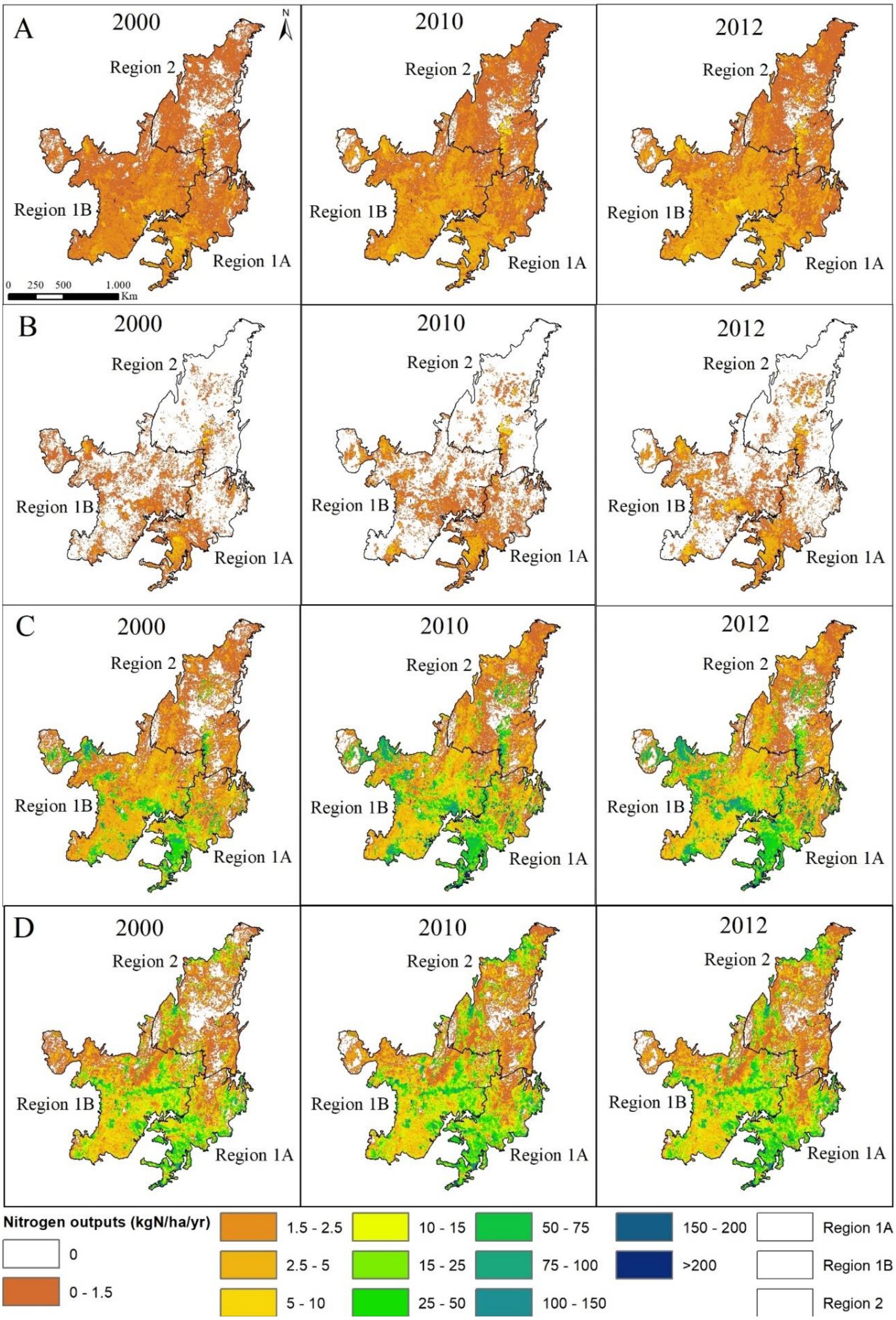
At the regional scale, the highest nitrogen outputs occurred in agriculturally consolidated regions, *Region 1B* followed by *Region 1A* (Table 3.5). The largest nitrogen outputs via $OUT_{crop/prod}$ and OUT_{ero} occurred in *Region 1B*. *Region 2* had the smallest nitrogen outputs of the Cerrado.

In both *Regions* (*1A* and *1B*), the main drivers of nitrogen exports were $OUT_{crop/prod}$ and OUT_{ero} (Table 3.4). *Region 1B* presented the highest $OUT_{crop/prod}$ values, mostly due to the large areas occupied by annual crops. The highest OUT_{ero} values, were mainly associated with degraded pasture areas (Table 3.4). In *Region 1A*, higher $OUT_{crop/prod}$ and OUT_{ero} are expected due to the vastness of the areas dedicated to semi perennial and perennial crops, silviculture, and pasturelands. Higher OUT_{gas} values in both regions were attributed to fertilizer input associated with areas of annual crops in *Region 1B* and to the agronomic practices and fertilization in semi perennial, perennial crops, and silviculture in *Region 1A*. Between 2000 and 2012, the total exported N (OUT, Table 3.5) increased by 58.82% and 32.10% in Regions *1B* and *1A*, respectively.

Region 2 presented the smallest nitrogen outputs (Table 3.5). Its strongest driver, the OUT_{ero}, is associated with large and commonly degraded pasture areas. However, the strong replacement of pasture areas by croplands led to an increase of 101.96% in total N-export (TOUT, Table 3.5) from this region. Major components are $OUT_{crop/prod}$ (168.75%) and OUT_{ero} (75.86%).

Figures 3.5A to 3.5D present the N-export variation ($kg.ha^{-1}.yr^{-1}$) at the local scale. The highest OUT_{gas} and OUT_{lea} (2.5-5 $kg.ha^{-1}.yr^{-1}$) rates were found in *Region 1A*, associated with intensive application of fertilizers. Due to the same reason, OUT_{gas} and OUT_{lea} began to intensify in *Region 1B* since 2010. Areas with high $OUT_{crop/prod}$ and OUT_{ero} (50-100 $kg.ha^{-1}.yr^{-1}$) appeared in both *Region 1A* and *1B*. The time sequence depicted in Figure 3.5A to 3.5D shows intensification of N-export in all regions.

Figure 3.5 Nitrogen outputs (kg.ha^{-1}.yr^{-1}) maps in 2000, 2010, and 2012. (A) Gaseous-outputs; (B) Leaching-outputs; (C) Harvested crops and animal products outputs; (D) Erosion-outputs.



Source: Author’s production.

Soil nitrogen balance

The trajectory of total soil nitrogen balance over 2000 to 2012 demonstrates a movement toward soil nitrogen depletion. In 2000 the balance shows a nitrogen surplus relatively small to a condition of nitrogen depletion in 2012 (Total, Table 3.4). It indicates that the increase in the land-use change, with non-adequate agricultural practices, is leading to soil nitrogen mining and affecting soil sustainability.

At intraregional scale, the same process is observed. The soil nitrogen balance reduced by 260% in the agricultural frontier (*Region 2*) between 2000 and 2012 (Table 3.5). Such sizeable decrease is attributed to the high speed of farming expansion (Table 3.2). In agriculturally consolidated regions, *1A* and *1B* the balance reduction was significantly smaller, reaching respectively 41.18% and 58.82%, reflecting agricultural intensification.

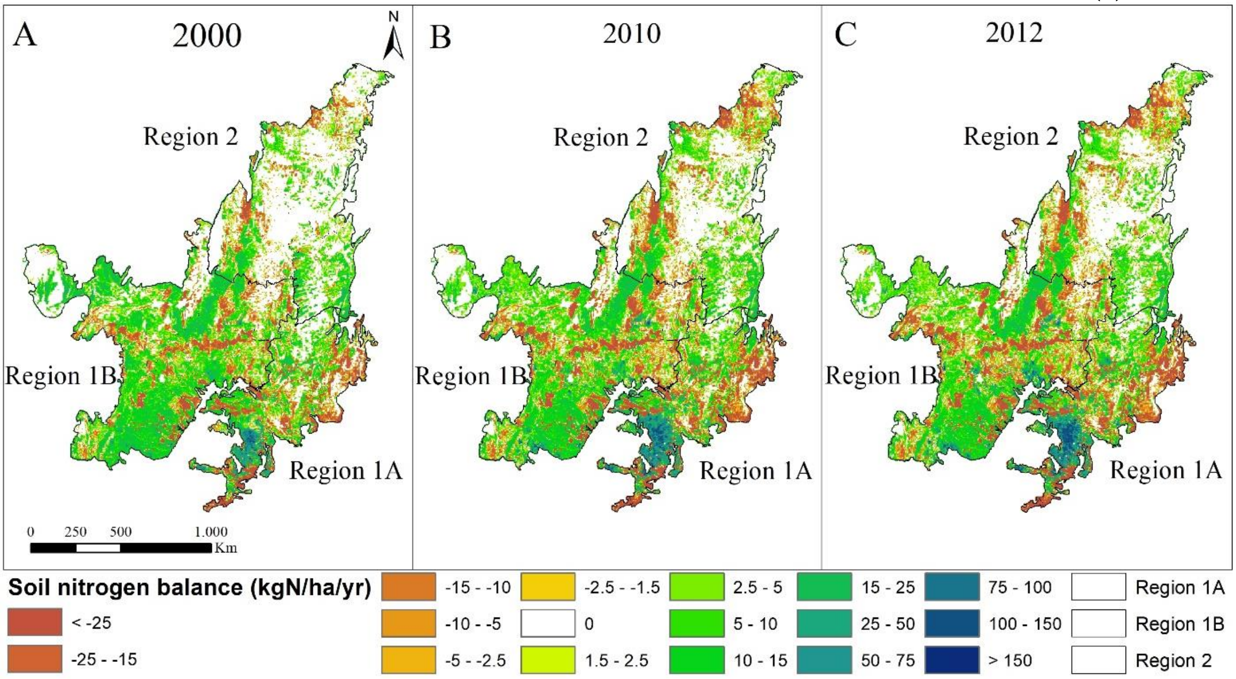
However, at local scale, soil nitrogen balance varied substantially among silviculture, crops and pasture. Taking into account the spatial resolution of 5km x 5km applied in this study, the Table 3.6 presents the average rates of soil nitrogen balance for each agricultural system. Semi perennial and perennial crops presented increasing nitrogen surplus rates from 2000 to 2012. In contrast, silviculture presented increasing nitrogen depletion rates. Pasture and annual crops changed from a balanced condition to a slight nitrogen depletion rates over 12 years.

Table 3.6 Average rates of soil nitrogen balance and nitrogen fluxes, and uncertainty expressed as standard deviation[1] ($kgN.ha^{-1}.yr^{-1}$), for each agricultural systems in the Brazilian Cerrado.

Years	Nitrogen Flows and balance ($kgN.ha-1.yr^{-1}$)											Balance
	IN					OUT						
	IN_{fer}	IN_{man}	IN_{dep}	IN_{fix}	TIN	$OUT_{crop/prod}$	OUT_{res}	OUT_{lea}	OUT_{gas}	OUT_{ero}	TOUT	
Pasture												
2000	0	0	2.5 (0.0)[1]	11.4 (6.4)	13.9 (6.4)	2.1 (0.0)	0	0	1.1 (0.0)	10.0 (1.0)	13.2 (1.0)	0.7 (7.5)
2010	0	0	2.6 (0.0)	11.7 (6.6)	14.3 (6.6)	2.7 (0.0)	0	0	1.4 (0.0)	11.6 (1.2)	15.7 (1.2)	-1.4 (7.8)
2012	0	0	2.5 (0.0)	11.5 (6.5)	14.1 (6.5)	2.8 (0.0)	0	0	1.4 (0.0)	11.8 (1.2)	16.0 (1.2)	-2.0 (7.7)
Annual crops												
2000	2.1 (0.3)	0	0.6 (0.0)	12.5 (0.9)	15.2 (1.2)	12.3 (1.6)	0	0.6 (0.2)	0.7 (0.3)	1.6 (0.2)	15.2 (2.3)	0.0 (3.5)
2010	5.8 (1.6)	0	0.9 (0.0)	18.5 (1.3)	25.1 (2.9)	22.4 (3.0)	0	0.8 (0.3)	0.9 (0.5)	2.6 (0.3)	26.7 (4.1)	-1.6 (7.0)
2012	7.0 (1.9)	0	0.9 (0.0)	18.5 (1.3)	26.5 (3.2)	23.4 (3.2)	0	1.0 (0.3)	1.1 (0.6)	3.1 (0.3)	28.6 (4.4)	-2.1 (7.6)
Semi perenial crops												
2000	16.0 (3.3)	19.0 (4.4)	1.3 (0.0)	11.2 (2.8)	47.5 (10.5)	10.6 (2.2)	0	1.1 (0.0)	1.0 (1.0)	10.2 (1.0)	22.8 (4.2)	24.6 (14.7)
2010	21.6 (5.6)	21.8 (5.0)	1.2 (0.0)	10.3 (2.6)	54.9 (13.2)	12.0 (2.5)	0	1.0 (0.0)	0.9 (0.9)	8.8 (0.9)	22.7 (4.3)	32.2 (17.5)
2012	23.4 (6.0)	23.6 (5.5)	1.3 (0.0)	11.2 (2.8)	59.5 (14.3)	13.0 (2.7)	0	1.1 (0.0)	1.0 (1.0)	10.0 (1.0)	25.1 (4.7)	34.4 (19.0)
Perennial crops												
2000	19.9 (0.5)	0	0.4 (0.0)	0	20.3 (0.5)	10.7 (1.1)	0	0.6 (0.3)	0.3 (0.1)	2.3 (0.2)	13.8 (1.7)	6.6 (2.2)
2010	22.7 (0.6)	0	0.5 (0.0)	0	23.2 (0.6)	12.2 (1.2)	0	0.7 (0.4)	0.3 (0.1)	3.0 (0.3)	16.1 (2.0)	7.1 (2.6)
2012	22.1 (0.6)	0	0.4 (0.0)	0	22.5 (0.6)	11.8 (1.2)	0	0.6 (0.4)	0.3 (0.1)	3.1 (0.3)	15.9 (2.0)	6.7 (2.6)
Silviculture												
2000	15.1 (3.4)	0	1.1 (0.0)	0	16.2 (3.4)	43.1 (16.3)	0	0	0	6.7 (0.7)	49.8 (17.0)	-33.5 (20.4)
2010	25.4 (5.7)	0	1.1 (0.0)	0	26.5 (5.7)	72.0 (27.3)	0	0	0	8.4 (0.8)	80.3 (28.1)	-53.9 (33.8)
2012	25.1 (5.6)	0	1.1 (0.0)	0	26.2 (5.6)	71.3 (27.0)	0	0	0	8.8 (0.9)	80.1 (27.9)	-53.9 (33.5)

Soil nitrogen accumulation or depletion varied at the local scale, as shown in Figure 3.6. *Region 1A* is the area with the highest nitrogen accumulation in soil (50- 150 $kg.ha^{-1}.yr^{-1}$) due to fertilizer application in semi perennial and perennial crops lands and manure in semi perennial crops. For the same reason, new areas showing nitrogen accumulation rates (25 - 50 $kg.ha^{-1}.yr^{-1}$) began to emerge in *Region 1B* from 2012. The areas with the highest soil nitrogen depletion were associated with silviculture (-25 - -10 $kg.ha^{-1}.yr^{-1}$) mostly in *Region 1A* and pasture (-25 - -10 $kg.ha^{-1}.yr^{-1}$) in all regions.

Figure 3.6 Spatio-temporal soil nitrogen balance ($kg.ha^{-1}.yr^{-1}$), 2000 (a), 2010 (b), and 2012 (c).



Source: Author's production.

3.4 DISCUSSION

Agricultural intensification and extensification have caused imbalances between nitrogen inputs and outputs in the Brazilian Cerrado. The soil nitrogen balance trajectory over 2000 to 2012 demonstrates a movement toward a soil nitrogen depletion. In 2000 the balance shows a slight nitrogen surplus to a condition of nitrogen depletion in 2012. The values estimated in our analyses are consistent with the findings of Liu *et al* (2010), who estimated a negative nitrogen balance in South America in 2000. Nitrogen deficits indicate that the major part of agricultural and silviculture systems have mined soil nitrogen and little have been replaced through fertilizers or manures (STOORVOGEL et al., 1993; VITOUSEK et al., 2009; DAVIDSON et al., 2016). Hence, our findings indicate that the reservoir, or stock, of nitrogen in soil may be declining over time, risking environment health and the sustainability of the Brazilian soil.

The main drivers of the increasingly negative soil nitrogen balance at the biome level are silviculture, pasture, and annual crops. Intensification and extensification of these uses are supported by Brazilian agricultural policy and encouraged by international demand for soybean, meat, and forest products. Brazilian agricultural policies have framed conditions to increase commodities production by investing in applied agricultural research and through incentives to farmers. The adoption of new technologies is encouraged through financial policies, rural extension services, and risk management mechanisms (as agricultural insurance) (WICKRAMASINGHE, 2012). In addition, international demand for agricultural commodities increased over the years, due to population growth, diet preferences and life style changes (KASTNER et al., 2012). When combined, those factors made the country a powerhouse in international agricultural trade, with soybean the most profitable of all agricultural exports, followed by meat and forest products (MENDES, 2016).

Tropical soils are highly weathered, deficient in nitrogen, and prone to degradation (PALM, 2007), requiring input-intensive processes (RADA, 2013).Without significant investments in material inputs and improvements in soil nutrient composition and agricultural practices, tropical soils are readily mined (HENAO & BAANANTE, 2006). This study indicates that nitrogen mining in annual crops, pasture, and silviculture systems can be attributed to low nitrogen inputs and high nitrogen outputs caused by yields and erosion losses. Although the country has strongly advanced in agricultural and silviculture yields and been able to meet national and international demands, the production system at the farm level and erosion processes have been partially responsible for soil nitrogen depletion.

Added to erosion processes, this region becomes a hotspot for land degradation (SCHERR & YADAV, 1996). Expansion of the agricultural frontier has occurred without regard for land support capacity and agricultural intensification has happened in more fragile lands in terms of soil and relief that were previously dedicated to pasture (GRECCHI *et al*., 2014). That has led to the intensification of soil degradation and erosion (GRECCHI *et al*., 2014) and increaseing annual rates of soil nitrogen loss, risking the sustainability of the agricultural production at the long-term.

At the regional or intraregional scales, soil nitrogen balance movement toward soil nitrogen depletion reflects the mix of land-uses and their processes of changes, as intensification and extensification, in both agriculturally consolidated regions (*1A* and *1B*) and agricultural frontier (*Region 2* - Matopiba, the newer agricultural frontier). However, at the local scale, nitrogen accumulation or depletion are directly related to land-use type, according to the difference in magnitude of nitrogen inputs and nitrogen outputs in each use.

In *Regions 1A* and *1B*, the main changes in land-use have occurred throughout the different farmland uses, as also observed by Barreto et al. (2013) and Dias et al. (2016). This is a common pattern for land-use intensification regions, where lands for agriculture are a constraining resource, usually more expensive than in frontier regions (BARRETO et al., 2013). However, our study also shows a stronger competition among all land uses, even more so between food and biofuels. Semi perennial crops, such as sugarcane for sugar and ethanol production, have vigorously expanded in detriment of annual crops and pasturelands. One powerfull reason for that is their higher profitability of this use in consolidated agricultural regions (BARRETO et al., 2013).

In these regions (*1A* and *1B*), the use of fertilizers has improve productivity, leading to high profits and inducing displacement of less profitable activities. It has also encouraged expansion of semi perennial and perennial crops. The positive outcome of agricultural intensification might affect other components of the landscape, such as biodiversity and ecosystem services, as result of the highest nitrogen accumulation rates of Cerrado are in these regions.

Soil nitrogen accumulation in agriculturally consolidated regions makes the Brazilian Cerrado an important trade-off region in the global warming scenario not only by deforestation but also by fertilizers emissions. The high availability of nitrogen in soils accelerates nitrous oxide (a potent greenhouse gas) production (SIGNOR et al., 2013) and promotes nitrogen leaching to groundwater (MARTINELLI *et al*., 2008) contributing to nitrogen export into rivers that drain heavily cultivated watershed (FILOSO et al. 2003). This issue also puts the Cerrado at the center another important global question: how to meet future food and biofuel needs while protecting biodiversity, and preventing soil and water degradation.

In the agricultural frontier (*Region 2*), pasture and annual crops expanded significantly by displacing natural vegetation (see also BARRETO et al., 2013, and DIAS et al., 2016), which usually happens where land is abundant and not expensive (BARRETO et al., 2013; SOARES-FILHO et al., 2014). Productivity gains caused by investments in fertilizers may also encourage agricultural expansion where land is not limited. Our results suggest that nitrogen inputs are supporting crops expansion in this region as a result of the low nitrogen surplus in the soil. However, the region needs attention due very fast increase in soil nitrogen depletion in some areas as consequence of erosion processes caused by agricultural expansion.

Recently, the agricultural frontier in the Cerrado area has been expanding over natural vegetation, leading to deforestation (MMA, 2015). Forested lands are, usually, less expensive, and the Brazilian legislation mandates that only at least 20% of native forest areas are preserved (BRAZIL, 2012). Flat relief, road availability, infrastructure, and proximity to maritime ports have also encouraged agricultural expansion in the agricultural frontier (FERREIRA et al., 2013; LAPOLA et al., 2014). Consequently, unless an effective program on sustainable land management, areas with inefficient nitrogen management may expand, compromising the agricultural production in the future.

During the last decade, Brazilian environmental policy prioritized the reduction of emissions through deforestation and was successful at that. However, it is imperative that land use systems start to be dealt with as open systems. As long as it is possible to displace land-use to other regions, environmental conservation actions focused on specific biomes risk becoming inefficient. Moreover, environmental conservation strategies must consider the inclusion of other ecosystem services such as biodiversity maintenance, water resource protection, and soil nitrogen balance. Otherwise, the effective contribution of planned or adopted policies will remain uncertain. Integrated actions are needed, since measures focusing on forested areas rich in carbon, such as PNMC (Brazilian Plan about Climate Change), INDC (Intended Nationally Determined Contributions) and REDD+ (Reduce Emissions from Deforestation and Degradation), may further pressure the allocation of agriculture toward biomes and natural vegetation of low carbon content, such as the Cerrado.

CHAPTER 4 - TRAJECTORIES OF AGRICULTURAL EXPANSION AND AGRICULTURAL INTENSIFICATION AND THEIR IMPACTS ON SOIL NITROGEN BALANCE IN THE BRAZILIAN CERRADO

4.1 INTRODUCTION

Land use change processes have been intensified in the tropics (LAMBIN et al., 2003; GIBBS et al., 2009; LAURENCE et al., 2014) and a large and growing fraction of it is related to commodities production (GIBBS et al., 2009; LAURENCE et al., 2014; LAMBIN & MEYFROIDT, 2011). This increase is driven by factors such as world population growth, current dietary consumption of more meat and dairies, high income-elasticity, and a growing demand for bioenergy crops (LAURENCE et al., 2014). Due to the growing concern about sustainability, interventions such as national land use planning, private and public land use regulations, and global trade agreements (LAMBIN et al., 2014) have been implemented. The interplay between these drivers has contributed to the regulation of land use systems in the tropics and will certainly help with future trends.

In this sense, tropical regions will undoubtedly feel the increasing pressure on resources, resulting from a globalized world (LAMBIN & MEYFROIDT, 2011). Good quality soil, water, biodiversity and nutrient elements are all finite resources, and competing claims on them are global (SDSN, 2013; EU NITROGEN EXPERT PANEL, 2015). Aiming to understand future changes in land use systems and their implications on natural resources, several land use models have been developed to explore trajectories of change in Brazil (DALLA-NORA et al., 2014; CÂMARA et al., 2015; AGUIAR et al., 2016a; STRASSBURG et al., 2017). The main process assessed is deforestation (FERREIRA et al., 2013; AGUIAR et al., 2012; DALLA-NORA et al., 2014; AGUIAR et al., 2016; GOLLNOW et al., 2017) and its implication on biodiversity (Strassburg et al., 2017) and climate regulation (CÂMARA et al., 2015; AGUIAR et al., 2016a). However, few models have been developed to explore land use transitions following the deforestation processes (GOLLNOW et al., 2017), focusing on agricultural production systems and their impacts on natural resources.

This study investigates trajectories of land use change, with emphasis on agricultural production systems, and their implications to nitrogen cycle in a dynamic manner. In order to accomplish that, we developed a spatially explicit modeling approach to represent land use changes and soil nitrogen balance for the Brazilian Cerrado, which corresponds to approximately 24% of Brazil's total land. We focused on nitrogen because it can be used as an integrative indicator of agriculture production efficiency and environmental risks or benefits. Many environmental issues arise due to unbalanced nitrogen in the natural system. Although nitrogen is a crop-yield limiting factor, its management is not easy and its lack or excess may affect natural resources. High nitrogen levels may lead to environmental pollution, whereas low nitrogen levels may lead to soil degradation (ZHANG et al., 2015; GALLOWAY et al., 2003; GALLOWAY et al., 2008; CLARK et al., 2008; AUSTIN et al., 2013).

Besides, exploring future trends of agricultural systems expansion in the Brazilian Cerrado seems to be essential to discover sustainable pathways for agricultural production. Sparing lands to protect the integrity of ecosystems and its services may be a way to reach sustainable agricultural development (STRASSBURG et al., 2017). Animal and crops production could be increased in lands already converted once large yield gaps are overcome (STRASSBURG et al., 2017). However, increased productivity depends on knowing what the land use status is (BINDRABAN et al., 2000). The use of nitrogen as an integrative indicator of the land use status and environment risks or benefits allows us to explore trajectories that may lead to improvements in agricultural production and land yield while using natural resources in a sustainable way.

4.2 MATERIAL AND METHODS

The Brazilian Cerrado was divided into two agricultural regions, as presented in Chapter 3. Aiming to investigate how agriculture intensification and extensification will affect the nitrogen cycle in the Brazilian Cerrado, we developed a land use modeling approach that represents, in the same environment, changes in land-use, land-cover and soil nitrogen balance. We built three future trajectories (scenarios A, B, and C) of land use change and soil nitrogen balance for the year 2050. LuccMe (Land Use and Cover Change Modeling Environment), developed at National Institute for Space Research (INPE), was the framework we chose to work with. The following section was divided into (1) modelling approach and (2) soil nitrogen balance.

4.2.1 Modeling Approach

Our land-use spatially explicit modeling approach combined a new version of the CLUE model (VERBURG et al., 1999) implemented in the LuccMe (AGUIAR et al., 2012) framework, with land use and cover spatial data, potential driving factors of land use change, agriculture and livestock census data, and projections. The classes of land use considered were: annual crops (soybean and maize), semi perennial crops (sugarcane), perennial crops (coffee and citrus), pasture, silviculture, and natural vegetation. The modeling protocol is presented in three steps: (1) database; (2) model description, parametrization, and validation; and (3) scenario assumptions.

Land use database

The database considered both dependent variables (land use and cover maps) and independent variables (spatial driving factors of annual, semi perennial and perennial crops, pasture, silviculture and natural vegetation). All data were compiled in a GIS (Geographic Information System) environment and organized in a Geographic Database.

The dependent variables were land use and cover maps produced by the Brazilian Institute for Geography and Statistics (IBGE, 2015) for the years 2000, 2010, and 2012. The three original maps were reclassified in order to emphasize the following classes of interest: *Agriculture, Pasture*; *Silviculture*; *Natural vegetation* and *Others*, as described in Chapter 3 (Land Use Dataset). The *Agriculture* class was divided into three classes: annual (soy and maize), semi perennial (sugarcane), and perennial (coffee and citrus), based on spatially explicit data on grains (CONAB, 2001, 2011a, 2013a), sugarcane (RUDORFF et al., 2010), coffee (BERNARDES et al., 2012; MOREIRA et al., 2010; CONAB, 2011b, 2013b) and citrus (MOREIRA et al., 2010) production. After that, all three seven-class maps (2000, 2010, and 2012) - *Pasture*, *Natural vegetation*, *Silviculture*, *Annual crops*, *Semi perennial crops*, *Perennial crops* and *Others* – were decomposed into a regular grid of 5km x 5km and the percentages of each class were computed for each grid (85,382 cells in total). Land use maps from 2000, 2010, and 2012 were used for statistical analysis, model calibration, and model validation, respectively.

Municipality-based agricultural censuses (IBGE, 2000a, 2010a, 2012a) were used to obtain the soybean and maize distribution in the *Annual crops* class for the years 2000, 2010, and 2012. These data were converted from polygon-based information into grid cells of 5km x 5km as in Espindola *et al*. (2012). This computation assumes that that the proportion of soybean and maize was uniformly distributed over the *Annual Crops* class, in each grid for the years 2000, 2010, and 2012. As for the scenarios, the proportion of soybean and maize in the *Annual crops* class was based on EPE projections (EPE, 2014). Soybean and maize area will increase by 2.38% and 1.18% per year from 2012 to 2050, respectively. Thus in 2050, we assumed that 66.8% of the *Annual crops* area will consist of soybean and 33.2% will consist of maize.

The independent variables were grouped into four types: (1) distance; (2) economic attractiveness; (3) public policies; and (4) environmental. *Distance* is related to accessibility, as in distance to ports, roads, railways, waterway and rivers. *Economic attractiveness* makes it possible to include new occupation areas, such as distance from or presence of sugar-ethanol mills, pulp-paper mills, slaughterhouses, mining companies, power transmission lines and irrigation pivots, as well as the presence of ports, waterways, and roads. *Public policies* is related to governmental actions of environmental conservation, such as the distance from or the presence of protected areas and indigenous lands. *Environmental* is related to land conditions, such as climate, potential agricultural map, topography, and hydrography. All independent variables were decomposed into a cellular database of 5km x 5km based on different spatial operators.

Model description, parametrization, and validation

We developed a land-use modeling approach for the Brazilian Cerrado by using an open-source framework, the LuccMe, for the development of spatially explicit land-use and cover models (AGUIAR et al., 2012). LuccMe was developed at INPE and built as an extension to the TerraMe programming environment (CARNEIRO et al 2013). This framework allows us to create deforestation, agricultural expansion, desertification, forest degradation, and urban sprawl, spatial models at different scales and areas of study, combining existent model components and/or creating new ones (AGUIAR et al, 2012; AGUIAR et al., 2016a; AGUIAR et al., 2016b).

A common structure can be identified in the land use and cover change models (VERBURG, 2006). In general, there are three model components: (1) Demand, responsible for the calculation of the magnitude of change; (2) Potential, responsible for the calculation of the suitability or propensity of change for each cell; and (3) Allocation, responsible for the spatial distribution of changes based on land demand and potential of change for each cell. Besides, all components are organized in a top-down manner, in which the demand is allocated according to cell suitability (DALLA-NORA et al., 2014; AGUIAR et al., 2016a; AGUIAR et al., 2016b).

The demand component (*PreComputedValues*) was calculated based on the observed expansion rate of farmland, silviculture and deforestation in the 2000-2012 period, from land use and cover maps. For the scenarios, the demand was based on different assumptions, as described in the Scenarios storylines section and Tables 4.2 and 4.3. The allocation component (*AllocationClueLike*) was modified to include the demand in proportion to the potential of each cell. The potential component (*SpatialLagRegression*) was accounted for by spatial autocorrelation (AGUIAR et al., 2012), allowing for dynamic updates at each time step.

Model parametrization was done by conducting an exploratory analysis that selected the most relevant independent variables for each land-use classe in the year 2000. First, correlation analysis was performed to identify highly correlated independent variables (over 50%). Subsequently, those were removed from the modeling protocol. Then, an automatic linear regression with stepwise variable selection mode was applied to discard non-significant variables. Different groups of variables were tested and selected based on their coefficient of determination, R^2. Exploratory analysis and linear regressions were carried out in the RStudio. Afterwards, we conducted a spatial regression, SpatialLag, for each resulting group of variables. The variables with low significance were excluded and the resulting groups were analyzed. The final variable groups were those that had the highest R^2 and high significance for the model as a whole. We used GeoDa software for this step. Finally, the final variable groups and their coefficients were used to parameterize the LuccMe/Cerrado-N model and the simulations were performed. In the model, several iterations were performed at each time step to allocate the calculated demand value in the 5km x 5km resolution based on each cell´s potential (*SpatialLagRegression*). The model ran in annual time step from 2000 to 2010 to calibrate and adjust model parameters. Figures A.1 – A.6 (Appendix) show the independent variables selected for each land use. Table 4.1 presents LuccMe general description, independent variables and their coefficients, and potential parameters.

In order to establish its capacity to consistently represent changes in land use and cover, we validated the LuccMe/Cerrado-N model. The validation methods consisted of comparing the land use and cover map observed in the year 2012 with the simulated map for the same year. The comparison between observed and simulated maps shows how efficient the model is in representing the evaluated systems (PONTIUS, 2002). We used the Analysis of Multiple Resolution (CONSTANZA et al., 1989; PONTIUS, 2002) validation method, which allows for the quantification of erros in the allocation pattern at different patterns. Based on the adjusted model, we ran the different scenarios from 2013-2050. Table 4.1 details the final LuccMe Potential (*SpatialLagRegression*), Table 4.2 shows Allocation (*ClueLikeAllocation*), and Table 4.3 presents Demand components (*PreComputedValues*).

Table 4.1. LuccMe/Cerrado-N general description and potential parameters.

General parameters					
Spatial scale	Extent	Brazilian Cerrado area (MMA 2015)			
	Resolution	Regular cells of 5 x 5 km^2			
Temporal scale	Extent	2013-2050 (scenarios)			
	Resolution	Yearly			
	Calibration/Validation	2000-2010-2012 (IBGE, 2015)			
Land use / cover classes	Percent of natural vegetation, pasture, silviculture, annual crops, semi perennial crops, perennial crops and others (urban zones, road systems, non-agricultural systems, continental water bodies, coastal water bodies, and uncovered lands (e.g. rocky outcrops and sand dunes) in the cell.				

Potential: SpatialLagRegression parameters				
Selected natural vegetation spatial drivers		Scenario dependent	Std B	Significance
W_use00_4	Spatial autoregressive coefficient		0.9073185	0.000
Constant	Regression constant		0.1181064	0.000
percdecl_3	Percentage of cell area covered by a slope flat (up to 3%) in each cell (VALERIANO et al., 2009)		-0.188645	0.000
lrod_d_tod	Euclidean distance to the closest paved and unpaved road - log10 transformed (DNIT, 2013)		0.02398592	0.000
ti_2000_p	Presence of Protected Areas and Indigenous land (MMA, 2015; FUNAI, 2015)	Y*	0.02600939	0.000
min_2000_p	Presence of timber extraction and processing centre		-0.02825637	0.000
hgrafia_d	Euclidean distance to the closest river (ANA, 2010)		-0.0000004136858	0.000

*dynamic variable.

Table 4.1. LuccMe/Cerrado-N general description and potential parameters (continued).

Potential: SpatialLagRegression parameters				
Selected pasture spatial drivers		Scenario dependent	Std B	Significance
W_use00_1	Spatial autoregressive coefficient		0.8837113	0.000
Constant	Regression constant		-0.03043586	0.000
percdecl_3	Percentage of cell area covered by a slope flat (up to 3%) in each cell (VALERIANO et al., 2009)		0.1415314	0.000
frigo_d	Euclidean distance to the closest slaughterhouse (LAPIG, 2016)		0.00000004068182	0.000
lrod_d_tod	Euclidean distance to the closest paved and unpaved road - log10 transformed (DNIT, 2013)		-0.01781405	0.000
hgrafia_d	Euclidean distance to the closest river (ANA, 2015)		0.000000522762	0.000
Selected silviculture spatial drivers		Scenario dependent	Std B	Significance
W_use00_2	Spatial autoregressive coefficient		0.8503611	0.000
Constant	Regression constant		0.006356088	0.000
ferro_2000	Euclidean distance to the closest railways (DNIT, 2013)		0.000000003336829	0.003
Celulose	Euclidean distance to the closest pulp-paper mills (CTBE, 2013)		-0.00000000803281	0.000
hgrafia_d	Euclidean distance to the closest river (ANA, 2010)		0.00000008350324	0.000
percdecl_8	Percentage of cell area covered by a slope flat (> 3% and ≤ 8%) in each cell (VALERIANO et al., 2009)		-0.007357911	0.000

Table 4.1. LuccMe/Cerrado-N general description and potential parameters (continued).

Potential: SpatialLagRegression parameters				
Selected annual crops spatial drivers				
		Scenario dependent	Std B	Significance
W_use00_5	Spatial autoregressive coefficient		0.8968881	0.000
Constant	Regression constant		0.01906389	0.000
percdecl_8	Percentage of cell area covered by a slope flat (> 3% and ≤ 8%) in each cell (VALERIANO et al., 2009)		-0.03236881	0.000
ti_2000_p	Presence of Protected Areas and Indigenous land (MMA, 2015; FUNAI, 2015)		-0.004086402	0.000
lrod_d_tod	Euclidean distance to the closest paved and unpaved road - log10 transformed (DNIT, 2012)		-0.003525084	0.000
hgrafia_d	Euclidean distance to the closest river (ANA, 2010)		0.0000001518448	0.000
solo_1	Presence of suitable soil for agriculture (IBGE, 2002)		0.003551268	0.000
Selected semi perennial crops spatial drivers				
		Scenario dependent	Std B	Significance
W_use_6	Spatial autoregressive coefficient		0.9127246	0.000
Constant	Regression constant		-0.006017116	0.000
usin000_d	Euclidean distance to the closest sugar-ethanol mills (MMA, 2015)		-0.000000007240436	0.000
portos_d	Euclidean distance to the closest ports (DNIT, 2012)		-0.000000002177284	0.000
percdecl_3	Percentage of cell area covered by a slope flat (up to 3%) in each cell (VALERIANO et al., 2009)		0.004481676	0.000
lrod_d_pav	Euclidean distance to the closest paved road - log10 transformed (DNIT, 2012)		0.001342927	0.000
ferro_2000	Euclidean distance to the closest railways (DNIT, 2013)		-0.000000001783443	0.005

Table 4.1. LuccMe/Cerrado-N general description and potential parameters (continued).

Potential: SpatialLagRegression parameters			
Selected perennial crops spatial drivers			
	Scenario dependent	Std B	Significance
W_use00_7	Spatial autoregressive coefficient	0.8357644	0.000
Constant	Regression constant	0.001860638	0.000
hgrafia_d	Euclidean distance to the closest river (ANA, 2010)	0.00000003393153	0.000
percdecl_8	Percentage of cell area covered by a slope flat (> 3% and ≤ 8%) in each cell (VALERIANO et al., 2009)	-0.001602238	0.000
lrod_d_tod	Euclidean distance to the closest paved and unpaved road - log10 transformed (DNIT, 2012)	-0.0004057246	0.000
pivo_p	Euclidean distance to the closest irrigation pivot (EMBRAPA, 2013)	0.001775506	0.000

Table 4.2 LuccMe/Cerrado-N allocation parameters.

Allocation: ClueLikeAllocation parameters				
Natural vegetation allocation parameters				
		Scenario A	Scenario B	Scenario C
maxError	Maximum allocation error allowed for each land use	300 km2	300 km2	300 km2
minValue	Minimum value (percentage) allowed for that land use as a result of new changes	20%	20%	20%
maxValue	Maximum value (percentage) allowed for that land use as a result of new changes	100%	100%	100%
ChangeLimiarValue	Threshold applied to the level of saturation in each cell. The saturation level is dynamically computed according to the available natural vegetation in the neighborhood, deconsidering the protected areas. The speed of change of a given land use in the cell is modified according to the threshold.	100%	100%	100%
minChange	Minimum change in a given land use in a cell in a time step until (saturation) threshold	12%	12%	12%
maxChange	Maximum change in a given land use allowed in a cell in a time step until (saturation) threshold	75%	75%	75%
MaxChangeAboveLimiar	Maximum change in a given land use allowed in a cell in a time step after (saturation) threshold	0%	0%	0%

Table 4.2 LuccMe/Cerrado-N allocation parameters (continued).

Allocation: ClueLikeAllocation parameters				
Pasture allocation parameters				
		Scenario A	Scenario B	Scenario C
maxError	Maximum allocation error allowed for each land use	300 km2	300 km2	300 km2
minValue	Minimum value (percentage) allowed for that land use as a result of new changes	0%	0%	0%
maxValue	Maximum value (percentage) allowed for that land use as a result of new changes	80%	80%	100%
ChangeLimiarValue	Threshold applied to the level of saturation in each cell. The saturation level is dynamically computed according to the available pasture in the neighborhood. The speed of change of a given land use in the cell is modified according to the threshold.	100%	100%	100%
minChange	Minimum change in a given land use in a cell in a time step until (saturation) threshold	10%	10%	10%
maxChange	Maximum change in a given land use allowed in a cell in a time step until (saturation) threshold	80%	80%	80%
MaxChangeAboveLimiar	Maximum change in a given land use allowed in a cell in a time step after (saturation) threshold	0%	0%	0%

Table 4.2 LuccMe/Cerrado-N allocation parameters (continued).

Allocation: ClueLikeAllocation parameters				
Silviculture allocation parameters				
		Scenario A	Scenario B	Scenario C
maxError	Maximum allocation error allowed for each land use	300 km2	300 km2	300 km2
minValue	Minimum value (percentage) allowed for that land use as a result of new changes	0%	0%	0%
maxValue	Maximum value (percentage) allowed for that land use as a result of new changes	80%	80%	100%
ChangeLimiarValue	Threshold applied to the level of saturation in each cell. The saturation level is dynamically computed according to the available silviculture in the neighborhood. The speed of change of a given land use in the cell is modified according to the threshold.	100%	100%	100%
minChange	Minimum change in a given land use in a cell in a time step until (saturation) threshold	12%	12%	12%
maxChange	Maximum change in a given land use allowed in a cell in a time step until (saturation) threshold	73%	73%	73%
MaxChangeAboveLimiar	Maximum change in a given land use allowed in a cell in a time step after (saturation) threshold	0%	0%	0%

Table 4.2 LuccMe/Cerrado-N allocation parameters (continued).

Allocation: ClueLikeAllocation parameters				
Annual crops allocation parameters				
		Scenario A	Scenario B	Scenario C
maxError	Maximum allocation error allowed for each land use	300 km2	300 km2	300 km2
minValue	Minimum value (percentage) allowed for that land use as a result of new changes	0%	0%	0%
maxValue	Maximum value (percentage) allowed for that land use as a result of new changes	80%	80%	100%
ChangeLimiarValue	Threshold applied to the level of saturation in each cell. The saturation level is dynamically computed according to the available annual crops in the neighborhood. The speed of change of a given land use in the cell is modified according to the threshold.	100%	100%	100%
minChange	Minimum change in a given land use in a cell in a time step until (saturation) threshold	13%	13%	13%
maxChange	Maximum change in a given land use allowed in a cell in a time step until (saturation) threshold	57%	57%	57%
MaxChangeAboveLimiar	Maximum change in a given land use allowed in a cell in a time step after (saturation) threshold	0%	0%	0%

Table 4.2 LuccMe/Cerrado-N allocation parameters (continued).

Allocation: ClueLikeAllocation parameters				
Semi perennial crops allocation parameters				
		Scenario A	Scenario B	Scenario C
maxError	Maximum allocation error allowed for each land use	300 km2	300 km2	300 km2
minValue	Minimum value (percentage) allowed for that land use as a result of new changes	0%	0%	0%
maxValue	Maximum value (percentage) allowed for that land use as a result of new changes	80%	80%	100%
ChangeLimiarValue	Threshold applied to the level of saturation in each cell. The saturation level is dynamically computed according to the available semi perennial crops in the neighborhood. The speed of change of a given land use in the cell is modified according to the threshold.	100%	100%	100%
minChange	Minimum change in a given land use in a cell in a time step until (saturation) threshold	12%	12%	12%
maxChange	Maximum change in a given land use allowed in a cell in a time step until (saturation) threshold	57%	57%	57%
MaxChangeAboveLimiar	Maximum change in a given land use allowed in a cell in a time step after (saturation) threshold	0%	0%	0%

Table 4.2 LuccMe/Cerrado-N allocation parameters (continued).

Allocation: ClueLikeAllocation parameters				
Perennial crops allocation parameters				
		Scenario A	Scenario B	Scenario C
maxError	Maximum allocation error allowed for each land use	300 km2	300 km2	300 km2
minValue	Minimum value (percentage) allowed for that land use as a result of new changes	0%	0%	0%
maxValue	Maximum value (percentage) allowed for that land use as a result of new changes	80%	80%	100%
ChangeLimiarValue	Threshold applied to the level of saturation in each cell. The saturation level is dynamically computed according to the available perennial crops in the neighborhood. The speed of change of a given land use in the cell is modified according to the threshold.	100%	100%	100%
minChange	Minimum change in a given land use in a cell in a time step until (saturation) threshold	12%	12%	12%
maxChange	Maximum change in a given land use allowed in a cell in a time step until (saturation) threshold	59%	59%	59%
MaxChangeAboveLimiar	Maximum change in a given land use allowed in a cell in a time step after (saturation) threshold	0%	0%	0%

Table 4.3 LuccMe/Cerrado-N demand parameters.

Demand: PreComputed values			
Natural vegetation rates (km2/year)	Scenario A	Scenario B	Scenario C
	Increasing from 974,950 km2 (2012) to 1,038,950 km2 (2030) and stabilizing until 2050	Decreasing from 974,950 km2 (2012) to 774,950 km2 (2050)	Decreasing from 974,950 km2 (2012) to 574,950 km2 (2050)
Pasture rates (km2/year)	Scenario A	Scenario B	Scenario C
	Decreasing from 903,092 km2 (2012) to 572,488 km2 (2050)	Decreasing from 903,092 km2 (2012) to 836,488 km2 (2050)	Decreasing from 903,092 km2 (2012) to 783,846 km2 (2050)
Silviculture rates (km2/year)	Scenario A	Scenario B	Scenario C
	Increasing from 20,273 km2 (2012) to 43,026 km2 (2050)	Increasing from 20,273 km2 (2012) to 43,026 km2 (2050)	Increasing from 20,273 km2 (2012) to 53,783 km2 (2050)
Annual crops rates (km2/year)	Scenario A	Scenario B	Scenario C
	Increasing from 150,776 km2 (2012) to 368,559 km2 (2050)	Increasing from 150,776 km2 (2012) to 368,559 km2 (2050)	Increasing from 150,776 km2 (2012) to 592,327 km2 (2050)
Semi perennial crops rates (km2/year)	Scenario A	Scenario B	Scenario C
	Increasing from 42,367 km2 (2012) to 67,167 km2 (2050)	Increasing from 42,367 km2 (2012) to 67,167 km2 (2050)	Increasing from 42,367 km2 (2012) to 78,348 km2 (2050)
Perennial crops rates (km2/year)	Scenario A	Scenario B	Scenario C
	Increasing from 9,519 km2 (2012) to 10,789 km2 (2050)	Increasing from 9,519 km2 (2012) to 10,789 km2 (2050)	Increasing from 9,519 km2 (2012) to 17,724 km2 (2050)

Scenarios storylines

Scenarios are ‘plausible, challenging, and relevant stories about how the future might unfold, which can be told in both words and numbers. Scenarios are not forecasts, projections, predictions, or recommendations. They are about envisioning future pathways and accounting for critical uncertainties (RASKIN et al., 2005). Scenarios approach is a valuable tool in the environmental area due to concerns about climate change, water availability, ecosystems functioning, air quality and land use changes (WILKINSON & EIDINOW, 2008; FOLHES et al., 2015). Here, we built three scenario storylines for the Brazilian Cerrado, focusing on consequences of agricultural intensification and extensification on the soil nitrogen balance. The scenarios assumptions were built based on Aguiar et al (2016), also applied by Tejada et al (2016). This approach combines exploratory (‘where are we plausibly heading to?’) and normative (‘what do we want and how do we get there?’) scenario approaches (AGUIAR et al., 2016). In general, scenario A (sustainability) is highly developed, both socioeconomically and environmentally, whereas scenarios B (middle of the road) and C (fragmentation and chaos) are characterized by medium and low socioeconomic and environmental development, respectively (AGUIAR et al., 2016). Table 4.4 and Table 4.5 present the boundary conditions and elements used in each scenario.

Table 4.4 General boundary conditions used in the sustainability (A), middle of the road (B), and fragmentation (C) scenarios.

Item	**Sustainability scenario (A)**	**Middle of the road scenario (B)**	**Fragmentantion scenario (C)**
General Descrition	High socioeconomic and environmental development.	Medium socioeconomic and environmental development.	Low socioeconomic and environmental development.
1) Environmental law enforcement	Restoration of priority areas and environmental debts (Forest Code), without further natural vegetation removal. Cerrado environmental debt is 6.4 Mha (SOARES FILHO et al. 2014).	Forest Code conservation measures are respected, but additional society/market deforestation control mechanisms are also in place. As a result, half of the area potentially available to deforest by law (net balance of 40 Mha) is converted to the expansion of crops and pasture. Forest Code Restoration (Legal Reserves and Permanet Protection Areas) targets are reached by compensation mechanisms, such as remote forest quotas, instead of local restoration.	Expansion of pasture and agricultural areas over the natural vegetation follow current trends. Little respect to the Forest Code, mainly as expansion areas become scarce. Deforestation control measures are descontinued.
2) Protected areas	Protected areas increase to 30% of the cerrado areas (surpassing AICH target) (MMA, 2016).	Protected areas increase to at least 17% (AICH target 11) (MMA, 2016).	Only 8% of the Cerrado remains protected.
3) Demand for agricultural products and productivity (are on the Table 4.5).	Increase in productivity gains and area expansion to meet high global and internal demand associated with sustainable agriculture.	Increase in productivity gains and area expansion to meet high global and internal demand associated to sustainable with conventional agricultural practices.	Not all actors are able to improve productivity. On average, only a small increase is noticed. Sustainable and conventional agricultural practices are applied.

Tabela 4.5 Detailed boundary conditions regarding the demand for agricultural products and productivity (Item 3, Table 4.4) used in the sustainability (A), middle of the road (B), and fragmentation (C) scenarios.

Item 3 Detailed - Demand for agricultural products and productivity			
	Sustainability scenario (A)	**Middle of the road scenario (B)**	**Fragmentation scenario (C)**
3.1 Productivity ($kg.ha^{-1}$) and area (km^2) of crops and silviculture	Increase in productivity and area of annual crops and semi-perennial crops from 2013 to 2050 are based on EPE (2014). Increase in productivity and area of silviculture and perennial crops from 2013 to 2050 are based on MCTIC (2017). Crops and silviculture expand over pasturelands. See the increase in each land use area in Figure A.7 (Appendix).	Increase in productivity and area of annual crops and semi-perennial crops from 2013 to 2050 are based on EPE (2014). Increase in productivity and area of silviculture and perennial crops from 2013 to 2050 are based on MCTIC (2017). Crops and silviculture expand over pasturelands and natural vegetation. See the increase in each land use area in Figure A.7 (Appendix).	Only a small increase in productivity of crops and silviculture is noticed. Annual and semi-perennial crops production from 2013 to 2050 are based on EPE (2014). Silviculture and perennial crops production from 2013 to 2050 are based on MCTIC (2017). Crops and silviculture expand over pasturelands and natural vegetation. See the increase in each land use area in Figure A.7 (Appendix).
3.2 Stocking rates ($head.ha^{-1}$) and area (km^2) of pasture	Pasture stocking rate reaches 2.74 ($head.ha^{-1}$) in 2050 based on Strassburg et al (2014). Pasture stocking rates increase due to considerable technological evolution available to all producers. Degraded pasture recovery of 1.7 Mha per year by 2020 (BRASIL, 2012). From 2021 to 2050, degraded pasture recovery of 1.4 Mha per year. Pasture area decreases from 2012 to 2050.	Pasture stocking rate reaches 1.88 ($head.ha^{-1}$) in 2050. Degraded pasture recovery of 1.7 Mha per year by 2020 (BRASIL, 2012). Pasture area decreases from 2012 to 2050.	Pasture stocking rate follows the trend from the 2000-2012 period and reaches 0.92 ($head.ha^{-1}$) in 2050. There is no degraded pasture recovery. Pasture area decreases from 2012 to 2050.
3.3 Soil management practices	Agricultural expansion and intensification adopt sustainable agricultural practices such as no-tillage, terracing, and level curves.	Agricultural expansion and intensification adopt conventional (deep plowing, subsoiling, or disk) and sustainable agricultural practices.	Agricultural expansion and intensification adopt conventional (deep plowing, subsoiling, or disk) and sustainable agricultural practices.

Tabela 4.5 Detailed boundary conditions regarding the demand for agricultural products and productivity (Item 3, Table 4.4) used in the sustainability (A), middle of the road (B), and fragmentation (C) scenarios (continued).

Item 3 Detailed - Demand for agricultural products and productivity			
	Sustainability scenario (A)	**Middle of the road scenario (B)**	**Fragmentation scenario (C)**
3.4 Nitrogen use	Nitrogen use is efficient, according to plant threshold. Biological nitrogen fixation occurs in 30% of maize area, 100% of soybean area, 100% of sugarcane area and 10% of silviculture area. Degraded pasture recovery of 1.7 Mha per year by 2020 (BRASIL, 2012) and 1.4 Mha per year by 2050 using biological nitrogen fixation.	Nitrogen use is not efficient. Biological nitrogen fixation occurs in 10% of maize area, 100% of soybean area and 100% of sugarcane area. Degraded pasture recovery of 1.7 Mha per year by 2020 (BRASIL, 2012) using nitrogen fertilizer in an inefficient way.	Nitrogen use is not efficient. Biological nitrogen fixation occurs in 100% of soybean and 100% of sugarcane area.

The quantification of the sustainability scenario (A) assumes (A.1, Table 4.4) that institutional and political conditions would favor a ‘zero (nonauthorized) deforestation rate from 2012, surpassing the current Brazilian Forest Code regulation. This scenario also assumes the regeneration of all illegally deforested areas located in private properties (Legal Reserve – LR and Permanent Protection Areas – PPA) through restoration mechanisms laid down in the Brazilian Forest Code (AGUIAR et al., 2016). Soares-Filho et al (2014) measured the total deforested areas to be regenerated in the Cerrado, 6.4 Mha. Through restoration mechanisms, natural vegetation areas will have increased since 2013, reaching their highest level in 2030. (A.2, Table 4.4) Institutional mechanisms will be in place to create and consolidate protected areas to 30% of the Cerrado by 2025, especially those with particular importance for biodiversity and ecosystem services, surpassing Brazil’s Biodiversity Strategy and Action Plan, Target 11 (MMA, 2016). Thus, 100% of priority areas extremely important for biodiversity conservation became protected areas, as well as, about 3% of priority areas with high importance for biodiversity conservation (MMA, 2017). (A.3, Table 4.4) Demand for areas and productivity gains of crops and silviculture will follow current Brazilian projections (EPE, 2014; MCTIC, 2017). Expansion and intensification of crops and silviculture will be associated with sustainable agriculture practices. It will be achieved based on four elements, as presented in Table 4.5:

(A.3.1) Area and productivity estimates for annual and semi-perennial crops will follow Empresa de Pesquisa Energética's projections (EPE, 2014). Area and productivity estimates for silviculture and perennial crops will follow MCTIC's projections (MCTIC, 2017). Both projections were chosen to build the scenarios due to their greater information availability. We adopted EPE and MCTIC projections (EPE, 2014) because they are the official Brazilian projections, with estimates of production, area and productivity from 2013 to 2050, and in line with other projections, such as FIESP's, from 2013 to 2023. In this scenario, crops and silviculture will only expand over pasturelands, decreasing these areas from 2012. (A.3.2) Since pasture area will decline from 2012 to 2050, we assumed that bovine stocking rate will reach 2.74 ($head.ha^{-1}.yr^{-1}$) in 2050 (STRASSBURG et al., 2014), which amounts to about 157 million cattle heads for the Cerrado. Brazilian projections indicate that the country will have 342 million cattle heads in 2050 (EPE, 2014), with 1.21 bovine heads per hectare (MCTIC, 2017). According to Strassburg et al. (2014), recovered pasture in Brazil is able to received 2.74 $head.ha^{-1}.yr^{-1}$, its carrying capacity. Degraded pasture will be recovered in 1.7 Mha per year by 2020, according to ABC Brazilian Plan (BRASIL, 2012). From 2021 to 2050, it will have recovered 1.4 Mha per year. (A.3.3) Agricultural expansion and intensification will carry out sustainable agricultural practices in all agricultural lands to reduce erosion processes, such as no-tillage, terracing, and contour curves. Thus, scenario A assumes soil erosion rates from 2013 to 2050 will remain equal to 2012 (A.3.4). Efforts will be made to develop best management practices aiming to improve nitrogen use efficiency (NUE) and reduce nitrogen losses. Adequate fertilization strategies will be adopted, such as application rates based on the demand of nitrogen by plants and the ability of soil to supply nitrogen. In this context, in scenario A, we will use nitrogen in a more efficient way to recover pasture and produce crops and silviculture, and agricultural technologies will be used to decrease nitrogen fertilization rates and increased biological nitrogen fixation. At the same time, agricultural productivity gains will be met. Thus, 77% (55.6 M ha) of pasture area will be recovered by biofixation; 30% of maize area will be inoculated with nitrogen fixing bacteria; 10% of silviculture area will be planted with nitrogen-fixing trees; and 100% of soybean and 100% of sugarcane plantations will fix nitrogen. The nitrogen inputs and outputs used in the scenarios are presented in the next section (Soil nitrogen balance) and in Table 4.6.

The middle of the road scenario (B) assumes (B.1, Table 4.4) the Brazilian Forest Code will be abided by. Only 20 Mha of the legally available forest will be used to meet the global and national demand for food, fibre, and biofuels. The regularization of the Legal Reserves will occur through the compensation mechanism in the same biome, as also allowed by the Forest Code (AGUIAR et al., 2016). (B.2, Table 4.4) Institutional mechanisms will be in place to create and consolidate protected areas to 17% of the Cerrado by 2025, especially those with particular importance for biodiversity and ecosystem services, in line with Brazil's Biodiversity Strategy and Action Plan, Target 11 (MMA, 2016). Thus, it was assumed that about 9% of priority areas extremely important for biodiversity conservation will become protected areas (MMA, 2017). (B.3, Table 4.4) Demand for agricultural and silviculture areas and productivity will follow Brazilian projections (EPE, 2014; MCTIC, 2017) and be associated with sustainable and conventional agricultural practices. That will be achieved based on four elements (see also Table 4.5):

(B.3.1) Area and productivity estimates are the same described for scenario A. However, crops and silviculture will expand over pasturelands and natural vegetation, leading to their reduction from 2012. (B3.2) Bovine stocking rate will reach 1.88 $head.ha^{-1}.yr^{-1}$, which amounts to about 157 million cattle heads in the Cerrado. Degraded pasture will be recovered in 1.7 Mha per year by 2020, according to ABC Brazilian Plan (BRASIL, 2012). (B3.3) Agricultural expansion and intensification will carry out sustainable (no-tillage, terracing, and level curves) and conventional (deep plowing, subsoiling, or disk) agricultural practices. Thus, in scenario B, the increase of soil erosion rates from 2013 to 2050 will be similar to the one from 2000 to 2012. (B.3.4) Efforts will *not* be made to develop best management practices, improving nitrogen use efficiency and reducing nitrogen losses. Thus, nitrogen fertilization rates in 2050 will be similar to the one from 2000 to 2012 for crops and silviculture, however, it will have increased according to productivity gains. The use of agricultural technologies in decreasing nitrogen fertilization rates will be limited. As a result, only 10% of the maize area will be inoculated with nitrogen fixing bacteria; and 100% of the soybean and 100% of the sugarcane plantations will fix nitrogen. Pasture areas (16%, i.e. 13.6 M ha) will be recovered with nitrogen fertilization (100 $kgN.ha^{-1}.yr^{-1}$), as suggested by Brazilian ABC Plan (BRASIL, 2012).

The fragmentation scenario (C) assumes (C.1, Table 4.4) that agricultural expansion will occur at the expense of environmental protection. Compliance to the Brazilian Forest Code will be low and 40 Mha of the legally available forest will be used to meet global and national demand for food, fibre, and biofuels by 2050. (C.2, Table 4.4) There will be no institutional efforts to create protected areas (LR and PPA), with only 8% of the Cerrado being protected. (C.3, Table 4.4) From 2013 to 2050, crops and silviculture production will follow Brazilian projections by EPE and MCTIC (EPE, 2014; MCTIC, 2017), but productivity gains will be insignificant. Agriculture will be associated with sustainable and conventional agricultural practices. It will be achieved based on four elements (see also Table 4.5):

(C.3.1) Only a small increase in productivity of crops and silviculture is noticed. Thus, silviculture and crops productivity are based on the average for the 2000-2012 period. Annual and semi-perennial crops production is based on EPE (2014) from 2013 to 2050. Silviculture and perennial crops production is based on MCTIC (2017) from 2013 to 2050. With little productivity gains, areas of crops and silviculture will be larger in this scenario than in the A and B scenarios. Crops and silviculture areas will expand over natural vegetation and pasture. (C.3.2) Pasture stocking rate will follow the trend from the 2000-2012 period and reach 0.92 ($head.ha^{-1}$) in 2050, which amounts to 72 M cattle heads. Scenario C assumes that there will be a leakage of livestock to other Brazilian biomes. Degraded pasture will not be recovered. (C.3.3) Agricultural expansion and intensification will carry sustainable and conventional agricultural practices, as described in scenario B. Thus, the increase in soil erosion rates from 2013 to 2050 will be similar to the one from 2000 to 2012. (C.3.4) Efforts will *not* be made to develop best management practices, improving nitrogen use efficiency and reducing nitrogen losses. Nitrogen fertilization rates in 2050 will be equal to the ones from the 2000-2012 period for crops and silviculture, as it was assumed that there will be no productivity gains. The use of agricultural technologies in decreasing nitrogen fertilization rates will be limited. As a result, 100% of soybean and 100% of sugarcane plantations will fix nitrogen.

In general, the modeling exercises that we performed are useful in showing how present and future decisions could affect soil nitrogen balance in the Brazilian Cerrado. However, a real-life scenario would be a combination of the three scenarios presented herein, depending on the institutional conditions and agricultural practices in place.

4.2.2 Nitrogen database

Soil nitrogen balance - Soil nitrogen balance was estimated for the year 2050 for scenarios A, B, and C. The methodology was based on several references (LIU et al., 2010, STOORVOGEL & SMALING, 1998; SMALING et al., 1993). As explained in Chapter 3, soil nitrogen balance is an agri-environmental indicator calculated from the total nitrogen inputs (IN) minus total nitrogen outputs (OUT) on the agricultural soil; where IN is divided into four factors and OUT is divided into five factors, as shown in Eqs 7 and 8. A positive nitrogen balance, or surplus, indicates potential environmental problems, such as nitrogen emission and leaching, whereas a negative balance indicates excess outputs or decline in soil fertility. This approach does not take into account the amount of nitrogen stored in the soil. The soil covers considered were pasturelands, annual crops, semi perennial crops, perennial crops, and silviculture.

$$IN = IN_{fer} + IN_{man} + IN_{dep} + IN_{fix} \quad 4.1$$

$$OUT = OUT_{crop/prod} + OUT_{res/man} + OUT_{lea} + OUT_{gas} + OUT_{ero} \quad 4.2$$

Where, for nitrogen:

IN and OUT - total input and output; IN_{fer}: mineral fertilizer input; IN_{man}: manure input in crops and silviculture (in pasture IN_{man} is not considered an input because it is an internal process); IN_{dep}: wet and dry atmospheric deposition; IN_{fix}: biological fixation. $OUT_{crop/prod}$: output from crops, wood harvested and animal products; $OUT_{res/man}$: output from crops, wood residues and manure exported from pasture; OUT_{lea}: output from leaching; OUT_{gas}: output from gaseous losses; and OUT_{ero}: output from erosion.

The nitrogen inputs and outputs initially used in the soil nitrogen balance for each scenario are presented in the Table 4.6. All values were obtained from literature. Nitrogen inputs and outputs are expressed in kilograms per hectare per year ($kgN.ha^{-1}.yr^{-1}$). In general, nitrogen inputs and outputs vary in space and time under Brazilian field conditions due to a diversity of landscape physical elements, soil chemical variety, and climate. However, in this study, a generalization was necessary for establishing soil nitrogen balance, given the large dimension of the study area (206 Mha) and the annual periodicity of the nitrogen input and output data.

Table 4.6. Average rates of nitrogen-input and nitrogen-output fluxes ($kgN.ha^{-1}.yr^{-1}$) for crops, pasture, and silviculture for the Brazilian Cerrado used in the land-use scenarios, sustainable (A), middle of the road (B), and fragmentation (C).

Input	**Land-use**	**Agro system**	**Scenario A $kgN.ha^{-1}.yr^{-1}$**	**Source**	**Scenario B $kgN.ha^{-1}.yr^{-1}$**	**Source**	**Scenario C $kgN.ha^{-1}.yr^{-1}$**	**Source**
IN_{fer}	Annual crop	Soybean	0	Hungria et al. (2013)	0	Hungria et al. (2013)	0	Mendes et al. (2007); Crispino et al. (2001)
		Maize	140	Silva et al 2011; Farinelli & Lemos (2012)	140	Silva et al 2011; Farinelli & Lemos (2012)	112.5	Alves et al. (2006); Cruvinel et al. (2011); Ribeiro et al. (1999); Mar et al 2003
	Semi perennial crop	Sugarcane	60	Otto et al. (2016); Franco et al. (2010)	110	Rosseto et al., 2005	102.5	Vitti et al. (2007); Vitti et al. (2002); Cantarella et al. (2008); Silva et al 2017
	Perennial crop	Coffee	400	Bortolloto et al. (2012)	400	Bortolloto et al. (2012)	273	Mesquita et al. (2016); Boaretto et al. (2007); Fenilli et al. (2008); Cantarella et al. (1992); Cantarella and Quaggio (1996)
		Citrus	200	Boaretto et al. (2007)	200	Boaretto et al. (2007)	200	
	Silviculture	Silviculture	156.3	Stape et al. (2010)	156.3	Stape et al. (2010)	125	Laclau et al. (2010); Barreto et al. (2008); Pulito et al. (2015)
	Pasture	Pasture	0	Oliveira et al. (2005)	100	BRASIL (2012)	0	Santos et al. (2002); Boddey et al. (2004); Cruvinel et al. (2011)

Table 4.6. Average rates of nitrogen-input and nitrogen-output fluxes ($kgN.ha^{-1}.yr^{-1}$) for crops, pasture, and silviculture for the Brazilian Cerrado used in the land-use scenarios, sustainable (A), middle of the road (B), and fragmentation (C) (continued).

Input	**Land-use**	**Agro system**	**Scenario A $kgN.ha^{-1}.yr^{-1}$**	**Source**	**Scenario B $kgN.ha^{-1}.yr^{-1}$**	**Source**	**Scenario C $kgN.ha^{-1}.yr^{-1}$**	**Source**
IN_{man}	Semi perennial	Sugarcane	134.8	Paredes et al. (2014); Oliveira et al. (2013); Canisares et al. (2017); Carmo et al. (2013)	134.8	Paredes et al. (2014); Oliveira et al. (2013); Canisares et al. (2017); Carmo et al. (2013)	103.3	Paredes et al. (2014); Oliveira et al. (2013); Canisares et al. (2017); Carmo et al. (2013)
IN_{dep}	All	All	5.5	Vet et al. (2013)	10	Vet et al. (2013)	10	Vet et al. (2013)
IN_{fix}	Annual crop	Soybean	271.2	Hungria et al. (2013)	271.2	Hungria et al. (2013)	174.8	Boddey et al. (1984); Filoso et al. (2006); Alves et al. (2006); Alves et al. (2003)
		Maize	30	Embrapa, 2015	30	Embrapa, 2015	-	-
	Semi perennial crop	Sugarcane	60	Martinelli et al. (2008); Boddey et al. (1991)	60	Martinelli et al. (2008)	48.8	Oliveira et al. (1994); Martinelli et al. (2008)
	Perennial crop	Coffee	-	-	-	-	-	-
		Citrus						
	Silviculture	Silviculture	100	Ataíde et al. (2013); EMBRAPA (2017)	-	-	-	-
	Pasture	Pasture	100	Oliveira et al., 2010	22.5	Filoso et al. (2006)	22.5	Filoso et al. (2006); Boddey and Victoria (1986)

Table 4.6. Average rates of nitrogen-input and nitrogen-output fluxes ($kgN.ha^{-1}.yr^{-1}$) for crops, pasture, and silviculture for the Brazilian Cerrado used in the land-use scenarios, sustainable (A), middle of the road (B), and fragmentation (C) (continued).

Output	**Land-use**	**Agro system**	**Scenario A $kgN.ha^{-1}.yr^{-1}$**	**Source**	**Scenario B $kgN.ha^{-1}.yr^{-1}$**	**Source**	**Scenario C $kgN.ha^{-1}.yr^{-1}$**	**Source**
$OUT_{crop/prod}$	Annual crop	Soybean	265.8	Hungria et al. (2013)	265.8	Hungria et al. (2013)	171.3	Alves et al. (2006); Hungria et al. (2003); Borkert et al. (1994)
		Maize	154.1	Alves et al. (2006)	154.1	Alves et al. (2006)	83.6	Alves et al. (2006); Coelho et al. (2003)
	Semi perennial crop	Sugarcane	74.3	Oliveira et al. (2000)	74.3	Oliveira et al. (2000)	56.9	Shultz et al. (2015); Coelho et al. (2003); Vitti et al. (2002)
	Perennial crop	Coffee	306.1	Fenilli et al. (2008)	306.1	Fenilli et al. (2008)	146.4	Fenilli et al. (2008); Boaretto et al. (2007); Boaretto et al. (2013)
		Citrus	58.7	Boaretto et al. (2007)	58.7	Boaretto et al. (2007)	50.7	
	Silviculture	Silviculture	443.4	Barreto et al. (2012)	443.4	Barreto et al. (2012)	354.7	Barreto et al. (2012)
	Pasture	Pasture	30.7	Boddey et al. (2004)	21.1	Boddey et al. (2004)	10.3	Boddey et al. (2004)
$OUT_{res/man}$	All	All	0	-	0	-	0	Smaling et al. (2008)

Table 4.6. Average rates of nitrogen-input and nitrogen-output fluxes ($kgN.ha^{-1}.yr^{-1}$) for crops, pasture, and silviculture for the Brazilian Cerrado used in the land-use scenarios, sustainable (A), middle of the road (B), and fragmentation (C) (continued).

Output	**Land-use**	**Agro system**	**Scenario A $kgN.ha^{-1}.yr^{-1}$**	**Source**	**Scenario B $kgN.ha^{-1}.yr^{-1}$**	**Source**	**Scenario C $kgN.ha^{-1}.yr^{-1}$**	**Source**
OUT_{lea}	Annual crop	Soybean	0	-	0	-	0	Lehmann et al. (2004)
		Maize	29.5	Wilcke and Lilienfen (2005)	29.5	Wilcke and Lilienfen (2005)	16	Wilcke & Lilienfen (2005); Coelho et al. (2003); Alves et al. (2006)
	Semi perennial crop	Sugarcane	6	Oliveira et al. (2002)	6	Oliveira et al. (2002)	4.6	Trivelien et al. (2002); Oliveira et al. (2002); Oliveira et al. (2000)
	Perennial crop	Coffee	16.3	Fenilli et al. (2008)	16.3	Fenilli et al. (2008)	7.8	Bortolloto et al. (2012); Fenilli et al. (2008); Cantarella et al. (2003)
		Citrus	41.7	Cantarella et al. (2003)	41.7	Cantarella et al. (2003)	36	
	Silviculture	Silviculture	0	Laclau et al. (2010)	0	Laclau et al. (2010)	0	Laclau et al. (2010)
	Pasture	Pasture	0	Costa et al. (2008)	0	Boddey et al. (2004)	0	Boddey et al. (2004)

Table 4.6. Average rates of nitrogen-input and nitrogen-output fluxes ($kgN.ha^{-1}.yr^{-1}$) for crops, pasture, and silviculture for the Brazilian Cerrado used in the land-use scenarios, sustainable (A), middle of the road (B), and fragmentation (C) (continued).

Output	Land-use	Agro system	Scenario A $kgN.ha^{-1}.yr^{-1}$	Source	Scenario B $kgN.ha^{-1}.yr^{-1}$	Source	Scenario C $kgN.ha^{-1}.yr^{-1}$	Source
OUT_{gas}	Annual crop	Soybean	0	Hungria et al. (2013)	0	Hungria et al. (2013)	0	Hungria et al. (2006)
		Maize	33.2	Alves et al. (2006)	33.2	Alves et al. (2006)	18	Alves et al. (2006); Zavaschi et al. (2014)
	Semi perennial crop	Sugarcane	5.7	Martinelli et al. (2008)	5.7	Martinelli et al. (2008)	4.4	Silva et al. (2017); Carmo et al. (2013)
	Perennial crop	Coffee	7.3	Bortolloto et al. (2013)	7.3	Bortolloto et al. (2013)	3.5	Fenilli et al. (2008); Dominghetti et al. (2016); Boaretto et al. (2013); Cantarella et al. (2003)
		Citrus	30.8	Cantarella et al. (2003)	30.8	Cantarella et al. (2003)	26.6	
	Silviculture	Silviculture	0	Laclau et al. (2010)	0	Laclau et al. (2010)	0	Laclau et al. (2010)
	Pasture	Pasture	0	Primavesi et al. (2001)	17.5	Primavesi et al. (2001)	-	-
			15.5	Boddey et al. (2004); Lessa et al. (2014)	10.6	Boddey et al. (2004); Lessa et al. (2014)	5.2	Boddey et al. (2004); Lessa et al. (2014)

Nitrogen inputs: all nitrogen inputs for scenario C were described in Chapter 3 (Nitrogen inputs). Nitrogen inputs for scenarios A and B are in line with productivity gains (Table 4.7) and nitrogen use efficiency (see Table 4.5, item 3.4). IN_{dep} ranges from 4 to 10 $kgN.ha^{-1}.yr^{-1}$ for South America, where values close to 10 $kgN.ha^{-1}.yr^{-1}$ correspond to high emission areas (VET et al., 2013). Thus, we assumed that in 2050 nitrogen deposition rate will reach 10 $kgN.ha^{-1}.yr^{-1}$ for scenarios B and C.

Table 4.7 Average productivity of crops ($ton.ha^{-1}.yr^{-1}$) and silviculture ($m^3.ha^{-1}.yr^{-1}$) for Brazil from 2020 to 2050 used in scenarios A and B.

Land-use	Agro system	Unit	Average 2000-2012	2020	2030	2040	2050	Reference
Annual crop	Soybean	$t.ha^{-1}.yr^{-1}$	2.7	2.9	3.3	3.8	4.5	EPE, 2014
	Maize	$t.ha^{-1}.yr^{-1}$	4.0	5.5	6.5	7.8	9.4	EPE, 2014
Semi perennial crop	Sugarcane	$t.ha^{-1}.yr^{-1}$	73.7	79.3	83.2	89.6	96.7	EPE, 2014
Perennial crop	Coffee	$t.ha^{-1}.yr^{-1}$	1.5	1.6	1.6	2.1	2.3	MCTIC, 2017
	Citrus	$t.ha^{-1}.yr^{-1}$	24.2	24.8	24.8	26.2	28.0	MCTIC, 2017
Silviculture	Silviculture	$m^3.ha^{-1}.yr^{-1}$	32	40.0	40.0	40.0	40.0	MCTIC, 2017

Nitrogen outputs: all nitrogen outputs for scenario C were described in Chapter 3 (Nitrogen outputs). Nitrogen outputs for scenarios A and B are in line with productivity gains (Table 4.7) and nitrogen use efficiency (see Table 4.5, item 3.4). For scenarios A and B, $OUT_{crop/prod}$ in pasture was estimated by multiplying livestock density by accumulated rate of nitrogen in live weight of animal. The livestock density for scenario A was based on pasture managed support capacity, which is 2.74 $head.ha^{-1}$ for Brazilian conditions of climate and soil, according to Strassburg et al. (2014). For scenarios B and C, it was 1.88 and 0.92 $head.ha^{-1}$, respectively. The nitrogen average in live weigh of animal (2.8 $kgN.ha^{-1}.yr^{-1}$) was obtained from Boddey *et al*. (2004) and corresponds to the accumulated nitrogen in 4 years of animal development (slaughter age).

OUT_{lea} varies according to soil texture, water balance, and nitrogen management practices. Thus, we assumed that nitrogen leaching rate (OUT_{lea}) in crops increased linearly with the increase in nitrogen fertilization (IN_{Fer}). In silviculture and pasture, we assumed that nitrogen leaching is irrelevant, as in Laclau et al. (2010) and Costa et al. (2008; 2006).

OUT_{gas} also varies with soil texture, water balance, temperature, and nitrogen management practices. Thus, we assumed that nitrogen gaseous rate (OUT_{gas}) in crops increased linearly with the increase in nitrogen fertilization (IN_{fer}). For pasture, OUT_{gas} was estimated through multiplying livestock density (2.74, 1.88, and 0.92 for A, B, and C, respectively) by average animal nitrogen excretion rates (dung and urine) (36 $kgN.ha^{-1}.yr^{-1}$) (Boddey *et al*., 2004). The result was then multiplied by the nitrogen emission rate from excreta (15.7%) (LESSA et al., 2014). Besides, for scenario B, we accounted for an extra nitrogen emission from nitrogen fertilizer application. Given that in Primavesi et al. (2001), OUT_{gas} in fertilized pasture is between 10 and 25% of applied nitrogen, we adopted a 17.5% value for nitrogen loss.

For scenario A, we assumed nitrogen erosion rate (OUT_{ero}) was similar to 2012, due to sustainable agricultural practices carried out that year (see Tables 4.4 and 4.5). For scenarios B and C, we assumed that OUT_{ero} between 2000 and 2012 was similar to the 2013-2050 period due to sustainable and conventional agricultural practices. Thus, the resulting OUT_{ero} in 2050 was given by nitrogen erosion values in 2012 added to the difference in nitrogen erosion between the years 2000 and 2012.

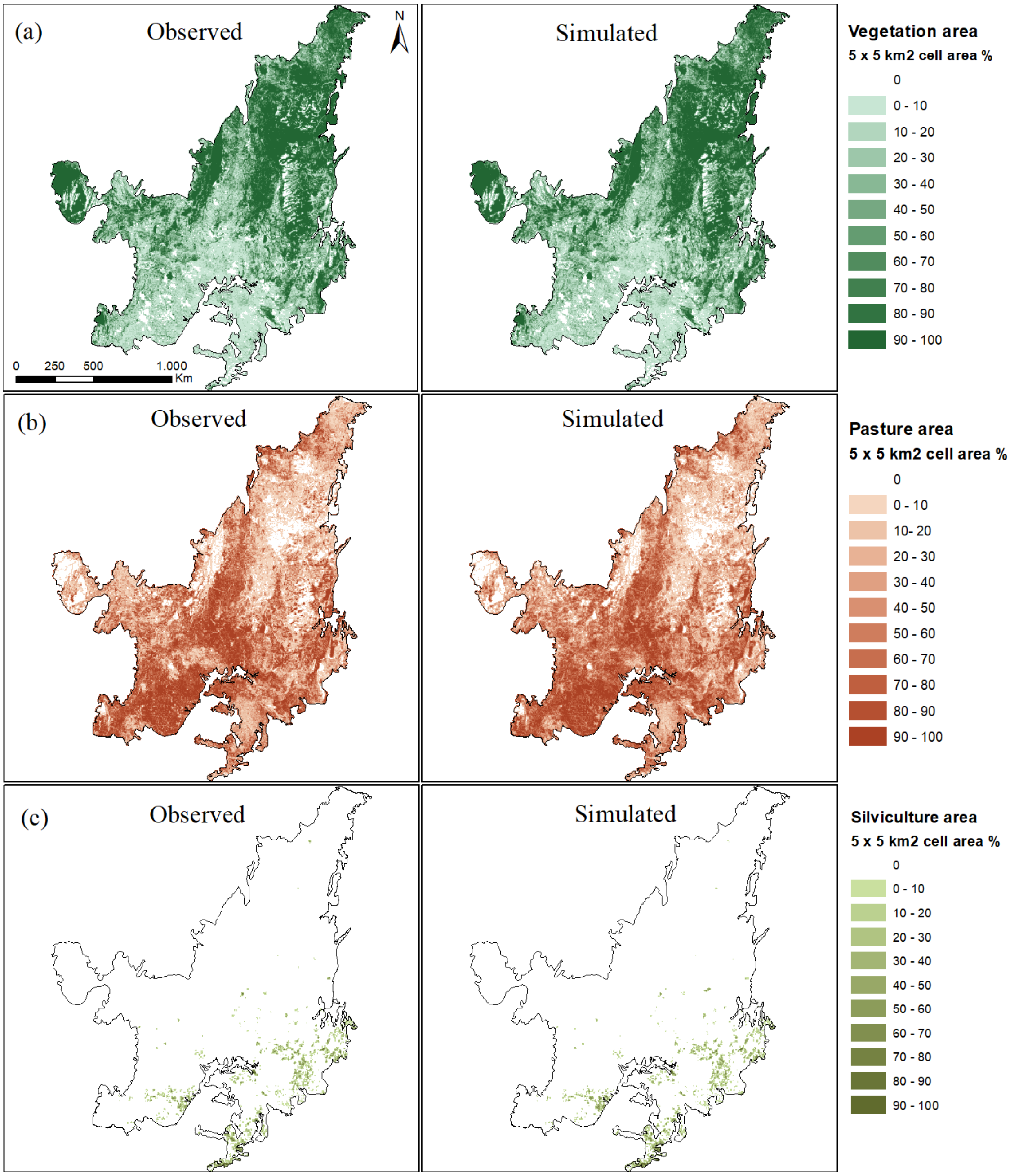
All nitrogen-input and nitrogen-output data were multiplied by the percentage of farmland and silviculture in each grid cell of the maps simulated for 2050. The difference between nitrogen inputs and nitrogen outputs resulted in the annual soil nitrogen balance maps for 2050.

4.3 RESULTS

Model's Performance

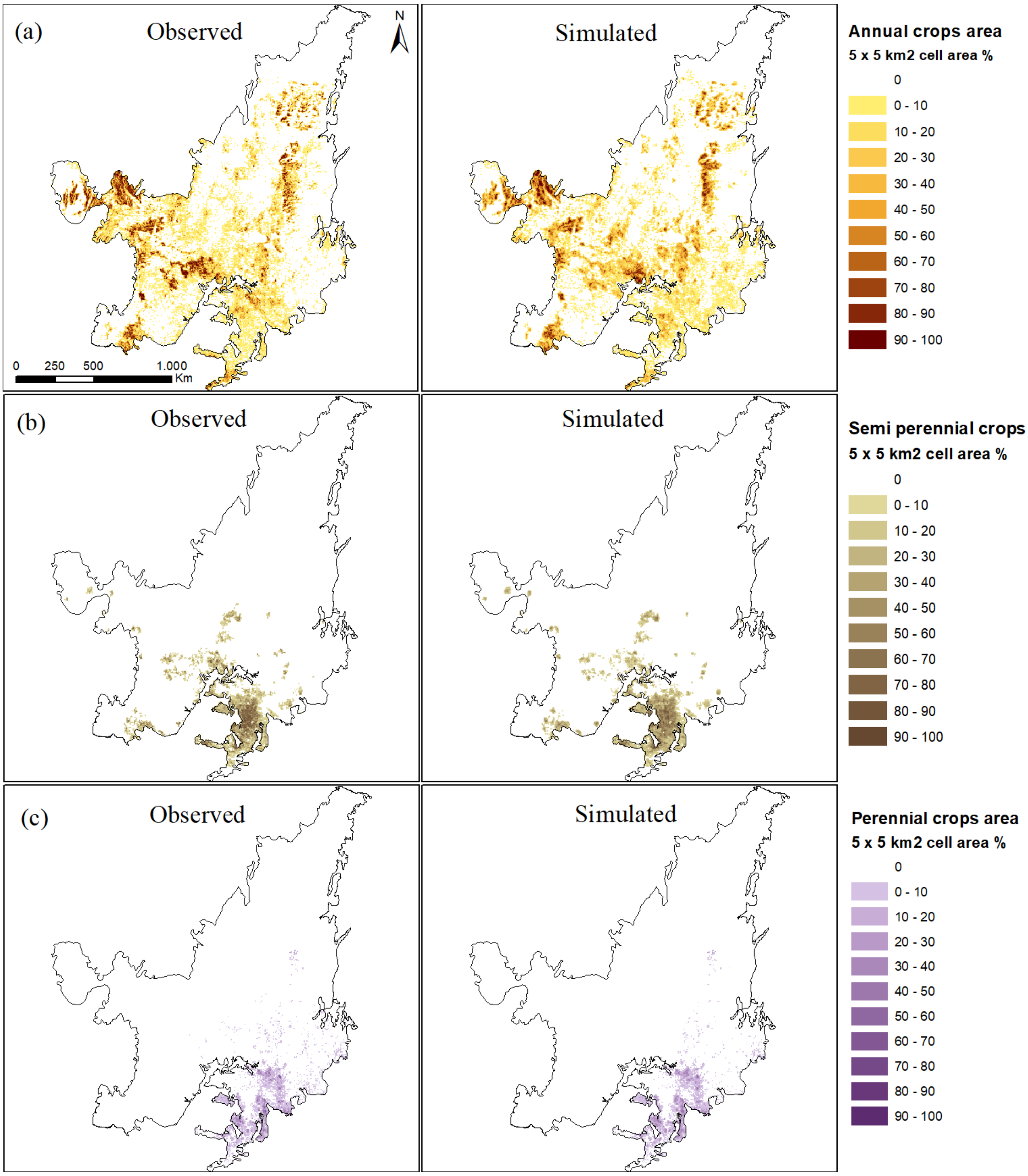
LuccME/Cerrado-N presented a reasonable performance on land demand allocation. The spatial model was validated based on multi resolution analysis (COSTANZA, 1989; PONTIUS, 2002) to quantify the pattern errors. LuccME/Cerrado-N was validated for the 2010-2012 period reaching a five-level spatial adjustment index of 71% for natural vegetation, 56% for pasture, 44% for silviculture, 51% for annual crops, 55% for semi perennial crops, and 42% for perennial crops (see Figure 4.1 and 4.2). The model effectively captured the spatial distribution of land uses and had a tendency to concentrate land demand allocation close to the areas already occupied, but still consistently with the general pattern observed over the whole area.

Figure 4.1 Spatial pattern of observed and simulated land uses in 2012. (a) Natural vegetation; (b) Pasture; and (c) Silviculture.



Source: Author’s production.

Figure 4.2 Spatial pattern of observed and simulated land uses in 2012. (a) Annual crops; (b) Semi perennial crops; and (c) Perennial crops.

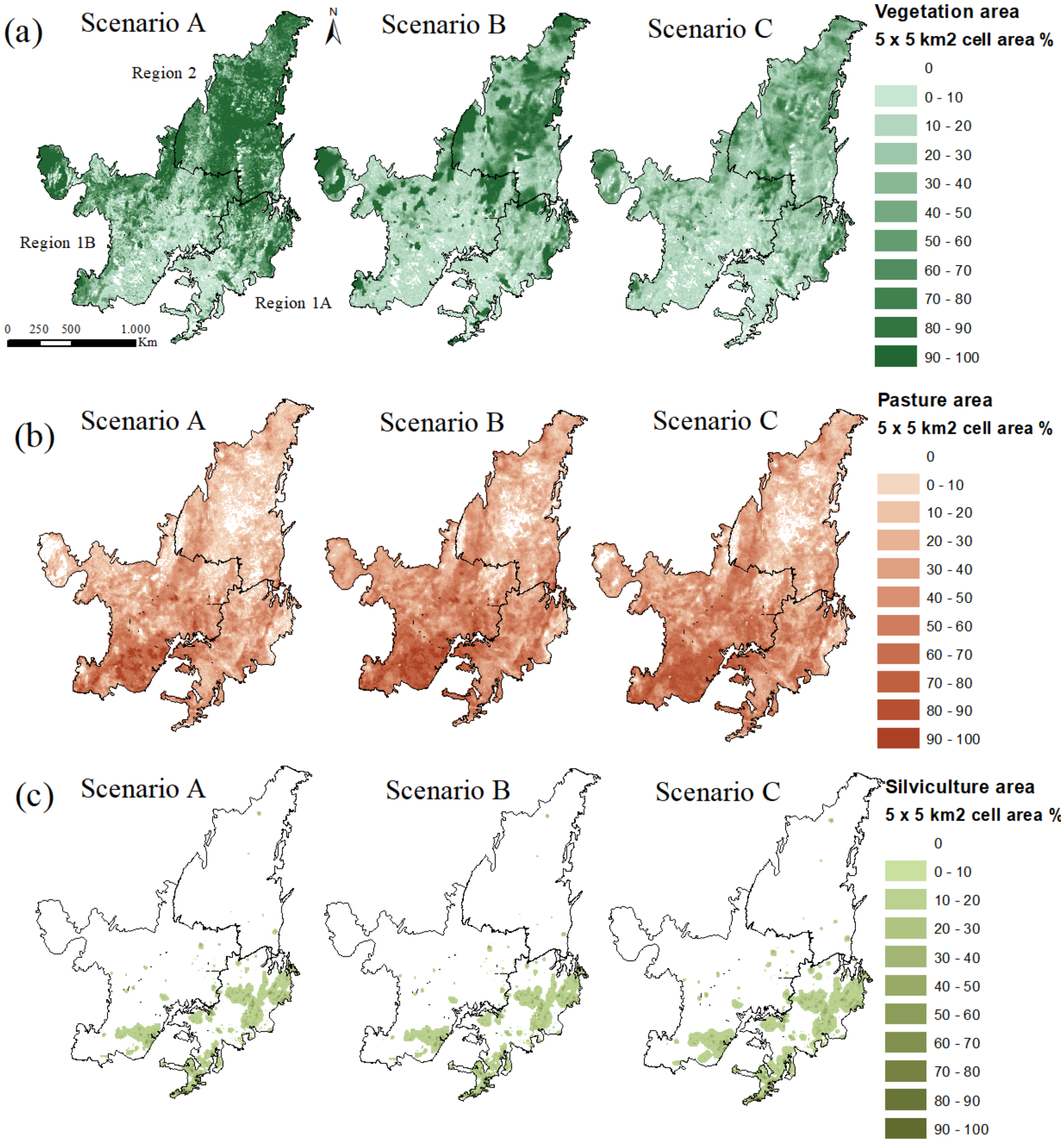


Source: Author's production.

Land use dynamic

This section presents the spatial projections for the Brazilian Cerrado land uses in 2050. Figure 4.3 shows spatial projections of natural vegetation, pasture, and silviculture for scenarios A, B, and C in 2050. Figure 4.4 illustrates spatial projections for annual, semi perennial and perennial crops. Subsequently, we present the areas occupied by each land use system for all scenarios in 2050 (Table 4.8).

Figure 4.3 LuccMe scenarios (A, B, and C) results for the year 2050 – (a) Spatial distribution of natural vegetation; (b) Pasture; and (c) Silviculture.



Source: Author's production.

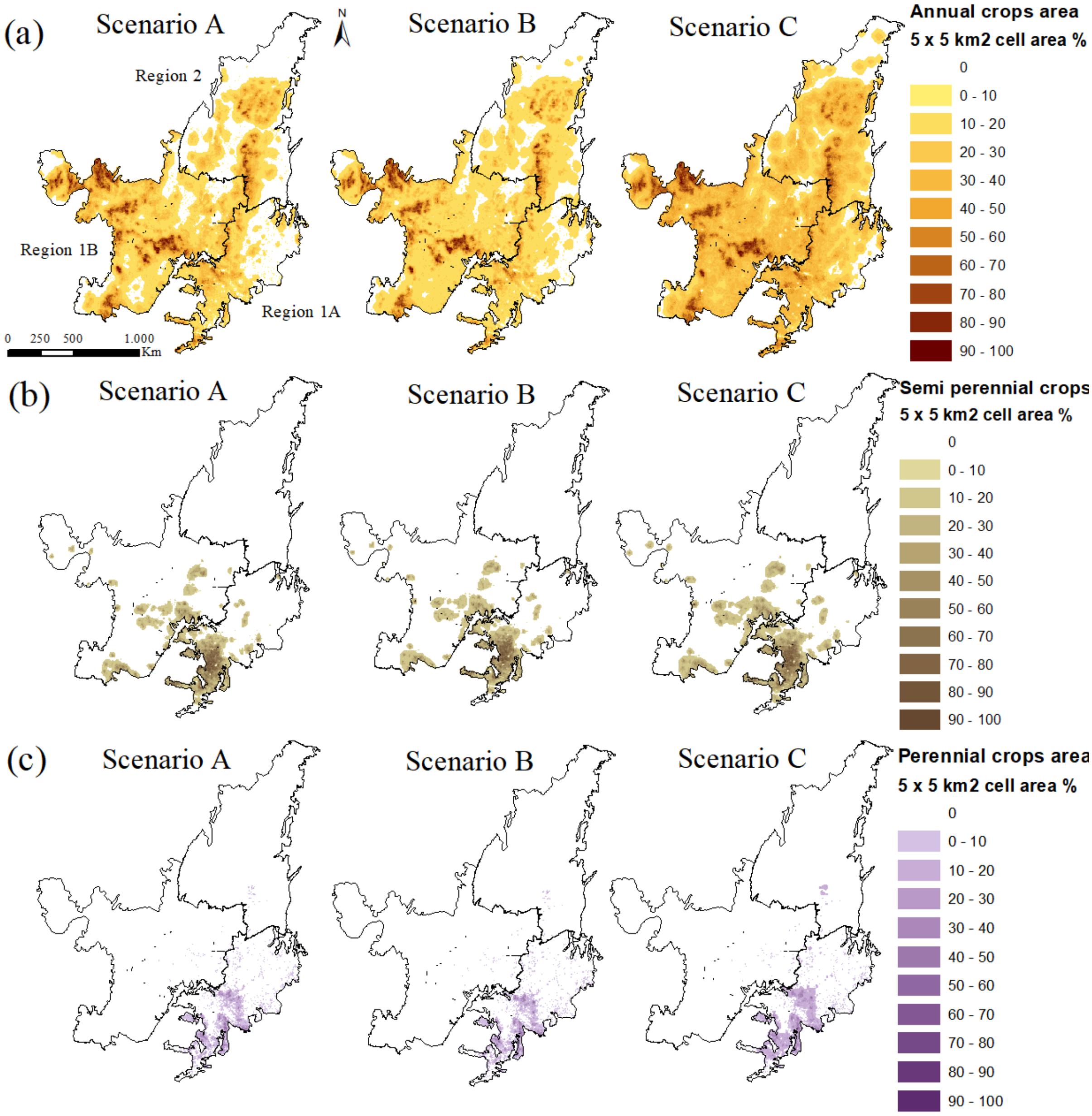
Figure 4.3a shows the spatially explicit natural vegetation distribution for the different scenarios in 2050. In scenario A, the spatial pattern of natural vegetation is similar to its spatial pattern in 2012 (please, see Figure 4.1a). Regenerated areas

(6.4Mha) were allocated around areas previously occupied by natural vegetation. This pattern results from protected area spatial driver (30% of Cerrado) and strong and effective environmental enforcement law that prevent deforestation in new areas. In scenarios B and C, deforestation occurred, with new deforestation areas being opened around previously deforested areas, a more intense process in Scenario C than in Scenario B. In both, vegetation protected areas went through deforestation processes. In Scenario B, more intense concentration of natural vegetation occurred where 17% of the natural vegetation area was protected. In Scenario C, due to little compliance to the Forest Code, few natural vegetation areas remain, as the protected areas nearby (8% of the Cerrado). In this scenario, all natural vegetation area legally available will be fully converted in 2050.

Figure 4.3b presents the spatially explicit pasture distribution for all scenarios in 2050. Spatial pattern of pasture was similar in the three scenarios. In general, new pasture areas were opened around previously opened areas. The dynamics between natural vegetation, crops, and silviculture accounts for the difference in pasture areas across the three scenarios. In the Scenario A, pasture concentration was less intense due to crops and silviculture expansion. In scenarios B and C, pasture concentration was more intense due to a less restrictive environmental legislation, resulting in crops and silviculture expansion over natural vegetation.

Spatially explicit distribution of silviculture is presented in the Figure 4.3c. In general, the spatial pattern of silviculture in 2050 was similar to the one from 2012 (see Figure 4.1c). New areas were opened around previously opened areas in all scenarios. In scenarios A and B, the area spread of silviculture was smaller than in scenario C. In scenario C, low productivity gains led to an increased silviculture spread area.

Figure 4.4 LuccMe scenarios (A, B, and C) results for the year 2050 – (a) Spatial distribution of annual crops; (b) spatial distribution of semi perennial crops; and (c) spatial distribution of perennial crops.



Source: Author's production.

Modeling results regarding the crops are illustrated in the Figure 4.4. In general, the spatial pattern of all crops were similar to their pattern in 2012 (please, see Figure 4.2a, 4.2b, and 4.2c). In 2050, new crop areas were opened around previously opened areas, with a larger spread in Scenario C, according to areas and productivity projections assumed (Tables 3.4 and 3.5).

Spatially explicit distribution of annual crops is presented in the Figure 4.4a. Although the area occupied by annual crops has been similar in scenarios A and B (see Table 4.8, Total), annual crops spatial distribution was different in these scenarios. That can be explained by a smaller spread of annual crops in Scenario A than in Scenario B, over pasturelands in the former and over pastureland and natural vegetation in the latter. In Scenario C, annual crops spread was larger than in scenario B due the greater availability of natural vegetation areas for conversion and its larger annual crops area (Table 4.8, Total).

Figure 4.4b and 4.4c present the spatial distribution of semi perennial and perennial crops for all scenarios in 2050. Spatial distribution of semi-perennial and perennial crops was similar in scenarios A and B. In Scenario C, semi-perennial and perennial crops spread was larger than in the other scenarios, due to the greater availability of land for agriculture and to the presence of larger semi perennial and perennial crops areas (Table 4.8, Total).

Table 4.8 Demand for the areas, in km^2 of natural vegetation, pasture, agricultural crops, and silviculture for the Brazilian Cerrado scenarios (A, B, and C) in 2050 and defined agricultural regions.

Scenarios 2050	Natural Vegetation		Pasture		Annual		Semi Perennial		Perennial		Silviculture	
	km^2	(%)[a]	km^2	(%)[a]	km^2	(%)[a]	km^2	(%)[a]	km^2	(%)[a]	km^2	(%)[a]
Region 1[a]												
2012	137,764	6.68	198,171	9.61	23,781	1.15	31,808	1.54	9,396	0.46	14,969	0.73
A	148,449	6.95	142,255	6.66	64,356	3.01	44,663	2.09	10,499	0.49	33,730	1.58
B	201,016	9.42	116,755	5.47	66,768	3.13	44,173	2.07	10,495	0.49	33,582	1.57
C	91,662	4.29	191,610	8.98	115,865	5.42	49,679	2.33	17,119	0.80	40,886	1.92
Region 1B												
2012	333,617	16.2	459,975	22.3	98,304	4.77	10,670	0.52	85	0.00	3,601	0.17
A	370,369	17.4	325,762	15.3	265,499	12.4	22,506	1.05	97	0.00	8,809	0.41
B	282,388	13.2	457,242	21.4	212,795	9.97	22,995	1.08	97	0.00	9,001	0.42
C	213,200	9.99	428,508	20.1	319,728	15.0	28,674	1.34	131	0.00	12,110	0.57
Region 2												
2012	504,284	24.4	183,007	8.87	29,355	1.42	0	0.00	0	0.00	216	0.01
A	519,736	24.4	103,775	4.86	82,955	3.89	0	0.00	127	0.00	488	0.02
B	375,806	17.6	177,887	8.33	88,994	4.17	0	0.00	139	0.00	429	0.02
C	270,091	12.7	163,395	7.65	156,733	7.34	0	0.00	472	0.02	787	0.06
Total												
2012	975,666	47.3	841,153	40.8	151,441	7.34	42,478	2.06	9,481	0.46	18,787	0.91
A	1,038,554	48.7	572,102	26.8	368,560	17.3	67,169	3.15	10,723	0.50	43,027	2.02
B	774,949	36.3	836,145	39.2	368,558	17.3	67,168	3.15	10,731	0.50	43,012	2.02
C	574,952	26.9	783,513	36.7	592,326	27.7	78,353	3.67	17,723	0.83	53,783	2.52

[a]Value relative to the Brazilian Cerrado total area (2,134,550.0 km^2).

At the intraregional scale, crops, pasture, and silviculture expansion in all scenarios was larger in the agriculturally consolidated *Regions*, *1A* and *1B* (see Table 3.8). According to the spatial allocation pattern observed (Figures 4.3 and 4.4), these systems expand around areas previously occupied. In these sense, in 2050 *Region 1A* will still be the largest area of semi-perennial crops, perennial crops, and silviculture. *Region 1B* will be the largest area of annual crops and pasture, and *Region 2*, the largest area of natural vegetation.

Soil nitrogen balance scenarios

In the study area, the input and output values represent N flows in different classes of land uses (see Table 4.9). N flows are presented for the agricultural regions as observed in Table 4.10. These results are described in the next sections.

Table 4.9 Nitrogen flows, in $TgN.yr^{-1}$, for the Brazilian Cerrado in the years 2012 and 2050 (A, B, and C scenarios).

Nitrogen Flows (TgN.yr-1)												
Years	IN					OUT						Balance
	IN_{fer}	IN_{man}	IN_{dep}	IN_{fix}	TIN	$OUT_{crop/prod}$	OUT_{res}	OUT_{lea}	OUT_{gas}	OUT_{ero}	TOUT	
Pasture												
2012	0	0	0.5	2.26	2.75	0.55	0	0	0.28	2.31	3.14	-0.38
A	0	0	0.32	4.41	4.73	1.76	0	0	1.06	1.33	4.15	0.58
B	1.34	0	0.84	1.58	3.76	1.76	0	0	1.57	2.18	5.51	-1.75
C	0	0	0.78	1.76	2.54	0.81	0	0	0.41	2.09	3.31	-0.77
Annual crops												
2012	0.53	0	0.07	1.4	2	1.77	0	0.08	0.08	0.23	2.16	-0.16
A	1.71	0	0.20	6.79	8.7	8.43	0	0.36	0.41	0.76	9.96	-1.26
B	1.71	0	0.37	6.72	8.8	8.43	0	0.36	0.41	0.90	10.10	-1.30
C	2.21	0	0.59	6.92	9.72	8.43	0	0.31	0.35	1.49	10.58	-0.86
Semi perenial crops												
2012	0.43	0.44	0.02	0.21	1.1	0.24	0	0.02	0.02	0.19	0.46	0.64
A	0.40	0.91	0.04	0.40	1.75	0.50	0	0.04	0.04	0.25	0.83	0.92
B	0.74	0.91	0.07	0.40	2.12	0.50	0	0.04	0.04	0.31	0.89	1.23
C	0.80	0.81	0.08	0.38	2.07	0.43	0	0.04	0.03	0.35	0.85	1.22
Perennial crops												
2012	0.26	0	0.01	0	0.27	0.14	0	0.01	0.01	0.04	0.19	0.08
A	0.43	0	0.01	0	0.44	0.33	0	0.02	0.01	0.05	0.41	0.03
B	0.43	0	0.01	0	0.44	0.33	0	0.02	0.01	0.05	0.41	0.03
C	0.48	0	0.02	0	0.50	0.26	0	0.01	0.01	0.09	0.37	0.13
Silviculture												
2012	0.25	0	0.01	0	0.26	0.72	0	0	0	0.09	0.81	-0.54
A	0.67	0	0.02	0.17	0.86	1.91	0	0	0	0.16	2.07	-1.21
B	0.67	0	0.02	0	0.69	1.91	0	0	0	0.18	2.09	-1.40
C	0.67	0	0.05	0	0.72	1.91	0	0	0	0.22	2.13	-1.41
Total												
2012	1.48	0.44	0.61	3.87	6.39	3.42	0	0.1	0.39	2.85	6.76	-0.37
A	3.21	0.91	0.59	11.77	16.48	12.93	0.00	0.42	1.52	2.55	17.42	-0.94
B	4.89	0.91	1.31	8.70	15.81	12.93	0.00	0.42	2.03	3.62	19.00	-3.19
C	4.16	0.81	1.52	9.06	15.55	11.84	0.00	0.36	0.80	4.24	17.24	-1.69

Table 4.10 Regional Breakdown of Brazilian Cerrado nitrogen flows ($TgN.yr^{-1}$) in 2050, for sustainable (A), middle of the road (B), and fragmentation (C) scenarios.

Nitrogen Flow ($TgN.yr^{-1}$)												
Year	IN					OUT						Balance
	IN_{fer}	IN_{man}	IN_{dep}	IN_{fix}	TIN	$OUT_{crop/prod}$	OUT_{res}	OUT_{lea}	OUT_{gas}	OUT_{ero}	TOUT	
						Region 1[a]						
2012	0.89	0.33	0.16	0.88	2.25	1.28	0	0.04	0.1	1.07	2.49	-0.24
A	1.51	0.60	0.16	2.59	4.86	4.06	0	0.11	0.33	1.05	5.55	-0.69
B	2.06	0.60	0.36	1.86	4.88	4.09	0	0.11	0.38	1.47	6.05	-1.17
C	1.92	0.51	0.42	2.03	4.88	3.83	0	0.10	0.20	1.38	5.51	-0.63
						Region 1B						
2012	0.48	0.11	0.32	2.27	3.18	1.71	0	0.05	0.21	1,27	3.24	-0.06
A	1.30	0.30	0.32	6.73	8.65	6.62	0	0.23	0.76	1.14	8.75	-0.10
B	2.12	0.31	0.70	4.88	8.01	6.41	0	0.22	0.86	1.57	9.06	-1.05
C	1.64	0.3	0.79	4.84	7.57	5.58	0	0.18	0.43	2.16	8.35	-0.78
						Region 2						
2012	0.11	0	0.12	0.72	0.95	0.43	0	0.02	0.08	0.51	1.03	-0.08
A	0.40	0	0.10	2.33	2.83	2.24	0	0.08	0.25	0.35	2.92	-0.09
B	0.71	0	0.27	1.96	2.94	2.44	0	0.09	0.34	0.58	3.45	-0.51
C	0.61	0	0.32	2.2	3.13	2.43	0	0.08	0.18	0.78	3.47	-0.34

Nitrogen inputs

Total nitrogen input (IN) increased 157.9%, 147.4%, and 143.4% in scenarios A, B, and C, respectively, from 2012 to 2050 (see Total, Table 4.9). In all scenarios, biofixation (IN_{fix}) was the largest input, accounting for 71.4% (A), 55.0% (B), and 58.3% (C) of all nitrogen inputs, followed by IN_{fer}, accounting for 19.5% (A), 30.9% (B), and 26.8% (C), and IN_{dep}, contributing with 3.6% (A), 8.3% (B), and 9.8% (C). IN_{man} contributed with 5.5% (A), 5.8% (B), and 5.2% (C). In general, Scenario A had the largest inputs via IN_{fix}, while scenarios B and C had the largest nitrogen inputs via IN_{fer}. That occurred mainly because of pasture areas being recovered through biofixation in A. In scenarios B and C, crops expanded more than in scenario A, which means that these areas require more nitrogen via fertilization.

Nitrogen inputs intraregional dynamic

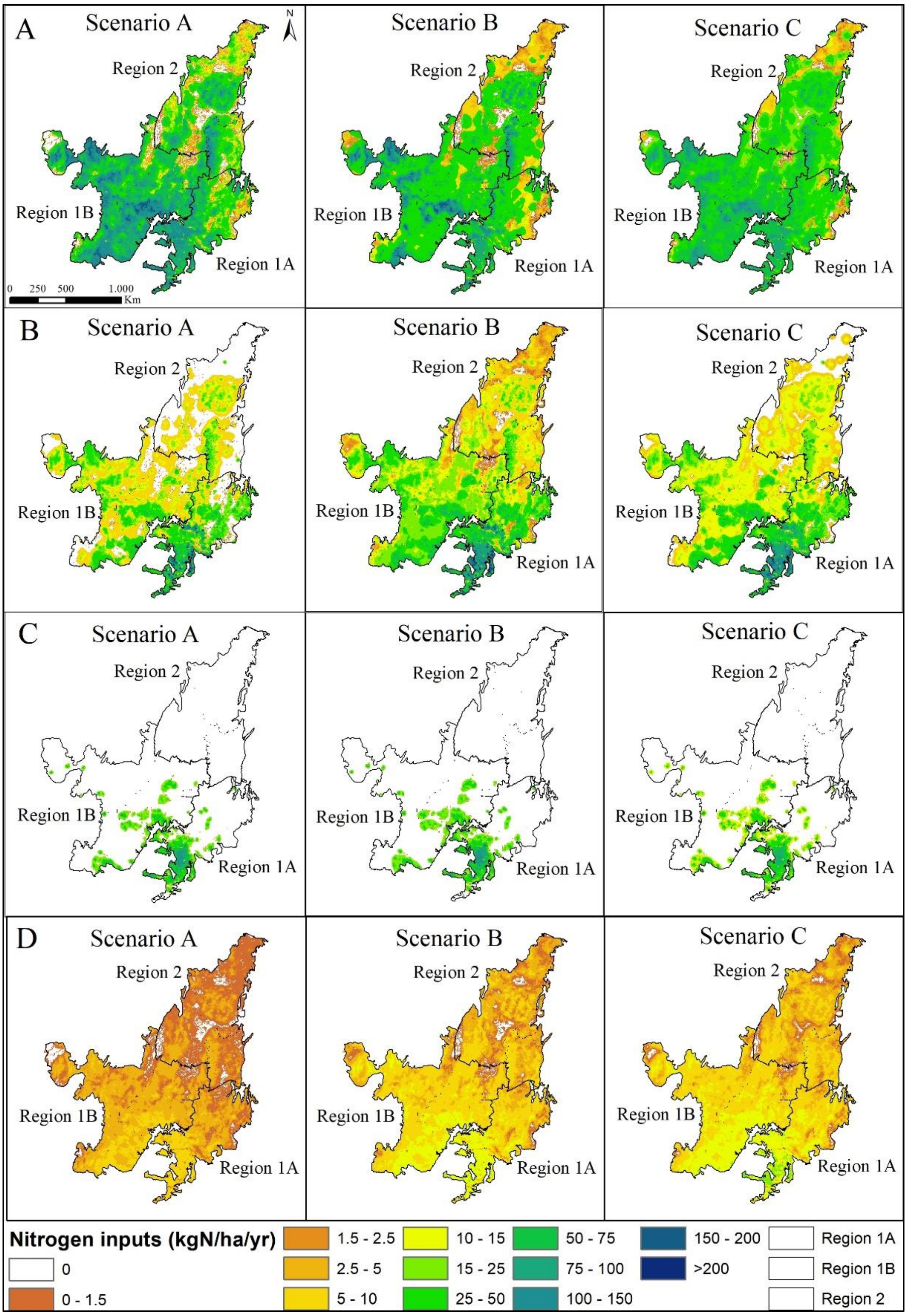
Intraregional nitrogen inputs reflects the kind of land use systems in each region and the boundary conditions adopted in modeling for each scenario. In scenario A, reduction in IN_{fer} in semi perennial crops and pasture, as well as~~,~~ investments in IN_{fix}~~,~~ in maize, silviculture, and pasture contributed to low values of nitrogen inputs via IN_{fer} when compared with scenarios B and C (see Total, Table 4.9). At the intraregional scale, *Region 1A* presented higher values of IN_{fer}, since its perennial crops, semi perennial crops, and silviculture need large nitrogen inputs. *Region 1B* had the highest values of IN_{fix} especially because of soybean (Table 4.10). In contrast, *Region 2* had low values of both IN_{fer} and IN_{fix} due to the predominance of natural vegetation.

Scenario B has the same crops and silviculture productivity gains as scenario A. However, in scenario B there was little investment~~s~~ in IN_{fix} (only in maize) and little reduction in IN_{fer}. Consequently, in all regions of scenario B, IN_{fer} were higher and IN_{fix} were lower than in scenario A (Table 4.10). *Region 1A* had more nitrogen inputs via IN_{fer}, and *Region 1B* had more nitrogen inputs via IN_{fix}.

In scenario C, crops productivity gains were not significant, which suggests that crops, pasture, and silviculture expanded vigorously over the Cerrado carrying nitrogen inputs, as in 2012. Thus, *Region 1A* had the highest values of IN_{fert} due to perennial, semi perennial, and silviculture, and *Region 1B* had high values of soy biofixation.

Figures 4.5A to 4.5D depict the N-input variation (kg.ha^{-1}.yr^{-1}) at the local scale in scenarios A, B, and C. The highest IN_{fer} (50-100 kg.ha^{-1}.yr^{-1}) was observed in *Region 1A,* due to fertilized areas of semi perennial crops, perennial crops, and silviculture. For the same reason, IN_{dep} was highest (5-15 kg.ha^{-1}.yr^{-1}) in *Region 1A* and *1B* of scenarios B and C. The highest IN_{fix} rates (>100 kg.ha^{-1}.yr^{-1}) were observed in *Region 1B* and *Region 1A* for all scenarios, being related mostly to the areas of annual crops and semi perennial crops, respectively. Scenario A had the largest areas with high IN_{fix} rates. The highest IN_{man} (25 - 75 kg.ha^{-1}.yr^{-1}) was observed in *Region 1B* and *Region 1A* due to semi perennial crops.

Figure 4.5 Nitrogen inputs (kg.ha^{-1}.yr^{-1}) maps in A, B, and C scenarios. (A) Biofixation-inputs; (B) Fertilizer-inputs; (C) Manure-inputs; (D) Atmospheric deposition inputs.



Source: Author's production.

Nitrogen outputs

Total nitrogen outputs (OUT) were larger than total nitrogen inputs (IN) in all scenarios (Total, Table 4.9), indicating that soil nitrogen mining is occurring. Total nitrogen output (OUT) increased 157.7%, 181.1%, and 155.1% from 2012 to 2050 in A, B, and C, respectively. Across all scenarios, harvested crops and animal products ($OUT_{crop/prod}$) had the largest outputs, accounting for 74.2% (A), 68.1% (B), and 68.7% (C), followed by $OUT_{ero,}$ accounting for 14.6% (A), 19.1% (B), and 24.6% (C). The nitrogen outputs from OUT_{gas} contributed with 8.7% (A), 10.7% (B), and 4.6% (C), while OUT_{lea} contributed with 2.4% (A), 2.2% (B), and 2.1% (C).

Nitrogen outputs intraregional dynamic

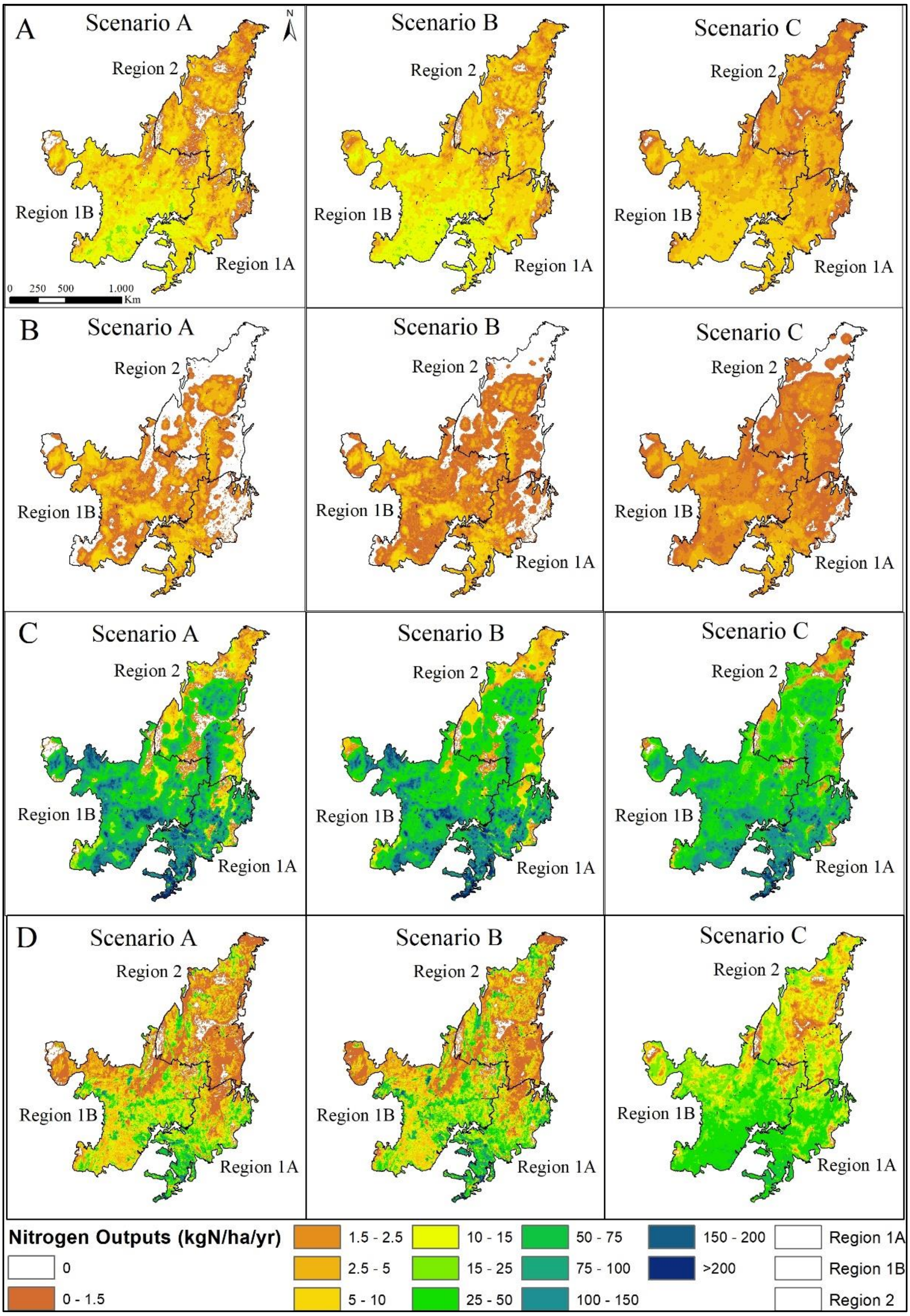
Intraregional nitrogen outputs also reflect the kind of land use systems in each region and the boundary conditions adopted in modeling for each scenario. Scenario A had the lowest values of OUT_{gas} when compared with scenario B, reflecting the absence of mineral fertilization in pasture (Table 4.9), even though scenario A had a higher bovine stocking rate (2.74 $head.ha^{-1}$). OUT_{ero} was reduced too, because of sustainable soil management. $OUT_{crop/prod}$ was similar to scenario B due to the same crops and silviculture productivity gains. *Region 1B* had the highest nitrogen losses because of the high concentration of annual crops and pasture in this region. In contrast, *Region 2* had the lowest nitrogen losses by virtue of its natural vegetation (Table 4.10).

In scenario B, high doses of fertilization rates and low investiments in biofixation caused a higher OUT_{gas} than in the scenario A. OUT_{ero} was high also due to conventional soil management (Table 4.9). In general, at the intraregional scale, nitrogen outputs have the same pattern in all scenarios due to land use systems. *Region 1B* had the highest nitrogen losses due to annual crops and pasture, and *Region 2* had the lowest ones due to natural vegetation (Table 4.10).

Low farmland productivity gains in scenario C caused the lowest nitrogen losses via $OUT_{crop/prod}$ in all scenarios (Table 4.9). This region also showed a low OUT_{gas} because of low bovine stocking rate (0.92 $head.ha^{-1}$), and a low OUT_{lea} because of inputs by mineral fertilizer similar to 2012. Even in scenario C, *Region 1B* had the highest nitrogen losses and *Region 2* had the lowest (Table 4.10).

Figures 4.6A to 4.6D present the N-export variation (kg.ha^{-1}.yr^{-1}) at the local scale in scenarios A, B, and C. Areas with high $OUT_{crop/prod}$ (>100 kg.ha^{-1}.yr^{-1}) occurred in both *Region 1A* and *1B*, the largest ones occuring in A because agricultural areas were more concentrated in this region. The highest OUT_{lea} (2.5-10 kg.ha^{-1}.yr^{-1}) and OUT_{gas} (10-15 kg.ha^{-1}.yr^{-1}) rates were found in *Region 1A*, associated with intensive application of fertilizers, and were higher than in B and C. OUT_{ero} was highest (15-50 kg.ha^{-1}.yr^{-1}) in *Regions 1A* and *1B*, accounting for large areas in B and C.

Figure 4.6 Nitrogen outputs (kg.ha^{-1}.yr^{-1}) maps in A, B, and C scenarios. (A) Gaseous-outputs; (B) Leaching-outputs; (C) Harvested crops and animal products outputs; and (D) Erosion-outputs.



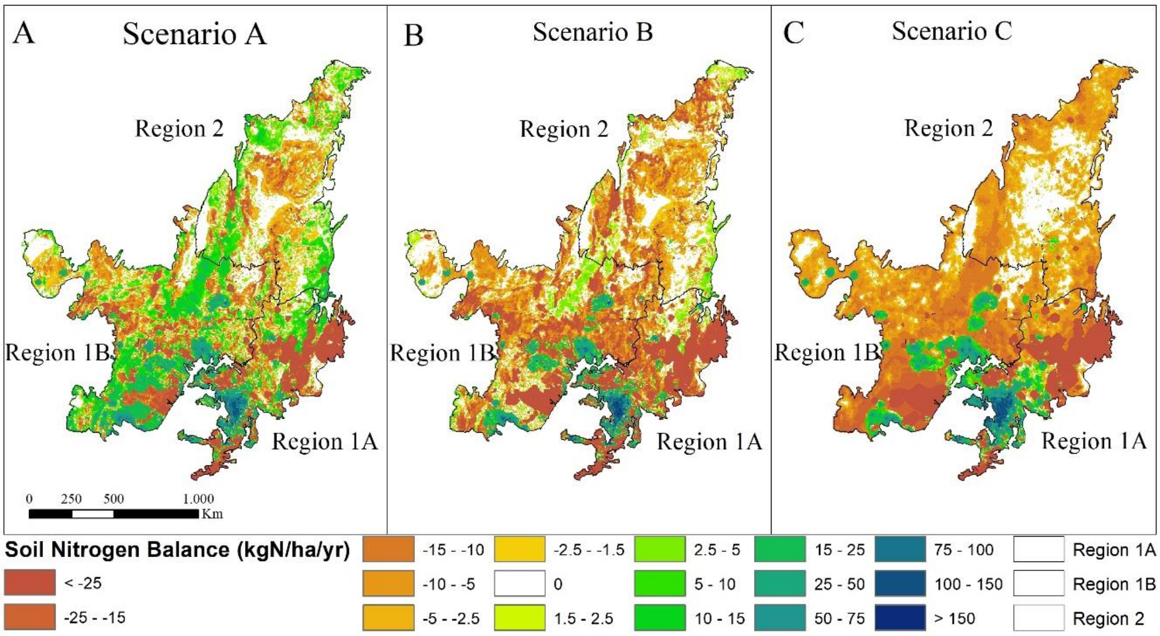
Source: Author’s production.

Soil nitrogen balance

Soil nitrogen balance was negative in all agricultural scenarios modeled for 2050 in the Brazilian Cerrado, indicating soil nitrogen mining, which jeopardizes soil sustainability (Total, Table 4.9). However, the technologies applied, such as investiment in biofixation, reduction in fertilization rate, and sustainable soil management contributed to soil nitrogen balance being less negative in Scenario A. In contrast, in Scenario B, soil nitrogen balance was highly negative. Nitrogen losses by gases were high due to nitrogen fertilization, and sustainable and conventional soil management practices continued to promote high losses via erosion. In Scenario C, soil nitrogen balance was also negative, with an intermediate value between scenarios A and B. In general, low crops and animal productivity resulted in lower nitrogen losses via harvested products. In contrast, high gains in area and conventional soil management practices resulted in high loss by erosion.

Soil nitrogen accumulation or depletion varied at the local scale, as shown in Figure 4.7. Scenario A shows the area with the highest accumulation of nitrogen in soil (15- 75 $kg.ha^{-1}.yr^{-1}$), mainly in the Region *1A*, due to semi perennial crops fertilization. The highest nitrogen depletion was in *Region 1A* due to silviculture. Scenario B shows the highest rate of nitrogen depletion (-25 - -10 $kg.ha^{-1}.yr^{-1}$), which occurred in *Regions 1A* and *1B*, mainly due to silviculture and pasture. In Scenario C, nitrogen accumulation (50 - 100 $kg.ha^{-1}.yr^{-1}$) occurred only in perennial and semi perennial crops areas. That was the scenario with the largest area of nitrogen depletion.

Figure 4.7 Spatially explicit soil nitrogen balance, scenarios A (A), B (B), C (C).



Source: Author's production.

4.4. DISCUSSION

The innovation of this study lies in exploring trajectories of land use focusing on agricultural production systems and their implications on nitrogen cycle. Modeling studies available for the Brazilian Cerrado have focused mainly in deforestation and biodiversity (FERREIRA et al., 2013; STRASSBURG et al., 2017). The LuccMe/Cerrado-N framework was capable of representing the main processes of land use change between 2000 and 2012 and simulate trajectories of land use and cover changes in a sensible way. In addition, the use of soil nitrogen balance as an indicator of land use status and environmental risks and benefits, made it possible to identify, at the regional and local scales, where the efficiency of production systems could be improved taking into account each agricultural scenario.

In general, agricultural extensification and intensification can continue affecting nitrogen cycle in the Brazilian Cerrado scenarios. Land use changes can lead to soil nitrogen mining in the year 2050. Only in the sustainability scenario (A), where natural vegetation was maintained and best practices in agricultural production were applied, soil nitrogen was less affected. Agricultural intensification in lands previously used for pasture promoted the conservation of the remaining Cerrado and the restoration of areas that are extremely important for biodiversity conservation, without compromising agricultural production progress. The recovery of remaining pasture areas also meets 46% of Brazilian projections for cattle production (EPE, 2014). These findings are consistent with Strassburg *et al* (2017), who simulated two land use deforestation scenarios for the Brazilian Cerrado in 2050. However, the agricultural intensification by means of best practices of agricultural production, such as sustainable soil management that reduces erosion and improvements in nitrogen use efficiency and biofixation, resulted in less nitrogen losses and ensured high production.

Some studies report that there is a clear relationship between plant responsiveness to nitrogen and soil tillage operations. Systems where conventional tillage operations (e.g., deep plowing, subsoiling, or disk) are established, show a limited plant responsiveness to nitrogen. Responsiveness increases under reduced tillage practices (OTTO et al., 2016). Thus, plant nitrogen requirements decrease under reduced tillage due to enhanced soil nitrogen mineralization and lower erosion, as a result low fertilization rate can be applied (OTTO et al., 2016). Besides, investiments in biofixation, either through fixing-bacteria inoculation or fixing-tree plantation, reduce leaching and gaseous losses (HUNGRIA et al., 2013). When applied to Scenario A, these soil improvements resulted in less soil nitrogen mining than in the other scenarios. A positive nitrogen balance occurred in pasture and semi perennial crops, where nitrogen use efficiency was increased by biofixation, the main nitrogen source. As biofixation is cheaper than nitrogen fertilizer (HUNGRIA et al., 2013; ATAÍDE et al., 2013), this technology may well be applied elsewhere. In silviculture, for exemple, soil nitrogen mining can be reduced to the extent that more areas are cultivated with fixing-plants. Thus, in a sustainable scenario, reduced magnitude of nitrogen losses and high nitrogen use efficiency are translated into lower environmental and financial costs (OTTO et al., 2016; HUNGRIA et al., 2013).

Research undertaken in Brazil have suggested that biofixation is the technology of the future (ATAÍDE et al., 2013) and its use in agricultural production reduces the fertilization costs by up to 2.5 times (HUNGRIA et al., 2013). Besides not having adverse effects on environmental services, these practices are accessible to and effective for farmers, and lead to improvements in food productivity (PRETTY, 2007). In line with that, the Brazilian Ministry of Agriculture, Livestock, and Supply has established goals for incorporating this technology into production systems (MAPA, 2012). By 2020, 5.5 Mha of Brazilian agricultural lands should be using biofixation, through bacteria-fixing inoculation or fixing-tree plantation, to produce food, fiber and biofuels (MAPA, 2012).

In contrast, when agricultural extensification and intensification use little sustainable practices of production, with little (or no) soil improvements, soil nitrogen mining tends to intensify, as in scenarios B and C. In the middle of the road scenario (B), where 20 Mha of natural vegetation was replaced by farmlands along with conventional practices of agricultural production, soil nitrogen mining was high. Agricultural production in both pasture and natural vegetation lands still conserved part of the remaning Cerrado and important areas for biodiversity. However, high productivity gains were not accompanied by satisfactory investments in soil improvement. Conventional use of fertilization and little investiments in biofixation resulted in large nitrogen losses by gases, while conventional tillage operations increased erosion. Pasture and silviculture were the main drivers of soil nitrogen mining in this scenario.

In the fragmentation scenario (C), soil nitrogen mining was less intense than in the middle of the road scenario (B). However, natural vegetation legally available for convertion was totally deforested and important areas for biodiversity were cleared. Combined, weak protection and the substantial pressure for agricultural expansion resulted in a landscape impaired in terms of biodiversity and ecosystems services. Soil nitrogen mining was less intense than in Scenario B because low crops and animal productivity resulted in lower nitrogen losses. Vigorous farmlands expansion with inefficient investments in soil improvement resulted in high erosion. The natural landscape and soil sustainability are strongly threatened in this scenario.

Silviculture, annual crops and pasture were the main drivers of soil nitrogen mining in these scenarios. In general, the prerequisite for any sustainable agricultural system is that the total output of nitrogen exported in useful products, or lost to the surrounding environment, does not exceed their input (BODDEY et al., 2004). Thus, silviculture, annual crops and pasture are the land use systems that require the highest nitrogen inputs. Consequently, *Regions 1A* and *1B* were those of greater impairment in terms of soil nitrogen mining. As these areas are fewer in the *Region 2*, soil nitrogen mining was less intense. Investments in cheaper and cleaner soil fertility technologies, as biofixation, could be an alternative to improve soil fertility in these systems.

When modeled for the year 2050, the agricultural systems expanded around areas that they occupied previously. This spatial allocation pattern can be a methodological limitation. Scientific evidence shows that land use change has been intense in the agricultural frontier region (*Region 2*, Matopiba) in the last years (BARRETO et al., 2013; DIAS et al., 2016). However, in our scenarios, there were few changes in land use in this region in 2050. The lack of important variables such as land price in different agricultural regions and the absence of dynamic variables, such as roads, may have contributed to the limitations of the model.

On the other hand, the scenarios herein discussed were capable of evidencing the landscape as an integrated system in which natural environment and agricultural production systems are connected. In an integrated system, productivity gains or losses are driven by practices of production that maintain soil fertility. Little or no investments in soil improvement can affect natural systems, e.g. through deforestation, jeopardizing ecosystems services and biodiversity. The use of soil nitrogen balance as an indicator that integrates landscape components, made it possible to visualize that increased agricultural production by using nitrogen in an efficient way, ensures high productivity gains, and consequently, conserve natural vegetation and secures its benefits.

CHAPTER 5 - CONCLUSIONS AND RECOMMENDATIONS

This thesis investigated how agricultural intensification currently affects the nitrogen cycle in the Brazilian Cerrado and how it could affect the nitrogen cycle in the future. Spatio-temporal soil nitrogen balances for the Brazilian Cerrado were performed based on the land use dynamics in the years 2000, 2010, and 2012. In addition, this thesis explored trajectories of land use change and soil nitrogen balance for the year 2050 using techniques of dynamic spatial modeling. The working hypothesis was that agricultural expansion and intensification in the Brazilian Cerrado may not be currently affecting the nitrogen balance in this region in a significant way, but could disrupt it in the future.

Section 5.1 synthesizes the major findings of the whole thesis and discusses how these findings confirm the working hypothesis. In addition, section 5.2 presents some policy recommendations.

5.1 Major findings

Chapter 2 provides estimates of annual soil loss rates for the Brazilian Cerrado. These estimates were used to calculate nitrogen loss by erosion processes (OUT_{ero}) in chapters 3 and 4. This initial chapter showed that the average estimated rate of soil loss had been increasing from 2000 to 2012 in the Brazilian Cerrado. However, a large part of the total Cerrado area (80%) is still under low soil loss, and only 16%, and 4% are moderate and high soil loss zones, respectively. With the exception of annual crops and pasture, that showed a low average rate of soil loss, all farm and silviculture areas showed moderate rates of soil loss. That indicates that good crop management practices, such as no-tillage, terrace, and green fertilizers, are important factors in preventing soil loss, and maintaining and improving land productivity in the Brazilian Cerrado.

Chapter 3 provides evidence that agricultural extensification and intensification have affected the nitrogen cycle in the Brazilian Cerrado. According to this study, agriculture has mined soil nitrogen, risking long term soil sustainability at the regional scale. Silviculture, annual crops (e.g soybeans and maize), and pasture are the main drivers of soil nitrogen depletion, with harvested products and erosion as the main nitrogen outputs. At the local scale, the spatio-temporal soil nitrogen balances showed areas with nitrogen accumulation and depletion mainly in agriculturally consolidated regions, where semi perennial and perennial crops account for nitrogen accumulation, and silviculture and pasture account for nitrogen depletion. All these findings confirm the hypothesis that agricultural expansion and intensification are currently affecting the nitrogen cycle in the Brazilian Cerrado.

Chapter 4 provides evidence that the nitrogen cycle in the Brazilian Cerrado could be intenselly affected in the future depending on future trajectories of agricultural expansion and intensification. When agricultural expansion is conducted by little sustainable practices of production, with low or no soil improvements and natural vegetation conservation, soil nitrogen mining tends to intensify, as in the middle of the road (B) and fragmentation scenarios (C). In contrast, a sustainable trajectory of agricultural expansion and intensification indicates that soil nitrogen mining can be reduced if best practices in agricultural production are applied. Sustainable soil management practices to reduce erosion, improvements in nitrogen use efficiency and biofixation adoption result in less nitrogen losses for the environment and can ensure high agricultural production, as in the sustainability scenario (A). Thus, these findings confirm the hypothesis that agricultural expansion and intensification may intensify the nitrogen cycle unbalance in the Brazilian Cerrado in the future.

In summary, the innovation of this thesis is that soil nitrogen balance was spatially explicit, allowing for the identification, at the regional and local scales, of a soil nitrogen imbalance. Only a few studies made use of spatially explicit database to estimate nitrogen flows in agricultural lands (LESSCHEN et al., 2007; LASSALETA et al., 2012). In general, studies consider a country or a whole region to be homogenous (FILOSO et al., 2006; MARTINELLI et al., 2012). This study innovated further in exploring future trends of agricultural expansion using soil nitrogen balance as an integrative indicator of the land use status and environmental risks or benefits. In general, not many studies explore land use transitions following the deforestation processes (GOLLNOW et al., 2017). The main processes they assess are deforestation (FERREIRA et al., 2013; AGUIAR et al., 2012; DALLA-NORA et al., 2014; AGUIAR et al., 2016; GOLLNOW et al., 2017) and its implication on biodiversity (Strassburg et al., 2017) and climate regulation (CÂMARA et al., 2015; AGUIAR et al., 2016a). This work is the first to explore future trajectories of agricultural expansion focusing on their implications on the nitrogen cycle in the Brazilian Cerrado.

5.2 Policy recommendations

We suggest basically three main ways to address the problem of nitrogen imbalance: i) Scientific research and technological development, such as improved agricultural techniques based on nitrogen biological fixation, to increase soil nutrition and agricultural productivity gains without compromising the environment through nitrogen loss. Moreover, improved agricultural production techniques to help obtain reasonable nitrogen fertilizer inputs by increasing the recovery rate by crops and reducing nitrogen fertilizer losses, as cited by JU et al. (2004). ii) Economic instruments, such as subsidies to farmers for environmentally-sound farming practices or indirect effects through prices of agricultural produce for those that conserve soil, water, and natural vegetation. iii) Public information and education, such as training courses for farmers and support for advisory services (JU et al,. 2004).

In terms of land use change, we suggest broader land use policies to reduce deforestation in the Brazilian Cerrado, considering that this biome is under deforestation risk in any scenario. An urgent and planned conservation policy aimed at the biodiversity and endemic-rich areas, could reach that goal by creating new protected areas. In addition, the country's Soy Moratorium, a key element in preventing almost all direct conversion of the Amazon to soy cultivation, could be applied to the Cerrado. It would encourage agricultural expansion towards degraded pasture and, as our results show, without compromising livestock production.

REFERENCES

AGÊNCIA NACIONAL DE ÁGUAS (ANA). **Bacias hidrográficas brasileiras**. Hidrografia 1:2.500.000. Retrieved from: http://hidroweb.ana.gov.br/HidroWeb.asp?TocItem=4100>. Access on 15 set. 2015.

AGUIAR, A.P.D.; DALLA-NORA, E.L.; ASSIS, T.O.; MELO, D.; BEZERRA, F.G.B. **Working with LuccMe.** A user's guide. p. 34, 2016b.

AGUIAR, A.P.D.; OMETTO, J.P.; NOBRE, C.A.; LAPOLA, D.M.; ALMEIDA, C.; VIEIRA, I.C.; SOARES, J.V.; ALVALA, R.; SAATCHIK, S.; VALERIANO, D.; CASTILLA-RUBIO, J.C. Modeling the spatial and temporal heterogeneity of deforestation-driven carbon emissions: the INPE-EM framework applied to the Brazilian Amazon. **Global Change Biology**, v. 18, n. 11, p. 3346–3366, Nov. 2012, doi: 10.1111/j.1365-2486.2012.02782.x. Disponível em: https://doi.org/10.1111/j.1365-2486.2012.02782.x

AGUIAR, A.P.D.; VIEIRA, I. C. G.; ASSIS, T.O.; DALLA-NORA, E.L.; TOLEDO, P.M.; SANTOS-JUNIOR, R.A.O.; BATISTELLA, M.; COELHO, A.S.; SAVAGET, E.K.; ARAGÃO, L.E.O.C.; NOBRE, C.A.; OMETTO, J.P.H. Land use change emission scenarios: anticipating a forest transition process in the Brazilian Amazon. **Global Change Biology**, v. 22, p. 1821–1840, 2016a. https://doi.org/10.1111/gcb.13134

AHMAD, N.; MERMUT, A. **Vertisols and technologies for their management**. Amsterdam: Elsevier, p.152. 1996.

ALEXANDRATOS, N.; BRUINSMA, J. **World agriculture towards 2030/2050**: the 2012 revision. Rome: FAO, 2012. (ESA Working paper No. 12-03).

ALVES B.J.R.; FERNANDES F.M.; HECKLER J.C. et al. Fixação biológica de nitrogênio e fertilizantes nitrogenados no balanço de nitrogênio em soja, milho e algodão. **Pesquisa agropecuária bras.**, v. 41,p. 449-456, 2006. doi:10.1023/A:1024191913296

ALVES, B.J.R.; BODDEY R.M.; URQUIAGA S. The success of BNF in soybean in Brazil. **Plant and Soil**, v. 252, n. 1, p. 1-9, 2003. https://doi.org/10.1023/A:1024191913296

ASSOCIAÇÃO BRASILEIRAS DE FLORESTAS PLANTADAS (ABRAF). **Anuário estatístico da ABRAF**: ano base 2005. Brasília, 2006.

ASSOCIAÇÃO BRASILEIRAS DE FLORESTAS PLANTADAS (ABRAF). **Anuário estatístico da ABRAF**: ano base 2012. Brasília, 2013.

ATAÍDE, D.H.S.; SANTOS, F.M.; DINIZ, A. R.; CHAER, G.M.; BALIEIRO, F.C. Acúmulo e eficiência de uso de nutrientes na parte aérea de Eucaliptus urograndis em plantios puros e mistos com Acacia mangium Willd. In: CONGRESSO BRASILEIRO DE CIÊNCIA DO SOLO, 34., 2013, Florianópolis. **Anais...** Viçosa, MG: SBCS, 2013.

AUSTIN A.T.; BUSTAMANTE, M.M.C.; NARDOTO, G.B. et al. Latin America's Nitrogen Challenge. **Science**, v. 340, n.149, 2013. doi:10.1126/science.1231679.

BALCOMBE, K.; RAPSOMANIKIS, G. Bayesian estimation and selection of nonlinear vector error correction models: the case of the sugar-ethanol-oil nexus in Brazil. **American Journal of Agricultural Economics**, v. 90, p. 658-668, 2008. doi:10.1111/j.1467-8276.2008.01136.x.

BALMFORD A.; GREEN R.E.; SCHARLEMANN J.P.W. Sparing land for nature: exploring the potential impact of changes in agricultural yield on the area needed for crop production. **Global Change Biology**, v.11, p.1594-1605, 2005. doi:10.1111/j.1365-2486.2005.001035.x.

BARRETO A.G.O.P.; BERNARDES G.; SPAROVEK G.; WIRSENIUS S. Agricultural intensification in Brazil and its effects on land-use patterns: an analysis of the 1975–2006 period. **Global Change Biology**, v. 19, p. 1804-1815, 2013. doi:10.1111/gcb.12174.

BARRETO P.A.B.; GAMA-RODRIGUES A.C. GAMA-RODRIGUES, E.F.; BARROS, N.F. Nitrogen balance in soil under eucalyptus plantations. **Revista Bras. Ci. Solo**, v. 36, p. 1239-1248, 2012. doi:10.1590/S0100-06832012000400018.

BARRETO, P.A.B.; GAMA-RODRIGUES, E.F.; GAMA-RODRIGUES, A.C.; BARROS, N.F.; FONSECA, S. Atividade microbiana, carbono e nitrogênio da biomassa microbiana em plantações de eucalipto, em sequência de idades. **Revista Brasileira de Ciência do Solo**, v. 32, p. 611-619, 2008.

BERNARDES, T.; MOREIRA, M.A.; ADAMI, M.; GIAROLLA, A.; RUDORFF, B.F.T. Monitoring Biennial Bearing Effect on Coffee Yield Using MODIS Remote Sensing Imagery. **Remote Sensing**, v. 4, n. 9, 2492-2509, 2012. doi:10.3390/rs4092492.

BERTOL I.; SHICK j.; BATISTELA, O. Razão de perdas de solo e fator C para as culturas de soja e trigo em trêssSistemas de preparo em um cambissolo húmico alumínico. **Revista Brasileira de Ciência do Solo**, v. 25, p. 451-461, 2001. doi:10.1590/S0100-06832001000200021.

BERTOL, I.; SHICK, J.; BATISTELA, O. Razão de perdas de solo e fator C para milho e aveia em rotação com outras culturas em três tipos de preparo de solo. **Revista Brasileira de Ciência do Solo**, v. 26, p.545-552, 2002.

BESKOW, S.; MELLO, C.R.; NORTON, L.D.; CURI, N.; VIOLA, M.R.; AVANZI, J.C. Soil erosion prediction in the Grande River Basin, Brazil using distributed modelling. **Catena,** v. 79, v. 49-59, 2009. https://doi.org/10.1016/j.catena.2009.05.010.

BINDRABAN, P.S.; STOORVOGEL, J.J.; JANSEN D.M.; VLAMING J.; GROOT, J.J.R. Land quality indicators for sustainable land management: proposed method for yield gap and soil nutrient balance. **Agriculture, Ecosystems and Environment** , v. 81, p. 103-112, 2000. https://doi.org/10.1016/S0167-8809(00)00184-5.

BOARETTO, R.M.; MATTOS JR, D.; QUAGGIO, J.A.; CANTARELLA, H.; TRIVELIN, P.C.O. Absortion of 15 NH3 volatilized from urea by Cutrus trees. **Plant Soil**, v. 365, p. 283-290, 2013.

BOARETTO, R.M.; MATTOS JUNIOR, D.; TRIVELIN, P.C.O.; MURAOKA, T.; BOARETTO, A.E. Acúmulo de nutrients e destino do nitrogênio (15N) aplicado em pomar jovem de laranjeira. **Revista Brasileira Fruticultura**, v. 29, p. 600-605, 2007. doi:10.1590/S0100-29452007000300035.

BODDEY R.M.; MACEDO R.; TARRÉ R.M. et al. Nitrogen cycling in Brachiaria pastures: the key to understanding the process of pasture decline. **Agriculture, Ecosystems & Environment**, v.103, p. 389-403, 2004. doi:10.1016/j.agee.2003.12.010.

BODDEY, R. M.; URQUIAGA, S.; REIS, V.; DOBEREINER, J. Biological nitrogen fixation associated with sugar cane. **Plant and Soil**, v. 137, p. 111-117, 1991. https://doi.org/10.1007/BF02187441.

BODDEY, R.M.; CHALK, P.M. Nitrogen fixation by nodulated soybean under tropical field conditions estimated by the 15N isotope dilution technique. **Soil Biology and Biochemical**, v.16, p. 583-588, 1984.

BODDEY, R.M.; VICTORIA, R.L. Estimation on biological nitrogen fixation associated with Brachiaria and Paspalum grasses using 15N labelled organic matter and fertilizer. **Plant and Soil**, v.90, p. 265-292, 1986.

BORKERT, C.M; YORINORI, J.T.; CORRÊA-FERREIRA, B.S.; ALMEIDA, A.M.R.; FERREIRA, L.P.; SFREDO, G.J. Seja o doutor da sua soja. **Arquivo do Agrônomo – n°5**, p.17, 1994.

BORTOLLOTO R.P.; BRUNO, I.P.; REICHARD K. et al. Nitrogen fertilizer (15N) leaching in a central pivot fertigated coffee crop. **Revista Ceres**, v.59, p. 466-475, 2012. doi:10.1590/S0034-737X2012000400006.

BORTOLOTTO, R.P.; BRUNO, I.P.; DOURADO-NETO, D.; TIMM, L.C.; DA SILVA, A.N.; REICHARDT, K. Nitrate leaching through climatologic water balance in a fertigated coffee plantation. **Revista Ceres**, v. 60, p. 785-792, 2013.

BRASIL. MINISTÉRIO DA AGRICULTURA, PECUÁRIA E ABASTECIMENTO. **Plano setorial de mitigação e de adaptação às mudanças climáticas para a consolidação de uma economia de baixa emissão de carbono na agricultura**: plano ABC (Agricultura de Baixa Emissão de Carbono) / Ministério da Agricultura, Pecuária e Abastecimento, Ministério do Desenvolvimento Agrário, coordenação da Casa Civil da Presidência da República. – Brasília : MAPA/ACS, 2012. 173 p.

BRASIL. MINISTÉRIO DO MEIO AMBIENTE. **Mapeamento do uso e cobertura da terra do Cerrado:** projeto TerraClass Cerrado 2013 / Ministério do Meio Ambiente, coordenação da Casa Civil da Presidência da República. – Brasília: MMA, 2015. 69 p.

BROOKS, K.N.; FOLLIOTT, P.F.; GREGERSEN, H.M.; DEABANO, L.F. **Hydrology and the management of watershed.** Ames, Blackwell Publishing, 2003. 825p.

BUSTAMANTE M. M.; FERREIRA, J.L.G. Land use change and the carbon budget in the Brazilian Cerrado. In: HILL M.J.; HANAN N.P. (eds.). **Ecosystem function in savannas:** measurement and modeling at landscape to global scales. CRC Press, 2010.

BUSTAMANTE, M.M.C.; MARTINELLI, L.A.; SILVA, D.A.; CAMARGO, P.B.; KLINK, C.A.; DOMINGUES, T.F.; SANTOS, R.V. 15N natural abundance in woody plants and soils of central Brazilian savannas (Cerrado). **Ecological Applications**, v. 14, p. 200-213, 2004.

BUSTAMANTE, M.M.C.; NARDOTO, G.B.; PINTO, A.S.; RESENDE, J.C.F.; TAKAHASHI, F.S.C.; VIEIRA, L.C.G. Potential Impacts of Climate Change on Biogeochemical Functioning of Cerrado Ecosystems. **Braz. Journal Biology**, v. 72, p. 655-671, 2012. https://doi.org/10.1590/S1519-69842012000400005

CABRAL, J.B.P.; BECEGATO, V.A.; SCOPEL, I : LOPES, R.M. Uso de técnicas de geoprocessamento para mapear o potencial natural de erosão da chuva na Bacia Hidrográfica do Reservatório de Cachoeira Dourada – GO/MG. **Revista Raega**, v. 10, p. 107-116, 2005.

CÂMARA, G.; SOTERRONI, A.; RAMOS, F.; CARVALHO, A.; ANDRADE, P.; SOUZA, R.C.; MOSNIER, A.; MANT, R. ; BUURMAN, M.; PENA, M.;

HAVLIK, P.; PIRKER, J.; KRAXNER, F.; OBERSTEINER,M.; KAPOS, V.; AFFONSO, A.; ESPÍNDOLA, G.; BOCQUEHO, G. **Modelling land use change in Brazil:** 2000–2050. São José dos Campos, Brasília, 2015.

CANISARES, L.P.; CARMO, J.B.; PITOMBO, L.M.; PIRES, E.C. Digested bioenergy byproduct with low concentration of nutrients increased greenhouse gas emissions from soil. **Geoderma**, v. 307, p. 81-90, 2017.

CANTARELLA H.; MATTOS D.; QUAGGIO, J.A.; RIGOLIN A.T. Fruit yield of Valencia sweet orange fertilized with different N sources and the loss of applied N. **Nutrient cycling in agroecosystems**, v. 67, p. 215-223, Piracicaba, 2003. doi:10.1023/B:FRES.0000003600.20499.76

CANTARELLA, H.; QUAGGIO, J.A. Adubação com macro e micronutrientes em citros. In: SEMINÁRIO INTERNACIONAL DE CITROS, 4., 1996, Bebedouro. **Anais...** Campinas: Fundação Cargill, 1996. p.161-178.

CANTARELLA, H.; QUAGGIO, J.A.; BATAGLIA, O.C.; RAIJ, B. Response of citrusvto NPK fertilization in a network of field trials in São Paulo state, Brazil. In: International citrus congress, Acireale, 1992. **Proceedings. Acireale: International Society of Citriculture**, 1992. v.2, p. 607-612.

CANTARELLA, H.; TRIVELIN, P.C.O.; CONTIN, T.L.M.; DIAS, F.L.F.; ROSSETTO, R.; MARCELINO, R.; COIMBRA, R.B.; QUAGGIO, J.A. Ammonia volatilization from urease inhibitor-treated urea applied to sugarcane trash blankets.**Sciencia Agricola**, v. 65, n. 4, p.397-401, 2008.

CARMO, J.B.; FILOSO, S.; ZOTELLI, L.C.; SOUSA NETO, E.R.; PITOMBO, L.M.; DUARTE-NETO, P. J.; VARGAS, V.P.; ANDRADE, C.A.; GAVA, G.J.C.; ROSSETTO, R.; CANTARELLA, H.; NETO, A.E.; MARTINELLI, L.A. Infield greenhouse gas emissions from sugarcane soils in Brazil: effects from synthetic and organic fertilizer applicatioin and crop trash accumulation. **Global Change Biology Bioenergy**, v. 5, p. 267-280, 2013.

CARNEIRO, T.G.S.; ANDRADE, P.R.; CÂMARA, G.; MONTEIRO, A.M.V.; PEREIRA; R. R. An extensible toolbox for modeling nature-society interactions. **Environmental Modelling & Software**, v. 46, Issue C, p. 104–117, 2013. https://doi.org/10.1016/j.envsoft.2013.03.002

CASTRO, W.J.; LEMKE-DE-CASTRO, M.L.; LIMA, J.O.; OLIVEIRA, L.F.C.; RODRIGUES, C. ; FIGUEIREDO, C.C. Erodibilidade de solos do Cerrado Goiano. **Revista em Agronegócios e Meio Ambiente**, v. 4, n. 2, p. 305-320, 2011.

CLARK C.M.; TILMAN D. Loss of plant species after chronic low-level nitrogen deposition to prairie grasslands. **Nature** 451, p. 712-715, 2008. doi:10.1038/nature06503

COELHO, A.M.; FRANÇA, G.E. **Seja o doutor do seu milho.** Arquivo do agrônomo n°2, p.25, 1995.

COELHO, C.H.M.; MEDEIROS, A.F.A.; POLIDORO, J.C.; XAVIER, R.G.; RESENDE, A.; QUESADA, D.M.; ALVES, B.J.R.; BODDEY, R.; URQUIAGA, S. Identificação de genótipos de cana-de-açúcar quanto ao potencial de contribuição da fixação biológica de nitrogênio. **Agronomia**, v. 37, p. 37-40, 2003.

COMISSÃO DE FERTILIDADE DO SOLO DO ESTADO DE MINAS GERAIS (CFSEMG). **Recomendações para o uso de corretivos e fertilizantes em Minas Gerais:** 5º aproximação. RIBEIRO, A. C.; GUIMARÃES, P.T.G.; ALVAREZ V, V. H. (eds), Minas Gerais, 1999. 359 p.

COMPANHIA NACIONAL DE ABASTECIMENTO (CONAB) **Acompanhamento da safra brasileira:** grãos – Safra 2010/2011. Brasília, 2011.

COMPANHIA NACIONAL DE ABASTECIMENTO (CONAB) **Séries históricas de área plantada, produtividade e produção relativas às safras 1976/77 a 2015/2016 de grãos**. Brasília, 2016.

COMPANHIA NACIONAL DE ABASTECIMENTO (CONAB). **Séries históricas de área plantada relativa às safras 2000/01 de grãos.** Brasília, 2001. Available at http://www.conab.gov.br/conteudos.php?a=1252&t= (accessed 25 November 2015).

COMPANHIA NACIONAL DE ABASTECIMENTO (CONAB). **Séries históricas de área plantada relativa às safras 2010/11 de café.** Brasília, 2011b. Available at http://www.conab.gov.br/conteudos.php?a=1252&t= (accessed 30 November 2015).

COMPANHIA NACIONAL DE ABASTECIMENTO (CONAB). **Séries históricas de área plantada relativa às safras 2010/11 de grãos.** Brasília, 2011a. Available at http://www.conab.gov.br/conteudos.php?a=1252&t= (accessed 25 November 2015).

COMPANHIA NACIONAL DE ABASTECIMENTO (CONAB). **Séries históricas de área plantada relativa às safras 2012/13 de café**. Brasília, 2013b. Available at http://www.conab.gov.br/conteudos.php?a=1252&t= (accessed 30 November 2015).

COMPANHIA NACIONAL DE ABASTECIMENTO (CONAB). **Séries históricas de área plantada relativa às safras 2012/13 de grãos.** Brasília, 2013a. Available at http://www.conab.gov.br/conteudos.php?a=1252&t= (accessed 25 November 2015).

COSTA M.H.; BOTTA A.; CARDILLE J.A. Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia.

Journal of Hydrology, v. 283, p. 206-217, 2003. doi:10.1016/S0022-1694(03)00267-1

COSTA, K.A.P. **Adubação nitrogenada para pastagens do gênero Brachiaria em solos do Cerrado.** EMBRAPA Arroz Feijão, 2006.

COSTA, K.A.P.; FAQUIN, V.; OLIVEIRA, I.P.; RODRIGUES, C.; SEVERIANO, E.C. Doses e fontes de nitrogênio em pastagem de capim-marandu. I – Alterações nas características químicas do solo. **Revista Brasileira de Ciência do Solo**, v. 32, p. 1591-1599, 2008.

COSTANZA, R. Model goodness of fit: a multiple resolution procedure. **Ecological Modelling**, v. 47, n. 3, p. 199-215, 1989.

COUTINHO, L.M. O bioma do cerrado. In KLEIN, A.L. (eds) **Eugen Warming e o cerrado brasileiro: um século depois.** Editora Unesp, São paulo, 2002, p. 77-91.

CRISPINO, C.C.; FRANCHINI, J.C.; MORAES, J.Z.; SIBALDELLE, R.N.R.; LOUREIRO, M.F.; SANTOS, E.N.; CAMPO, R.J.; HUNGRIA, M. Adubação nitrogenada na cultura de soja. **Comunicado Técnico 75**, 2001.

CRUVINEL, E. B. F.; BUSTAMANTE, M.M.C.; KOZOVITS, A. R.; ZEPP, R.G. Soil emissions of NO, N2O and CO2 from croplands in the savanna region of central Brazil. **Agriculture, Ecosystems and Environment**, v. 144, p. 29-40, 2011.

DALLA-NORA, E. L.; AGUIAR, A. P. D.; LAPOLA, D. M.; WOLTJER, G. Why have land use change models for the Amazon failed to capture the amount of deforestation over the last decade? **Land Use Policy**, v. 39, July, p. 403–411, 2014.

DAVIDSON E.A.; NINFONG R.L.; FERGUSON R.B.; PALM C.; OSMOND D.L.; BARON J.S. Nutrients in the nexus. **Journal of Environmental Studies and Sciences**, v. 6, p. 25-38, 2016. doi:10.1007/s13412-016-0364-y

DEMARCHI, J.C. ; ZIMBACK, C.R.L. Mapeamento, Erodibilidade e Tolerância de Perda de Solo na Sub-bacia do Ribeirão das Perobas. **Energia na Agricultura**, v. 29, n. 2, p. 102-114, 2014. https://doi.org/10.17224/EnergAgric.2014v29n2p102-114

DEPARTAMENTO NACIONAL DE INFRAESTRUTURA DE TRANSPORTES (DNIT) **Infraestrutura rodoviária, aquaviária e ferroviária.** Brasília, 2013. Retrieved from: < http://www.dnit.gov.br/mapas-multimodais/shapefiles>. Access on: 01 set. 2015

DESMET P.J.J.; GROVERS, G. A GIS procedure for automatically calculating the USLE LS factor on topographically complex landscape units. J. **Soil and Water Cons**, v. 51, n. 5, p. 427-433, Rome, 1996.

DIAS L.C.P.; PIMENTA F.M.; SANTOS A.B.; COSTA M.H.; LADLE R.J. Patterns of land use, extensification, and intensification of Brazilian agriculture. **Global Change Biology**, v. 22, n. 8, p. 2887-2903, 2016. doi:10.1111/gcb.13314

DOMINGHETTI, A.W.; GUELFI, D.R.; GUIMARÃES, R.J.; CAPUTO, A.L.C.; SPEHAR, C.R.; FAQUIN, V. Nitrogen loss by volatilization of nitrogen fertilizers applied to coffee orchard. **Ciência e Agrotecnologia**, v. 40, p. 173-183, 2016.

EITEN G. The cerrado vegetation of Brazil. **The Botanical Review**, v. 38, n. 2, p. 201-341, 1972. doi:10.1007/BF02859158

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA (EMBRAPA). **Bactérias aumentam produtividade do milho e reduzem adubos químicos.** Brasília, 2015. Retrieved from: <https://www.embrapa.br/busca-de-noticias/-/noticia/2467608/bacterias-aumentam-produtividade-do-milho-e-reduzem-adubos-quimicos>. Access on 28 ago. 2017

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA (EMBRAPA). **Leguminosas eliminam aplicação de nitrogênio em florestas de eucalipto.** Brasília, 2017. Retrieved from: <https://www.embrapa.br/busca-de-noticias/-/noticia/23827807/legumes-eliminate-need-to-apply-nitrogen-in-eucalyptus-forests>. Access on 28 ago. 2017

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA (EMBRAPA). **Mapeamento da área irrigada e do número de equipamentos de irrigação por pivô central no Brasil.** Brasília, 2013. Retrieved from: <https://pastagem.org/index.php/pt-br/tools/mapa-interativo>. Access on: 19 jul. 2016

EMPRESA DE PESQUISA ENERGÉTICA (EPE) **Cenário econômico 2050. Nota Técnica DEA 12/14.** Série Estudos Econômimcos. Brasília, 2014. Retrieved from: <http://www.epe.gov.br/Estudos/Documents/DEA%2013-14%20Demanda%20de%20Energia%202050.pdf >. Access on: 29 ago. 2017

ERDOGAN, E.H., ERPULL, G.; BAYRAMIN, I. Use of USLE/GIS Methodology for Prediction Soil Loss in a Semiarid Agriculture Watershed. **Environmental Monitoring and Assessment**, v. 131, p. 153-161, 2007. http://dx.doi.org/10.107/s10661-006-9464-6

ESPÍNDOLA G.M.; AGUIAR A.P.D.; PEBESMA E.; CÂMARA G.; FONSECA L. Agricultural land use dynamics in the Brazilian Amazon based on remote sensing and census data. **Applied Geography**, v. 32, p. 240-252, 2012. doi:10.1016/j.apgeog.2011.04.003

EU NITROGEN EXPERT PANEL . **Nitrogen use Efficiency (NUE) - an indicator for the utilization of nitrogen in agriculture and food systems.** Wageningen, Wageningen University, 47p. 2015

FARHAN Y. ; NAWAISEH, S. Spatial assessment of soil erosion risk using RUSLE and GIS techniques. **Environ. Earth Sci**., v. 74, p. 4649-4669, 2015. https://doi.org/10.1007/s12665-015-4430-7

FARINASSO, M.; CARVALHO JÚNIOR, O.A.; GUIMARÃES, R.F.; GOMES, R.A.T.; RAMOS, V.M. Avaliação Quantitativa do Potencial de Erosão Laminar em Grandes Áreas por meio de EUPS – Equação Universal de Perdas de Solos Utilizando Novas Metodologias em SIG para os Cálculos dos seus Fatores na Região do Alto Parnaíba – PI – MA. **Revista Brasileira de Morfologia**, v. 7, n. 2, p. 73-85, 2006.

FARINELLI, R .; LEMOS, L. B. Nitrogênio em cobertura na cultura do milho em prepare convencional e plantio direto consolidados. **Pesq. Agropec. Trop.**, v. 42, n. 1, p. 63-70. Goiania, 2012.

FELFILI, J. M. A comparative study of cerrado (sensu stricto) vegetation in Central Brazil. **Journal of Tropical Ecology**, v. 9, p. 277-289, 1993.

FENILLI T.A.B.; KLAUS, R.; FAVARIN J.L., et AL. Fertilizer 15N balance in a coffee cropping system: a case study in Brazil. **R. Bras. Ci. Solo**, v. 32, n. 4, p.1459-1469, 2008. doi:10.1590/s0100-06832008000400010

FERREIRA L.G.; ANER G.P.; KNAPP D.E.; DAVISDON E.A.; COE M.; BUSTAMANTE M.M.C.; OLIVEIRA E.L. Equivalent water thickness in savanna ecosystems: MODIS estimates based on ground and EO-1 Hyperion data. **International Journal of Remote Sensing**, v. 32, n. 22, p.7423-7440, Reino Unido, 2011. doi:10.1080/01431161.2010.523731

FERREIRA M.E.; FERREIRA L.G.; MIZIARA F.; SOARES-FILHO B.S. Modeling landscape dynamics in the central Brazilian savanna biome: future scenarios and perspectives for conservation. **Journal of Land Use Science**, v. 8, p. 403-421, Reino Unido, 2013. doi:10.1080/1747423X.2012.675363

FILOSO S.; MARTINELLI L.A.; HOWARTH R.W.; BOYER E.W.; DENTENER F. Human activities changing the nitrogen cycle in Brazil. In: **Nitrogen Cycling in the Americas**: Natural and Anthropogenic Influences and Controls. (eds Martinelli LA, Howarth RW) p. 61-89, 2006. Dordrecht, Springer Netherlands. doi:10.1007/978-1-4020-5517-1_4

FILOSO S.; MARTINELLI L.A.; WILLIAMS M.R. et al. Land use and nitrogen export in the Piracicaba River basin, Southeast Brazil. **Biogeochemistry**, v. 65, p. 275-294, 2003. doi:10.1023/A:1026259929269

FOLEY J.A.; RAMANKUTTY, N.; BRAUMAN K.A. et al. Solutions for a cultivated planet. **Nature**, 478, p. 337-342, 2011. doi:10.1038/nature10452

FOLHES, R. T.; AGUIAR, A. P. D.; STOLL, E.; DALLA-NORA, E. L.; ARAUJO, R.; COELHO, A.; CANTO, O. Multi-scale participatory scenario methods and territorial planning in the Brazilian Amazon. **Futures**, v. 73, p. 86–99, 2015.

FOOD AND AGRICULTURE ORGANIZATION (FAO) . **The state of food and agriculture.** Livestook in the balance. Rome, 166p, 2009.

FOOD AND AGRICULTURE ORGANIZATION (FAO) **La erosión del suelo por el áqua. Algumas medidas para combartila en las tierras de cultivo.** Cuadernos de Fomento Agropecuário da Organizácion de Las Naciones Unidas, v. 81, 207p, Rome, 1967.

FOOD AND AGRICULTURE ORGANIZATION (FAO). **Soil Map of the world**: 1:5.000.000 legend. UNESCO, Rome, 1974.

FRANCO H.C.J.; TRIVELIN P.C.O.; FARONI C.E.; VITTI A.C.; OTTO R. Stalk yield and technological attributes of planted cane as related to nitrogen fertilization. **Sci Agric,** v. 67, n. 5, p. 579–590, 2010. doi:10.1590/S0103-90162010000500012

FREITAS, P.L ; LANDERS, J.N. The Transformation of Agriculture in Brazil through Development and Adoption of Zero Tillage Conservation Agriculture. **International Soil and Water Conservation Research**, v. 2, p. 35-46, 2014. https://doi.org/10.1016/S2095-6339(15)30012-5

FUNDAÇÃO NACIONAL DO ÍNDIO (FUNAI)**Terras indígenas.** Brasília, 2015. Retrieved from: <http://www.funai.gov.br/index.php/shape>. Access on: 10 set. 2015

GALDINO S. **Estimativa da perda de terra sob pastagens cultivadas em solos arenosos da bacia hidrográfica do Alto Taquari - MS/MT**. PhD Universidade Estadual de Campinas, 99 p, 2012. Available at http://www.bibliotecadigital.unicamp.br/document/?code=000872767

GALLOWAY J.N.; ABER J.D.; ERISMAN J.W.; SEITZINGER S.P.; HOWARTH R.W.; COWLING E.B.; COSBY B.J. The Nitrogen Cascade. **BioScience**, v. 53, p. 341-356, 2003. doi:10.1641/0006-3568(2003)053[0341:TNC]2.0.CO;2

GALLOWAY J.N.; TOWSEND A.R.; ERISMAN J.W. et al. Transformation of the Nitrogen Cycle: Recent Trends, Questions, and Potential Solutions. **Science**, v. 320, 889p , 2008. doi:10.1126/science.1136674

GARES, P.A., SHERMAN, D.J. ; NORDSTROM, K.F. Geomorphology and Natural Hazards. **Geomorphology**, v. 10, p. 1-18, 1994.

GASNARI, B.P. ; RAMESH, H. Assessment of Soil Erosion by RUSLE Model Using Remote Sensing and GIS – A Case Study of Nethravathi Basin. **Geoscience Frontiers**, v. 7, p. 953-961, 2016. https://doi.org/10.1016/j.gsf.2015.10.007

GIBBS, H.K.; RUESCH, A.S.; ACHARD, F.; CLAYTOND, M.K.; HOLMGRENE, P.; RAMANKUTTYF, N.; FOLEYG, J.A. Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. **PNAS**, v. 107, p. 16732–16737, 2010.

GOLLNOW, F.; GOPEL, J.; HISSA, L.B.V.; SCHALDACH, R.; LAKES, T. Scenarios of land-use change in a deforestation corridor in the Brazilian Amazon: combining two scales of analysis. **Regional Environmental Change**, 2017. DOI 10.1007/s10113-017-1129-1

GRECCHI, R.C., GWYN, Q.H.J., BENIE, G.B., FORMAGGIO, A.R. ; FAHL, F.C. Land Use and Land Cover changes in the Brazilian Cerrado: A Multidisciplinary Approach to Asses the Impacts of Agricultural Expansion. **Applied Geography**, v. 55, p. 300-312, 2014. https://doi.org/10.1016/j.apgeog.2014.09.014

HENAO J. ; BAANANTE C. **Agricultural Production and Soil Nutrient Mining in Africa**: Implications for Resource Conservation and Policy Development, Africa, 2006 . An International Center for Soil Fertility and Agricultural Development. Available at http://agris.fao.org/agris-search/search.do?recordID=GB2013202609 (accessed at 30 June 2016).

HUNGRIA M.; FRANCHINI J.C.; CAMPO R.J. et al. Nitrogen nutrition of soybean in Brazil: Contributions of biological N2 fixation and N fertilizer to grain yield. **Canadian Journal of Plant Science**,v. 86, p. 927-939, 2006. doi:10.4141/P05-098

HUNGRIA M.; MENDES, I.C.; MERCANTE, F.M. **A Fixação biológica do nitrogênio como tecnologia de baixa emissão de carbono para as culturas do feijoeiro e da soja**. Londrina. EMBRAPA Soja. Brasília, 2013.

HUNGRIA, M.; CAMPO, R.J.; MENDES, I. Benefits of inoculation of the common bean (Phaseolus vulgaris) crop with efficient and competitive Rhizobium tropici strains. **Biology fertility soils**, v.39, p. 88-93, 2003.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (IBGE) **Censo agropecuário.** . Sistema IBGE de Recuperação Automática – SIDRA. Rio de Janeiro, 1996. Available at https://sidra.ibge.gov.br/pesquisa/censo-agropecuario/censo-agropecuario-1995-1996 (accessed 1 December 2015).

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (IBGE) **Produção agrícola municipa**l. Sistema IBGE de Recuperação Automática – SIDRA. Rio de Janeiro, 2010a. Available at https://sidra.ibge.gov.br/tabela/1612 (accessed 5 October 2015).

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (IBGE) **Produção agrícola municipal**. Sistema IBGE de Recuperação Automática – SIDRA. Rio de Janeiro, 2012a. Available at https://sidra.ibge.gov.br/tabela/1612 (accessed 5 October 2015).

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (IBGE) **Produção pecuária municipal**. Sistema IBGE de Recuperação Automática – SIDRA. Rio de Janeiro, 2012b. Available at https://sidra.ibge.gov.br/tabela/3939 (accessed 6 October 2015).

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (IBGE) (**Produção agrícola municipal**. Sistema IBGE de Recuperação Automática – SIDRA. Rio de Janeiro, 2000a. Available at https://sidra.ibge.gov.br/tabela/1612 (accessed 5 October 2015).

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (IBGE) . **Mudança na Cobertura e Uso da Terra 2000-2010-2012-2014.** Rio de Janeiro, 2015. Available at ftp://geoftp.ibge.gov.br/informacoes_ambientais/cobertura_e_uso_da_terra/mudancas/vetores/ (accessed 1 December 2015).

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (IBGE) . **Produção pecuária municipal**. Sistema IBGE de Recuperação Automática – SIDRA. Rio de Janeiro, 2000b. Available at https://sidra.ibge.gov.br/tabela/3939 (accessed 6 October 2015).

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (IBGE) . **Rendimento médio da produção das lavouras**. Sistema IBGE de Recuperação Automática – SIDRA. Rio de Janeiro, 2000c. Available at <http://www2.sidra.ibge.gov.br/bda/tabela/listabl.asp?c=99&z=t&o=11>. Accessed 20 ago. 2017).

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (IBGE) 2010b . **Produção pecuária municipal**. Sistema IBGE de Recuperação Automática – SIDRA. Rio de Janeiro, 2010b. Available at https://sidra.ibge.gov.br/tabela/3939 (accessed 6 October 2015).

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (IBGE) **Rendimento médio da produção das lavouras**. Sistema IBGE de Recuperação Automática – SIDRA. Rio de Janeiro, 2000c. Available at<http://www2.sidra.ibge.gov.br/bda/tabela/listabl.asp?c=99&z=t&o=11>. Accessed 20 ago. 2017).

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (IBGE) **Rendimento médio da produção das lavouras.** Sistema IBGE de Recuperação Automática – SIDRA. 2010c. Available at <http://www2.sidra.ibge.gov.br/bda/tabela/listabl.asp?c=99&z=t&o=11>. Accessed 20 ago. 2017).

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (IBGE) **Rendimento médio da produção das lavouras.** Sistema IBGE de Recuperação Automática – SIDRA. 2012c. Available at <http://www2.sidra.ibge.gov.br/bda/tabela/listabl.asp?c=99&z=t&o=11>. Accessed 20 ago. 2017).

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (IBGE). **Censo agropecuário.**. Sistema IBGE de Recuperação Automática – SIDRA. Rio de Janeiro, 2006. Available at https://sidra.ibge.gov.br/pesquisa/censo-agropecuario/censo-agropecuario-2006/segunda-apuracao (accessed 1 December 2015).

INSTITUTO CHICO MENDES DE CONSERVAÇÃO E BIODIVERSIDADE (ICMBIO). Retrieved from: http://www.icmbio.gov.br/portal/unidadesdeconservacao/biomas-brasileiros/cerrado. Access 23/10/2017.

JU, X.; XUEJUN, L.; ZHANG, F.; ROELCKE, M. Nitrogen fertilization, soil nitrate accumulation, and policy recommendations in several agricultural regions of China. **Royal Swedich Academy of Sciences**, v.33, p. 300-305, 2004.

KANTER, D. R.; ZHANG, X.; HOWARD, C. M. Nitrogen and the sustainable development goals. In: INTERNATIONAL NITROGEN INITIATIVE CONFERENCE, SOLUTIONS TO IMPROVE NITROGEN USE EFFICIENCY FOR THE WORLD, 7.,2016, 4 – 8 December 2016, Melbourne, Australia. **Proceedings…** Melbourne: The University of Melbourne, 2016.

KASTNER T.; RIVAS M.J.I.; KOCH W.; NONHEBEL S. Global changes in diets and the consequences for land requirements for food. **Proceedings of the National Academy of Sciences**, v. 109, n. 18, p. 6868-6872, 2012. doi:10.1073/pnas.1117054109

KINNEL, P.I.A. Event Soil Loss, Runoff and the Universal Soil Loss Equation family of models: A Review. **Journal of Hydrology**, v. 385, p. 384-397, 2010. https://doi.org/10.1016/j.jhydrol.2010.01.024

LABORATÓRIO DE PROCESSAMENTO DE IMAGENS E GEOPROCESSAMENTO (LAPIG) .**Matadouros e Frigoríficos do Brasil: Localização de matadouros e frigoríficos no Brasil.** Goiania. Retrieved from: <https://pastagem.org/index.php/pt-br/tools/mapa-interativo>. Access on: 19 jul. 2016

LABORATÓRIO NACIONAL DE CIÊNCIA E TECNOLOGIA DO BIOETANOL (CTBE) . **Localização das usinas de cana de açúcar e destilarias de álcool.** Campinas, 2013. Retrieved from:<http://ctbe.cnpem.br/pesquisa/producao-biomassa/cana-info/mapas/>. Access on: 09 set. 2015.

LACLAU J-P; RANGER J.; GONÇALVES J.L.M. et al. Biogeochemical cycles of nutrients in tropical Eucalyptus plantations: Main features shown by intensive monitoring in Congo and Brazil. **Forest Ecology and Management**, v .259, p. 1771-1785, 2010. doi:10.1016/j.foreco.2009.06.010

LAHSEN M.; BUSTAMANTE M.M.C.; DALLA-NORA E.L. Undervaluing and Overexploiting the Brazilian Cerrado at Our Peril. **Environment: Science and Policy for Sustainable Development**, v. 58, p. 4-15, 2016. doi:10.1080/00139157.2016.1229537

LAMBIN E.F. ; MEYFROIDT, P. Global land use change, economic globalization, and the looming land scarcity. **Proceedings of the National Academy of Sciences**, v. 108, p. 3465-3472, 2011. doi:10.1073/pnas.1100480108

LAMBIN E.F.; GEIST H.J.; LEPERS E. DYNAMICS OF LAND-USE AND LAND-COVER CHANGE IN TROPICAL REGIONS. **Annual Review of Environment and Resources**, v. 28, p. 205-241, 2003. doi:10.1146/annurev.energy.28.050302.105459

LAPOLA D.M.; MARTINELLI L.A.; PERES C.A. et al. Pervasive transition of the Brazilian land-use system. **Nature Clim. Change**, v. 4, p. 27-35, 2014. doi:10.1038/nclimate2056

LAPOLA D.M.; SCHALDACH R.; ALCAMO J.; BONDEAU A.; KOCH J.; KOELKING C.; PRIESS J.A. Indirect land-use changes can overcome carbon savings from biofuels in Brazil. **Proceedings of the National Academy of Sciences**, v. 107, p. 3388-3393, 2010. doi:10.1073/pnas.0907318107

LASSALETA L.; ROMERO E.; BILLEN G.; GARNIER J.; GARCIA-GOMES H.; ROVIRA J.V. Spatialized N budgets in a large agricultural Mediterranean watershed: high loading and low transfer. **Biogeosciences,** v. 9, p. 57-70, 2012. doi:10.5194/bg-9-57-2012

LAURENCE, W.F.; SAYER, J.; CASSMAN, K.G. Agricultural expansion and its impacts on tropical nature. **Trends in Ecology & Evolution**, v. 29, n. 2, p. 107-116, 2014.

LEHMANN J.; LILIENFEIN J.; REBEL K.; CARMO LIMA S, WILCKE W. Subsoil retention of organic and inorganic nitrogen in a Brazilian savanna Oxisol. **Soil Use and Management**, v. 20, p. 163-172, 2004. doi:10.1079/SUM2004240

LEITE R.C.C.; LEAL M.R.L.V.; CORTEZ L.A.B.; GRIFFIN W.M.; SCANDIFFIO M.I.G. Can Brazil replace 5% of the 2025 gasoline world demand with ethanol? **Energy**, v. 34, p. 655-661, 2009. doi:10.1016/j.energy.2008.11.001

LESSA A.C.R.; MADARI B.E.; PAREDES D.S.; BODDEY R.M.; URQUIAGA S.; JANTALIA C.P.; ALVES B.J.R. Bovine urine and dung deposited on Brazilian savannah pastures contribute differently to direct and indirect soil nitrous oxide emissions. **Agriculture, Ecosystems & Environment**, v. 190, p. 104-111, 2014. doi:10.1016/j.agee.2014.01.010

LESSCHEN J.P.; STOORVOGEL J.J.; SMALING E.M.A.; HEUVELINK G.B.M.; VELDKAMP A. A spatially explicit methodology to quantify soil nutrient balances and their uncertainties at the national level. **Nutrient Cycling in Agroecosystems**, v. 78, p. 111-131, 2007. doi:10.1007/s10705-006-9078-y

LEWINSOHN T.M.; PPRADO P.I. How Many Species Are There in Brazil? Cuantas Especies Hay en Brasil? **Conservation Biology**, v. 19, p. 619-624, 2005. doi:10.1111/j.1523-1739.2005.00680.x

LIU J.; YOU L.; AMINI M.; OBERSTEINER M.; HERRERO M.; ZEHNDER A.J.B.; YANG H. A high-resolution assessment on global nitrogen flows in cropland. **Proceedings of the National Academy of Sciences**, v. 107, p. 8035-8040, 2010. doi:10.1073/pnas.0913658107

LU, D.; LI, G.; VALLADARES, G.S. ; BATISTELLA, M. Mapping soil erosion risk in Rondônia, Brazilian Amazonia: using RUSLE, Remote Sensing and GIS. **Land Degradation & Development**, v. 15, p. 499-512, 2004. https://doi.org/10.1002/ldr.634

MACEDO, J. Solos dos Cerrados. In: Pereira, V.P., Ferreira, M.E. ; Cruz, M.C.P. **Solos altamente suscetíveis à erosão**., Jaboticabal: FCAV-UNESP/SBCS, p. 69-75, 1994.

MANNIGEL, A.R.; CARVALHO, M.P.; MORETI, D. ; LUCIANO, R.M. Fator Erodibilidade e Tolerância de Perda de Solos do Estado de São Paulo. **Acta**

Scientiarum, v. 24, p. 1335-1340, 2002. https://doi.org/10.4025/actasciagron.v24i0.2374

MAR, G.D.; MARCHETTI, M.E.; SOUZA, L.C.F.; GONÇALVES, M.C.; NOVELINO, J.O. Produção do milho safrinha em função de doses e éopcas de aplicação de nitrogênio. **Bragantia**, v. 62, p. 267-274, 2003.

MARTINELLI L.A.; FILOSO, S. Expansion of sugarcane ethanol production in Brazil: environmental and social challenges. **Ecol Appl**, v. 18, p. 885-898, 2008. doi:10.1890/07-1813.1

MARTINELLI L.A.; PINTO, A.S.; NARDOTO G.B.; OMETTO J.P.; FILOSO S.; COLETTA L.D.; RAVAGNANI E.C. Nitrogen mass balance in the Brazilian Amazon: an update. **Braz J Biol**, v. 72, p. 683-690, 2012. doi:10.1590/S1519-69842012000400007

MATSON P.A.; VITOUSEK P.M. Agricultural Intensification: Will land spared from farming be land spared for nature? **Conservation Biology**, v. 20, p. 709-710, 2006. doi:10.1111/j.1523-1739.2006.00442.x

MCCOOL D.K. BGR, FOSTER G.R., MEYER L.D. Revised slope steepness factor for the Universal Soil Loss Equation. **Am. Soc. Agric. Eng**., v. 30, p. 1387-1396, 1987. doi:10.13031/2013.30576

MEDINA E. Mineral Nutrition: Tropical Savannas. In: BEHNKE HD, LÜTTGE U, ESSER K, KADEREIT JW, RUNGE M. (eds). **Progress in botany / Fortschritte der Botani**k: Structural Botany Physiology Genetics Taxonomy Geobotany / Struktur Physiologie Genetik Systematik Geobotanik. Berlin, Heidelberg, Springer Berlin Heidelberg, 1993. doi:10.1007/978-3-642-78020-2_12

MENDES P. **Volume exportado de soja em grão, milho, café, frango e celulose bate recorde em 2015**. Bras: Ministério da Agricultura Pecuária e Abastecimento, 2016. Available at http://www.agricultura.gov.br/noticias/volume-exportado-de-soja-em-grao-milho-cafe-frango-e-celulose-bate-recorde-em-2015 (acessed 1 December 2016).

MENDES, I.C.; REIS JUNIOR, F.B.; HUNGRIA, M.; SOUSA, D.M.G.; CAMPO, R.J. Adubação nitrogenada suplementar tardia em soja cultivada em latossolos do Cerrado. **Pesquisa Agropecuária Brasileira**, v.43, p. 1053-1060, 2008.

MENDONÇA, R. C. Flora vascular do bioma Cerrado: checklist com 12.356 espécies. In: SANO, S. M. **Cerrado:** ecologia e flora. Brasília: Embrapa Informação Tecnológica, v. 2, 2008. p. 421-442.

MERRIT, W.S., LETCHER, R.A. ; JAKEMAN, A.J. A Review of Erosion and Sediment Transport Models. **Environmental Modelling & Software**, v. 18, p. 761-799, 2003.
https://doi.org/10.1016/S1364-8152(03)00078-1

MESQUITA, C.M. **Manual do café: manejo de cafezais em produção**. Belo Horizonte: EMATER-MG, 2016. p. 72.
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA, INOVAÇÕES E COMUNICAÇÕES (MCTIC). Trajetórias de mitigação e instrumentos de políticas públicas para alcance das metas brasileiras no acordo de Paris, Brasília, 2017. Retrieved from: <http://sirene.mcti.gov.br/documents/1686653/2098519/Contribuic%CC%A7a%CC%83o+MCTIC+II_NDC_1.pdf/8db5a027-ccd3-4f1c-af01-23dacbd6d6a9>. Access on: 29 ago. 2017

MINISTÉRIO DO MEIO AMBIENTE (MMA) . **Áreas prioritárias** – mapas por Bioma. Brasília, 2017. Retrieved from: <http://www.mma.gov.br/legislacao/item/489 >. Access on: 26 ago. 2017

MINISTÉRIO DO MEIO AMBIENTE (MMA) . **Monitoramento do desatamento nos biomas brasileiros por satélite**. Acordo de Cooperação Técnica MMA/IBAMA. Monitoramento do Bioma Cerrado 2009-2010. Ministério do Meio Ambiente. Brasília, 2011.

MINISTÉRIO DO MEIO AMBIENTE (MMA) 2015. **Fábricas de papel e celulose**. Retrieved from: <http://mapas.mma.gov.br/i3geo/mma/openlayers.htm?ibaj6gqbon2pgvta3gstuvfo96>. Access on: 19 jul. 2016

MINISTÉRIO DO MEIO AMBIENTE (MMA**). Biomas**. Brasília. Retrieved from: < http://mapas.mma.gov.br/i3geo/datadownload.htm >. Access on: 09 set. 2015

MINISTÉRIO DO MEIO AMBIENTE (MMA). **Ministry of the environment. national biodiversity strategy and action plan**. Brasília, 2016. Retrieved from: <https://www.cbd.int/doc/world/br/br-nbsap-v3-en.pdf>. Access on: 26 ago. 2017

MINISTÉRIO DO MEIO AMBIENTE (MMA). **Unidades de conservação**. Brasília. Retrieved from: < http://mapas.mma.gov.br/i3geo/datadownload.htm >. Access on: 09 set. 2015

MIRANDA, H. S. The fire factor. In: OLIVEIRA, P. S. **The cerrados of Brazil:** ecology and natural history of Neotropical savanna. New York: Columbia University Press, 2002. p. 51-68.

MITTERMEIER, R.A.; GIL, P.R.; HOFFMAN, M.; PILGRIM, J.; BROOKS, T., MITTERMEIER, C.G., LAMOREUX, J. ; FONSECA, G.A.B. Hotspot revisited:

earth's biologically richest and most endangered terrestrial ecoregions. 2th Edition, University of Chicago Press, Boston, 2005.MINISTÉRIO DO MEIO AMBIENTE (MMA) . **Monitoramento do desmatamento nos biomas brasileiros**: Cerrado 2010-2011. Brasília, 2015. Available at http://siscom.ibama.gov.br/monitora_biomas/PMDBBS%20-%20CERRADO.html (accessed 15 June 2016).

MOREIRA M.A.; RUDORFF B.F.T.; BARROS M.A.; FARIA V.G.C.D.; ADAMI M. Geotecnologias para mapear lavouras de café nos estados de Minas Gerais e São Paulo. **Engenharia Agrícola**, v. 30, n. 6, p. 1123-1135, 2010. doi:10.1590/S0100-69162010000600013

MÜLLER-HANSEN F.; CARDOSO M.F.; DALLA-NORA E.L.; DONGES J.F.; HEITZIG J.; KURTHS J.; THONICKE K. A matrix clustering method to explore patterns of land-cover transitions in satellite-derived maps of the Brazilian Amazon. **Nonlinear Processes of Geophysics**, v. 24, p. 113-123, 2017. doi:10.5194/npg-24-113-2017

MYERS N.; MITTERMEIER R.A.; MITTERMEIER C.G.; FONSECA G.A.B. ; KENT J. Biodiversity hotspots for conservation priorities. **Nature**, v.403, p.853-858, 2000. doi:10.1038/35002501

NARDOTO, G. B. Effects of fire on soil nitrogen dynamics and microbial biomass in savannas od Central Brazil. **Pesquisa Agropecuária Brasileira**, v. 38, p. 955-962, 2003.

OECD/Food and Agriculture Organization of the United Nations. **OECD-FAO Agricultural Outlook 2015**. OECD Publishing Paris, 2015. Available at http://dx.doi.org/10.1787/agr_outlook-2015-en (accesses at 22 June 2016).

OLIVEIRA J.B. **Solos do Estado de São Paulo: descrição das classes registradas no mapa pedológico. Campinas:** Instituto Agronômico de Campinas, 1999.

OLIVEIRA M.W.; TRIVELIN, P.C.O.; BOARETTO, A.E.; et al. Leaching of nitrogen, potassium, calcium and magnesium in a sandy soil cultivated with sugarcane. **Pesq. agropec. bras.**, v. 37, p. 861-868, 2002.

OLIVEIRA P. P. A.; TRIVELIN, P.C.O.; OLIVEIRA W.S.; CORSI, M. Fertilização com N and S na recuperação de pastagem de Brachiaria brizantha cv. Marandu em neossolo quartzarênico. **Revista Brazileira de Zootecnologia**, v. 34, p. 1121-1129, 2005.

OLIVEIRA, A.M.M.D.; PINTO, S.D.A.F. ; LOMBARDI NETO, F. Caracterização de Indicadores de Erosão do Solo em Bacias Hidrográficas com Suporte de Geotecnologias e Modelo Preditivo. **Est. Geogr.**, v. 5, p. 63-86, 2007.

OLIVEIRA, G.O.; CARVALHO, J.L.N.; CERRI, C.E.P.; CERRI, C.C.; FEIGL, B.J. Soil greenhouse gas fluxes from vinasse application in Brazilian sugarcane areas. **Geoderma**, v. 200, p. 77-84, 2013.

OLIVEIRA, J.C.M.; REICHARDT, K.; BACCHI, O.O.S.; TIMM, L.C.; DOURADO-NETO, D.; TRIVELIN, P.C.O.; TOMINAGA, T.T.; NAVARRO, R.C.; PICCOLO, M.C.; CÁSSARO, F.A.M. Nitrogen dynamics in a soil-sugarcane system. **Scientia Agricola**, v. 57, p. 467-472, 2000.

OLIVEIRA, O.C.; URQUIAGA, S.; BODDEY, R.M.Burning cane: The long term effects. **Int. Sugar J.**,V. 96, p. 272-275, 1994.

OLIVEIRA, P.; KLUTHCOUSKI, J.; FAVARIN, J. L.; SANTOS, D. C. **Sistema Santa Brígida – Tecnologia EMBRAPA:** consorciação de milho com leguminosas. Circular Técnica 88, 2010.

OLIVEIRA, P.T.S., NEARING, M.A. ; WENDLAND, E. Orders of magnitude increase in soil erosion associated with land use change from native to cultivated vegetation in a Brazilian Savannah environment. **Earth Surface Processes and Landforms**, v. 40, p. 1524-1532, 2015. https://doi.org/10.1002/esp.3738

OLIVEIRA, P.T.S.; SOBRINHO, T.A.; RODRIGUES, D.B.B. ; PANACHUKI, E. Erosion Risk Mapping Applied to Environmental Zoning. **Water Resource Management**, v. 25, p. 1021-1036, 2011. https://doi.org/10.1007/s11269-010-9739-0

OLIVEIRA, P.T.S.; WENDLAND, E. ; NEARING, M.A. Rainfall Erosivity in Brazil: A Review. **Catena**, v. 100, p. 139-147, 2012. https://doi.org/10.1016/j.catena.2012.08.006

OTTO, R.; CASTRO, S.A.Q; MARIANO, E.; CASTRO, S.Q.G., FRANCO, H.C.J.; TRIVELIN, P.C.O. Nitrogen use efficiency for sugarcane-biofuel production: what is next? **Bioenergy Res**., v. 9, n. 4, p.1272-1289, 2016.

PALM C.; SANCHEZ, P.; AHAMED S.; AWITI, A. Soils: a contemporary perspective. **Annual Review of Environment and Resources**, v. 32, p. 99-129, 2007. doi:10.1146/annurev.energy.31.020105.100307

PANDEY, A.; CHOWDARY, V.M.; MAL, B.C. Identification of critical erosion prone areas in the small agricultural watershed using USLE, GIS and remote sensing. **Water Resour. Management**, v. 21, p. 729-746, 2007.

PAREDES, D.S.; LESSA, A.C.R.; SANT'ANNA, S.A.C.; BODDEY, R.M.; URQUIAGA, S.; ALVES, B.J.R. Nitrous oxide emission and ammonia volatilization induced by vinasse and N fertilizer application in a sugarcane crops at Rio de Janeiro, Brazil. **Nutr Cycl Agroecosyst**, v. 98, p. 41-55, 2014.

PARVEEN R. ; KUMAR, U. Integrated Approach of Universal Soil Loss Equation (USLE) and Geographical Information System (GIS) for Soil Loss Risk Assessment in Upper South Koel Basin, Jharkhand. **Journal of Geographic Information System**, v. 4, p. 588-596, 2012. https://doi.org/10.4236/jgis.2012.46061

PERON, A.J.; EVANGELISTA, A.R. Degradação de Pastagens em Regiões de Cerrado. **Ciênc. Agrotec.**, v. 28, p. 655-661, 2003. https://doi.org/10.1590/S1413-70542004000300023

PIMENTEL, D.; ALLEN, J.; BEERS, A.; GUINAND, L.; LINDER, R.; MCLAUGHLIN, P.; MEER, B.; MUSONDA, D.; PERDUE, D.; POISSON, S.; SIEBERT, S.; SOTNER, K.; SALAZAR, R.; HAWKINS, A. World Agriculture and Soil Erosion. **BioScience**, v. 37, p. 277-283, 1987.

PIMENTEL, D.; HARVEY, C.; RESOSUDARMO, P.; SINCLAIR, K.; KURZ, D.; MCNAIRS, M.; CRIST, S.; SHPRITZ, L.; FITTON, L.; SAFFOURI, R. ; BLAIR, R. Environmental and Economic Costs of Soil Erosion and Conservation. **Science**, v. 267, p. 1117-1123, 1995. https://doi.org/10.1126/science.267.5201.1117

PONTIUS, R.; BOERSMA, W.; CASTELLA, J-C.; CLARKE, K.; de NIJS, T.; DIETZEL, C.; DUAN, Z.; FOTSING, E.; GOLDSTEIN N, KOK, K.; KOOMEN, E.; LIPPITT, C.; MCCONELL, W.; MOHD SOOD, A.; PIJANOWSKI, B.; PITHADIA, S.; SWEENEY, S.; TRUNG, T.; VELDKAMP, A.; VERBURG, P.H. Comparing the input, output, and validation maps for several models of land change. **The Annual Regional Science**, v. 42, p. 11–37, 2008.

PRETTY, J. Agricultural sustainability: concepts, principles and evidence. **Philosophical Transactions of The Royal Society**, v. 363, p. 447-465, 2007.

PRIMAVESI, A.C.P.A.; RODRIGUES, A.A.; PAINO, C.R.S.; ALENCAR, S.B. Adubação com uréia em pastagem de Cynodon dactylon cv. Coastcross sob manejo rotacionado: Eficiência e perdas. **Embrapa Pecuária Sudeste. Circular Técnica**, 30, 2001.

PROCHNOW, D.; DECEHEN, S.C.F.; MARIA, I.C., CASTRO, O.M. ; VIEIRA, S.R. Razão de Perdas de Terra e Fator C da Cultura do Cafeeiro em Cinco Espaçamentos, em Pindorama (SP). **Revista Brasileira de Ciência do Solo**, v. 29, p. 91-98, 2005. https://doi.org/10.1590/S0100-06832005000100010

PULITO, A.P.; GONÇALVES, J.L.M.; SMETHURST, P.J.; ARTHUR JUNIOR, J.C.; ALVARES, C.A.; ROCHA, J.H.T.; HUBNER, A.; MORAES, L.F.; MIRANDA, A.C.; KAMOGAWA, M.Y.; GAVA, J.L.; CHAVES, R.; SILVA, C.R. Available nitrogen and responses to nitrogen fertilizer in Brazilian Eucalypt plantations on soil of contrasting texture. **Forests**, v. 6, p. 973-991, 2015.

RADA, N. Assessing Brazil's Cerrado Agricultural Miracle. **Food Policy**, v. 28, p. 146-155, 2013.
https://doi.org/10.1016/j.foodpol.2012.11.002

RAMALHO-FILHO, A. ; BEEK, K.J. Sistema de Avaliação da Aptidão Agrícola das Terras. 3th Edition, **EMBRAPA-CNPS**, Rio de Janeiro, 1995.

RASKIN, P.; MONKS, F.; RIBEIRO, T.; VANVUUREN, D.; ZUREK, M. Global Scenarios in Historical Perspectives. In: CARPENTER P.L.P.S.R., BENNET, E.M.; ZUREK, M.B. (eds.). **Ecosystems and human well-being**: scenarios - findings of the scenarios working group of the Millennium Ecosystem Assessment., Washington, DC, USA: Island Press, 2005. p. 35–44.

RATTER J.A.; RIBEIRO, J.F.; BRIDGEWATER S. The Brazilian Cerrado Vegetation and Threats to its Biodiversity. **Annals of Botany**, v. 80, p. 223-230, 1997. doi:10.1006/anbo.1997.0469

RENARD, K.G., FOSTER, G.R., WEESIES, G.A., MCCOOL, D.K. ; YODER, D.C. **Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE).** U.S. Department of Agriculture, Agriculture Handbook No. 703, USDA, 1997.

RIBEIRO, A.C.; GUIMARÃES, P.T.G.; ALVAREZ V, V.H. Recomendações para o uso de corretivos e fertilizantes em Minas Gerais. 5ª Aproximação. **Comissão de Fertilidade do Solo do Estado de Minas Gerais (CFSEMG)**, Viçosa, 1999.

ROSSETO, R.; DIAS, F.L.F. 2. Nutrição e adubação da cana-de-açúcar: indagações e reflexões. **Encarte do Informações Agronômicas n° 110**, 2005.

RUDEL T.K.; SCHNEIDER L.; URIARTE M. et al. Agricultural intensification and changes in cultivated areas, 1970–2005. **Proceedings of the National Academy of Sciences**, v. 106, p. 20675-20680, 2009. doi:10.1073/pnas.0812540106

RUDORFF B.F.T.; AGUIAR D.A.; SILVA W.F.; SUGAWARA L.M.; ADAMI M.; MOREIRA M.A. Studies on the Rapid Expansion of Sugarcane for Ethanol Production in São Paulo State (Brazil) Using Landsat Data. **Remote Sensing**, v. 2, n. 4, p. 1057, 2010. doi:10.3390/rs2041057

SALGADO-LABOURIAU, M. L. Fire in the cerrado 32,000 years ago. **Current Research in the Pleistocene**, v. 11, p. 85-87, 1994.

SANO, S. M. **Cerrado. Ecologia e Flora**. Brasília: Embrapa , v. 1, 2008.

SANTOS, H.G.; CARVALHO JUNIOR, W.; DART, R.O.; ÁGLIO, M.L.D.; SOUSA, J.S.; PARES, J.G.; FONTANA, A.; MARTINS, A.L.S. ; OLIVEIRA, A.P. O Novo Mapas de Solos do Brasil. Legenda Atualizada – Dados Eletrônicos. **EMBRAPA** Solos, 67p, 2011.

SANTOS, S.A.; PELLEGRIN, A.O.; MORAES, A.S.; BARROS, A.T.M.; COMASTRI FILHO, J.A.; SERENO, J.R.B.; SILVA, R.A.M.S.; ABREU, U.G.P. **Sistema de produção de gado de corte do Pantanal.** EMBRAPA Pantanal, 2002.

SAYER, J.; SUNDERLAND, T.; GHAZOUL, J.; PFUND, J.L.; SHEIL, D.; MEIJAARD, E.; VENTER, M.; BOEDHIHARTONO, A.K.; DAY, M.; GARCIA, C.; OOSTEN, C.V.; BUCK, L.E. Ten principles for a landscape approach to reconciling agriculture, conservation, and other competing land uses. **PNAS**, v. 110, p. 8349-8356, 2013

SCHERR, S.J.; YADAV, S. **Land degradation in the developing world: implications for food, agriculture, and the environment to 2020**. Rome, FAO, 1996. Food, Agriculture, and the Environment Discussion Paper 14.

SCHULTZ, N.; REIS, V.M.; URQUIAGA,S. **Resposta da cana-de-açúcar à adubação nitrogenada: fontes nitrogenadas, formas de aplicação, épocas de aplicação e efeito varietal.** EMBRAPA Agrobiologia, 2015.

SDSN. Solutions for sustainable agriculture and food systems. Technical report for the post-2015 development agenda. **Sustainable Development Solutions Network (SDSN),** New York, 99p. 2013. http://unsdsn.org/resources/publication/type/thematic-network-reports/

SHI, Z.H., CAI, C.F., DING, S.W., WANG, T.W ; CHOW, T.L. Soil Conservation Planning at the Small Watershed Level Using RUSLE with GIS: A Case Study in the Three Gorge Area of China. **Catena**, v. 55, p. 33-48, 2014. https://doi.org/10.1016/S0341-8162(03)00088-2

SIGNOR D.; CERRI C.E.P.; CONANT R. N2O emissions due to nitrogen fertilizer applications in two regions of sugarcane cultivation in Brazil. **Environmental Research Letters**, V. 8, 015013, 2013. doi:10.1088/1748-9326/8/1/015013

SILVA, A.M.; AVARES, C.A. Levantamento de Informações e Estruturação de um Banco de Dados sobre a Erodibilidade de Classes de Solos no Estado de São Paulo. **Geociências**, v. 24, n. 1, p. 33-41, 2005.

SILVA, A.M.; SILVA, M.L.N.; CURI, N.; AVANZI, J.C.; FERREIRA, M.M. Erosividade da Chuva e Erodibilidade de Cambissolo e Latossolo na Região de Lavras, Sul de Minas Gerais. **R.Bras. Ci. Solo**, v. 33, n. 6, p. 1811-1820, 2009. https://doi.org/10.1590/S0100-06832009000600029

SILVA, B.P.C.; SILVA, M.L.N.; BATISTA, P.V.G.; PONTES, L.M.; ARAÚJO, E.F.; CURI, N. Soil and water losses in eucalyptus plantation and natural forest and determinantion of the USLE factors at a pilot sub-basin in Rio Grande do Sul, Brazil. **Ciência e Agrotecnologia**, v. 40, p. 432-444, 2016.

SILVA, D.R.G; PEREIRA, A.F.; DOURADO, L. R.; SILVA, F.P.; AVILA, F.W.; FAQUIN, V. Productivity and efficiency of nitrogen fertilization in maize under different levels of urea and NBPT – treated urea. **Ciência Agrotec.** V. 35, n. 3, p. 516-523, maio/jun., 2011. https://doi.org/10.1590/S1413-70542011000300012

SILVA, J.F.; CARVALHO, A.M.; REIN, T.A.; COSER, T.R.; RIBEIRO JUNIOR, W.Q.; VIEIRA, D.L.; COOMES, D.A. Nitrous oxide emissions from sugarcane fields in the Brazilian Cerrado. **Agriculture, Ecosystems and Environment**, v. 246, p. 55-65, 2017.

SILVA, J.M.C.; BATES, J.M. Biogeographic patterns and conservation in the South American Cerrado: a tropical savanna hotspot. **Bioscience**, v. 52, p. 225-233, 2002.

SILVA, M.A.; SILVA, M.L.N.; CURI, N.; OLIVEIRA, A.H.; AVANZI, J.C.; NORTON, L.D. Water erosion risk prediction in eucalyptus plantations. **Ciência e Agrotecnologia**, v. 38, n. 2, p. 160-172, 2014.

SMALING E.M.A.; FRESCO L.O. A decision-support model for monitoring nutrient balances under agricultural land use (NUTMON). **Geoderma**, v. 60, p. 235-256, 1993. doi:10.1016/0016-7061(93)90029-K

SMALING E.M.A.; ROSCOE R.; LESSCHEN, J.P.; BOUWMAN A.F.; COMUNELLO E. From forest to waste: Assessment of the Brazilian soybean chain, using nitrogen as a marker. **Agriculture, Ecosystems & Environment**, v. 128, p. 185-197, 2008. doi:10.1016/j.agee.2008.06.005

SOARES-FILHO B.; RAJÃO R.; MACEDO M. et al. Cracking Brazil's Forest Code. **Science**, v. 344, p. 363, 2014. doi:10.1126/science.1246663

SPRENT, J. I. **Legume nodulation:** A global perspective. Ed. Wiley, 2009. p. 200.

STAPE, J.L.; BINKLEY D.; RYAN, M.G. et al. The Brazil Eucalyptus Potential Productivity Project: Influence of water, nutrients and stand uniformity on wood production. **Forest Ecology and Management**, v. 259, p. 1684-1694, 2010. doi:10.1016/j.foreco.2010.01.012

STOORVOGEL, J.J.; SMALING E.M.A. Research on soil fertility decline in tropical environments: integration of spatial scales. **Nutrient Cycling in Agroecosystems**, v. 50, p. 151-158, 1998. doi:10.1023/A:1009732126336

STOORVOGEL, J.J.; SMALING E.M.A.; JANSSEN B.H. Calculating soil nutrient balances in Africa at different scales. **Fertilizer research**, v. 35, p. 227-235, 1993. doi:10.1007/BF00750641

STRASSBURG B.B.N.; BROOKS, T.; FELTRAN-BARBIERI, R.; IRIBARREM, A.; CROUZEILLES, R.; LOYOLA, R.; LATAWIEC, A.E.; OLIVEIRA FILHO, F.J.B.; SCARAMUZZA, C.A.M.; SCARANO, F.R.; SOAREAS-FILHO, B.; BALMFORD, A. Moment of truth for the Cerrado hotspot. **Nature Ecology & Evolution** 1, 0099, 2017.

STRASSBURG B.B.N.; LATAWIEC, A.E.; BARIONI L.G. et al. When enough should be enough: Improving the use of current agricultural lands could meet production demands and spare natural habitats in Brazil. **Global Environmental Change**, v. 28, p. 84-97, 2014. doi:10.1016/j.gloenvcha.2014.06.001

SUTTON, M.A.; BLEEKER, A.; HOWARD C.M.; BERKUNDA M.; GRIZZETTI B.; DE VRIES W.; VAN GRINSVEN, H.J.M.; et al. Our Nutrient World: The challenge to produce more food and energy with less pollution. Global Overview of Nutrient Management. Centre for Ecology and Hydrology, Edinburgh on behalf of the Global Partnership on **Nutrient Management and the International Nitrogen Initiative**, 2013. Available at http://www.initrogen.org/node/63 (accessed 30 June 2016).

TEJADA, G.; DALLA-NORA, E.; CORDOBA, D.; LAFORTEZZA, R.; OVANDO, A.; ASSIS, T.; AGUIAR, A.P. Deforestation scenarios for the Bolivian lowlands. **Environmental Research**, v. 144, p. 49–63, 2016. https://doi.org/10.1016/j.envres.2015.10.010

THE ECONOMIST. **The miracle of Cerrado**. Brazil has revolutionized its own farms. Can it do the same for others? 2010. Available at: http://www.economist.com/node/16886442

TILMAN D.; BALZER C.; HILL J.; BELFORT B.L. Global food demand and the sustainable intensification of agriculture. **Proceedings of the National Academy of Sciences**, v. 108, p. 20260-20264, 2011. doi:10.1073/pnas.1116437108

TRABAQUINI, K.; GALVÃO, M.S.P.; FORMAGGIO, A.R. ; GALVÃO, L.S. Estimates of land use and land cover change and soil loss in the Brazilian Cerrado through geotecnology. In: IEEE INTERNATIONAL GEOSCIENCE AND REMOTE SENSING SYMPOSIUM (IGARSS), 2012, Munich. **Proceedings…** IEEE, 2012. p. 6321-6324.

TRIVELIN, P.C.O.; VITTI, A.C.; OLIVEIRA, M.W.; GAVA, G.L.C.; SARRIES, G.A. Utilização de nitrogênio e produtividade da cana-de-açúcar (cana-planta) em solo arenoso com incorporação de resíduos da cultura. **Revista Brasileira de Ciência do Solo**, v. 26, p. 637-646, 2002.

TURNER B.L.; LAMBIN E.F.; REENBERG A. The emergence of land change science for global environmental change and sustainability. **Proceedings of the National Academy of Sciences**, v. 104, p. 20666-20671, 2007. doi:10.1073/pnas.0704119104

UNITED NATIONS SUSTAINABLE DEVELOPMENT CHALLENGES. **World economic and social survey 2013**. New York: United Nation Publication, 2013.

VALERIANO, M. M.; ROSSETI, D.F.; ALBUQUERQUE, P. C. G. Topodata: desenvolvimento da primeira versão do banco de dados geomorfométricos locais em cobertura nacional. In: In: SIMPÓSIO BRASILEIRO DE SENSORIAMENTO REMOTO, 14. (SBSR), 2009, Natal. **Anais...** São José dos Campos: INPE, 2009. p. 5499-5506. DVD, On-line. ISBN 978-85-17-00044-7. (INPE-16060-PRE/10669). Disponível em: <http://urlib.net/dpi.inpe.br/sbsr@80/2008/11.14.21.06>.

VALERIANO, M.M. **TOPODATA:** guia de utilização de dados geomorfométricos locais. São José dos Campos: Instituto Nacional de Pesquisas Espaciais, 2008. Relatório Técnico (INPE-15318-RPQ/818).

VERBURG, P. H. Simulating feedbacks in land use and land cover change models. **Landscape Ecology**, v. 21, p. 1171–1183, 2006. https://doi.org/10.1007/s10980-006-0029-4

VERBURG, P.H.; de KONING, G.H.J.; KOK, K.; VELDKAMP, A.; BOUMA, J. A spatial explicit allocation procedure for modelling the pattern of land use change based upon actual land use. **Ecological Modelling**, v. 116, p. 45–61, 1999. https://doi.org/10.1016/S0304-3800(98)00156-2

VET R.; ARTZ R.S.; CAROU S. et al. A global assessment of precipitation chemistry and deposition of sulfur, nitrogen, sea salt, base cations, organic acids, acidity and pH, and phosphorus. **Atmospheric Environment**, v. 93, p. 3-100, 2014. doi:10.1016/j.atmosenv.2013.10.060

VITOUSEK, P.M.; NAYLOR, R.; CREWS, T. et al. Nutrient Imbalances in Agricultural Development. **Science,** v. 324, p. 1519, 2009. doi:10.1126/science.1170261

VITTI, A.C.; TRIVELIN, P.C.O.; GAVA, G.J.C.; PENATTI, C.P.; BOLOGNA, I.R.; FARONI, C.E.; FRANCO, H.C.J. Produtividade da cana-de-açucar relacionada ao nitrogênio residual da adubação e do sistema radicular. **Pesquisa Agropecuária Brasileira**, v.42, p. 249-256, 2007.

VITTI, G.C.; MAZZA, J.A.; Planejamento, estratégias de manejo e nutrição da cultura de cana-de-açúcar. **Encarte do Informações Agronômicas**, n. 97, p. 1-16, 2002.

WEILL, M.A.M**. Estimativa da erosão do solo e avaliação do seu Impacto na Microbacia do Ceveiro (Piracicaba, SP) através do índice de tempo de vida**. Ph.D. Thesis, Universidade de São Paulo, Piracicaba, 1999.

WICKRAMASINGHE, U.; SYED, S. ; SIREGAR, H. The Role of Policies in Agricultural Transformation. Lessons from Brazil, Indonesia and the Republic of Korea. **CAPSA** Working Paper No. 106, CAPSA, 2012.

WILCKE W. ; LILIENFEIN J. Nutrient leaching in oxisols under native and managed vegetation in Brazil. **Soil Sci Soc Am Journal**, v. 69, p. 1152-1161, 2005. doi:10.2136/sssaj2004.0350

WILKINSON, A.; EIDINOW, E. Evolving practices in environmental scenarios: a new scenario typology. **Environmental Research Letters**, v. 3, 045017, 2008. https://doi.org/10.1088/1748-9326/3/4/045017

WISCHMEIER, W.H. ; MANNERING, J.V. Soil and Water Management and Conservation. Relation of Soil Properties to its Erodibility. **Soil Sci. Soc. Amer. Proc**., v. 33, p. 131-137, 1969. https://doi.org/10.2136/sssaj1969.03615995003300010035x

WISCHMEIER, W.H. ; SMITH, D.D. **Predicting rainfall erosion losses: a guide to conservation planning**. U.S. Department of Agriculture, Agriculture, 1978. Handbook No. 537, USDA.

ZAVASCHI, E.; FARIA, L.A.; VITTI, G.C.; NASCIMENTO, C.A.C.; MOURA, T.A.; VALE, D.W.; MENDES, F.L.; KAMOGAWA, M.Y. Ammonia volatilization and yield components after application of polymer-coated urea to maize. **Revista Brasileira de Ciência do Solo**, v. 38, p. 1200-1206, 2014.

ZHANG X.; DAVIDSON, E.A.; MAUZERALL D.L.; SEARCHINGER T.D.; DUMAS, P.; SHEN Y. Managing nitrogen for sustainable development. **Nature**, v. 528, p. 51-59, 2015. doi:10.1038/nature15743

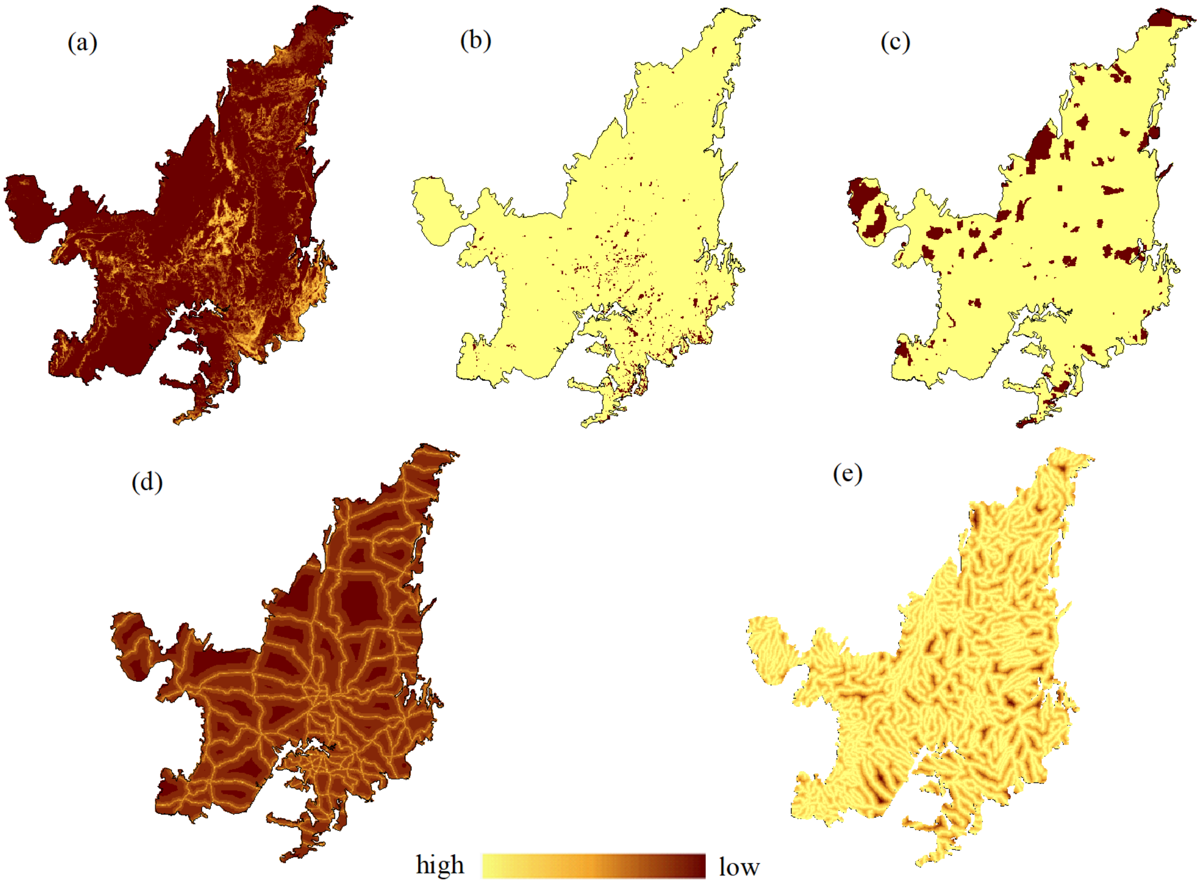
ZHANG, H.; YANG, Q.; LI, R.; LIU, Q.; MOORE, D.; HE, P.; RITSEMA, C.J. ; GEISSEN, V. Extension of a GIS procedure for calculating the RUSLE equation LS factor. **Computer & Geoscience**, v. 52, p. 177-188, 2013. https://doi.org/10.1016/j.cageo.2012.09.027

ZHANG, L.; O'NEILL, A.; LACY, S. Spatial analysis of soil erosion in catchments: a review of modelling approaches. **Water Res. Ecol.**, v. 3, p. 58-64, 1995.

APPENDIX

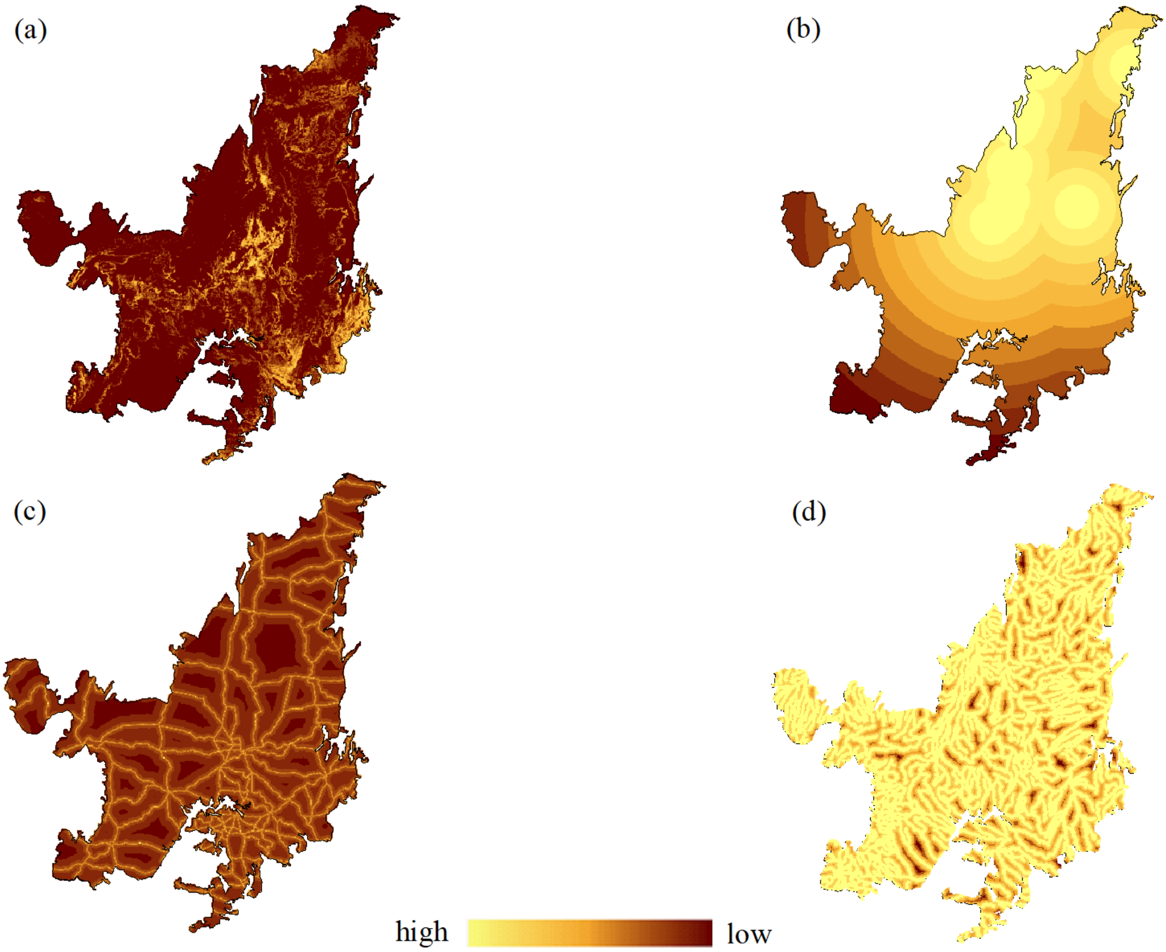
SUPPORTING INFORMATION

Figure A.1. Spatial drivers of natural vegetation selected to run LuccMe/Cerrado-N model: (a) Slope flat (up to 3%); (b) Presence of timber extraction and processing centre; (c) Presence of protected areas and indigenous land; (d) Distance to paved and unpaved roads; and (e) Distance to rivers.



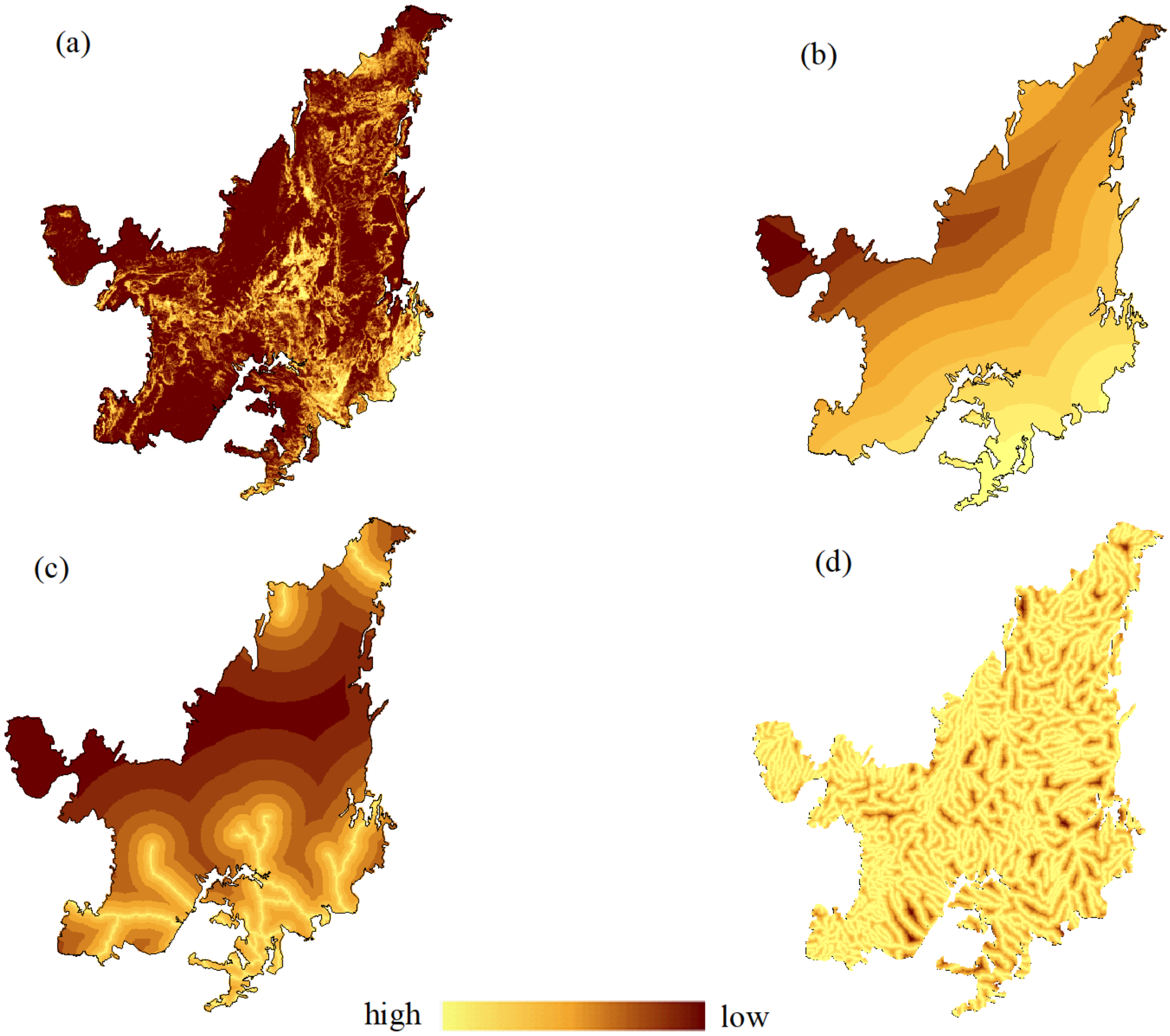
Source: Author's production.

Figure A.2. Spatial drivers of pasture selected to run LuccMe/Cerrado-N model: (a) Slope flat (up to 3%); (b) Distance to the closest slaughterhouse; (c) Distance to paved and unpaved roads; and (d) Distance to rivers.



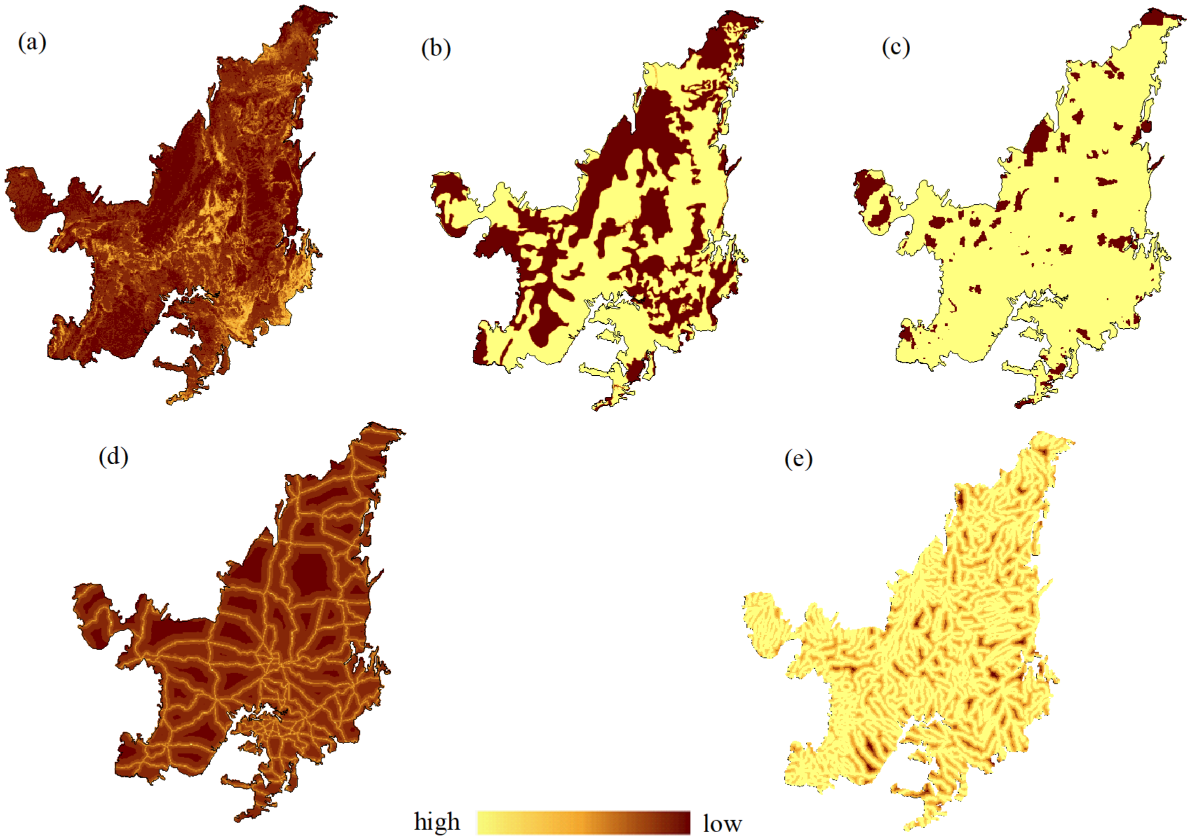
Source: Author’s production.

Figure A.3. Spatial drivers of silviculture selected to run LuccMe/Cerrado-N model: (a) Slope flat (> 3% and ≤ 8%); (b) Distance to the closest pulp-paper mills; (c) Distance to the closest railways; and (d) Distance to rivers.



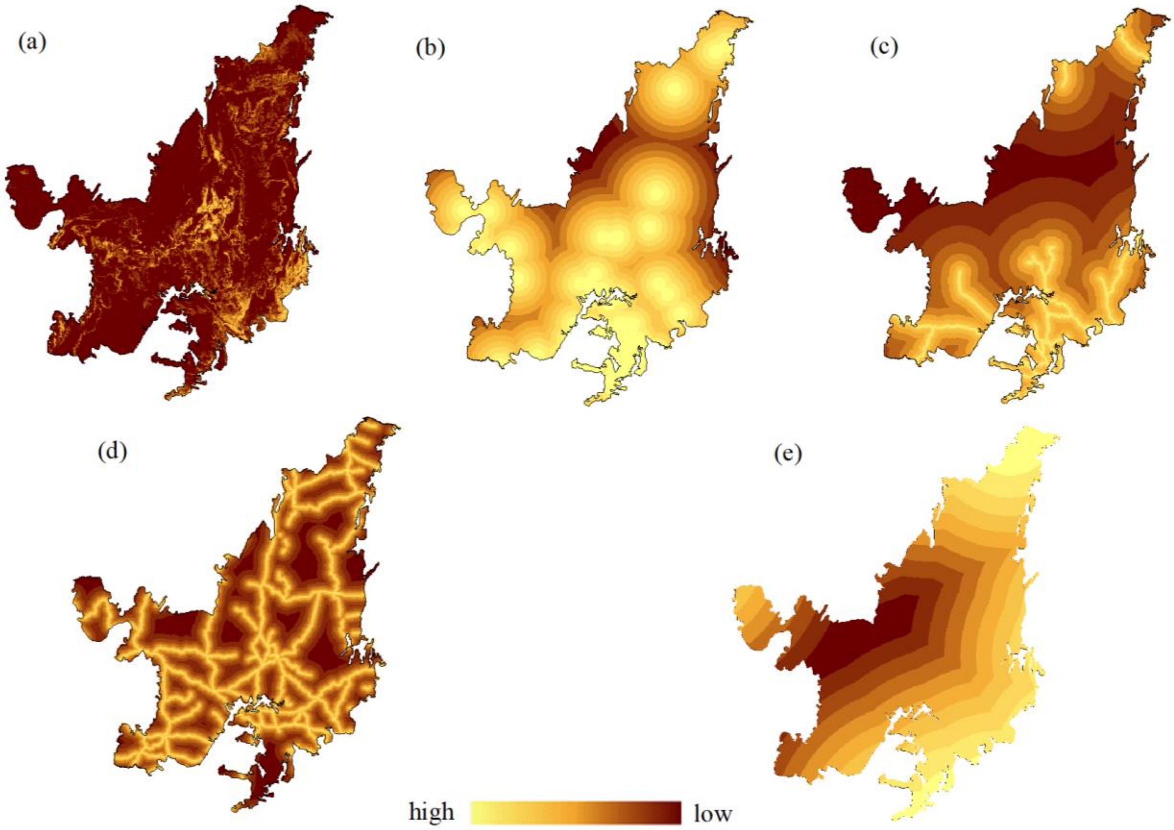
Source: Author's production.

Figure A.4. Spatial drivers of annual crops selected to run LuccMe/Cerrado-N model: (a) Slope flat (> 3% and ≤ 8%); (b) Presence of suitable soil for agriculture; (c) Presence of protected areas and indigenous land; (d) Distance to the closest paved and unpaved roads; and (e) Distance to rivers.



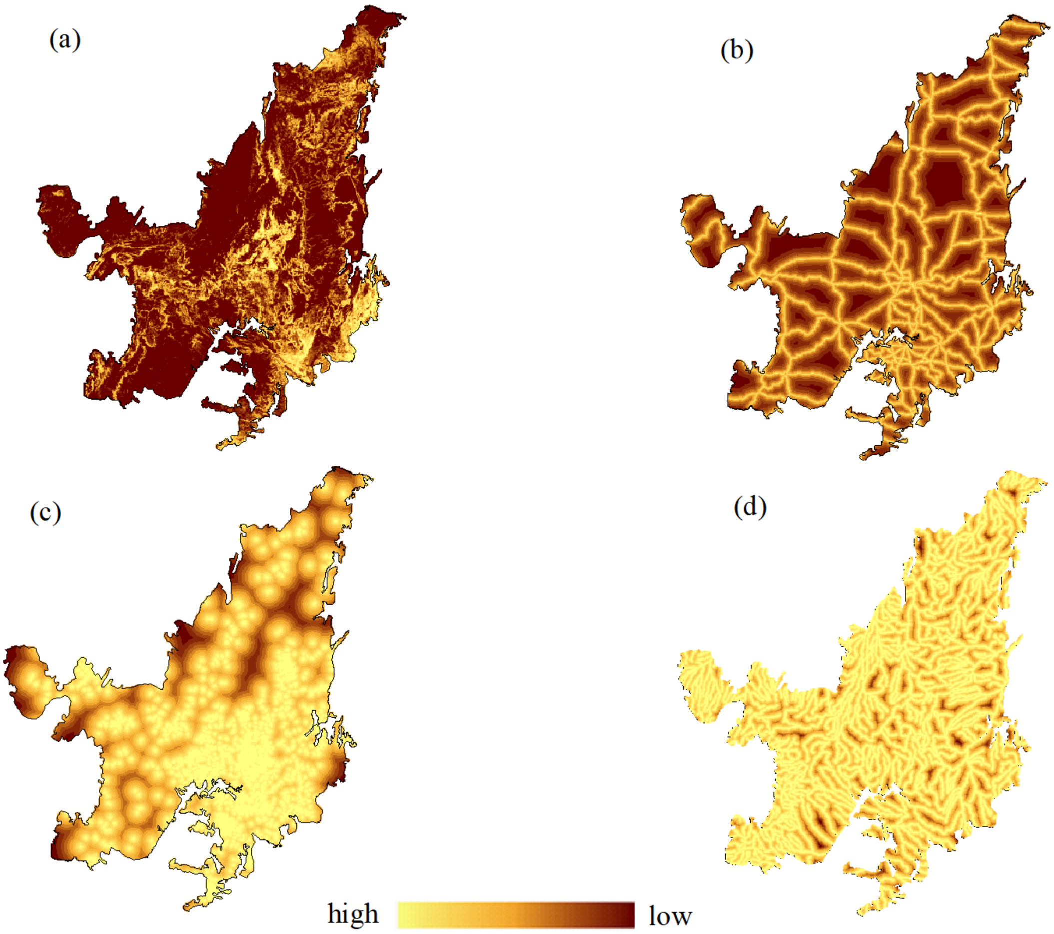
Source: Author's production.

Figure A.5. Spatial drivers of semi perennial crops selected to run LuccMe/Cerrado-N model: (a) Slope flat (up to 3%); (b) Distance to the closest sugar-ethanol mills; (c) Distance to the closest railways; (d) Distance to the closest paved roads; and (e) Distance to ports.



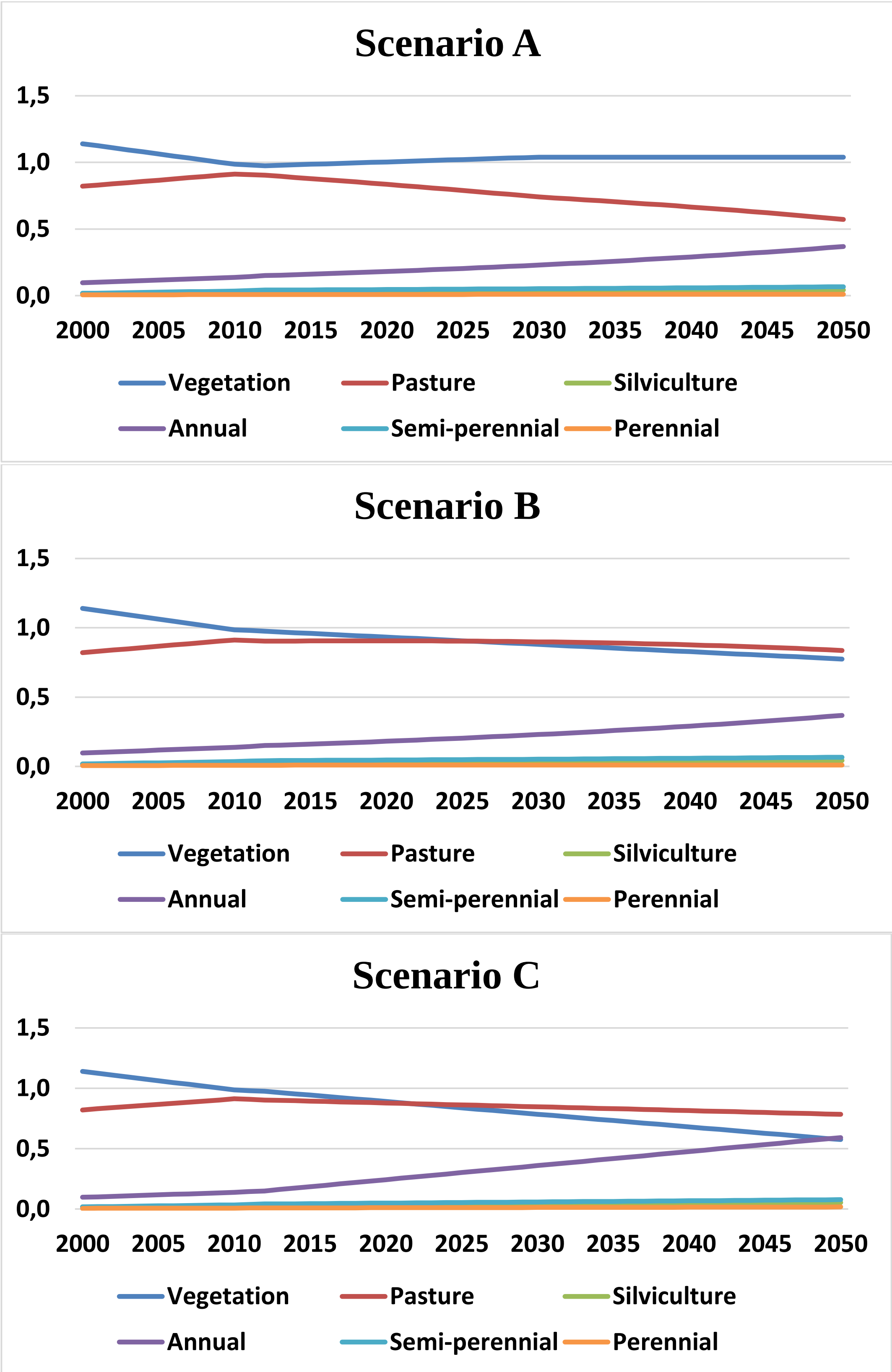
Source: Author's production.

Figure A.6. Spatial drivers of perennial crops selected to run LuccMe/Cerrado-N model: (a) Slope flat (> 3% and ≤ 8%); (b) Distance to the closest paved and unpaved roads; (c) Distance to the closest irrigation pivot; and (e) Distance to rivers.



Source: Author’s production.

Figure A.7. Area evolution (Mkm^2) of each land use in scenarios A, B, and C.



Source: Author's production.