Land change dynamics in the Brazilian Cerrado:
The interaction of biofuels, markets, and biodiversity

by

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B.S., University of São Paulo, 2008
M.Sc., University of São Paulo, 2012

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Geography
College of Arts and Sciences

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Abstract

Biofuel ethanol has been proposed as the most viable solution to mitigate greenhouse gas emissions (GHG) from the transportation sector; however, the impact of such production on the environment is not completely known. Environmental impacts are of more concern when ethanol production occurs in areas of high biodiversity value such as the Cerrado (Brazilian savanna). The Cerrado is a global biodiversity hotspot and an important breadbasket—at the same time, it is on a path to becoming the major sugarcane ethanol-producing region in Brazil. The main goal of this dissertation is to examine the impacts of sugarcane expansion on farmers' land use decision processes in the Cerrado and to consider its consequences on biodiversity and the impacts of climate change.

In the following chapters, land change dynamics are investigated using a combination of theory and methods from geography, GIScience, economics, and ecology. Chapter 2 presents an examination of the drivers for the sugarcane expansion. The findings suggest that the Cerrado attracted mills because of the good agricultural conditions, affordable land prices, and favorable state-level fiscal incentive policies, while factors that have prevented traditional sugarcane-producing regions from meeting the increasing demand for ethanol. Chapter 3 develops a procedure to identify intensification and extensification responses at the field level. The main finding is that extensification is the main response. Additionally, this response has a higher probability of occurrence the farther an area is from a mill. Chapter 4 applies the partial adjustment framework to understand farmers' land use decisions regarding sugarcane production. Estimates found that price of cattle have the largest cross-price elasticity with sugarcane acreage. In addition, the results suggest that acreage of sugarcane and soybean double-crop are positively correlated. Chapter 5 focuses on the impacts of climate change on land suitability for sugarcane and amphibian species. The findings show that land suitability for sugarcane is vulnerable to climate change and that the Brazilian zoning policy for sugarcane is not addressing this issue. Additionally, amphibians are affected by climate change and conflict with areas suitable for sugarcane in climate change scenarios.

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In the following chapters, land change dynamics are investigated using a combination of theory and methods from geography, GIScience, economics, and ecology. Chapter 2 presents an examination of the drivers for the sugarcane expansion. The findings suggest that the Cerrado attracted mills because of the good agricultural conditions, affordable land prices, and favorable state-level fiscal incentive policies, while factors that have prevented traditional sugarcane-producing regions from meeting the increasing demand for ethanol. Chapter 3 develops a procedure to identify intensification and extensification responses at the field level. The main finding is that extensification is the main response. Additionally, this response has a higher probability of occurrence the farther an area is from a mill. Chapter 4 applies the partial adjustment framework to understand farmers' land use decisions regarding sugarcane production. Estimates found that price of cattle have the largest cross-price elasticity with sugarcane acreage. In addition, the results suggest that acreage of sugarcane and soybean double-crop are positively correlated. Chapter 5 focuses on the impacts of climate change on land suitability for sugarcane and amphibian species. The findings show that land suitability for sugarcane is vulnerable to climate change and that the Brazilian zoning policy for sugarcane is not addressing this issue. Additionally, amphibians are affected by climate change and conflict with areas suitable for sugarcane in climate change scenarios.

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Dedication

I dedicate this dissertation and all my life to Sara, my loving wife. Thank you for joining me on this journey, and for leading us to the finish line. This work is also dedicated to the loving memory of our dog Chuleta.

Chapter 1 - Introduction

1.1 Land dynamics motivated by the increasing demand for agricultural products

Biofuel ethanol has been proposed as a viable solution to mitigate greenhouse gas emissions (GHG) from the transportation sector; however, the impact of such production on the environment is not completely known. Environmental impacts are more concerning when ethanol is produced in areas of high biodiversity value such as the Cerrado (Brazilian savanna). The Cerrado is a global biodiversity hotspot and an important agricultural breadbasket [*Myers et al.*, 2000]; at the same time, it is on the path to becoming the major sugarcane ethanol-producing region in Brazil [*Shikida*, 2013; *Granco et al.*, 2015].

Ethanol demand has been supported by governmental policies interested in mitigating global environmental change; an example of such policies is blend mandates (i.e., the Brazilian government mandates a 25% blend of ethanol on gasoline; the U.S. Energy Independence and Security Act of 2007 set a consumption target for biofuel). Ethanol in Brazil is obtained from processing sugarcane, a crop with a highly efficient photosynthesis process and high-yield potential per hectare, though it is produced in a large-scale setting [*Goldemberg and Guardabassi*, 2009].

Biofuel demand has triggered the expansion of sugarcane into the Cerrado, raising land demand and competition between food, fuel, and native vegetation. Previous studies have identified increases in agricultural activities, such as soy and cattle ranching, as drivers of deforestation and biodiversity loss in the Cerrado [*Klink and Machado*, 2005; *Sawyer*, 2008; *Carvalho et al.*, 2009]. Furthermore, biofuel crop production has environmental consequences such as intensification of input usage, simplification of the land mosaic, and landscape fragmentation. What is not yet established is the connection between farmers' land use decisions to plant sugarcane and Cerrado biodiversity.

Knowledge on what motivates farmers to change a previous land use to sugarcane is paramount to better-inform policy makers and society on the advantages and impairments of sugarcane production in the Cerrado. Lack of such knowledge is a problem because the effectiveness of ethanol as a mitigation policy can be hindered by its impact on biodiversity and vulnerability to climate change. Therefore, the main goal of this dissertation is to examine the impacts of sugarcane expansion on farmers' land use decision processes in the Cerrado and to consider its consequences on biodiversity and the effects of climate change. More specifically, this dissertation has four objectives:

Objective 1: Examine the drivers of sugarcane expansion in the states of Goiás and Mato Grosso do Sul;

Objective 2: Identify and analyze land use response promoted by the expansion of sugarcane;

Objective 3: Estimate farmers' land use decision responses to sugarcane expansion and land use change in the states of Goiás and Mato Grosso do Sul; and

Objective 4: Evaluate the change on sugarcane's land suitability and the vulnerability of Cerrado's amphibians to climate change.

1.2 Motivation

Global agriculture has been under pressure to meet the rising demand for food and fiber while maintaining environmental services [*Foley et al.*, 2011]. At the same time, public awareness of the relationship of fossil fuel consumption and human-induced climate change has stimulated the adoption of biofuels as a mitigation strategy to reduce emissions of GHG [*Sorda et al.*, 2010]. With growing demand, worldwide ethanol production increased from 4.5 to 22.5 billion gallons between 2000 and 2012 [*EIA*, 2012]. Currently, sugarcane ethanol is the most viable alternative biofuel for gasoline [*Lynd and de Brito Cruz*, 2010]. Under these circumstances, the Brazilian sugarcane ethanol industry flourished in the 2000s [*Goldemberg*, 2007]. Brazil is the second main producer of ethanol, and it is the largest U.S. partner in the ethanol trade [*Kristoufek et al.*, 2016]. The development of this industry is supported by the international recognition of sugarcane ethanol as the most advanced commercial biofuel providing the largest reduction in GHG [*Nassar et al.*, 2011; *Cavalett et al.*, 2013]. Since 2004, more than 100 new sugarcane mills went online, representing a gain of 60% in production capacity in 2012 with more than 5.8 billion gallons [*Unica*, 2014c].

Brazil has a long and successful history of adopting and consuming sugarcane ethanol. Sugarcane ethanol has been blended with gasoline since 1933, but it was the oil crisis in the 1970s that really established ethanol as an alternative fuel in Brazil [*Szmrecsányi and Moreira*, 1991]. Because of the shock caused by oil prices, the Brazilian government established the Proalcool Program in strong support for the production of sugarcane ethanol [*Hira and de Oliveira*, 2009]. With economic reforms in the 1990s, the Brazilian government withdrew its support, forcing the industry to reorganize itself [*Moraes*, 2011]. Additionally, the concentration of sugarcane mills (for sugar and ethanol production) in the state of São Paulo during the Proalcool years raised concerns of their environmental impact [*Martinelli and Filoso*, 2008], pushing for stricter enforcement of environmental laws in the 2000s [*Moraes and Zilberman*, 2014]. This was the business environment when ethanol demand started to rise again in 2003 with the introduction of flex-fuel cars (cars that can be fueled with any mixture of gasoline and ethanol). In order to meet this rising demand, ethanol industries had to expand their operations, leading some of them to the Brazilian Cerrado.

Sugarcane ethanol expansion is even greater in the Brazilian Cerrado than in the rest of the country [*Shikida*, 2013]. The expansion of the sugarcane industry to these states is illustrated in Figure 1-1. From 2005 to 2013, Goiás and Mato Grosso do Sul attained 40 new mills, and their ethanol production expanded from 0.3 to 1.6 billion gallons. Furthermore, sugarcane-producing areas that supply feedstock for the new mills expanded from 0.3 to 1.5 million ha, representing an expansion of 430% in production area [*CONAB*, 2016].

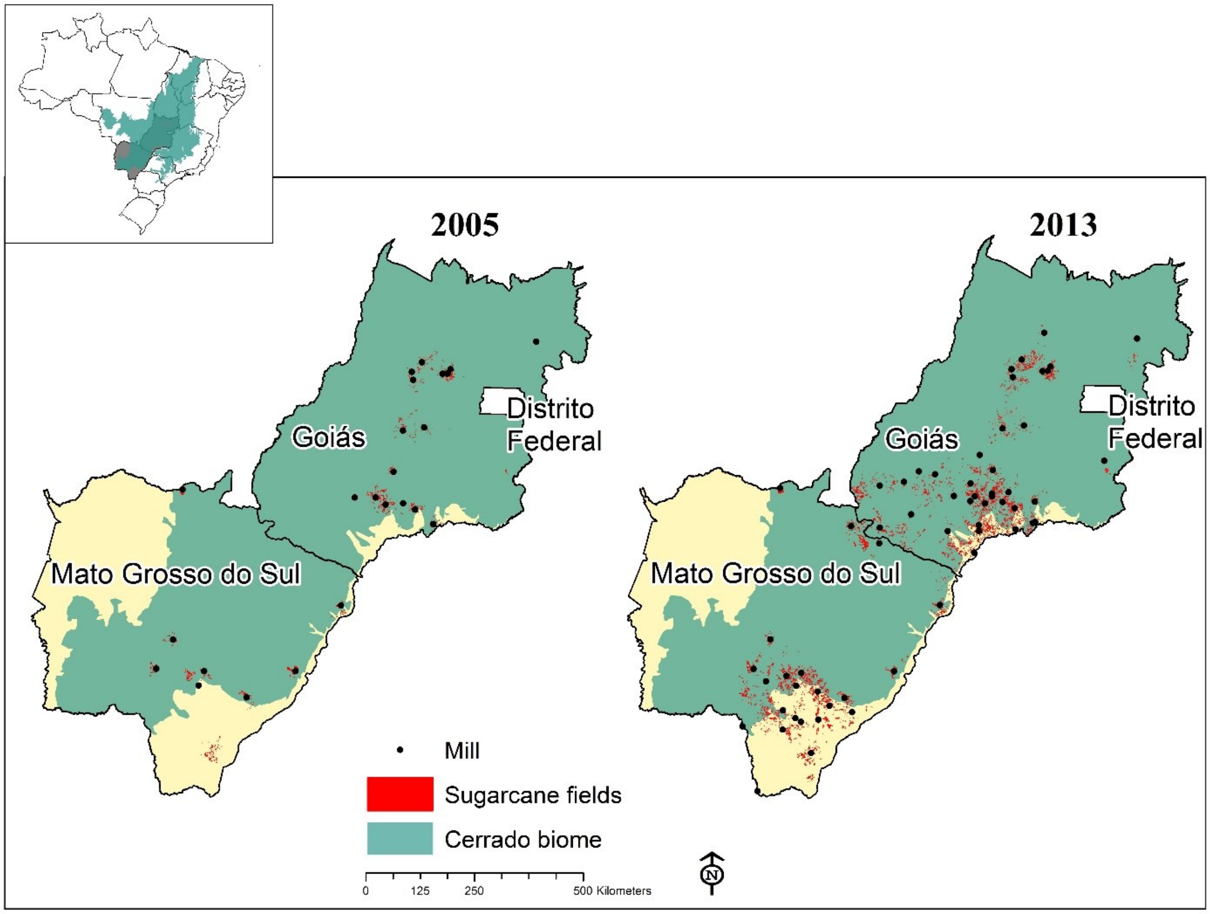

Figure 1-1 – The expansion of sugarcane industry in the states of Goiás and Mato Grosso do Sul.

This expansion is taking place in the Brazilian Cerrado. The Cerrado is the most biodiverse savanna in the world, with high endemism of plants and vertebrates. However, the Cerrado is regarded as a global biodiversity hotspot given the threat to its biodiversity by anthropogenic use of the region [*Myers et al.*, 2000; *Klink and Machado*, 2005; *Ministério do Meio Ambiente*, 2007a]. Agriculture expansion has been associated with deforestation of the Cerrado. Up to 2013, more than 975,000 km2, or 46% of the Cerrado area, has been converted to anthropogenic use, mostly to pasture and grain production [*Brasil*, 2015]. The potential emission of GHG associated with the conversion of areas motivated studies on measuring and quantifying carbon emissions caused by land use change, because they may result in a carbon debt greater than what would be avoided from burning gasoline [*Fargione et al.*, 2008; *Lapola et al.*, 2014]. More recently, research of agricultural effects on the environment started to broaden the focus from GHG to encompass impacts on ecosystem services, such as water quality and regime, soil, and biodiversity [*Moran et al.*, 2005; *Chaplin-Kramer et al.*, 2015].

1.3 The study area

Goiás and Mato Grosso do Sul are neighboring states in west-central Brazil occupying a total area of 697,000 km^2: 340,000 km^2 in Goiás and 357,000 km^2 in Mato Grosso do Sul. Goiás shares borders with the states of Tocantins to the north, Bahia to the northeast, Minas Gerais to the east, and Mato Grosso to the west. Mato Grosso do Sul also neighbors Mato Grosso and Minas Gerais; additionally, it neighbors São Paulo and Paraná (Figure 1-1). The study area encompasses 325 counties: 246 in the state of Goiás and 79 in the state of Mato Grosso do Sul.

Originally, the Cerrado covered 98% of Goiás and more than 60% of Mato Grosso do Sul. The Cerrado in these states exhibits a variety of vegetative covering, ranging from open grassland to closed woodland in a soil that is deep, well drained, and resistant to compaction (although it is acidic, with poor nutrient content and a high concentration of aluminum) [*Klink and Machado*, 2005; *Brannstrom et al.*, 2008]. The Cerrado native vegetation remains present in 137,500 km^2 in Goiás (46% of the original cover) and in 67,900 km^2 in Mato Grosso do Sul (31% of the original cover) [*Brasil*, 2015].

A major driver for land cover change in the Cerrado is the expansion of agricultural uses [*Klink and Machado*, 2005; *Carvalho et al.*, 2009; *Ferreira et al.*, 2012]. The main agricultural products are cattle, soybeans, and corn. Pastureland is the main anthropogenic use, covering 139,000 km^2 in Goiás and more than 121,000 km^2 in Mato Grosso do Sul [*Brasil*, 2015]. Annual row crop production is conducted on 34,900 and 13,300 km^2 in Goiás and Mato Grosso do Sul respectively. Perennial crops, which include sugarcane, are the land use on 9,400 and 4,700 km^2 in Goiás and Mato Grosso do Sul respectively [*Brasil*, 2015].

1.4 Conceptual framework

Few studies have focused on farmers' land use decisions in the Cerrado and even fewer on factors affecting farmers' land use decisions and sugarcane expansion. Consequently, the process by which existing agricultural cropland, pasture, or native vegetation is being converted to sugarcane remains unclear. This research advances knowledge in land change science by examining farmers' land use decision processes throughout the years of rapid sugarcane expansion in the Cerrado (2005 to 2013).

This dissertation research will follow the conceptual framework outlined in Figure 1-2 to study sugarcane expansion in the states of Goiás and Mato Grosso do Sul. The framework is centered on farmers' land use decision processes, broadened to consider the sugarcane ethanol industries' decisions and biodiversity consequences.

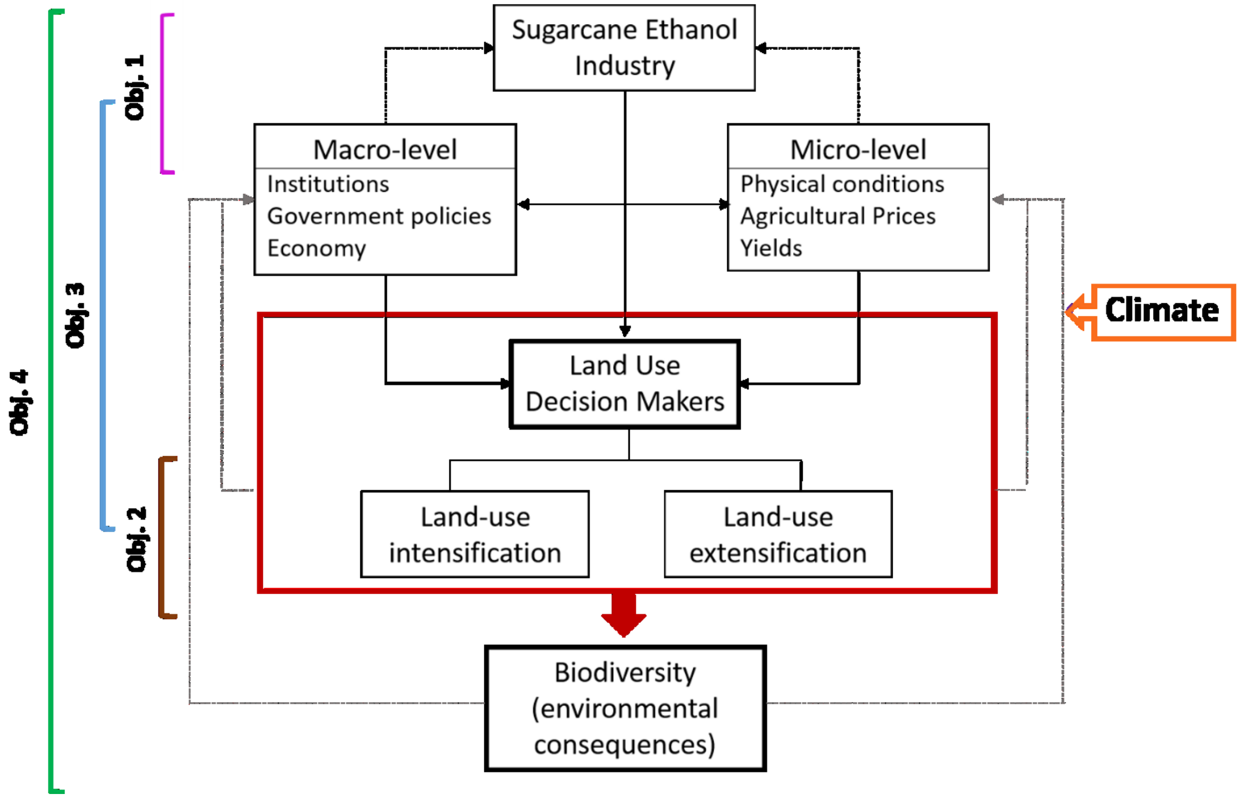

Figure 1-2 – Conceptual framework of sugarcane-induced land use change in the Cerrado.

Objective 1 focuses on understanding the driver for the sugarcane industry's decision to expand to the Cerrado. The 'sugarcane industry' is a term that encompasses the mill and the agricultural area. This strict relationship between the mill and the sugarcane-producing areas is because sugarcane needs to be processed right after harvest to avoid loss of sugar content [*Neves et al.*, 1998]. Goiás and Mato Grosso do Sul are two states with no tradition in sugarcane production; nevertheless, they are the new frontier for the sugarcane ethanol industries [*Shikida*, 2013]. To understand the factors that attracted this industry, I consider macro- and micro-level factors. The macro-level includes the political and economic factors that influence the sugarcane industry [*Moraes and Zilberman*, 2014]. In Figure 1-2, factors are listed that are related to institutions (e.g., producers' association and governmental agencies), government policies (e.g., state tax, blend mandate, and zoning), and the economy (e.g., fuel prices, ethanol demand, and the exchange price) [*Goldemberg*, 2007]. Micro-level factors are important for the ethanol industries because feedstock acquisition is a large portion of their production cost [*Haddad et al.*, 2009]. Micro-level factors are those related to the agricultural operation: for instance, agricultural conditions (e.g., soil quality, slope, precipitation regime), prices (e.g., crops and land), and agricultural yields [*Macedo*, 2005b; *Goldemberg et al.*, 2008a; *Martinelli and Filoso*, 2008]. Notably, we cannot understand sugarcane expansion to the Cerrado without considering farmers' land use decisions. For farmers, micro-level factors have a direct impact on their decisions; however, macro-level factors also influence their decisions [*Walker et al.*, 2009]. Governmental policies can modify the conditions for agricultural production. For example, changes in zoning policy can restrict farmers' production options, while the exchange rate can favor one specific production. Furthermore, the presence of the ethanol mill can also influence farmers' decisions by offering services such as sugarcane harvesting and transportation from the fields to the mills.

Objectives 2 and 3 focus on the farmers' land use decision process. Objective 2 is dedicated to identifying land use response (LUR) and analyzing how macro- and micro-level factors promote each LUR to sugarcane production. The land use and land cover change (LULCC) promoted by the expansion of sugarcane can be studied by considering the process of agricultural transition. This process refers to how land was previously used and how it was converted to its current use [*DeFries et al.*, 2004]. Farmers' decisions of allocating land to the production of sugarcane promote LULCC, which in turn can take the form of an LUR: intensification or extensification [*Secchi et al.*, 2011; *Arvor et al.*, 2012; *Brown et al.*, 2014]. In our framework, intensification is the conversion of cropland to sugarcane, while extensification is the conversion of noncropland to sugarcane. We hypothesize that each land use transition has a different response to the factors promoting sugarcane expansion.

Objective 3 examines farmers' land use decisions, highlighting the changes promoted by the arrival of ethanol mills. A farmers' land use decision-making process can be considered as an optimization problem where farmers try to allocate land to the use that results in the highest economic return [*Hennessy*, 2006]. Farmers decide which agricultural production to pursue under a certain technological package in a specific field in order to maximize production and reduce costs, thus maximizing profits. These are considered micro-level factors and decisions. However, farmers do not control all the factors to maximize their profits. The farmers' decision process is also conditioned by macro-level factors, such as government policies and laws, demand for agricultural products, and climate, among others [*Bergtold et al.*, 2014; *Caldas et al.*, 2014, 2015].

For this study, the focus is on the expansion of sugarcane and on measuring farmers' responses to change in factors affecting the sugarcane expansion. In this conceptual framework, I assume that farmers are rational economic agents, making informed decisions and seeking to maximize profits [*Hausman*, 2012]. With this assumption, I can use a hypothetical representative farmer which exhibits the same behavior than an individual farmer. I recognize this assumption is a simplification of the reality of farmers in the study area. Nevertheless, this simplification is still in line with the behavior of most commercial farmers in the Cerrado. Further assumptions are needed to develop a crop acreage model, I assume that farmers are risk neutral and that agricultural land is a fixed but allocable input (exhibiting constant returns to acreage) [*Wu and Brorsen*, 1995; *Hausman*, 2012; *Kaminski et al.*, 2013; *Carpentier and Letort*, 2014; *Hendricks et al.*, 2014].

Objective 4 is focused on the interaction between land use, climate change, and biodiversity. Sugarcane is a perennial crop and can be considered a long-term investment. In our framework, this long-term investment is incorporated through climate change. Given that farmers' land use decisions are influenced by micro-factors, which are affected by climatic conditions, knowledge on future climate conditions impact farmers' land use decisions. Concurrently, land use change interacts with biodiversity in several ways, such as deforestation, landscape fragmentation, and the intensity of use of resources [*Green et al.*, 2005; *Vandermeer and Perfecto*, 2007; *Phalan et al.*, 2011; *Tscharntke et al.*, 2012]. However, few studies have focused on the environmental consequences of agricultural-based ethanol production [*Chaplin-Kramer et al.*, 2015; *Manning et al.*, 2015]. The relationship explored in this conceptual framework is the exposure of amphibians to areas of high agricultural potential. The use of amphibian species is a small set of the whole biodiversity, but the spatial distribution of species' potential habitat can be used as a surrogate for broad environmental quality. Amphibia is the fastest declining group among the Animalia kingdom. Species are also affected by climate change [*Becker et al.*, 2007], thus this framework enables an understanding of land use, biodiversity, and climate change.

1.5 Dissertation's outline

The next chapter (Chapter 2) focuses on exploring the policy and social factors fueling the expansion and shift of sugarcane production to the states of Goiás and Mato Grosso do Sul. Within the past decade, the sugarcane ethanol industry in Brazil has increased its production capacity to meet rising domestic and international demand for ethanol [*Goldemberg et al.*, 2014]. However, to achieve this growth, the industry has expanded into new frontiers in the Brazilian

Cerrado, specifically in the states of Goiás and Mato Grosso do Sul. The literature is vast exploring the development, concentration, and consolidation of this industry in Brazil; nevertheless, most of these studies are concerned with the industry located in São Paulo [*Goldemberg*, 2007; *Lucon and Goldemberg*, 2010; *Alonso-Pippo et al.*, 2013; *Moraes and Zilberman*, 2014]. The main goal of this research is to understand the factors motivating the sugarcane ethanol industry's expansion into Goiás and Mato Grosso do Sul.

We argue that different factors curbed the expansion in the traditional production region at the same time that other factors attracted the industry to the new frontier, stimulating farmers to convert previous land uses to sugarcane. The approach used is a review of the literature and secondary data on the sugarcane industries' drivers and farmers' motivations. To examine these relations, the political economic theory is used to look at the macro-level drivers, while the von Thünen land rent theory is used to examine effects of the micro-level factors on farmers' motivation toward sugarcane.

After the study of the drivers for the expansion, this dissertation focus on the land change dynamics promoted by sugarcane. Chapter 3 addresses Objective 2 by identifying the dynamics of land use response in the Brazilian Cerrado. The Cerrado is not a traditional sugarcane-producing region, and it is considered a global biodiversity hotspot [*Myers et al.*, 2000]. The rapid development of sugarcane in the region has prompted a discussion over the impact of sugarcane production on land use [*Leal et al.*, 2013]. On one hand, researchers are concerned that sugarcane expansion is driving noncropland into production (extensification response) with potentially severe impacts on the local environment. On the other hand, it is argued that sugarcane is expanding because of crop shifts and increases in yields (intensification response) [*Brown et al.*, 2014]. Previous studies have demonstrated the occurrence of both LUR in Brazil

[*Adami et al.*, 2012; *Ferreira Filho and Horridge*, 2014]; however, no study on the spatial configuration of these LUR has been done. To achieve objective 2, first we identify and classify the LUR prompt by sugarcane; next, we run a statistical analysis of explanatory factors of each LUR.

Another aspect of land dynamics investigated in this research is the land allocation to sugarcane (Chapter 4). From 2005 to 2013 the area planted to sugarcane increased by 54%, reaching 9 million ha in Brazil. The rapid expansion of sugarcane production in Brazil has the potential to reorganize the agricultural production landscape [*Goldemberg et al.*, 2014; *Strassburg et al.*, 2014]. However, little is known on how farmers decide which agricultural production to pursue and which land use to replace in the new frontier of sugarcane production. Previous studies were conducted at a larger scale and did not examine the relationship of farmers and ethanol mills [*Lapola et al.*, 2010a; *Hausman*, 2012; *Ferreira Filho and Horridge*, 2014].

The goal of this chapter is to analyze farmers' land use decision processes. The hypothesis is that farmers' decisions are influenced by the presence of ethanol mills and sugarcane in nearby farms. The approach used is to develop an acreage response model [*Haile et al.*, 2016]. The model is estimated using a dynamic panel at the county level. In addition to the acreage response, this model presents price and yield elasticity of sugarcane acreage.

The future of sugarcane expansion with its vulnerability to climate change and impacts to biodiversity is the topic of Chapter 5. While the consumption of sugarcane-based ethanol has been proposed as a mitigation action against global climate change, its production can suffer with climate change—as in any other agricultural production [*Rosenzweig et al.*, 2014]. More recently, impacts on biodiversity have gained attention because the production of feedstock for biofuel can promote fragmentation of the landscape, thus threatening the environment's capability of sustaining biodiversity [*Walter et al.*, 2014; *Chaplin-Kramer et al.*, 2015; *Kline et al.*, 2015]. The fast expansion of ethanol demand in the 2000s pushed the Brazilian government to implement a zoning policy known as the Sugarcane Agroecological Zoning (SAZ). The SAZ has the goal to coordinate sugarcane expansion, defining areas suitable, areas nonsuitable, and areas not allowed to be converted to sugarcane.

This chapter has two objectives. The first objective is to assess SAZ vulnerability to climate change. The second objective is to identify the conflict between SAZ and biodiversity. To measure SAZ vulnerability, an ecological niche model was developed for the three classes of land suitability defined by the SAZ. Later these models were projected using several climate change scenarios. This framework produced a spatially explicit probability model of land suitability given climate change. To identify areas of potential conflict between SAZ and biodiversity, first ecological niche models were developed for 68 amphibian species, later these species were projected using the climate change scenarios used for SAZ analysis. A spatial intersection of these projections defines areas of high potential risk of conflict.

The final chapter of this dissertation brings the main conclusions by connecting the findings of the previous chapters.

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Chapter 2 - Exploring the policy and social factors fueling the expansion and shift of sugarcane production in the Brazilian Cerrado

2.1 Introduction

The increasing usage of fossil fuels has raised public concern about the emission of greenhouse gases (GHG) and their effects on human-induced climate change [*Cerqueira Leite et al.*, 2009; *Leal et al.*, 2013]. Together with these concerns, high oil prices and uncertainty over sustained oil supplies have instigated a search for alternatives to the use of fossil fuels [*Sparovek et al.*, 2009], biofuels have been put forward as a possible substitute. At the present moment, ethanol seems to be the most viable alternative biofuel option for fossil-fuel based gasoline [*Lynd and de Brito Cruz*, 2010]. Among the diverse types of crops that can be used to produce ethanol, sugarcane has emerged as a suitable alternative [*Goldemberg*, 2007].

Sugarcane is a plant with a highly efficient photosynthesis process and high yield potential per hectare, desirable characteristics for a biofuel crop [*Goldemberg and Guardabassi*, 2009]. Sugarcane is well adapted to tropical climate conditions and has been cultivated in several countries in this climate zone [*Buckeridge et al.*, 2012]. Brazil is the main producer of this crop and its products, ethanol, and sugar [*Unica*, 2014c]. The production and use of sugarcane ethanol in this country date back to the 1930s, but it was the Brazilian National Alcohol Program (Proalcool Program), established in 1975, that definitively introduced ethanol into the energy matrix for Brazil [*Hira and de Oliveira*, 2009]. This program supported the expansion of sugarcane ethanol production, especially in São Paulo State, where the sugarcane ethanol industry became heavily concentrated and responsible for more than 73% of national production of ethanol in 1994 [*Mapa. Ministério da Agricultura*, 2013]. Over the past 20 years, the state of São Paulo has witnessed decreasing importance of its ethanol production as other parts of Brazil expand their production, although this state remains the main ethanol producer, comprising 51% of national ethanol production [*Unica*, 2014b].

The concentration of ethanol production in São Paulo has led to consolidation in the ethanol industry and, consequently, to new challenges to its operation and future expansion, such as intensification of the competition for areas and increase of land prices in the region [*Shikida*, 2013]. In addition, the expansion of the industry has drawn attention to environmental issues that motivated the state to develop new environmental policies and practices. For example, the AgriEnvironmental Protocol bans the burning of sugarcane straw prior to harvest in areas that can be mechanized [*Martinelli and Filoso*, 2008; *de Cerqueira Leite et al.*, 2009; *Aguiar et al.*, 2011].

Even though these challenges and policies have created difficulties for the ethanol industry, they have not impeded the growth of sugarcane ethanol production. Indeed, high domestic demand for ethanol from sugarcane and its derivatives, together with international awareness for these products, are stimulating the expansion of sugarcane area and production in the Brazilian Cerrado—especially in the states of Goiás and Mato Grosso do Sul, the new frontier for sugarcane ethanol production. The expansion has allowed these states to become responsible for approximately 19% of the national sugarcane ethanol production, which accounts for about 1.2 million ha of land, representing 13% the area planted to sugarcane nationwide in 2012 [*Instituto Brasileiro de Geografia e Estatística*, 2014; *Unica*, 2014b].

Although several studies have discussed the benefits of the sugarcane ethanol industry and its consolidation in Brazil [*Coelho et al.*, 2006; *Nass et al.*, 2007; *Sparovek et al.*, 2009; *van* *den Wall Bake et al.*, 2009; *La Rovere et al.*, 2011; *Moraes*, 2011; *Goldemberg*, 2013; *Horta Nogueira et al.*, 2013], there is a lack of literature related to the drivers of sugarcane expansion to the Brazilian Cerrado. Thus, the purpose of this paper is to examine the factors affecting sugarcane ethanol expansion into the new frontier of Goiás and Mato Grosso do Sul states in the Brazilian Cerrado.

In order to achieve this goal, the paper is divided into six parts, including this introduction. In the second part, we present our theoretical framework which draws from the political economy and from the von Thünen location theory. The third part presents the historical evolution of governmental intervention on the sugarcane sector, reviewing the development of the ethanol industry (through the Proalcool Program) and the factors that have favored its consolidation in the state of São Paulo. The fourth part looks at the expansion of sugarcane production into new areas in the Brazilian Cerrado and at the factors driving this expansion to the states of Goiás and Mato Grosso do Sul. The fifth section presents a discussion of the implications of this expansion, and the last section offers our conclusions.

2.2 Theory for agricultural biofuel frontier analysis

The recent surge of interest in biofuels has motivated research regarding the drivers of biofuels crop expansion. Such studies have relied on policy reviews, econometrics analysis, and case studies to understand the rise of biofuel crop production system and to project future developments [*Fargione et al.*, 2008; *Stattman et al.*, 2013; *Goldemberg et al.*, 2014; *Strassburg et al.*, 2014; *van Eijck et al.*, 2014]. Among these studies, the ethanol industry in Brazil received much attention owing to its history of success, political interventions and economic development [*Alonso-Pippo et al.*, 2013].

The historical evolution of sugarcane ethanol industry in Brazil has been the object of political and economic studies interested in understanding the development of this industry [*Goldemberg et al.*, 2008b; *Alonso-Pippo et al.*, 2013; *Moraes and Zilberman*, 2014]. The study of political factors as drivers of the sugarcane industry evolution has been motivated by many factors, especially by the severe intervention of the Brazilian government on the sugarcane ethanol industry since the 1930s, the success of Brazilian National Alcohol Program (Proalcool Program), and more recently by the development of ethanol demand due to concerns regarding greenhouse gases emission. Previous research demonstrated that the Brazilian government has several forms to interact with the industry. In general, this interaction occurs through direct interference, such as governmental control on the ethanol sector and government investment in sugarcane technology, and indirect stimulus, like fiscal incentives to attract industry, public policies to stimulate ethanol demand, and governmental investment in infrastructure [*Szmrecsányi and Moreira*, 1991; *Goldemberg*, 2007; *Goldemberg et al.*, 2008b; *Hira and de Oliveira*, 2009]. Alternatively, studies on the economic factors driving the industry focused on market demand and access, market price for ethanol and sugar, production cost, and transportation cost [*van den Wall Bake et al.*, 2009; *Leal Jr and D'Agosto*, 2011; *de Gorter et al.*, 2013; *Du and Carriquiry*, 2013; *Moraes et al.*, 2014]. Given the complexity of the interaction between the government and the private sector in the sugarcane industry, political economy has been used to better understand this industry.

Political economy studies articulate the role of political and economic factors in promoting the sugarcane ethanol industry. These studies intertwined a historical analysis of governmental actions and policies to the domestic and international markets in order to explain the growth of sugarcane ethanol industry in Brazil. This literature demonstrated how different political structures were important in specific time periods, but changes in the Brazilian economy and in the sugar and ethanol markets prompted shifts in the policies for the ethanol industry and in the organization of this industry [*De Mello and Paulillo*, n.d.; *Szmrecsányi and Moreira*, 1991; *Puppim de Oliveira*, 2002; *Vian and Belik*, 2003; *Ramos*, 2012; *Goldemberg*, 2013; *Guimarães*, 2013; *Horta Nogueira et al.*, 2013; *Moraes and Zilberman*, 2014]. Even though the evolution of the sugarcane industry had been analyzed using the political economy framework, it is important to note that the expansion of sugarcane is not only a result of macro-level decisions of politicians and industrialists; it is also a result of farmers' land use decisions.

Farmers' land use decision-making process can be considered as a maximization problem. Farmers decide the optimal allocation of land to any activity in order to obtain the highest economic return under certain constraints, such as technology, agricultural conditions, and demand [*Hennessy*, 2006; *Mann et al.*, 2014]. In such context, political economy alone cannot explain the expansion process. A suitable model for this agriculture allocation problem is the von Thünen location theory [*Thünen*, 1966].

The Thunian theory relates the location of agricultural land use with its ability to create rent based upon location factors, such as distance to market, transportation costs, yield, market prices and production costs. Under this theory, farmer chooses the land use that maximizes his or her profits [*Kellerman*, 1989; *O'Kelly and Bryan*, 1996]. Changes in the location factors such as reduction of transportation cost or higher market price can result in land rent increase for a particular use, making it more profitable. Farmers respond to this new scenario by changing their land allocation to the more profitable use, thus creating land use change [*Walker et al.*, 2009]. That is not to say that farmers' land use decision under Thunian theory is independent of external factors [*Walker*, 2004; *Hersperger et al.*, 2010]. Farmers are influenced by actions from government and industry as these external actors can modify the location rent process [*Walker et al.*, 2009]. For instance, the government can set a tax reduction for specific economic activity thus changing the production cost of such activity. Government investment in transportation network affects land rent by reducing transportation cost. Sugarcane industry impacts land rent through offering other agricultural services to farmers, such as planting and harvesting, thus reducing the production cost of the crop, and smaller sugarcane transportation cost from the field to the industry. In these examples, the impact would be an increase in the land rent.

Both political economy and von Thünen location theory are integrated into the conceptual framework developed in the present paper to examine the drivers of sugarcane expansion to the new frontier in the states of Goiás and Mato Grosso do Sul. The conceptual framework uses the political economy to identify macro-level drivers by analyzing the connections between government policies, the sugarcane ethanol industry and demand for ethanol. In addition, this framework also considers farmers' land use decision under the agricultural location theory of von Thünen. This theory is employed to examine not only traditional location factors such as agricultural conditions, land price, transport infrastructure, but also the influence of government and sugarcane industry in farmers' land use decision-making. Thus, the combination of these two approaches improves the understanding of the connection between farmers' land use decision in the Brazilian Cerrado, the institutional environment of the region and the influence of the political process outside of the region.

2.3 Results: Ethanol policy in Brazil and the new frontier

2.3.1 The early years

The production of sugar has been an important source of income for Brazil and for the sugarcane industry since the Portuguese colonization. However, the sugar industry is vulnerable to fluctuations in the international price of sugar [*Goldemberg*, 2013]. In the late 1920s and early 1930s, Brazil experienced consecutive years of overproduction of sugar and a reduction of international demand. This scenario deteriorated international sugar prices and prompted the Brazilian sugar industry into a crisis. With an interest in protecting the sugar industry because of its importance on the trade balance, the Brazilian government developed two important policies [*Szmrecsányi and Moreira*, 1991]. The first policy consisted of governmental acquisition of excess sugar production in 1931. The second consisted of governmental stimulus for the production of anhydrous sugarcane ethanol by establishing a blend mandate that would add 5% of anhydrous ethanol to gasoline [*Moraes*, 2007]. The second policy illustrates the government perspective of ethanol as a byproduct of sugar production, which should be stimulated to compensate for losses in the sugar market [*Goldemberg*, 2013].

The acquisition of excess sugar production resulted in the regulation of the market through the formation of a regulatory stock; however, the stocks did not successfully reduce price fluctuations in the domestic sugar market [*Guimarães*, 2013]. Also, the blend mandate faced resistance from sugar producers [*de Cerqueira Leite et al.*, 2009]. These producers were not willing to accept the government's intervention in their production decisions. More than that, they argued against the cost of building an annex distillery for producing anhydrous sugarcane ethanol. In addition, they were in disagreement as to how the price of anhydrous sugarcane ethanol was to be defined by the government [*Guimarães*, 2013]. Thus, to overcome this opposition and enforce its blend policy, the Brazilian government created the Institute of Sugar and Alcohol (Instituto de Açúcar e Álcool – IAA) in 1933.

The IAA had powers to control the production of anhydrous sugarcane ethanol and its commercialization and to coordinate prices. The idea behind national control was to ensure competitiveness in the blend of imported gasoline and anhydrous sugarcane ethanol in the face of imported gasoline. This control also gave the government a monopoly over the exports of sugar, such that the IAA could control exports and stimulate the transformation of the overproduction of sugar into ethanol instead of exporting it [*Guimarães*, 2013].

To stimulate the expansion of anhydrous sugarcane ethanol, the IAA established the anhydrous ethanol to sugar quota. To implement this policy, the IAA offered financial incentives to sugar producers to establish private distilleries. Another action by the IAA was to build its own distilleries, called central distilleries. These installations were built to help sugar producers that needed to convert sugarcane to ethanol but did not have their own distilleries [*Szmrecsányi and Moreira*, 1991]. The first two central distilleries were built in Rio de Janeiro (1938) and Pernambuco (1940) [*Guimarães*, 2013]. These decisions by the IAA would have important consequences for the sugarcane sector during the World War II years.

One immediate consequence was the increase of the blend rate to 40% in order to minimize the impacts of the oil shortage [*Hira and de Oliveira*, 2009]. Another consequence was the interruption of domestic commerce of sugar that, at that time, was conducted by coastal navigation. World War II isolated traditional producers in the northeast from the consumers located in southeastern Brazil. These consequences aggravated the decline of the northeast sugarcane region while encouraging the development of the sugarcane industry in the southeast. As a result, the main area of production for sugarcane moved from the traditional areas in the northeast to the southeast, where São Paulo State became the main producer [*Szmrecsányi and Moreira*, 1991].

With the end of the war, oil prices decreased and so did the demand for anhydrous sugarcane ethanol along with the attention of the Brazilian government, as demonstrated by the decrease of the blend ratio to 7.5% over the next decade [*Nogueira et al.*, 2008]. During the period of 1950 to 1975, the sugar industry faced favorable prices that improved the conditions to export sugar [*Nitsch*, 1991]. Under these circumstances, the IAA allowed higher sugar export quotas for producers in the northeast region to prevent financial hardships and bankruptcy for these producers. At the same time, the IAA allowed producers from São Paulo State to become self-sufficient in sugar and sugarcane ethanol production by increasing allocations of production quotas to this state [*Hira and de Oliveira*, 2009].

Notably, the decade of the 1970s witnessed a change in the status of sugarcane ethanol from a byproduct of sugar production to an important energy source for Brazil [*Hammond*, 1977]. In this period of time, Brazil was going through industrialization and urbanization, with the economy expanding at a 10% growth rate [*Baer*, 2001]. Brazil was importing 80% of the oil it consumed [*Goldemberg*, 2013]. The production boycott organized by the Organization of the Petroleum Exporting Countries (OPEC) in 1973 resulted in the first oil shock to the macroeconomy. This boycott caused an increase in the international oil price from US$ 2.90/barrel in 1973 to US$ 11.65/barrel in 1974. As expected, the consequences to the Brazilian economy were severe. Expenditures on oil imports grew from US$ 600 million in 1973 to US$ 2.5 billion in 1974, generating a trade deficit of US$ 4.7 billion [*Nogueira et al.*, 2008].

After the first oil shock, the military government saw the dependency of imported oil as a threat to the development of Brazil [*Nass et al.*, 2007]. The solution identified by the government was to promote the use of sugarcane ethanol because it was a Brazilian product substituting a foreign product and because the production structure and technology already existed [*Hira and de Oliveira*, 2009]. Thus, on 14 November 1975, the government created the Brazilian National Alcohol Program (Proalcool Program), with the aim of raising the ethanol blend rate with gasoline to 25% until 1980. To achieve this goal, the production of anhydrous sugarcane ethanol would have to increase to 2 billion l/y by 1980—although in 1974/1975 Brazil's ethanol production was only at 595 million l/y [*Mapa. Ministério da Agricultura*, 2013].

2.3.2 The Proalcool Program

As a result of the first oil crisis, the Proalcool Program started with its focus on the supply side of the ethanol market. The demand side was dealt with by an increase of the blend mandate of anhydrous sugarcane ethanol with gasoline [*Goldemberg*, 2007]. The sugarcane industry was willing to collaborate with the government this time as it was facing another crisis of low international sugar prices. The idea was to join forces with the IAA to establish the Proalcool Program in order to compensate the low international sugar prices and to establish a new market for their products [*Hira and de Oliveira*, 2009].

The Proalcool Program consisted of two main policies. The first policy was centered in subsidized credit for expanding industrial capacity and agricultural production. The second was based on price policy that compensated the producer for the production of ethanol instead of sugar (Brazil, 1975). The credit policy financed the installation or enlargement of annex distilleries to sugar mills and also the installation of autonomous distilleries. Consequently, two industrial plants, mills, would produce ethanol: one that could produce ethanol and sugar, called as flex mills, and the other that could only produce ethanol, called ethanol mills. The second policy was designed to influence the producer decision toward sugarcane ethanol instead of sugar, in order to guarantee the supply of anhydrous sugarcane ethanol [*Shikida and Bacha*, 1999; *Goldemberg*, 2006]. The result was the production of 3.4 billion liters in 1980, exceeding the original goal of 2 billion liters [*Mapa. Ministério da Agricultura*, 2013]. By the end of the 1970s, 209 distilleries had been created, mainly in the traditional regions of São Paulo and Rio de Janeiro and in the northeast states of Alagoas and Pernambuco [*Shikida and Bacha*, 1999].

A second oil shock in 1979 increased the price of oil by 34% at its peak, motivating the government to intensify the Proalcool Program [*La Rovere et al.*, 2011]. A new ethanol production goal was defined aiming 10.7 billion liters of sugarcane ethanol by 1985, but the more ambitious goal of this new phase of the Proalcool Program was to establish a car fleet powered primarily by hydrous sugarcane ethanol [*Goldemberg*, 2006; *Hira and de Oliveira*, 2009; *La Rovere et al.*, 2011]. This goal was necessary to avoid the problem of the blend-wall, the maximum blend rate that can be used without engine adaptations for an automobile fleet [*Taheripour and Tyner*, 2008; *Lynd and de Brito Cruz*, 2010]. For the Brazilian car fleet, the blend-wall was 25%, which Brazil was close to meeting. For this reason, the mandate for a large car fleet that could use hydrous ethanol represented a continuity of the substitution of gasoline by sugarcane ethanol [*Nogueira et al.*, 2008]. This policy change shifted the focus from supply to demand, thus increasing the complexity of the program, owing to the fact that it had to continue to stimulate the sugarcane sector, while creating favorable conditions for customers to buy new cars at the same time that the government had to negotiate with the automobile manufacturers to produce hydrous ethanol cars [*Stattman et al.*, 2013].

The main consequences of the negotiations with automobile manufacturers were a fixed price for ethanol at 65% of the price of gasoline to the consumer and an easy credit for those willing to buy cars powered by sugarcane ethanol, accompanied by a reduction in the cars' registration fees [*Hira and de Oliveira*, 2009]. These policies were well accepted as demonstrated by the high participation of sugarcane ethanol cars (96%) in the sales of new cars in 1985, only 6 years after it was introduced in the market [*Colares*, 2007]. Also, these policies stimulated the production of 11.9 billion liters of sugarcane ethanol in 1985, once again surpassing the goal proposed by the program of 10.7 billion liters [*Mapa. Ministério da Agricultura*, 2013].

However, by the end of the 1980s, the sugarcane ethanol industry suffered three new external shocks. The first shock was the drastic decrease in the international price of oil [*Paulillo et al.*, 2007]. The second shock was an economic crisis in Brazil because of its large external debt [*Baer*, 2001]. The last shock was an increase in the international price of sugar. These three shocks worked together to motivate the removal of governmental incentives [*Nitsch*, 1991; *Hira and de Oliveira*, 2009], but the main consequence of these events appeared in 1989/1990 with a supply crisis of sugarcane ethanol that undermined the consumer's trust in the Proalcool Program [*Soccol et al.*, 2005]. These problems culminated in the end of the Proalcool Program in the following years.

2.3.3 The consolidation of the São Paulo sugarcane ethanol industry

The 1990s began with two important changes in the institutional environment. First, the government removed its control of the sugarcane sector by ending the Instituto de Açúcar e Álcool (IAA) and revoking Proalcool Program's administrative councils, thus promoting deregulation of the sector [*Hira and de Oliveira*, 2009]. The deregulation was gradual because the government was concerned that without its intervention the sugarcane sector would not work properly [*Moraes*, 2007; *Paulillo et al.*, 2007]. The second important change was the development of the Plano Real, an economic plan that stabilized the Brazilian economy after decades of economic crises and inflation. The implementation of Plano Real made the internal market stronger, thus raising the demand for sugar. Furthermore, economic stabilization allowed the industry to make long-term investment plans, stimulating the expansion of industry capacity to meet growing demands.

The deregulation process and the success of Plano Real promoted a new business environment, which had different results for the two traditional sugarcane-producing regions. Producers in São Paulo were able to operate in this new business environment in part because of their entrepreneurial skills and investments in technology [*Furtado et al.*, 2011; *Lehtonen*, 2011]. In contrast, producers in the northeast suffered with this change because of their paternalist culture, their considerable interest in political power, and their dependence on IAA's support and quotas [*Compean and Polenske*, 2011].

Under these circumstances, the deregulation led to a drastic reduction in the northeast's share of sugar and ethanol production (Table 2-1). For instance, the region's participation in the total production of sugarcane ethanol and sugar decreased from 17% and 43% in 1990 to 9% and 13% in 2012, respectively. In contrast, the southeast flourished with this new business environment, expanding its production of sugarcane ethanol and sugar. This expansion was more significant in the sugar market, where the southeast increased its share of the market from 53% to 68% of national production in 2012. Equally important to note is the concentration of the sugarcane sector in São Paulo. In 2012, this state produced 51% of all Brazilian ethanol and 59% of all sugar.

Table 2-1 – Evolution of sugarcane ethanol and sugar production.

	1990		2003		2008		2012	
Ethanol, 10^3 m^3	Production	(%)	Production	(%)	Production	(%)	Production	(%)
Southeast	8,537	72	8,638	68	15,475	69	13,981	62
São Paulo	7,775	65	7,691	61	13,325	59	11,598	51
Northeast	2,022	17	1,471	12	2,096	9	2,139	9
Alagoas	883	7	568	4	853	4	673	3
Pernambuco	583	5	307	2	417	2	358	2
Other states	1,364	11	2,514	20	4,851	22	6,561	29
Brazil	11,923	100	12,623	100	22,422	100	22,682	100
	1990		2003		2008		2012	
Sugar, 10^6 ton	Production	(%)	Production	(%)	Production	(%)	Production	(%)
Southeast	3,856	53	15,812	70	21,553	70	24,558	68
São Paulo	3,032	42	14,348	64	19,105	62	21,068	59
Northeast	3,074	43	3,789	17	4,551	15	4,621	13
Alagoas	1,281	18	1,994	9	2,509	8	2,348	7
Pernambuco	1,317	18	1,231	5	1,433	5	1,482	4
Other states	284	4	2966	13	4615	15	6746	19
Brazil	7,214	100	22,567	100	30,719	100	35,925	100

Source: Prepared by the authors with data from MAPA (2013) and UNICA (2014a).

Notably, it was not only the changes in the 1990s that helped to concentrate the sugarcane industry in São Paulo State. Three characteristics helped to build this state's leadership in the sugar and ethanol sector. First, São Paulo has good agricultural conditions, such as favorable weather and soil for sugarcane production [*Martinelli and Filoso*, 2008]. Second, sugarcane is a traditional sector in the state with producers and mills dominating the know-how to operate within the sector [*van den Wall Bake et al.*, 2009]. Third, the sugarcane sector in São Paulo invested in technological developments, such as new sugarcane varieties, agricultural treatment, improvement of yeasts, and development of a membrane filter to increase industrial production [*Shikida and Bacha*, 1999; *Martines-Filho et al.*, 2006; *Compean and Polenske*, 2011]. All these factors led to impressive increases in production, with average sugarcane yields increasing from 52 t/ha in 1970 to 78 t/ha by 2012 [*Instituto Brasileiro de Geografia e Estatística*, 2014].

Additionally, mills and distilleries improved their production efficiency. Sugar extraction from sugarcane had an average annual improvement of 0.3% between 1977 and 2004, while the ethanol production process increased its efficiency by 3.77%/y from 1975 to 2004 [*Goldemberg et al.*, 2008b].

Although technological improvements were important for gains in productivity and in reducing the need for new areas of sugarcane expansion, these advances alone were not enough to meet the increased demand for sugarcane products [*Macedo*, 2005a]. Better international sugar prices, a stronger domestic market for sugar, and the use of ethanol as a renewable fuel were important drivers of demand. Additionally, the development of flex-fuel cars in Brazil allowed consumers to fuel their cars with any proportion of ethanol and/or gasoline [*Shikida*, 2013]. Thus, in order to quickly meet this demand, the sugarcane industry needed to significantly expand its production. Naturally, São Paulo was the main focus of this development, reinforcing the concentration of the sector in this state [*Rudorff et al.*, 2010; *Aguiar et al.*, 2011].

The concentration of the sugarcane sector in São Paulo had important consequences for the industry. From 1995 to 2012, the harvested area in São Paulo more than doubled (Figure 2-1). Sugarcane occupied 21.7% of all land in the state of São Paulo in 2011; and the competition with other agricultural land uses grew more intense, reducing the options for further expansion (Adami et al., 2012; Shikida, 2013). As expected, this competition for land increased the cost of land rental rates (Figure 2-1). The average land rental rate for sugarcane was R$ 167/ha in 1995 and R$ 916/ha in 2012, an increase of 548% (Camargo et al., 2008; Torquato et al., 2009; IEA, 2013). Consequently, the rise of land prices resulted in higher operational costs for the sugarcane industry in the state of São Paulo. The industry was affected because, since the

1990s, it has become more vertically integrated being responsible for sugarcane production in order to guarantee its supply (Oliveira and Ramalho, 2006).

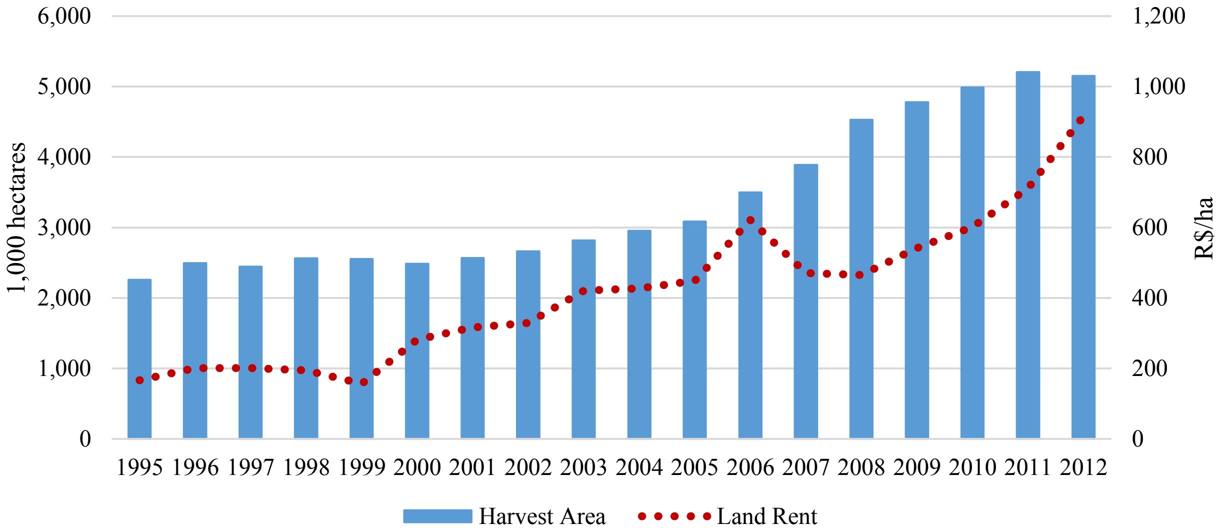

Figure 2-1 – Expansion of sugarcane's harvest area and land rent in São Paulo.

Markedly, the concentration of sugarcane production in São Paulo affected not only the industry but also had negative socio-environmental impacts. Atmospheric pollution caused by pre-harvest burn, nitrogen pollution, deterioration of aquatic systems, soil degradation, loss of biodiversity, and destruction of riparian ecosystems were some of the environmental impacts related to the intensification of sugarcane production [*Martinelli and Filoso*, 2008; *Sawyer*, 2008; *Smeets et al.*, 2008; *Martinelli et al.*, 2013; *Walter et al.*, 2013]. Furthermore, social problems were also created, such as the exploitation of cane cutters and higher rural unemployment in the offseason [*Moraes*, 2007, 2011; *Martinelli and Filoso*, 2008; *Nogueira and Capaz*, 2013]. As a response to these impacts, the state government developed new regulations and enforced previous environmental and labor laws more strictly [*Lucon and Goldemberg*, 2010; *Martins et al.*, 2011].

One of the laws that received more attention was Law 11,241/2002, which established a process of phasing-out the pre-harvest burn. This law established two phase-out chronograms. The first chronogram specified the end of the pre-harvest burn until 2021 for areas that could be mechanized; the second stipulated the end of pre-harvest burn until 2031for areas that could not be mechanized [*São Paulo*, 2002]. The law was considered weak by the public, which motivated the government and the sugarcane sector to work toward a faster phase-out of pre-harvest burn. The result was the Agri-Environmental Protocol (AEP) of 2007, a volunteer agreement between the sugarcane sector and the São Paulo government. For the participants of the AEP, the deadline to end the pre-harvest burn was reduced to 2014 for possible mechanized areas and to 2017 for other areas [*Martins et al.*, 2011].

Since the implementation of the AEP in 2007, the use of a pre-harvest burn on sugarcane areas decreased from 2.13 to 1.28 million ha in 2012/2013. In response, mechanized harvest expanded from 1.11 to 3.38 million ha in the same period. Data for the 2013/2014 crop year indicates that 84.8% of the areas that could be mechanized are under this type of harvest [*IEA-Instituto de Economia Agrícola*, 2014]. These results demonstrated that the AEP was effective in reducing pre-harvest burn. However, it is expected that the goal of no pre-harvest burning in areas that can be mechanized will not be achieved by 2014 as stated in the Protocol [*Aguiar et al.*, 2011].

Thus, the costs associated with mechanization and the increase of land prices because of the stronger competition for land resulted in higher production costs, motivating producers to the search for potential new areas of production. Consequently, the new areas should have lower land prices than São Paulo, and mechanization could occur without much problem. In this context, the states of Goiás and Mato Grosso do Sul in the Brazilian Cerrado emerged as the new frontier for sugarcane expansion.

2.3.4 The new frontier of sugarcane expansion

The states of Goiás and Mato Grosso do Sul are well known as having been the focus of intense agricultural expansion in the last 40 years. These states are part of the Cerrado Biome, an ecosystem that covers 2 million km^2 of central Brazil. The Cerrado covers 98% of Goiás and more than 60% of Mato Grosso do Sul [*Ministério do Meio Ambiente*, 2007b]. This region displays a variety of vegetation patterns, ranging from open grassland fields to closed woodland in a soil that is deep, well-drained, and resistant to compaction—although it is acidic, with poor nutrient content and a high concentration of aluminum [*Abelson and Rowe*, 1987; *Klink and Machado*, 2005; *Miranda et al.*, 2005; *Jepson*, 2006; *Brannstrom and Filippi*, 2008].

Until the 1970s, this region was known for its lack of connection with other regions of Brazil and for its weak economic development. The economy of this region was centered on low-density cattle ranching, with low economic returns [*Abelson and Rowe*, 1987; *Ratter et al.*, 1997]. This situation raised geopolitical concerns in the Brazilian government for development strategies to connect the region to the rest of the country, thus promoting economic development and stimulating the occupation of this vast area [*Jepson*, 2006; *Castro et al.*, 2010]. Among these strategies were the construction of the capital (Brasília) and the technological modernization of Cerrado agriculture, the latter coordinated by the Brazilian Agricultural Research Corporation (EMBRAPA). With abundant subsidized credit, this region was transformed into a breadbasket [*Miranda et al.*, 2005; *Rada*, 2013]. However, subsidized credits were not the only factor attracting farmers to this region. Inexpensive land prices also stimulated farmers from southern

Brazil to buy large properties on the Cerrado [*Klink and Machado*, 2005; *Jepson*, 2006; *Rada*, 2013].

Under these conditions, the Cerrado states witnessed the development of large-scale monoculture farming based on intensive use of capital [*Jepson*, 2006; *Brannstrom and Filippi*, 2008]. The introduction of large-scale agricultural farming established the grain sector, especially soybeans and corn, which became the main agricultural cash crops in this region. The profitability of this sector enhanced the attraction of farmers to this agricultural frontier [*Ratter et al.*, 1997; *Klink and Machado*, 2005; *Rada*, 2013]. Although large-scale agriculture crop production developed in the region during this time, cattle ranching was also an important agricultural activity in these states. However, the growth of crop production promoted competition for land, pushing ranchers to intensify their production in order to be more profitable [*Klink and Machado*, 2005; *Rodrigues and Miziara*, 2008]. Ranchers that could not compete were displaced to regions not as attractive for crop farming inside the Cerrado or to the Amazon [*Sawyer*, 2008; *Walker et al.*, 2009; *Arima et al.*, 2011; *Walker*, 2011].

The process of agriculture expansion encountered difficulties in the 1990s because of the end of governmental support and increases in production costs. Additionally, in the beginning of the 2000s the region suffered with an outbreak of soybean rust and low international commodity prices [*Yorinori et al.*, 2005; *Goldsmith and Hirsch*, 2006]. If on one hand, farmers in this region were responsive to changes in soybean prices [*Hausman*, 2012], low prices signaled farmers to plant less soybeans; on the other hand, prices for sugarcane were increasing because of strong demand for ethanol [*Agrianual*, 2004]. However, even though sugarcane was an attractive option, farmers in this region could not start planting sugarcane owing to timing concerns. Sugarcane is a crop that starts to lose its sugar content soon after being harvested, thus reducing the amount of sugar and ethanol that can be obtained. In this context, sugarcane needs to be promptly processed after harvest. This implies that sugarcane fields need to be located close to the mill. For farmers in Goiás and Mato Grosso do Sul, this requirement became a problem. Few mills were operating in the region, consequently limiting the expansion of the crop. Until 2005, only 22 mills had been established in Goiás and Mato Grosso do Sul.

The small number of mills in the region signaled a solution for the expansion problems faced by the sugarcane sector in the state of São Paulo. Investors identified an opportunity for investments and an alternative for the land competition and for production costs in the state of São Paulo. In addition, Goiás and Mato Grosso do Sul had large areas suitable for mechanization with good agricultural conditions for producing sugarcane at affordable land prices when compared to São Paulo [*Silva and Miziara*, 2011; *Silva and Peixinho*, 2012; *Agrianual*, 2013].

Complementary to these attributes, governmental support from federal, state, and municipal levels further enhanced the attractiveness of the region through fiscal incentives and investment in transportation infrastructure [*Silva and Peixinho*, 2012]. For instance, the state of Goiás developed a program to promote industrial development called PRODUZIR. This program offers financial incentives by postponing 73% of ICMS tax (which is the main state-level tax) by 2020. From 2003 to 2010, PRODUZIR funded R$ 28.1 billion in investments in the sugarcane sector [*Sauer and Pietrafesa*, 2012]. Similarly, the State of Mato Grosso do Sul has the MS EMPREENDEDOR program to assist its industrial sector. The program provides a 15-year tax exemption of 67% of ICMS taxes [*Sul*, 2001]. Municipalities from both states also offered tax exemptions for industry [*Domingues and Júnior*, 2012; *Silva and Peixinho*, 2012].

Federal fiscal incentives occurred through the constitutional fund to west central Brazil (Fundo Constitucional do Centro-Oeste, FCO) and through the Brazilian Development Bank

(BNDES). The FCO's main mission is to promote the economic and social development of west central Brazil. The FCO developed special credit lines for investment in the west-central region, which are cheaper than regular credit lines from commercial banks [*Sauer and Pietrafesa*, 2012; *Silva and Peixinho*, 2012]. The BNDES not only offered more credit to the sugarcane sector but also created new lines to supply credit specifically for the sugarcane sector, the Programa de Apoio ao Setor Sucroalcoleeiro (Pass Program). During 2008 to 2010, BNDES distributed R$ 20.45 billion in credit to the sector, with R$ 400 million through Pass [*Garcia et al.*, 2011].

Notably, it was not only credit lines that stimulated the sugarcane expansion. Investment in transportation infrastructure created by the federal government played a fundamental role in the development of the sugarcane industry in the region. Roads are the main transportation mode in Goiás and Mato Grosso do Sul [*Rada*, 2013]. This mode is used to transport sugarcane to the mills and to deliver ethanol and sugar production to other states or ports for export. However, road transportation has problems related to the quality of the roads, cost of freight, and environmental impacts [*Leal Jr and D'Agosto*, 2011]. For these reasons, investments in improving the condition of existing roads and for the construction of new ones were priorities for federal investments [*Milanez et al.*, 2010a]. As a result of these actions, together with agricultural attributes and economic conditions of the region, the states of Goiás and Mato Grosso do Sul witnessed a strong increase in the number of mills and areas planted to sugarcane (Figure 2-2).

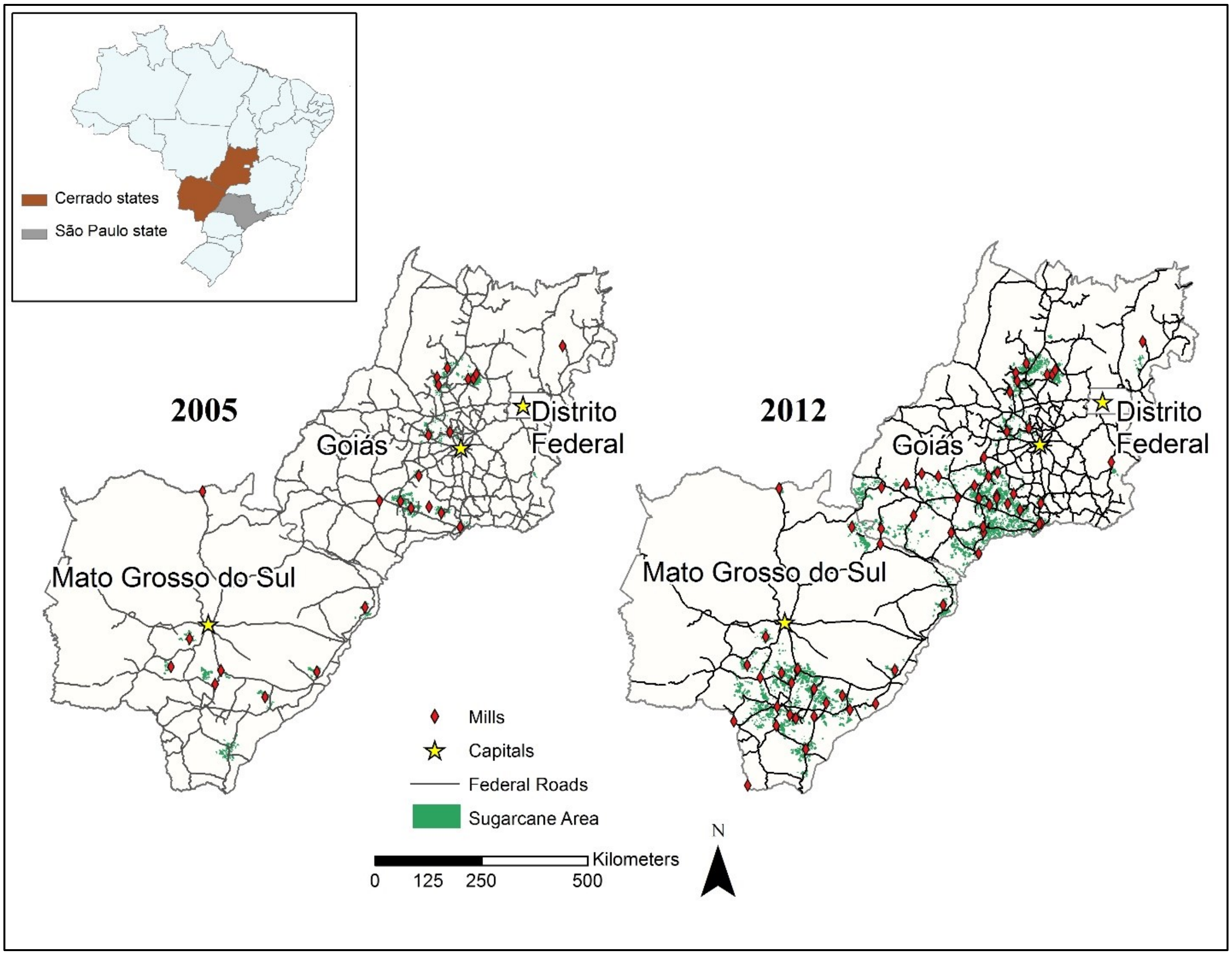

Figure 2-2 – Sugarcane expansion in the new frontier of Goiás and Mato Grosso do Sul

From 2005 to 2013, 40 new mills started operation in the region. These mills are located close to paved roads, reinforcing the importance of investments in transport infrastructure. For instance, in the state of Goiás, we see an expansion in the number of mills installed in the southern part of the state, a region that is closer to São Paulo State, the main domestic market for ethanol [*Milanez et al.*, 2010a; *Unica*, 2014a]. A similar spatial pattern can be seen in Mato Grosso do Sul, with a concentration of sugarcane mills in the southern portion of the state. This spatial distribution facilitates the logistics and transport of ethanol, as this region has better road infrastructure. In addition, the southern portion of Mato Grosso do Sul has railroads and a waterway connecting it with São Paulo State [*Leal Jr and D'Agosto*, 2011].

All the factors mentioned above transformed the states of Goiás and Mato Grosso do Sul into the second largest producing area of ethanol and sugar, after São Paulo. Given the increase in the number of mills in these states, the sugarcane area has significantly expanded since 2005, rising from 341,000 ha in 2005 to more than 1.2 million ha in 2012. In addition, the Cerrado states produced 6 billion liters of ethanol in 2012 and were responsible for 16% of the total sugarcane area in Brazil.

2.4 Discussion

The previous sections presented a historical overview of the sugarcane industry and its movement first from the northeast region to São Paulo and, later, the expansion to the new frontier in the states of Goiás and Mato Grosso do Sul. From the review, we can identify the drivers of expansion to the Cerrado states. These drivers reveal an intricate relation between the sugarcane private sector and the government. Even though the mills and agriculture land are privately owned and operated, the influence of government is very strong in the decision-making processes of these firms and farms [*Moraes and Zilberman*, 2014]. For instance, the Brazilian government initiated its intervention into the sector in the 1930s, with the blend mandate and the creation of the IAA. Later on, the Proalcool Program was implemented to further develop the sugarcane ethanol sector. The involvement and support of the Brazilian government was a decisive step to introduce ethanol into the Brazilian energy matrix.

However, governmental actions may either promote or discourage investments in specific regions [*North*, 1990]. It is possible to recognize this influence when examining the end of Proalcool Program, and the subsequent deregulation of the sugarcane and ethanol industry, which had a negative influence on the industry in the northeastern region but had positive influences in the state of São Paulo. Also, new environmental laws in São Paulo were an important factor that stimulated the industry to look for new areas to invest [*Shikida*, 2013]. Although the federal government was an important player, state government in Goiás and Mato Grosso do Sul also implemented fiscal incentives to attract the sugarcane industry to these states [*Silva and Miziara*, 2011; *Sauer and Pietrafesa*, 2012].

Remarkably, the private sector had significant influence in the decision-making process of expansion of the sugarcane and ethanol sectors to the Cerrado. In a process that follows the Thunian theory of location, the private sector considered agricultural conditions, land price, and access to market before making the decision to invest in the region [*Sauer and Pietrafesa*, 2012; *Silva and Peixinho*, 2012]. In these states, agricultural conditions were favorable for sugarcane, with flat land suitable for mechanization and adequate rain during the growing season. The soil could be enhanced to compensate for its lack of nutrients and acidity. Additionally, the land price was cheaper than in São Paulo. In 2005, the most expensive land in the Cerrado was dedicated to grain production, and it was estimated to be 46% of the value of the most expensive sugarcane land in São Paulo [*Agrianual*, 2007]. This difference in price stimulated the industry and the agricultural producers to move to the region in order to achieve higher economic returns from their land [*Silva and Miziara*, 2011; *Shikida*, 2013].

Nevertheless, access to markets has been a stumbling block to the Cerrado’s economy. Transportation cost is an important variable in the Thunian model, as it partially determines the profitability of agricultural production. Aware of such problem, the Brazilian government have built several roads since the 1970s when the Cerrado emerged as a potential strong agricultural producing region. More investments are being made to improve the transportation network in the region today [*Milanez et al.*, 2010a]. Besides new roads, railroads and waterway projects are being pursued. When concluded, these projects will offer different transportation options for the region, enabling a more cost-efficient logistical solution for mills and farmers to move their products [*Milanez et al.*, 2010a].

Logistics is not only related to road and railroad development. The private sector, together with the federal government, initiated the construction of an ethanol pipeline that will connect the southern portion of Goiás to São Paulo, the main domestic market for ethanol. The first phase, which connects two regions of São Paulo State, was finished in 2013; and the complete pipeline is expected to be ready by 2018 [*Roque*, 2014].

The interaction between these different factors has driven the Cerrado states to become the new frontier for sugarcane production. This evolution is even more remarkable in the hydrous ethanol market, where the Cerrado states already produce approximately 27% of Brazil's total hydrous ethanol production [*CONAB*, 2016]. São Paulo is currently the main producer of hydrous ethanol; however, Goiás and Mato Grosso do Sul are rapidly increasing their proportion. Forecasts for 2014 indicate that the production in the Cerrado states will match 72% of São Paulo's production. Nevertheless, when we analyze the sugar market, Goiás and Mato Grosso do Sul have not been able to increase their share as fast as they have in the ethanol market [*CONAB*, 2016].

The preponderance of ethanol over sugar production in the Cerrado states is an outcome of the business orientation of the mills. Supported by a positive federal government toward ethanol, the mills in the Cerrado were built to meet the increasing demand for hydrous ethanol in the mid-2000s [*Newberry*, 2014]. Because their production focus was on ethanol, 49% of the mills operating in the region are ethanol mills; whereas in São Paulo, 76% of the mills are flex mill, it can produce ethanol and sugar, and only 21% are ethanol mills. This difference in the industrial structure and business orientation could explain the different rate of expansion in sugar and ethanol within the region [*CONAB*, 2013].

The expansion of the sugarcane area needed to supply feedstock for ethanol production promoted a discussion of its impacts on the agricultural production structure of the region. By examining state-level data of the planted area, we see that sugarcane gained a share of the agricultural land in both Goiás and Mato Grosso do Sul [*Instituto Brasileiro de Geografia e Estatística*, 2014]. However, not only do corn and soybeans remain with the largest share of land, but these crops also expanded their areas in the period between 2005 and 2012. In 2012, Goiás used 974,000 ha more of cropland than in 2005, while Mato Grosso do Sul added 808,000 ha of cropland in the same period. The expansion of sugarcane accounted for more than 53% of the combined 1.7 million ha that the two states pushed into cropland [*Instituto Brasileiro de Geografia e Estatística*, 2014]. Notably, a recent study demonstrated that sugarcane's expansion in the south-central region of Brazil in the period between 2000 and 2009 occurred mainly on pastureland, which accounts for 69.7% of the expansion area while the transition from annual crops to sugarcane was only responsible for 25% of the expansion area [*Adami et al.*, 2012].

Pasture is a major land use in the Cerrado states. However, two important factors could be used to explain the expansion of sugarcane into Cerrado's pastureland. First, pastureland has suffered with poor management practices, resulting in degraded pasture and low profits. Degraded pasture was estimated to represent more than 50% of the total pasture area [*Bustamante et al.*, 2012]. Second, the livestock sector faced an outbreak of foot-and-mouth disease in 2005 that was initiated in Mato Grosso do Sul. This disease had economic consequences as it reduced the sector's international market share and the livestock price in Brazil, thus reducing pasture competitiveness among other land uses in the region. Consequently, pastureland has been displaced and reestablished in other regions inside the Cerrado or in the Amazon Biomes [*Walker et al.*, 2009; *Arima et al.*, 2011; *Walker*, 2011]. The displacement of agricultural land has raised concerns about the direct and indirect effects that land use and land cover change related to biofuel production could be causing in the Cerrado and in the Amazon [*Searchinger et al.*, 2008a; *Lapola et al.*, 2010b; *Arima et al.*, 2011; *Walter et al.*, 2011; *Adami et al.*, 2012; *Ferreira Filho and Horridge*, 2014]. Additionally, the expansion of sugarcane could be increasing the land competition between food and fuel production as the Cerrado is an important producer of grains and cattle [*Gauder et al.*, 2011; *Rada*, 2013].

Concerns about land cover change in the Cerrado pushed the Brazilian government to promote the implementation of the Sugarcane Agroecological Zoning in 2009 [*Manzatto et al.*, 2009]. The zoning was established to enhance the sustainability of sugarcane expansion. Among its guidelines, it ruled out any conversion of native vegetation and gave priority to areas that could be mechanized and rain-fed. It also encouraged the sugarcane's conversion of degraded pasture instead of cropland in order to reduce possible impacts of sugarcane production on food production. Goiás and Mato Grosso do Sul have the largest suitable areas for growth with more than 14 million ha, representing 41% of all suitable areas in Brazil as defined by the zoning [*Manzatto et al.*, 2009].

The interaction of good agricultural conditions, fiscal incentives, investment in transportation, and the advantage of holding the largest suitable area for sugarcane should have promoted a continuous expansion of the industry in these states. However, since 2010 the rate of expansion in the Cerrado states has begun to decline under a severe financial crisis that engulfed the Brazilian sugarcane sector [*Unica*, 2014c]. The origin of this crisis is rooted in the large investments made by the private sector since the mid-2000s, which were possible because of private bank credit. The amount of private investments is calculated at US$ 30 billion [*Unica*, 2014c]. This investment was initially supported by the federal government, which was interested in selling the image of Brazil as a green economy. However, with the international financial crisis in 2008, the sugarcane sector ran out of credit. Thus, the sector reduced investments in new projects and in the renovation of sugarcane fields and obtained sugarcane production from older and less-productive fields, resulting in more costly production [*Angelo*, 2012].

The increase in production costs of ethanol promoted the rise of the sugarcane ethanol price at the pump, consequently, less ethanol was consumed by the Brazilian population. The competition for the preference of consumers between ethanol and gasoline was altered by the Brazilian government's decision to intervene in the fuel market by keeping the gasoline price fixed. This policy was implemented as a mechanism to control inflation and to fight the impacts of the international financial crisis in the Brazilian economy. By keeping gasoline prices fixed, the government reduced the competitiveness of sugarcane ethanol against gasoline. Furthermore, in 2012 the government removed a tax from gasoline reducing the difference in taxation between the two fuels [*Angelo*, 2012]. The result was a sharp reduction of ethanol and a rise in gasoline consumption, with severe consequences for the industry.

The Brazilian Sugarcane Industry Association indicated that more than 60 mills went offline and more than 66 mills have been under judicial recovery in the last decade [*Unica*, 2014c]. The Cerrado states also suffered with this crisis. Only three mills have been installed in the region since 2012. For comparison, the average for the 2005–2012 period was five new mills each year. More than that, one mill that was built during the expansion has closed because of financial difficulties.

2.5 Conclusion

The present paper contributes to the literature by examining sugarcane expansion into the Cerrado through the historical evolution of its drivers and the interaction among them. We used political economy and the von Thünen location theory as a conceptual framework for our analysis. The expansion of the sugarcane sector toward the new frontier in Goiás and Mato Grosso do Sul can be attributed to different factors. First, the increase in demand for ethanol: in the mid-2000s, Brazil was excited about flex-fuel cars and its cheap and clean sugarcane ethanol promoting the growth of this industry. Second, the influence of political action: different levels of the government were sending positive stimuli to the private sector to invest. Third, consolidation of the sugarcane sector in the state of São Paulo: with a consequent increase in land competition and environmental problems, resulting in new environmental regulations and raising the cost of production in that state, motivating industry to search elsewhere. Fourth, agricultural conditions and land prices: the Cerrado states have suitable conditions for the production of sugarcane, and its producing areas can be easily mechanized; furthermore, the land prices in these states were more affordable than in São Paulo. Fifth, access to markets: the connection of the Cerrado with the main markets has been developed since the agricultural transformation of the region; also, new transportation projects are being developed to further enhance the transport of ethanol.

It is important to highlight that it was the complex relation among these factors that allowed Goiás and Mato Grosso do Sul to become the second main producer region of ethanol and sugar. With their ethanol-oriented sugarcane industry, these states have seized the opportunity to expand their industry to meet the increasing demand for ethanol. The sugarcane private sector was attracted to expand into the Cerrado states by its good agricultural conditions and by long-term, state-level fiscal incentive policies. This movement was possible as São Paulo State was confronted by the consolidation of its industry.

For the near future, these attributes apparently should continue to attract investments to these states. On the demand side, sugarcane ethanol is an important part of the energy matrix of Brazil and the flex-fuel fleet keeps increasing. On the supply side, state-level governments continue to stimulate the ethanol industry with fiscal incentives. In addition, Cerrado agricultural conditions continue to be a positive factor to the private sector. Land prices in the Cerrado states remain relatively low compared to São Paulo, and these states have the largest area suitable for sugarcane expansion. Moreover, the mills installed during this expansion have not reached their full capacities, indicating that more ethanol production could be achieved in the region given that more sugarcane was produced in these states.

Nevertheless, the sugarcane industry has been facing a crisis since 2009. The high debt level of the mills, three years with adverse weather, and governmental control over gasoline prices has collaborated to put the sector in crisis. This time of crisis reinforces the need for long-term policies, given that the interaction between the sugarcane sector and government is likely to continue into the future. The influence and changes in governmental position toward ethanol bring more uncertainty to the ethanol market that is already suffering from adverse weather and the financial health of the industry. For the Cerrado states, this crisis promotes the weakening of one of the expansion drivers—the demand. Thus, understanding the interaction among the sugarcane expansion drivers can help the development of policies to curb the effects of the crisis in the new sugarcane frontier.

In this context, future research should pay attention to the micro-level, that is, to farmers' decision-making process and their impacts on sugarcane expansion. We highlight the need to link the micro-level to the macro-level through land use impacts and the zoning policy that have been implemented in Brazil. Finally, a factor not well-developed in the literature is the discussion of regional development policies given the presence of the sugarcane sector in the Brazilian Cerrado.

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Chapter 3 - Identifying dynamics of land use responses to sugarcane ethanol expansion in the Brazilian Cerrado

3.1 Introduction

The increasing demand for biofuels has stimulated the expansion of bioenergy crop production worldwide adding new land uses to agricultural sectors [*Strassburg et al.*, 2014]. Land use competition has been intensified by the need to produce more food, fiber, and now fuel for a growing, and wealthier, global population. At the same time, agricultural production needs to incorporate practices that mitigate its impacts on the environment [*Rudel et al.*, 2009].

Two alternative land use responses (LUR) have been proposed as a way to address this challenge. On one hand, land users may engage in an intensification response. This response is based on the idea that biofuel crops can replace nonbiofuel crops on existing cropland concurrent with offsetting increases of nonbiofuel crop production on remaining cropland, thus sparing native vegetation from conversion and reducing impacts on the environment [*Stevenson et al.*, 2013; *Brown et al.*, 2014; *Cohn et al.*, 2014; *Strassburg et al.*, 2014]. On the other hand, land users may engage in an extensification response. This response consists of an increase in biofuel cropland at the expense of converting noncropland (i.e. pasture, forest, native grassland); thus, it spares the competition with food production but may prompt conversion of native vegetation [*Arvor et al.*, 2012; *Brown et al.*, 2014]. Each of these LUR reacts differently to proximate and underlying factors of land change, such as agricultural conditions (soil, slope, climate), agricultural trade, governance, and market prices, among others [*Walker et al.*, 2009; *Ceddia et al.*, 2014].

An important case for the discussion about LUR is how Brazilian farmers have responded to the increased demand for biofuel production in Brazil. The rise in demand for ethanol has stimulated the Brazilian ethanol industry to expand its production into areas of the Brazilian Cerrado (Figure 3-1) [*Shikida*, 2013; *Granco et al.*, 2015]. The region is a global biodiversity hotspot because of the rapid habit loss caused by the conversion of native vegetation is threatning the endemic species [*Myers et al.*, 2000; *Strassburg et al.*, 2017], and achieving the demand for food and fuel while reducing impact on the environment is a challenge in this biome. The Cerrado is already an important producer of grain and livestock [*Rada*, 2013] and is rapidly becoming a major source of land for sugarcane ethanol in Brazil, especially in the states of Goiás and Mato Grosso do Sul [*de Cerqueira Leite et al.*, 2009; *Shikida*, 2013]. The production of ethanol has increased by 400% in these states, with a more than 400% increase in production areas for the period of 2006-2013 [*Granco et al.*, 2015].

In addition, the discussion on biofuels' ability to reduce greenhouse gas (GHG) emission requires consideration of the land use response to biofuel expansion [*Searchinger et al.*, 2008b; *Lapola et al.*, 2010b, 2014]. Conversion of cropland to a biofuel crop (intensification response) results in a relatively small carbon deficit (or no carbon deficit), while conversion of native vegetation to a biofuel crop produces a carbon deficit large enough to potentially offset the GHG savings of biofuel usage [*Fargione et al.*, 2008; *Tilman et al.*, 2009]. This difference is very significant in Brazil where the conversion of native vegetation in the Amazon or the Cerrado can result in a carbon deficit [*Lapola et al.*, 2010b]. However, some studies have demonstrated that the extensification response such as the conversion of degraded pastureland can also have a small (or negative) carbon deficit by recovering the soil and improving the biomass carbon stocks [*Cohn et al.*, 2014; *Mann et al.*, 2014; *Graesser et al.*, 2015]. Previous works also suggest that sugarcane expansion over pastureland (extensification response) may not affect the production of beef cattle because the cattle ranching sector in Brazil can release land by increasing its cattle stockage by hectare [*Cohn et al.*, 2014; *Alkimim et al.*, 2015]. Gains in the cattle stocking rate from 1950 to 2006 have potentially spared 525 million ha from conversion to pasture in Brazil and with the adoption of new technologies and management practices more land can be dedicated for crop production [*Martha Jr et al.*, 2012; *Cohn et al.*, 2014; *Mann et al.*, 2014].

Moreover, prior research on land use response in Brazil has focused on agricultural yield-gains to avoid deforestation in the Amazon [*Arvor et al.*, 2012; *Gibbs et al.*, 2015] and scenarios of cattle stockage increases to release land to sugarcane production [*Goldemberg et al.*, 2014; *Strassburg et al.*, 2014; *Alkimim et al.*, 2015]. What is not understood yet is which factors influence farmers' land use decisions leading to land use intensification (conversion of cropland) or extensification (conversion of noncropland) responses. In this context, a need exists for accurate measurements of LUR and a deeper understanding of its dynamics in order to comprehend the impact of sugarcane ethanol expansion into the Cerrado, concerning not only GHG mitigation but also land use competition and conservation of native vegetation. Therefore, the assessment of LUR is extremely important for the biofuel industry, policy makers, and society. With this knowledge, policies aiming at developing agriculture to meet the demand for more food and fuel can be put in place, minimizing environmental impacts [*Dias et al.*, 2016].

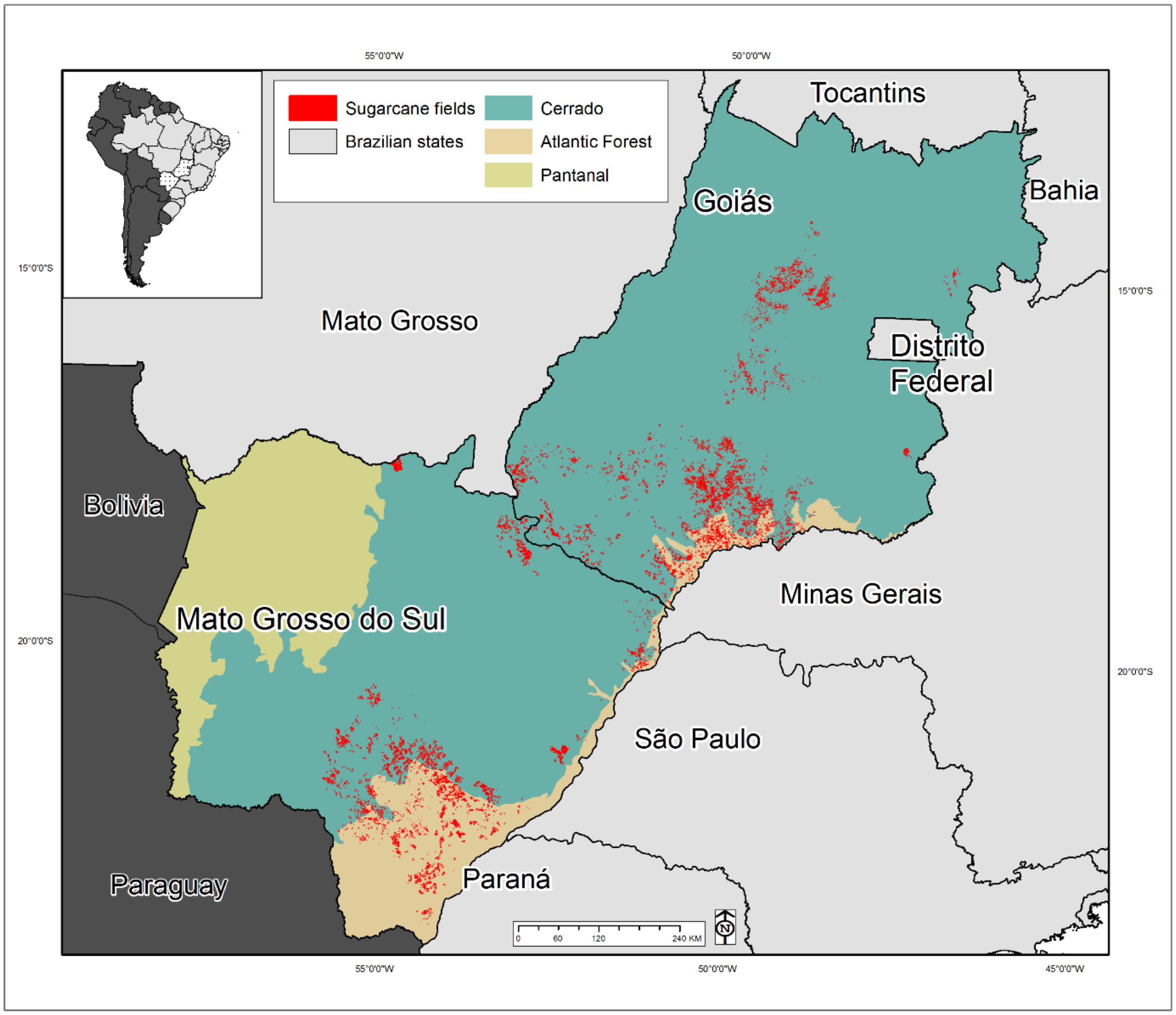

Figure 3-1 – Sugarcane fields in the states of Goiás and Mato Grosso do Sul.

The purpose of this chapter is to examine sugarcane expansion into the states of Goiás and Mato Grosso do Sul. More specifically, we seek to identify farmers' LUR regarding sugarcane production and to determine which factors promote each outcome. To achieve this goal, we analyzed the evolution of sugarcane-producing areas in the states of Goiás and Mato Grosso do Sul for the period of 2006-2013 through remotely sensed imagery. In doing this, we estimated a statistical model to understand the contribution of each factor toward each LUR. Our model imposes a simplification of the farmers' behavior by assuming that farmers are profit-maximizers and exhibit the same decision-process.

The chapter encompasses five sections beyond this introduction. The following section presents our conceptual framework of LUR to sugarcane expansion. The next section discusses the study area and land use data, followed by a presentation of the methods employed to identify the LUR and the statistical method used to determine the influence of each factor to LUR. With the methods and data explained, we present our results and the discussion that led us to our conclusions.

3.2 Conceptual framework

Given our interest in understanding the factors motivating farmers' LUR, we developed an economic model for sugarcane LUR. First, let us assume that farmers have already decided to grow sugarcane. Once this decision is made, farmers face a follow-up LUR decision regarding which land use they should replace with sugarcane. In the proposed economic model, farmers' LUR is assumed to be driven by a profit-maximization strategy, where farmers are considered as rational economic agents using the information available to achieve their goal of maximum profit. The term farmer(s) is used to refer to an economic agent engaged in agricultural and/or cattle ranching activity or is a landowner. Under these assumptions, Equation 3-1 represents the LUR decision for a two-land-use case.

Equation 3-1

$$E(\pi_{sc}) - E(\pi_i) > E(\pi_{sc}) - E(\pi_j)$$

$$E(\pi_j) > E(\pi_i)$$

where

$E(\pi_{sc})$ is the expected profit for sugarcane (*sc*) production;

$E(\pi_i)$ is the expected profit for land use *i*;

$E(\pi_j)$ is the expected profit for land use *j;*

Equation 3-2

$$\pi_k = R_k - C_k - S_k$$

where

π_k is the profit function considered on Equation 3-1, with k assuming the values of (*sc*, i, j);

R_k is the revenue from a specific land use;

C_k is the production cost of a specific land use;

S_k is the transportation cost for a specific land use;

Equations 3–1 and 3–2 demonstrate how this decision process can be related to profit. In this example, an area dedicated to *i* would be converted to sugarcane production because the expected profit from land use *j* was greater than the expected profit of *i,* assuming sugarcane's profit is the same in both regions. For instance, let us consider a farmer in Goiás that has areas dedicated to cropland and to pastureland. Once the farmer has decided to produce sugarcane, he needs to decide which area will be dedicated to sugarcane. Our model says that the land use that generates the least amount of profit will be the one converted to sugarcane. This framework can be expanded to an *n*-land-use case by considering *n* alternatives land use *j* on Equation 3-1.

3.2.1 Empirical framework

We cannot observe, however, the true LUR decision process. Rather, we just observe the realization of the process by identifying the LUR. Researchers can only observe which land use was converted to sugarcane and the characteristics of a given location. To address this observational limitation, we implement a latent discrete choice empirical framework. Let us define $LR*$ as a latent choice variable given by Equation 3-3:

Equation 3-3

$$\boldsymbol{LR}^{*} = \boldsymbol{\pi_j} - \boldsymbol{\pi_i} = \boldsymbol{\beta' x} + \boldsymbol{\varepsilon}$$

where the researcher can observe $\beta' x$, where *x* is a column vector of variables and β is a column vector of parameters, and the researcher cannot observe one component given by random ε. The farmer will engage in LUR when LR^{*} makes available a higher relative profit (Equation 3-4).

Equation 3-4

$$LR = \begin{cases} 1, & LR^{*} \geq 0 \\ 0, & LR^{*} < 0 \end{cases}$$

where *LR* represents the observed land use response decision by the farmer. When $LR^{*} \geq 0$, it means that the potential profit gains associated with other locations are higher than at location *i* and that the farmer will choose to convert field *i* to sugarcane. Analogously, when $LR^{*} < 0$ then the profit gain associated with other locations are less than at location *i*, thus the farmer will prefer not to convert *i* to sugarcane. In the case where location *i* is noncropland (cropland) and $LR^{*} \geq 0$, we identify LR^{*} as extensification (intensification). Therefore, the probability of LUR being driven by sugarcane is:

Equation 3-5

$$Pr[LR = 1] = \Pr[LR^{*} \geq 0] = Pr[\varepsilon > -\beta' x] = 1 - F(-\beta' x) = \frac{e^{\boldsymbol{\beta}' x}}{1 + e^{\boldsymbol{\beta}' x}}$$

where ε is the distributed logistic, and *F* is a cumulative probability distribution function. The probability can be defined as the closed-form expression of a binary logit model. The advantage of this approach is to incorporate a set of explanatory factors to indicate the odds of intensification or extensification taking place at a chosen location.

3.3 Methods

3.3.1 Study area

Goiás and Mato Grosso do Sul are neighboring states in west-central Brazil occupying a total area of 697,000 km^2, being 340,000 km^2 in Goiás and 357,000 km^2 in Mato Grosso do Sul. Goiás shares borders with the states of Tocantins to the north, Bahia to the northeast, Minas Gerais to the east, and Mato Grosso to the west. Mato Grosso do Sul also neighbors Mato Grosso and Minas Gerais; additionally, it neighbors São Paulo and Paraná (Figure 3-1). The study area encompasses 325 counties: 246 in the state of Goiás and 79 in the state of Mato Grosso do Sul.

Originally, the Cerrado covered 98% of Goiás and more than 60% of Mato Grosso do Sul. The Cerrado in these states exhibits a variety of vegetative covering, ranging from open grassland to closed woodland in a soil that is deep, well drained, and resistant to compaction (although it is acidic, with poor nutrient content and a high concentration of aluminum) [*Klink and Machado*, 2005; *Brannstrom et al.*, 2008]. The Cerrado native vegetation remains present in 137,500 km^2 in Goiás (46% of the original cover) and in 67,900 km^2 in Mato Grosso do Sul (31% of the original cover) [*Brasil*, 2015].

A major driver for land cover change in the Cerrado is the expansion of agricultural uses [*Klink and Machado 2005; Carvalho, De Marco Júnior and Ferreira 2009; Ferreira et al. 2012*]. The main agricultural products are cattle, soybeans, and corn. Pastureland is the main anthropogenic use covering 139,000 km^2 in Goiás and more than 121,000 km^2 in Mato Grosso do Sul [*Brasil*, 2015]. Annual row crop production is the land use on 34,900 and 13,300 km^2 respectively in Goiás and Mato Grosso do Sul. Perennial crop production, which includes sugarcane, is the land use on 9,400 and 4,700 km^2 respectively in Goiás and Mato Grosso do Sul [*Brasil*, 2015].

3.3.2 Detecting land use responses

To determine if sugarcane expansion has driven intensification or extensification responses, we require information on the land use converted to sugarcane. Consequently, the research team from the NSF-1227451 developed a thematic time series of maps for Goiás and Mato Grosso do Sul. This data set classifies land use/land cover (LULC) from 2005 to 2013 into six classes: 1 – annual single crop, 2 – annual double-crop, 3 – pasture/cerrado/forest, 4 – sugarcane, 5 – urban, and 6 – water. However, for the present study, only the first four classes were used.

During the summer of 2014, research team members conducted interviews with sugarcane farmers in both Goiás and Mato Grosso do Sul. Following the protocols described in Wardlow, Egbert, and Kastens (2007) and Brown et al. (2013), land cover histories from 137 sugarcane field sites (76 from Goiás, 61 from Mato Grosso do Sul) were acquired, many of which extended back to the 2005 crop year. From these data, 464 pre-sugarcane ground reference samples were obtained (2005 – 70, 2006 – 65, 2007 – 52, 2008 – 46, 2009 – 45, 2010 – 47, 2011 – 40, 2012 – 34, 2013 – 34, 2014 – 31). Sixty-eight of the samples represented annual single-crop, 191 represented annual double-crop, and 205 represented pasture/cerrado.

Original imagery—consisting of the 250-m, 16-day composite MOD13Q1 Normalized Difference Vegetation Index (NDVI) data from the Moderate Imaging Spectroradiometer (MODIS) covering the study area for crop years 2005-2014—was downloaded from the Land Processes Distributed Active Archive Center (LP DAAC; https://lpdaac.usgs.gov/data_access).

These data were reprojected to the WGS84 projection with a grid size of approximately 240 m. Applying the pure pixel approach utilized in Wardlow, Kastens, and Egbert (2006), Wardlow, Egbert, and Kastens (2007), Wardlow and Egbert (2008), and Brown et al. (2013), annual MODIS NDVI profiles were extracted in correspondence with the ground reference data. Using the 23-date MODIS profiles as independent variables and ground reference cover class as the dependent variable, a random forest (RF) classification model [*Breiman*, 2001; *Clark et al.*, 2010] was developed using the ‘treebagger’ function in MATLAB®. One thousand trees were included in the forest, with each developed using a 5-element random subset of the 23 candidate predictors (MODIS time periods).

To estimate the error of the full RF model, the out-of-bag (OOB) error estimate was used. OOB is an unbiased estimator and it is estimated internally with each run of the RF. Each tree is constructed using a different bootstrap sample from the original data. About one-third of the cases are left out of the bootstrap sample and not used in the construction of the 1000 trees. These remaining data points are referred to as OOB samples. To compute OOB error for the RF, each ground reference sample is processed (classified) using only the trees for which it is OOB (so ~1/3 of the trees), which ensures that all predictions will be out-of-sample. From the OOB estimates (Table 3-1), it shows a good separation between the three classes, and the overall classification accuracy for the 3-class model outputs ranged is 82%, considered a satisfactory result. The Kappa value used to measure if the classification rule is more efficient than a random classification rule returned a value of 0.7 indicating that the classification rule is statistically different from a random classification.

Table 3-1 – Random forest model out-of-bag confusion matrix (3 classes)

		Actual		
	Classes	Pasture/Cerrado	Annual Single Crop	Annual Double Crop
Predicted	Pasture/Cerrado	186	21	3
	Annual Single Crop	18	160	30
	Annual Double Crop	1	10	35
	Producer's Accuracy	91%	84%	51%
	User's Accuracy	89%	77%	76%
	Overall Accuracy	81.9%		
	Kappa	0.70		

The LULC is complemented by the forest and the sugarcane land use classes. Annual forest cover layers were developed using Global Forest Change data (2000-2014), which is in 30-m raster format available from http://earthenginepartners.appspot.com/science-2013-global-forest [*Hansen et al.*, 2013]. This data set contains tree canopy cover for the year 2000 and year-specific forest cover gain and loss data for the years 2000-2014. The Global Forest Watch interactive map (www.globalforestwatch.org), the collaborative map for this data set, identifies forest/deforestation as >30% canopy cover. This threshold was used to identify forest pixels at the resolution of the MODIS-based LULC grid. These data were burned into the LULC maps obtained from the RF model. Forest pixels, which comprised a marginal fraction of the pre-sugarcane area, were grouped with the pasture/cerrado class to obtain the pasture/cerrado/forest class. Information on the location of sugarcane fields was developed by the Canasat Program of the Brazilian National Institute for Space Research (INPE) [*Rudorff et al.*, 2010], and these data were provided by the stewards of that data set. Static urban and water layers were obtained from the Brazilian Institute of Geography and Statistics (IBGE) and burned into the maps.

From this data set, each cell can be represented as $c_{l,t}$, where *l* is the cell location, *t* is year (2005-2013), and its value corresponds to one of the land use classes defined above. The annual sugarcane expansion ($e_{l,t}$) is defined by the following raster calculation (Equation 3-6):

Equation 3-6

$$e_{l,t} = \begin{cases} 1 & if\ c_{l,t} = 4\ and\ c_{l,t-1} \neq 4\ (sugarcane\ expansion) \\ 0 & otherwise\ (no\ sugarcane\ expansion) \end{cases}$$

This procedure created annual sugarcane expansion masks for 2006 to 2013. We identified the land use response of each field converted to sugarcane by overlaying the mask on the land use map for the previous year. Equation 3-7 gives the classification rule used to define the LUR of each new sugarcane area into the intensification or extensification response for each year.

Equation 3-7

$$LR_{l,t} = \begin{cases} 0 & if\ c_{l,t-1} = 1\ or\ 2\ (intensification\ response) \\ 1 & if\ c_{l,t-1} = 3\ (extensification\ response) \end{cases}$$

Once we detect and identify LUR to sugarcane expansion, we focus our attention on modeling this process.

3.3.3 Statistical model of land use responses

To examine the intensification or extensification response to sugarcane expansion given the new ethanol mills located in the states of Goiás and Mato Grosso do Sul, we developed a statistical analysis of the relationship between observed land use responses and farmers' profit maximization behavior. Given that we cannot observe the true decision process described in the conceptual framework, the method used in this paper is a logit regression with dependent variables given by extensification (y = 1) or intensification ($y = 0$)

(see Equation 3-7) and a set of independent variables representing economic, physical, and locational factors that are hypothesized to influence land use response. Because our focus is the LUR prompted by the expansion of sugarcane, each observation is unique for each year, resulting in a cross-sectional model with 267,794 observations (y = 1 for 181,063 observations).

Our data set is formed by land use maps with a cell size of about 240 m, corresponding to an area of 5.8 ha/pixel. Even though our unit of analysis is a sugarcane field, the unit of decision is the county because we do not have access to data representing all the farms located in the study area. The county level is an effective scale for the problem at hand because it accentuates the comparison between cropland and noncropland inside the same county [*Brown et al.*, 2014]. Although this limitation is important, our results still hold as other studies facing the same data constraints demonstrate that the county can serve as a surrogate for farmers' decisions [*Wu and Brorsen*, 1995]. This limitation implies estimating a logit regression with clustered standard errors at the county level (Equation 3-8). Explanatory variables selected for this model are presented in Table 3-2.

Equation 3-8

$$y = \beta_0 + \beta_1 Distance\ to\ Mill + \beta_2 Distance\ to\ paved\ road + \beta_3 Slope$$
$$+ \beta_4 Soybean\ yield + \beta_5 Soybean\ area + \beta_6 Herd + \beta_7 Year + \beta_8 State + \varepsilon$$

Table 3-2 – Statistics summary of explanatory variables

Variables	Mean	Std.Dev.	Minimum	Maximum	Obs.
LUR	0.68	0.468	0	1	267794
Dist_Mill (km)	27.31	19.268	0	222.935	267794
Dist_Roads (km)	8.55	6.923	0	42.0665	267794
Slope (degree)	1.56	0.945	0	20.4306	267794
Soybeans Yield (ton/ha)	2.64	0.749	0	4.5	267793
Soybeans Area (1000 ha)	51.07	61.877	0	290	267793
Herd (1000 heads)	173.51	113.898	12	657.781	267793
Year	2009.98	2.140	2006	2013	267794
State	0.571	0.494	0	1	267793

An important element in our conceptual model is farmers' ability to differentiate between profits generated by cropland or by pastureland. To implement this treatment, we have included the variables *Soybean Yields* and *Herd*. *Soybean Yields* is a proxy for the revenue that could be achieved with a soybean field. Its value is equal to the total soybean production in a county divided by the area under land use classes Annual Single Crop and Annual Double Crop. County-level soybean production data are from Pesquisa Agrícola Municipal [*Instituto Brasileiro de Geografia e Estatística*, 2016b]. *Herd* is a proxy for revenue from pastureland and is the total cattle herd in a county. Data on cattle herd are from Pesquisa da Pecuária Municipal [*Instituto Brasileiro de Geografia e Estatística*, 2016a].

Each sugarcane area was also characterized by its slope. Steeper areas (>12°) are not suitable for the mechanized production of sugarcane. The slope was calculated from 30-m Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) data. We further aggregated this layer to match the spatial resolution of our land use maps (cell size 240 m).

Sugarcane fields need to be located close to mills, given the crop's loss of sugar content once harvested. Therefore, we included a variable describing the distance of each sugarcane area to the nearest mill (Figure 3-2), which is defined as the Euclidean distance from the nearest mill to the centroid of each sugarcane field for each year. Maps similar to Figure 3-2 were produced for each year from 2006 to 2013. The mill location data was collected from CONAB (2013) and updated following the report from the Brazilian Petroleum Agency [*ANP*, 2016].

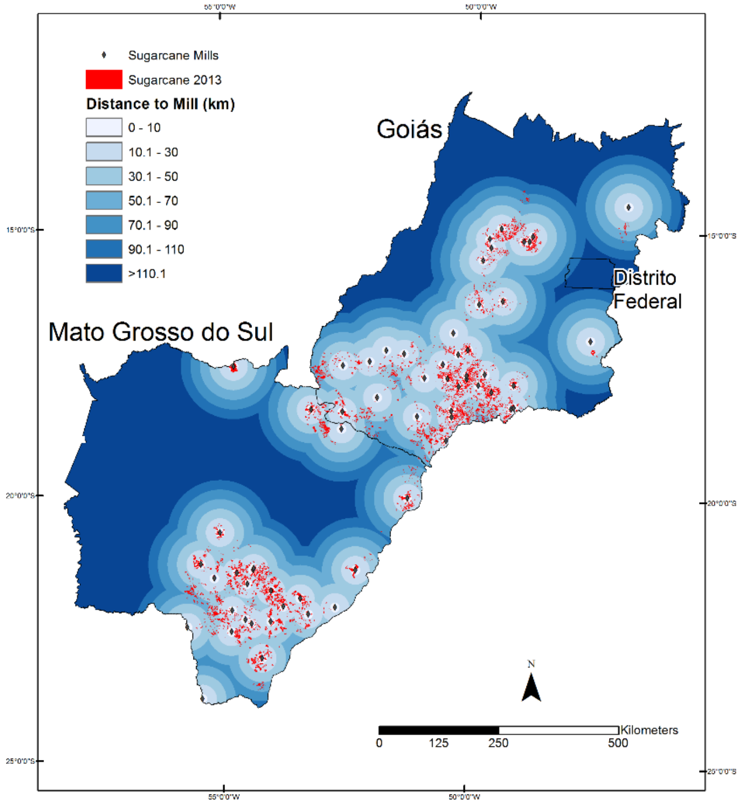

Figure 3-2 – Sugarcane fields distance to the nearest mill in 2013.

The infrastructure in the producing area is represented by the distance between each sugarcane area and the nearest paved road (Figure 3-3). The calculation of this variable included the minimum Euclidean distance from the roads to the centroid of each sugarcane field. The original roads data is from the Banco de Informações e Mapas de Transportes - BIT [*MT. Ministério dos Transportes*, 2010].

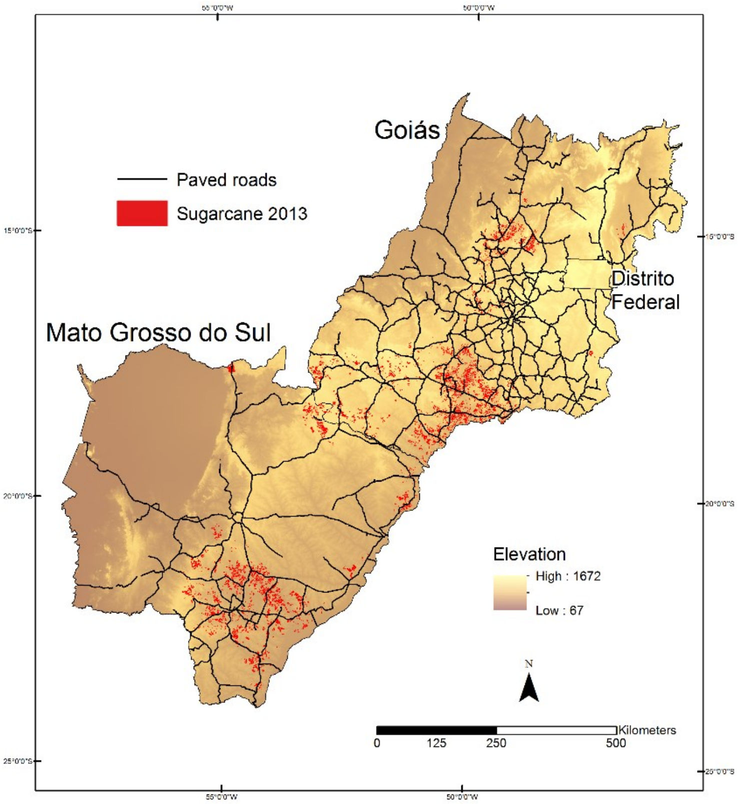

Figure 3-3 – Distribution of sugarcane fields and paved roads.

Two control variables are added to the empirical model. First, the variable *Year* to capture the annual trend of LUR. Second, a dummy variable (*State*) to separate the two states with areas in Goiás = 1 and areas in Mato Grosso do Sul = 0. Even though these states are part of the same expansion process of the ethanol industry [*Shikida*, 2013; *Granco et al.*, 2015], the states have a diverse agricultural development history that can lead to differences in LUR [*Castro et al.*, 2010; *Abdala and Ribeiro*, 2011; *Domingues and Júnior*, 2012; *Sant'Anna et al.*, 2016]. The *States* variable is testing for these differences.

3.4 Results

3.4.1 Measuring the land use responses

The importance of sugarcane is assessed by comparing the evolution of production areas from 2006 to 2013 (Figure 3-4). The year 2009 presented the biggest expansion with 264,000 ha of new sugarcane fields. The next two years had smaller area expansion, followed by strong growth in 2012 and 2013. This variation can indicate the installation phases of the new mills: where the first year's focus is on the development of a core of suppliers that later expand the suppliers' number in order to reach the full crushing capacity of the mill. Throughout this process, sugarcane expanded over more than 1.5 million ha, and it has converted cropland and noncropland for every year examined. The measurement of LUR indicates that extensification was the dominant response, representing more than 68% of all the LUR.

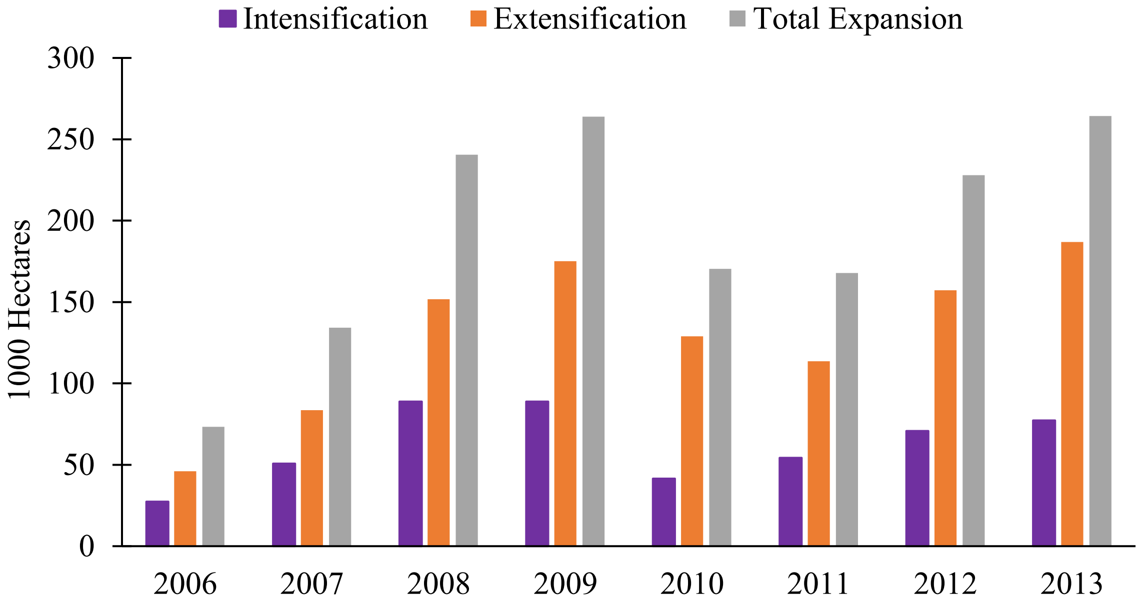

Figure 3-4 – Annual total expansion of sugarcane area and the classification into intensification and extensification responses, in Goiás and Mato Grosso do Sul.

The results show that in 2006 and 2007, extensification had a small advantage in relation to intensification. However, since 2008 there is a strong trend of more extensification. Figure 3-4 shows that 2010 was the year with the largest difference in LUR, though this year is not the one with the largest expansion. In addition, the results indicate that 2010 was a turning point with extensification being more than twice the size of intensification, a pattern that persisted for the last three years of the study. Furthermore, intensification is losing importance throughout the period of analysis. This result offers support to the claim that sugarcane has expanded over pastureland, thus avoiding competition with crop production [*Leal et al.*, 2013; *Goldemberg et al.*, 2014]. Nevertheless, intensification was the response in approximately one-third of the new producing areas across the entire study period for a total area of 499,500 ha.

The spatial distribution of the LUR also contributes to the understanding of the expansion process. Notably, there is a difference in LUR between Goiás and Mato Grosso do Sul with a larger presence of intensification response in Goiás, while extensification has been the predominant LUR in Mato Grosso do Sul (Figure 3-5).

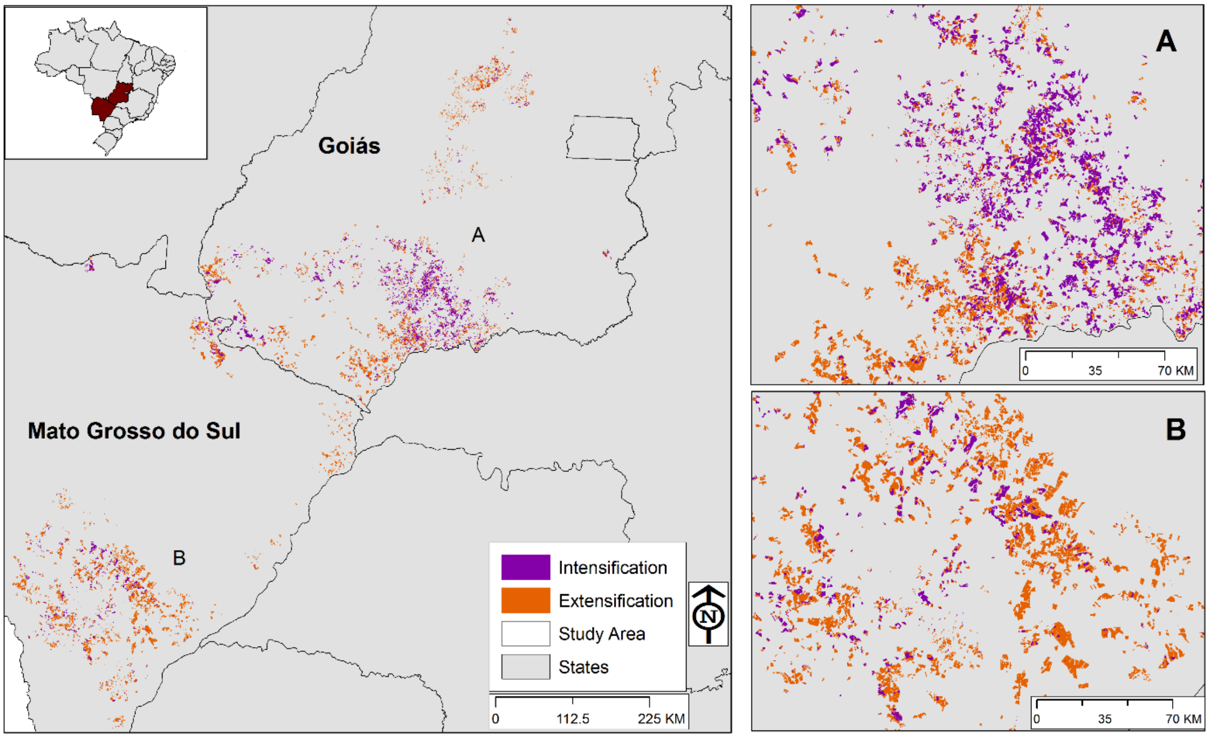

Figure 3-5 – Intensification and extensification promoted by sugarcane expansion in the states of Goiás and Mato Grosso do Sul, 2006-2013. (A) Calls attention to the southeast of Goiás, a region with a large presence of intensification. (B) Calls attention to the southeast of Mato Grosso do Sul, a region with a large presence of extensification.

To explain these responses and to further explore the patterns of sugarcane's LUR, we implemented a statistical analysis of binary choice. With this model, we discuss the impact of different factors on the LUR decision process.

3.4.2 Sugarcane's land use responses model

The previous section identified and quantified the intensification and extensification responses that incorporated sugarcane into the agricultural production landscape of the Cerrado. The importance of this measure goes beyond a simple identification exercise. By estimating a statistical model of LUR, we investigated some of the factors affecting the new sugarcane frontier of Goiás and Mato Grosso do Sul.

Table 3-3 presents the results for the estimation of Equation 3-8. The model correctly estimates the response in ~73% of the sample, indicating that the model is a good representation of the original processes. The interpretation of the coefficients is not straightforward, given that the model was estimated using the logit link function. Distance to mill (*Dist Mill*) and *Slope* show a positive correlation with extensification. Considering the previous land uses, only the area dedicated to soybeans (*Soybeans Area*) has a negative correlation with extensification. For the control variables, *Year* is correlated with extensification, while the dummy variable *State* indicates a negative relationship between areas in Goiás and extensification. Distance to roads (*Dist Roads*) is the only variable not statistically significant.

Table 3-3 – Results for the statistical logit model of land use responses

Variables	Coefficient		Standard Error	95% Confidence Interval	
Constant	-99.926	***	18.576	-136.336	-65.517
Dist Mill (km)	0.0079	***	0.001	0.005	0.009
Dist Roads (km)	-0.0032		0.003	-0.009	0.003
Slope (degree)	0.3561	***	0.013	0.330	0.381
Soybeans Yield (ton/ha)	0.3495	***	0.048	0.254	0.444
Soybeans Area (1000 ha)	-0.0045	***	0.000	-0.005	-0.004
Herd (1000 head)	0.00315	***	0.000	0.002	0.003
Year	0.0495	***	0.009	0.031	0.067
State	-1.4973	***	0.048	-1.591	-1.402

Note: *significant at 0.1, **significant at 0.05, ***significant at 0.01.

The analysis of the marginal effects (Table 3-4) provides for more direct interpretation on the effects of each independent variable on the LUR. The computation of marginal effects advances our understanding of the LUR processes by estimating the impact of a marginal change in an independent variable in the occurrence of extensification. We are reporting the marginal effects at the mean of the observation sample. The variables keep the same sign, and as before, *Dist Roads* is not significant.

Table 3-4 – Estimation results for the marginal effects, at means

Variables	Marginal Effects		Standard Error	95% Confidence Interval	
Dist Mill (km)	0.00147	***	0.00019	0.0010	0.0018
Dist Roads (km)	-0.0006		0.00062	-0.0018	0.0006
Slope (degree)	0.06577	***	0.00243	0.061	0.0705
Soybeans Yield (ton/ha)	0.06456	***	0.00891	0.0471	0.0820
Soybeans Area (1000 ha)	-0.00084	***	0.00053	-0.0009	-0.0007
Herd (1000 head)	0.00058	***	0.00033	0.0005	0.0006
Year	0.00915	***	0.00171	0.0057	0.0125
State	-0.27895	***	0.00718	-0.2930	-0.2648

Note: *significant at 0.1, **significant at 0.05, ***significant at 0.01.

The interpretation of the effects in Table 3-4 indicates that an increase of 1 km in the distance to nearest mill (*Dist Mill*) raises the probability of extensification response by 0.147%. *Slope* is also positively correlated to extensification with an increase of 1° increasing the probability of extensification by 6.5%. An increase of 1000 head to a county's herd positively impacts extensification probability by 0.05%, while an increase in the soybean yield increases the same probability by 6.4%. *Soybeans Area* is negatively correlated, thus indicating a reduction in the probability of extensification response by 0.08%, or alternatively, it indicates an increase in the probability of intensification response. The trend (*Year*) is positively correlated to extensification, increasing the probability by 0.9%. The *State* variable indicates a reduction in the extensification probability for areas in Goiás (*State* = 1) of 27.8%. This result reinforces the analysis of the spatial distribution of LUR (Figure 3-5) that Goiás' LUR is different from Mato Grosso do Sul's LUR.

3.5 Discussion

These results show that during the 2006-2013 period, farmers planted more sugarcane on noncropland (extensification) than on cropland (intensification) and that both LUR are influenced by the presence of mills. Arguably, intensification and extensification responses to sugarcane expansion are co-occurring responses. Sugarcane mills seek installation locations that offer access to large areas to develop their fields. From the LUR map (Figure 3-5), the prevalence of noncropland land uses leading to extensification is noticeable. On the other hand, mills also want to reduce transportation costs, thus locating closer to roads and better transportation infrastructure [*Granco et al.*, 2015]. These are the same factors that attract grain producers and industrial facilities to the region [*Silva and Miziara*, 2011].

The statistical model confirms the influence of mill proximity on the LUR, with fields farther away from the mill supporting extensification. This process can be explained as a cost minimization strategy by the mill. By going farther away to secure sugarcane, mills would give preference to larger farms in order to gain scale and reduce harvest costs—and such areas are more commonly used as pastureland.

The presence of paved roads is vital for the sugarcane mill's workflow because harvested sugarcane is transported to the mill by large trucks (Figure 3-2). Even though unpaved roads can be used, paved roads are preferred given the speed and lower cost of maintenance on trucks [*Milanez et al.*, 2010b; *Leal Jr. and D'Agosto*, 2011]. These same advantages also attract crop farmers to locate close to paved roads. Even though *Dist Roads* was not statistically significant in the statistical model, intensification is expected to be higher closer to roads because cropland density typically is higher in these areas as well, while extensification frequency increases with distance to roads.

Farmers that adopted sugarcane in the Cerrado were already aware of the requirements for the mechanized harvest of sugarcane, mainly the restriction on slope being <12° [*Aguiar et al.*, 2011]. The implementation of mechanized harvest has two goals: (i) reducing carbon emission from the preharvest burning, thus improving sugarcane's ethanol carbon life-cycle, and (ii) reducing the labor cost and litigation from hiring a large contingent of workers during harvest season [*Capaz et al.*, 2013]. Most ethanol companies that own mills in Goiás and Mato Grosso do Sul have already operated in the state of São Paulo, where mechanized harvest legislation is enforced; thus they carry this knowledge to their new facilities [*Goldemberg*, 2008; *Horta Nogueira et al.*, 2013]. Also, the international market for sugar and ethanol demands certification to select products that use unburned sugarcane [*Bailis and Baka*, 2011; *Goldemberg et al.*, 2014].

The slope requirement indicates another point of competition with oilseed and grain production because the slope is also an important factor for those land uses. The statistical model shows that steeper slope is correlated with an increase in the probability of extensification. This positive correlation may come from the fact that most croplands (as most sugarcane fields) are located in low slope areas, while pastureland can be found in a larger gradient.

The variables related to previous land use (*Soybean Yield*, *Soybean Area*, and *Herd)* are important not only to indicate if one use is important in that county but also to give the trajectory of the previous land use at the county level. The positive relation of *Soybean Yield* and extensification indicates that sugarcane production is attracted to counties with higher soybean yields, which can reflect that croplands are located in better soils and probably have better management of soil fertility. However, because it is leading to extensification, we can infer that soybeans with high yields are competitive with sugarcane, thus promoting the conversion of noncropland to sugarcane. The negative correlation between *Soybean Area* with respect to extensification is expected because counties with large areas dedicated to soybean production can indicate that soy producers have already converted the best agricultural lands from pastureland to cropland. Hence, when sugarcane expands into such counties, it will take area off soybeans. The fact that the *Herd* variable is positively correlated to extensification indicates that sugarcane may be related to gain of cattle stockage because more pastureland has been converted from counties with large herds [*Cohn et al.*, 2014; *Alkimim et al.*, 2015].

As our analysis of the LUR showed, extensification has become more dominant throughout the period, a result that is confirmed by the statistical analysis of the trend variable (*Year*). This dominance reflects two conditions: (i) the prevalence of pastureland as the main land use in the study area, and (ii) oilseed and grain production—especially double-crop rotation of soybeans and corn—can generate more profit for farmers than pastureland.

The difference in the LUR from Goiás and Mato Grosso do Sul calls attention to the fact that the same driver, sugarcane ethanol expansion, can support diverse responses at state-level. For the present study, areas in Goiás are less probable of presenting extensification than areas in Mato Grosso do Sul. Previous studies looking at sugarcane expansion in Goiás had found that sugarcane was expanding to the same regions that soybeans have expanded in the past [*Abdala and Ribeiro*, 2011; *Silva and Miziara*, 2011].

Notably, sugarcane expansion has promoted both intensification and extensification; however, the statistical model indicates that extensification is more likely to continue in the future. This is in agreement with the Brazilian government's desire to stimulate sugarcane expansion on degraded pastureland, thus avoiding land use competition with cropland and reducing GHG emission from degraded pastureland [*Manzatto et al.*, 2009]. Nevertheless, these benefits will only occur assuming that cattle ranching is actually intensifying its production. A displacement of cattle production to new areas inside the Cerrado, or even to the Amazon biome, could result in more GHG emission from deforestation [*Lapola et al.*, 2010b].

One observation that needs to be made is the definition of LUR regarding only the fields that are converted to sugarcane. One can argue that our definition of intensification does not consider if more land is converted elsewhere to cropland and that extensification over pastureland can be a result of a gain in cattle stocking rate, thus releasing land to sugarcane without adding land to pastureland. Although we are aware of the limitations of the definitions used, we maintain the validity of our study despite the lack of data on cattle stocking and the technical difficulties in identifying indirect land use change. The inclusion of more explanatory variables, such as cattle stocking and commodity prices, can contribute to improving the statistical model in future research.

3.6 Conclusion

This study examines the land use responses promoted by the expansion of the sugarcane ethanol industry into the states of Goiás and Mato Grosso do Sul. The period of 2006-2013 covers the booming period of the industry, a useful moment to understand the introduction of a new agricultural land use to the Cerrado biome. To accomplish our goals, we developed a procedure to identify intensification and extensification responses at the field level. We then used this new information in a statistical model to explore how different factors affect each LUR.

For the period analyzed, our results indicate that sugarcane promoted both intensification and extensification responses, but extensification accounted for more than 68% of all LUR. These findings corroborate previous research results pointing to extensification of sugarcane over pastureland in other regions of Brazil [*Adami et al.*, 2012]. In addition, we identified a trend toward extensification, which was further validated by the statistical model. This tendency is consistent with the general notion that pastureland is less profitable than cropland, thus being selected more frequently to be replaced by sugarcane.

Furthermore, our model examined factors impacting LUR focusing on extensification. The highlight is the influence of sugarcane mill location and existing infrastructure on the LUR decision process, where increasing distance to the mill and to roads supports an extensification response. This dynamic can be an object of policies aiming to avoid land use competition between sugarcane and soybeans or to stimulate the development of sugarcane areas in counties with degraded pastureland.

The extensification response may actually be capturing a gain in the cattle stocking rate. In this case, farmers would improve their cattle herd stockage and release a portion of pastureland to sugarcane production. This would allow farmers to maintain their culture and status as cattle owners while being able to capture new income from sugarcane production. In fact, the Brazilian government is most interested in supporting this land use response to sugarcane expansion because it has the potential to reduce GHG from degraded pastureland and increase the productivity of the cattle ranching sector without interfering with food production. However, more research is needed on this topic to test if sugarcane extensification is actually leading to increase of cattle stocking rates and to verify if land use change spillover is not moving cattle production to other regions.

3.7 Acknowledgments

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Chapter 4 - Ethanol and farmer's land use decision-making in the Brazilian Cerrado

4.1 Introduction

Brazil is the focus of worldwide attention because of its growing agricultural production and large reserves of native vegetation and diverse biomes. The biggest concern is the conversion of native vegetation to agricultural land. Since the year 2000, agricultural land in Brazil increased by 21 million ha (FAOSTAT) (Food and Agricultural Organization (FAO), FAOSTAT: Land use, FAO Statistics Division, available at http://faostat.fao.org). Currently, most of the attention is focused on the Amazon biome, home to the Amazon rainforest—the largest continuous forest in the globe. However, another biome in Brazil has endured more conversion of its natural cover than the Amazon without receiving as much attention [*Strassburg et al.*, 2017].

This is the case of the Cerrado (Brazilian Savanna) biome, the second largest biome in Brazil after the Amazon. Originally, the Cerrado extended over more than 203 million ha; however, by 2013, only 54% remained under its natural cover [*Brasil*, 2015]. The main anthropogenic modification to this biome is the conversion of native vegetation to cropland and pastureland, which is threatening its biodiversity and ecosystem services [*Myers et al.*, 2000; *Carvalho et al.*, 2009]. The accelerated loss of habit due to anthropogenic modification put the Cerrado as a biodiversity conservation hotspot [*Myers et al.*, 2000] requiring special attention to protect its biodiversity and continue its role as Brazilian breadbasket [*Strassburg et al.*, 2017].

Agricultural use of the Cerrado gained traction in the 1970s with the adaptation of soybeans to the Cerrado environment creating a new agricultural frontier. Later, this region became the breadbasket for Brazil [*Klink and Machado*, 2005; *Diniz-Filho et al.*, 2008; *Rada*, 2013]. This transformation is based on a capital-intensive approach to agricultural production [*Jepson*, 2006; *Brannstrom and Filippi*, 2008; *Jepson et al.*, 2010; *Silva and Miziara*, 2011; *Ferreira et al.*, 2016]. The traditional commercial agricultural land uses in the Cerrado are pasture to sustain cattle ranching and grain production, including soybeans and corn [*Rodrigues and Miziara*, 2008; *Sano et al.*, 2010; *Ferreira et al.*, 2013, 2016]. The Cerrado continues to be the agricultural production frontier in Brazil.

Since the 2000s, the Cerrado has seen the sugarcane ethanol frontier [*Silva and Miziara*, 2011; *Shikida*, 2013; *Granco et al.*, 2015]. The recent rise in demand for sugar and ethanol has stimulated the expansion of the sugarcane industry in Brazil, especially with the installation of new mills in the Cerrado. The construction of new mills in Goiás and Mato Grosso do Sul is a combination of several factors. First, the mills demand large and flat expanses of land, which was available at low cost in these states [*Granco et al.*, 2015]. Second, environmental legislation is better enforced in the state of São Paulo [*Aguiar et al.*, 2011; *IEA- Instituto de Economia Agrícola*, 2014]. Third, the governments in Goiás and Mato Grosso do Sul provide political and fiscal support for expansion [*Picanço Filho and Marin*, 2012; *Granco et al.*, 2015; *Sant'Anna et al.*, 2016].

During the period between 2005 and 2013 (Figure 4-1), the area planted to sugarcane increased by 430% [*CONAB*, 2016], reaching 1.5 million ha, while the number of mills reached 60 [*ANP*, 2016]. Because of this expansion, these states represent 25% of the production of sugarcane ethanol in Brazil in 2016 [*CONAB*, 2016].

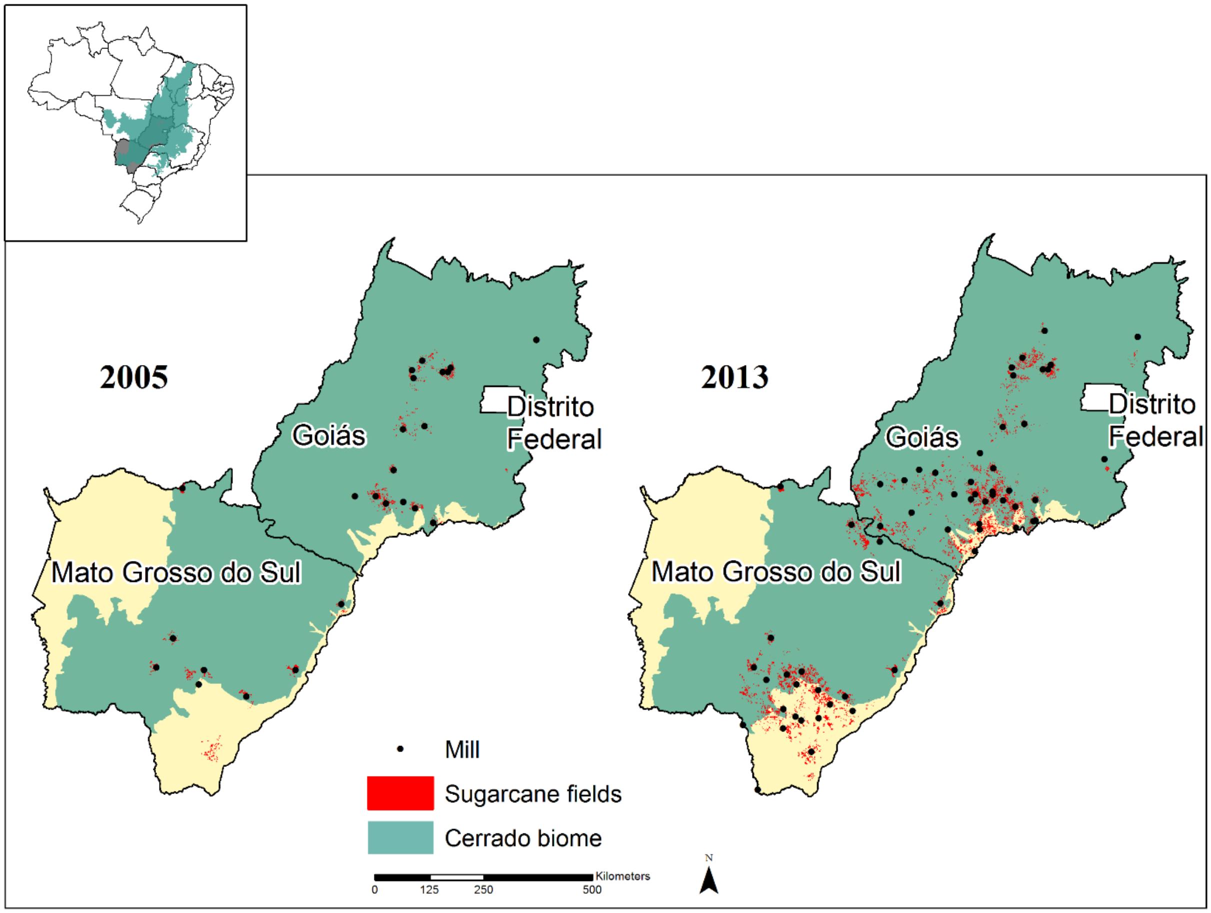

Figure 4-1 – Expansion of the sugarcane industry in the Cerrado areas of Goiás and Mato Grosso do Sul. Mill symbol is large to illustrate the spatial distribution.

This rapid expansion of sugarcane production in Brazil has the potential to reshape the agricultural production landscape [*Goldemberg et al.*, 2014; *Strassburg et al.*, 2014]. The addition of a new cash-crop to this biome has raised concerns over the sustainability of sugarcane and ethanol production [*Herreras Martínez et al.*, 2013; *Walter et al.*, 2013]. As a response to these concerns, the Brazilian government developed a land use policy to coordinate sugarcane expansion: the Sugarcane Agroecological Zoning (SAZ). The SAZ defines areas that are suitable or nonsuitable for sugarcane expansion considering natural conditions, mechanization, and previous land cover [*Manzatto et al.*, 2009]. The SAZ rules out any conversion of native vegetation to create sugarcane fields. Moreover, the SAZ aims to reduce the impact of sugarcane expansion on food production by indicating a preference toward sugarcane in replacing degraded pastureland instead of cropland [*Manzatto et al.*, 2009]. At least half of all pastureland in the Cerrado is under a degradation process due to poor management practices [*Bustamante et al.*, 2012]. This policy backing sugarcane substitution of degraded pastureland is supported by research results demonstrating that this land transition emits a small amount of greenhouses gasses (GHG) and has a minor impact on food production [*Leal et al.*, 2013; *Goldemberg et al.*, 2014; *Strassburg et al.*, 2014; *Alkimim et al.*, 2015]. According to the SAZ classification, Goiás and Mato Grosso do Sul have most of the areas suitable for sugarcane production [*Manzatto et al.*, 2009].

Sugarcane demand for land have been investigated by several studies such as Leal et al. (2013), Goldemberg et al. (2014), Strassburg et al. (2014), and Alkimim et al. (2015) do not analyze the farmers' land use decision-making process behind sugarcane expansion—more specifically, the factors affecting farmers' decisions to substitute pasture for sugarcane. To address this gap, we will investigate the expansion of sugarcane to Goiás and Mato Grosso do Sul effects by developing a farmer' land use decision-making model. The model assumes that farmers are profit-maximizers. This assumption reduces a large and complex land use decision process to a more tractable optimization problem where farmers allocate land to the use that results in the highest economic return [*Hennessy*, 2006]. To maximize profits, farmers decide the agricultural production to pursue given the technology available. Notably, farmers do not control all the factors in their decision-making process because those decisions are also conditioned by external factors such as government policies and laws, demand for agricultural products, and climate [*Bergtold et al.*, 2014; *Caldas et al.*, 2014, 2015].

The goal of this chapter is to examine farmers' land use allocation decisions in the Cerrado, specifically the states of Goiás and Mato Grosso do Sul, focusing on the sugarcane expansion. To accomplish this goal, a partial-adjustment model is estimated for Cerrado acreage response at a county level using a panel regression that treats each land use decision as a result of profit maximization, thus estimating the optimal allocation of land [*Wu and Brorsen*, 1995; *Hausman*, 2012; *Carpentier and Letort*, 2014; *Hendricks et al.*, 2014]. In this context, explanatory variables are considered representing the previous acreage for the main commercial land use and for the natural Cerrado vegetation, commodity prices, and yields. As a result, the model estimates the impact on land allocation and is conditional on changes in these factors.

4.2 Methods

4.2.1 Study area

The Brazilian Cerrado encompasses 204 million ha, across 11 states and the Federal District, including the states of Goiás and Mato Grosso do Sul. Originally, the Cerrado covered 98% of the Goiás territory (34 million ha) and more than 60% of the Mato Grosso do Sul territory (21 million ha) [*Ministerio do Meio Ambiente*, 2014]. In these states, the Cerrado exhibits a variety of vegetation patterns, ranging from open grassland to closed woodland in a soil that is deep, well drained, and resistant to compaction—although it is acidic, with poor nutrient content, and a high concentration of aluminum [*Klink and Machado*, 2005; *Ministério do Meio Ambiente*, 2007a]. Nevertheless, advances in agronomic technology allowed farmers to overcome soil deficiencies and transform the Cerrado into a breadbasket [*Jepson*, 2006].

The main agricultural production in this region are cattle, soybeans, and corn. Out of the three, pastureland is the main use covering more than 26 million ha in 2013 [*Brasil*, 2015], followed by soybeans with close to 5 million ha, while sugarcane covers around 1.4 million ha

[*CONAB*, 2016]. Together, both states are on the forefront of sugarcane expansion in the Cerrado with 60 processing mills (36 in Goiás and 24 in Mato Grosso do Sul) in 33 and 21 counties in each state respectively. The Cerrado now covers 13.7 million ha in Goiás and 6.7 million ha in Mato Grosso do Sul [*Brasil*, 2015].

The definition of the study area encompasses only the counties that are completely within the Cerrado biome. To identify these counties, first, the county borders are overlaid with the official shapefile delimiting the Cerrado (Instituto Brasileiro de Geografia e Estatística (IBGE), Biomas, available at http://mapas.ibge.gov.br/interativos/servicos/wms-do-arcgis); second, the counties are intersected with the PROBIO land-cover/land-use maps. The PROBIO program (Projeto de Conservação e Utilização Sustentável da Diversidade Biológica Brasileira: Conservation and Sustainable Use of Brazilian Biological Diversity Project) is a federal government effort to map and classify the remaining native vegetation in Brazil as of 2002 [*Ministério do Meio Ambiente*, 2008]. The study area encompasses 243 counties: 219 in the state of Goiás and 24 in the state of Mato Grosso do Sul (Figure 4-2).

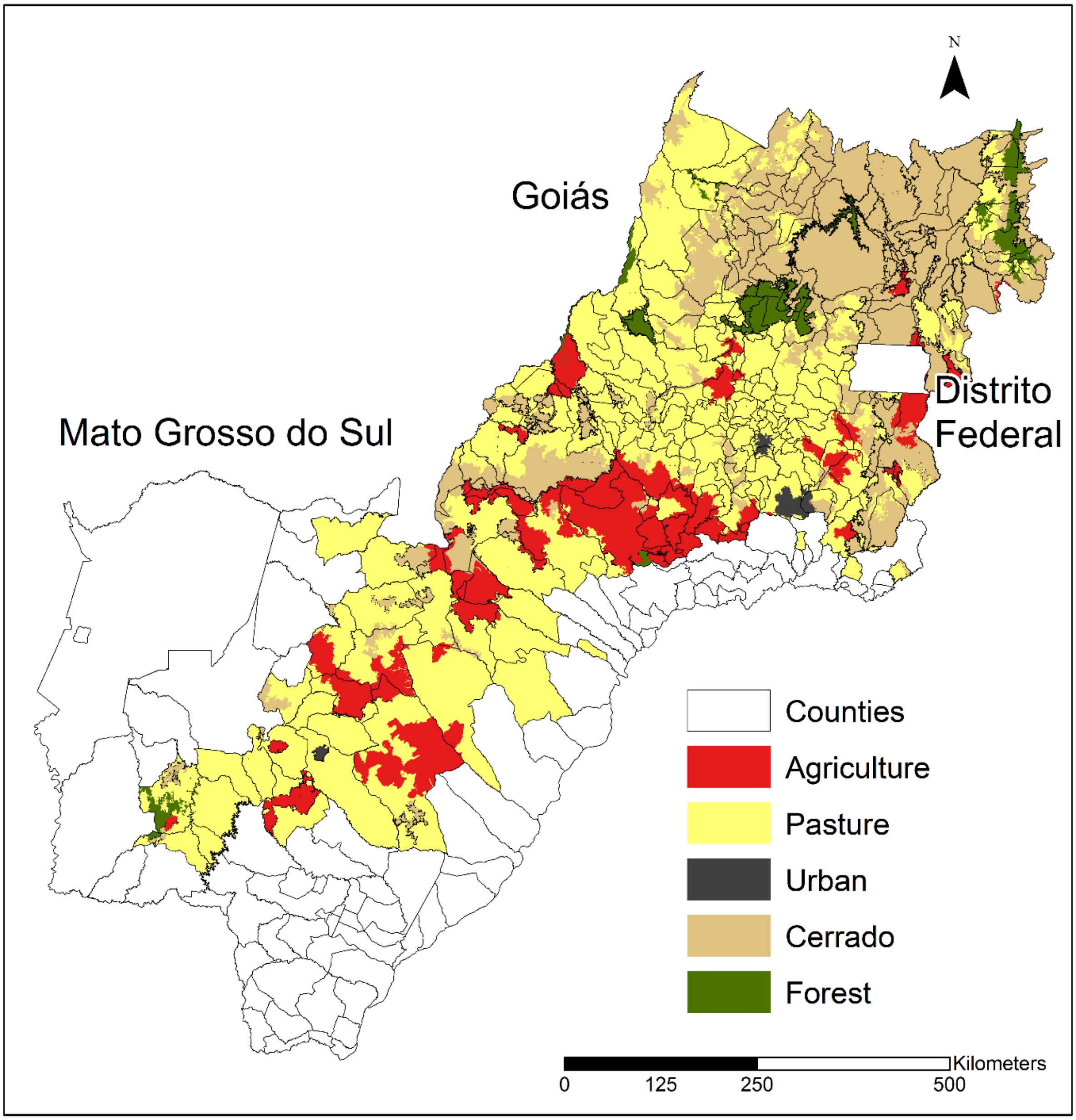

Figure 4-2 – Counties belonging to the Cerrado Biome and previously mapped for land cover and land use of 2002 by the PROBIO program.

4.2.2 Acreage response model

The study of farmers' land allocation can contribute to the understanding of land change dynamics and its impacts on the landscape [*Mallory et al.*, 2012; *Moraes et al.*, 2014]. The

Cerrado is still considered an agricultural frontier with areas to be opened, where farmers are working to determine the best use for the land. For instance, farmers face the decision to maintain (or not) the native Cerrado on their farm. The installation of sugarcane ethanol mills in the study area can affect land allocation.

Partial-adjustment models are an important tool for the study of farmers' acreage response to changes in crop and input prices [*Hendricks et al.*, 2014; *Haile et al.*, 2016]. The foundational study in this field is by Nerlove (1956) who transformed the field by proposing that farmers' acreage responses took longer to be completed than just one period (the short run), resulting in more elastic estimates of acreage response by considering the impact over longer period of time (the long run). This claim was supported by demonstrating that farmers' price expectations were not constrained to the previous year's prices. Following Nerlove (1956), the partial-adjustment model has been applied for a large number of crops in several different countries or larger regions [*Saddiq et al.*, 2014; *Haile et al.*, 2016]. Recently, partial adjustment models have been developed for examining biofuel crop expansion such as sugarcane and soybean acreage in Brazil [*Hausman*, 2012] and soybean and corn acreage in the U.S. [*Secchi et al.*, 2011; *Hendricks et al.*, 2014].

To understand land area allocated to sugarcane in the study area, a Nerlovian partial-adjustment acreage response model will be estimated. In this model, we assume a representative farmer whose decision of land allocation reflects a strategy of diversification of investments and optimization of expected profit [*Holt*, 1999]. This assumption emphasizes the importance of the total land available and the competition among uses. Considering the land allocation decision, our representative farmer can have expectation formed by the last period results. This is a naïve expectation process, however, there is no consensus in the literature on the best expectation process [*Haile et al.*, 2014]. Given the land use options available to farmers in the Cerrado, the partial-adjustment framework models current acreage as a function of last year's acreage, yield, and prices for the crop in question and for its land use substitutes. We use the previous acreage to verify the influence of previous investments and the influence of agricultural tradition in the adoption of sugarcane. The inclusion of yield is to capture the effect of technology and increase of productivity. Prices are used as a proxy for revenue. An exogenous variable to the farmers' land allocation decision processes is the distance to the mill. Given that sugarcane needs to be processed in a mill, the distance between the production area and mill can serve as a proxy for production cost, in which areas farther away would have a higher production cost than the area near mills. Consequently, the following specification is estimated:

Equation 4-1

$$A_{i,j,t} = \alpha A_{i,j,t-1} + \beta_{1,l} A_{l,j,t-1} + \beta_2 YLD_{i,j,t-1} + \beta_{3,l} YLD_{l,j,t-1} + \beta_4 P_{i,j,t-1} + \beta_{5,l} P_{l,j,t-1} + \beta_6 DMill_{j,t-1} + \nu_{i,j} + \mu_t + \varepsilon_{i,j,t}$$

where $A_{i,j,t}$ is the logged sugarcane (*i*) planted acreage on county j in hectares at period *t*; $A_{i,j,t-1}$ is the logged sugarcane (*i*) planted acreage on county j in hectares in the last period; $A_{l,j,t-1}$ is the logged county j acreage vector for the *l* substitute uses (pastureland, soybean single crop, soybean double crop, and Cerrado) in hectares in the last period; $YLD_{i,j,t-1}$ is the logged county j sugarcane yield in tons/ha in the last period; $YLD_{l,j,t-1}$ is the logged county j substitute *l* uses yield in tons/ha in the last period vector; P_i is the logged county j sugarcane deflated price in the last period; P_l is the logged county j substitute deflated prices in the last period vector; $DMill_{j,t-1}$ is the logged distance from county j to the nearest mill in the last period; $\nu_{i,j}$ are the county-level fixed effects; and μ_t are the year fixed effects. We assumed $\varepsilon_{i,j,t} \sim N(0, \sigma^2)$.

Short-run elasticities report the size and speed of response in land allocation for the next period given a 1% change in a given explanatory variable [*Hausman*, 2012; *Haile et al.*, 2016].

Long-run elasticities give the impact of a 1% change in a given explanatory variable extending for several periods [Hausman, 2012]. By construction, the coefficients α and β are short-run elasticities, and long-run elasticities are given by:

Equation 4-2

$$\beta_k/(1-\alpha)$$

where β_k are the coefficients estimates for Equation 4-1 and $k = 1,\ldots,6$, while α is the estimate for sugarcane own acreage at period *t-1*.

The implementation of this model requires an annual identification of the main agricultural land uses (including native vegetation) to characterize the land use transition. Equation 4-1 was estimated in a panel data analysis with 243 counties and 8 years (2006 to 2013) resulting in a strongly balanced panel. The model was estimated using the command *xtreg* with fixed-effects and robust variance in STATA IC 14.

4.2.3 Identifying Cerrado in a time-series of land use maps

Researchers have used remote sensing imagery to classify land cover–land use change in the Cerrado [*Brannstrom et al.*, 2008; *Sano et al.*, 2010; *Brown et al.*, 2013; *Brasil*, 2015; *Müller et al.*, 2015]. Given the dimension of this biome, most of the studies do not classify its totality; rather, they classify specific regions (spatial limitation). In addition, these studies focused on identifying land use change between two periods, hence only classifying land use for the start and end years of the study period. Developments in MODIS NDVI and EVI data sets now facilitate the detection of annual land use change [*Brown et al.*, 2013]. However, this advancement often groups different crops into a single category. Even though these studies advanced our knowledge on land use transition in the Cerrado given the spatial and temporal limitations, this approach does not support a robust economic model of a farmers' land allocation decisions [*Irwin and Geoghegan*, 2001]. One point of discussion is the classification of grassland into planted pastureland or native pastureland. This classification is fundamental for the study of land allocation and conservation of the Cerrado because pastureland is the main anthropogenic use of the area [*Brasil*, 2015].

To support our land allocation model, we developed a time-series database of land cover–land use maps for the study area that separates crops, pasture, and Cerrado for the period between 2005 and 2013. The creation of this database involved two processes. For the first process, the research team from the NSF-1227451 developed a thematic time series of maps for Goiás and Mato Grosso do Sul. This data set classifies land use/land cover (LULC) from 2005 to 2013 into seven classes: 1 – annual single crop, 2 – annual double-crop, 3 – pasture/cerrado, 4 – forest, 5 – sugarcane, 6 – urban, and 7 – water. Following the protocols described in Wardlow, Egbert, and Kastens (2007) and Brown et al. (2013), land cover histories from 137 sugarcane field sites (76 from Goiás, 61 from Mato Grosso do Sul) were acquired, many of which extended back to the 2005 crop year. From these data, 464 pre-sugarcane ground reference samples were obtained (2005 – 70, 2006 – 65, 2007 – 52, 2008 – 46, 2009 – 45, 2010 – 47, 2011 – 40, 2012 – 34, 2013 – 34, 2014 – 31). Sixty-eight of the samples represented annual single-crop, 191 represented annual double-crop, and 205 represented pasture/cerrado.

Original imagery—consisting of the 250-m, 16-day composite MOD13Q1 Normalized Difference Vegetation Index (NDVI) data from the Moderate Imaging Spectroradiometer (MODIS) covering the study area for crop years 2005-2014—was downloaded from the Land Processes Distributed Active Archive Center (LP DAAC; https://lpdaac.usgs.gov/data_access). These data were reprojected to the WGS84 projection with a grid size of approximately 240 m.

Applying the pure pixel approach utilized in Wardlow, Kastens, and Egbert (2006), Wardlow, Egbert, and Kastens (2007), Wardlow and Egbert (2008), and Brown et al. (2013), annual MODIS NDVI profiles were extracted in correspondence with the ground reference data. Using the 23-date MODIS profiles as independent variables and ground reference cover class as the dependent variable, a random forest (RF) classification model [*Breiman*, 2001; *Clark et al.*, 2010] was developed using the 'treebagger' function in MATLAB®. One thousand trees were included in the forest, with each developed using a 5-element random subset of the 23 candidate predictors (MODIS time periods).

To estimate the expected error of the full RF model, 10 iterations of a one-year-holdout cross validation (CV) exercise were used. For each iteration, 10 RF models were independently developed using unique 9-year subsets of the 10-year ground reference data set followed by an application of each model to ground reference data from its respective holdout year. Aggregating the results across all 10 holdout years for each CV iteration, overall classification accuracies across the 10 iterations for the 3-class model outputs ranged from 80.8 to 81.9%, which increased to 90.3-91.4% when grouping the single-crop and double-crop classes.

Annual forest cover layers were gathered using Global Forest Change data (2000-2014) [*Hansen et al.*, 2013]. These data were burned into the LULC maps obtained from the RF model. Information on the location of sugarcane fields was developed by the Canasat Program of the Brazilian National Institute for Space Research (INPE) [*Rudorff et al.*, 2010], and these data were provided by the stewards of that data set. Static urban and water layers were obtained from the Brazilian Institute of Geography and Statistics (IBGE) and burned into the maps. This step created a series of moderate resolution land use maps separating the commercial crops in the region. Nevertheless, given that the field-level data contains few samples of native vegetation, Cerrado and Pasture were unable to be separated.

The second process focused on splitting the class Cerrado/Pasture into individual classes: one for Cerrado and one for Pasture. The approach was to identify the areas that were classified as Cerrado in 2002 using PROBIO's classification [*Ministério do Meio Ambiente*, 2008; *Sano et al.*, 2010] and to update these areas given annual deforestation maps for the period 2003-2014 by the Cerrado Warning Deforestation System (SIAD) [*Ferreira et al.*, 2007, 2012]. Thus, a Cerrado-only data set was created for 2003 to 2014. This data was integrated into the time-series database by splitting the Cerrado/Pasture category as follows: areas that were overlaid with the Cerrado-only data set were reclassified as Cerrado; areas outside of the Cerrado-only areas were reclassified as Pasture. The time-series database now supports the implementation of more advanced econometric analysis of land allocation by presenting annual change among the main commercial uses and native vegetation (Figure 4-3).

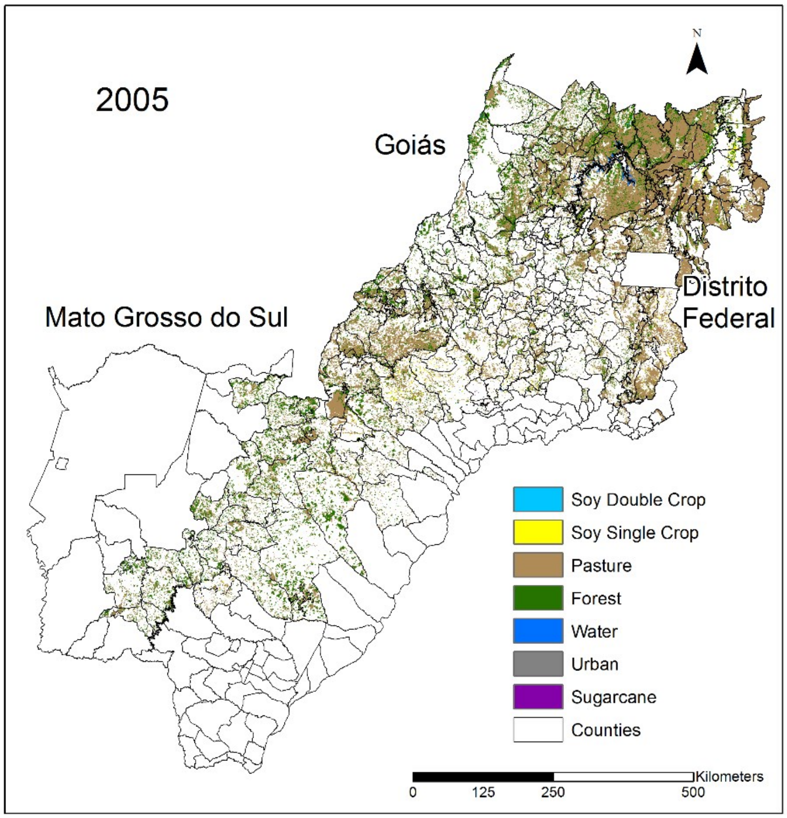

Figure 4-3 – Cerrado areas in 2005 represented by previous land use classification.

After the two process, the resulting LULC maps present eight land classes: 1 – Sugarcane, 2 – Soybean single crop, 3 – Soybean double crop, 4 – Pasture, 5 – Cerrado, 6 – Forest, 7 – Urban, and 8 – Water. The first five classes represent the main land uses available in the study area. Sugarcane represents the new commercial crop that is expanding throughout the region [*Shikida*, 2013; *Granco et al.*, 2015]. Soybean single crop is the traditional grain production that revolutionized the Cerrado in the 1970s [*Jepson*, 2006; *Rada*, 2013]. Soybean double crop is the new production system that intensifies production with the intensification of inputs. The usual crop rotation is a short-season soybean, followed by corn (called *milho safrinha* by Brazilian farmers) [*Arvor et al.*, 2012; *Brown et al.*, 2013]. Pasture is the main agricultural land use in the region [*Walker et al.*, 2009; *Newberry*, 2014]. Pasture are used for cattle ranching with the region exhibiting low cattle stocking per hectare and some level of degradation due to poor management practices [*Bustamante et al.*, 2012; *Martha Jr et al.*, 2012; *Cohn et al.*, 2014; *Strassburg et al.*, 2014]. The Cerrado class represents the native vegetation. For this study, we treat the Cerrado as a land cover. We recognize this is a simplification given that native grassland is frequently used as pasture. However, we do not have enough information to further divide the Cerrado into grassland used as pasture, grassland, arboreas, and other native vegetation. The observed transitions from class to class can be used to identify the farmers' revealed preference for one land use over another.

4.2.4 Data

For the econometric model, the dependent variable is the acreage allocated to sugarcane by county. Acreage is calculated from the land use maps described in the previous section. The selected explanatory variables that affect land allocation include previous acreage, yield, and price (Table 4-1). Crop yields and prices are from the Instituto Brasileiro de Geografia e Estatística (2016b). Cattle herd uses data from the Instituto Brasileiro de Geografia e Estatística (2016a) for the county-level herd; cattle price is from the CONAB at state-level for the period 2010 to 2013. The state price was interpolated to the county level using the same price gap recorded in the 2006 Agricultural Census calculated as the ratio between the value received and the number of animal slaughter [*Instituto Brasileiro de Geografia e Estatística*, 2006].

Land use acreages are dominated by the Pasture classification (Table 4-1). This land use has the largest mean, and it is the only land use present in each county of the study area. Cerrado is the second largest land use, while Sugarcane is the smallest land use in the study area. Price and yield of crops (sugarcane, corn, soybeans) are used in this model as a proxy for revenue:

sugarcane has the lowest price, but it is compensated by having a high yield. When considered together in a double crop rotation, corn and soybeans produce the highest revenue (Table 4-1).

Distance to the mill is incorporated into the model to capture the influence of ethanol mills in the land allocation decision. It is calculated as the Euclidean distance between the county's centroid and the nearest mill for each year. The location of the mill is derived from *CONAB (* 2013) and *ANP (* 2016). The Euclidean distance was calculated in ArcGIS 10.3.

Table 4-1 – Summary statistics for the variables included in the land allocation model

Variable (unit)	Mean	SD	Max	Min
Sugarcane (ha)	1,772.3	4,982.6	45,141.1	0
Cerrado (ha)	59,943.1	95,561.5	740,223.4	0
Soybean Double crop (ha)	2,477.9	12,080.1	220,515.8	0
Soybean Single crop (ha)	11,025.7	26,748.7	354,159.4	0
Pasture (ha)	89,671.3	133,403.5	1,327,962.0	1,866.2
Forest (ha)	7,199.7	13,238.8	120,412.8	17.3
Yield Sugarcane (tons/ha)	36.7	30.9	140.0	-
Yield Corn (tons/ha)	4.2	1.8	12.0	-
Yield Soy (tons/ha)	2.0	1.3	6.5	-
Cattle Stockage	1.449	0.6	5.555	0.107
Price Sugarcane (R$/ton)	42.7	38.1	430.0	-
Price Corn (R$/ton)	302.4	99.0	701.2	-
Price Soy (R$/ton)	393.3	294.9	1400.0	-
Price Herd (R$/ton)	89.5	17.0	163.0	-
Distance to Mill (km)	72.4	46.2	241.04	1.38

4.3 Results

The estimates for Equation 4-1 are presented in Table 4-2. Our model of land allocation for sugarcane shows that the previous acreage dedicated to sugarcane (Sugarcane (lagged)) has a positive relationship with current sugarcane given by the positive and statistically significant coefficient for Sugarcane (lagged) acreage (Table 4-2). Because the estimates in this model are short-run elasticities, it identifies sugarcane as inelastic to its own areas hence a change in the sugarcane area in the period *t-1* will result in a response equal proportion or no response in period *t*. From Equation 4-2, the long-run elasticity is a function of the sugarcane acreage (lagged) (the α in the Equation 4-2), which results in a long-run elasticity of 2.34. Therefore, the impacts of change in land allocation are greater in the long run. Soybean double crop acreage is the only other land use that is statistically significant and positive in sign, although the estimate is close to zero. This relation is also inelastic in the long run (0.06).

Table 4-2 – Acreage response of sugarcane in the states of Goiás and Mato Grosso do Sul

Variable	**Coefficient**		**Std.Err.**	**Short Run**	**Long Run**
Sugarcane (ha), (lagged)	0.573	***	0.025	0.573	1.342
Cerrado (ha), (lagged)	0.376		0.242	0.376	0.881
Soybean double crop (ha), (lagged)	0.029	***	0.013	0.029	0.068
Soybean single crop (ha), (lagged)	-0.012		0.013	-0.012	-0.028
Pasture (ha), (lagged)	0.575		0.453	0.575	1.347
Yield Sugarcane (tons/ha), (lagged)	0.116	*	0.061	0.116	0.272
Yield Corn (tons/ha), (lagged)	0.101		0.097	0.101	0.237
Yield Soybeans (tons/ha), (lagged)	-0.191		0.133	-0.191	-0.447
Cattle stockage (heads/ha), (lagged)	0.058		0.116	0.058	0.136
Price Sugarcane (R$/ton), (lagged)	-0.106	**	0.055	-0.106	-0.248
Price Corn (R$/ton), (lagged)	-0.026		0.018	-0.026	-0.061
Price Soybeans (R$/ton), (lagged)	0.039	*	0.021	0.039	0.091
Price Cattle Herd (R$/head), (lagged)	0.973	*	0.580	0.973	2.279
Nearest mill (km), (lagged)	-0.446	***	0.120	-0.446	-1.044
Constant	-11.423		7.170	-	-
R-squared (Within)	0.523				

Note: *significant at 0.1, **significant at 0.05, ***significant at 0.01.

Considering the sugarcane yield, the model presents a short run elasticity that is positive but inelastic, thus change in yield affect the following year sugarcane acreage by the same amount. The long run elasticity is also positive and inelastic. The short run acreage price elasticity for sugarcane is statistically significant and negative but inelastic (-0.106). This elasticity aligns with the economic theory showing that an increase in sugarcane price would make farmers unresponsive to reducing their sugarcane area. This response is intensified in the long run with an elasticity estimate of (-0.248) though it is still inelastic. Corn and soybean cross-price acreage elasticities are also close to zero (only soybean is statistically significant). Sugarcane cross-price elasticity with the price of cattle is 0.973, denoting that this is highly elastic. This estimate is important for two reasons. First, it indicates that the cattle ranching activity is important to sugarcane acreage. Second, it demonstrates that this factor has a greater impact in the future given the long-run elasticity of 2.27.

Distance to the nearest mill is statistically significant. Reduction in the distance to the mill increases the acreage of sugarcane. The acreage response to distance is stronger in the long run (-1.04) than in the short run (-0.442).

4.4 Discussion

The fast expansion of sugarcane in Brazil since 2005 has attracted attention given its possible impacts in land competition, agricultural intensification, and conversion of native vegetation [*Lapola et al.*, 2010b; *Hausman*, 2012; *Goldemberg et al.*, 2014]. The present research contributes with four main findings for these discussions by focusing on the case of sugarcane expansion to the Cerrado of the states of Goiás and Mato Grosso do Sul.

First, the estimation results allow a discussion on the land dynamics of sugarcane expansion. The model found sugarcane to be inelastic to its own acreage in the short run and elastic in the long-run. This elasticity reveals that sugarcane has a spatial inertia in the short run [*Hausman*, 2012]. The spatial inertia can be understood given the specificities of sugarcane production: (i) sugarcane has a long-term rotation, being economically viable for five growing seasons [*Goldemberg*, 2006], (ii) the plant grows in a ratoon system [*Horta Nogueira et al.*, 2013], (iii) implementation of a sugarcane farm is a costly process [*Sparovek et al.*, 2007; *Egeskog et al.*, 2016], (iv) the machinery involved in the farming of this crop is specially designed for it [*Coelho et al.*, 2006; *van den Wall Bake et al.*, 2009; *Aguiar et al.*, 2011], and (v) the contracts between suppliers and ethanol mills are based on the production cycles instead of years [*Sant'Anna et al.*, 2015]. All these factors combine to influence farmers to keep producing sugarcane until a drastic shock takes place. Positive shocks such as the increase in demand for ethanol in Brazil can propel a fast expansion. However, negative shocks such as low oil price and closing of mills can mitigate the expansion. Given the concept of inertia, it indicates that sugarcane may continue to expand in these states. This interpretation is significant in the long run given its elasticity of 2.34, indicating that the expansion can be more than proportional to the previous acreage.

One condition for this expansion is the presence of ethanol mills. Mills are the only destination of large-scale sugarcane production; as a result, sugarcane fields need to be located close to the mills [*Neves et al.*, 1998]. The constraint on the spatial distribution of sugarcane is because of the degradation of the sugar content used to fabricate ethanol. Once harvested, sugarcane needs to be processed in less than 72 hours [*Neves et al.*, 1998; *Capaz et al.*, 2013]. Therefore, the relation between mills and producing areas reinforces the spatial inertia of sugarcane. The estimate for the distance to the nearest mill shows that the acreage response is negative, thus an increase in the distance results in a decrease in the acreage of sugarcane. This response is stronger in the long run. Two consequences arise from these findings: (i) the areas surrounding existing (older) mills are more economically attractive to sugarcane farmers; and (ii) in the presence of new ethanol mills, the spatial inertia suggests an increase in the land allocated to sugarcane.

The second finding on the land allocation of sugarcane is the land dynamics with native vegetation. This dynamic is explicitly modeled by incorporating the acreage of native vegetation (Cerrado) as a competing use in the sugarcane allocation model. The results do not identify Cerrado as a statistically significant factor in the study area. This finding is aligned with previous research on land use prompted by sugarcane in Brazil that have shown sugarcane expansion mostly occurring over pasture [*Rudorff et al.*, 2010; *Aguiar et al.*, 2011; *Adami et al.*, 2012; *Ferreira Filho and Horridge*, 2014]. Several factors may influence this result. First, the SAZ policy implemented in 2010 ruled-out the conversion of native vegetation to sugarcane. Thus, counties with large areas under Cerrado are less attractive to sugarcane production. Second, producers may select cropland and/or pasture to sugarcane because they know the areas that will have the best return.

The last two findings from our study are related to land competition, one addressing crop and the other cattle production. For the third finding, let us focus on the competition between biofuel and food crop production. This competition is a growing topic of concern in the land use literature given its importance for policy making and its impact on the food supply [*Searchinger et al.*, 2008a; *Tilman et al.*, 2009; *Nassar et al.*, 2011; *Secchi et al.*, 2011; *Brown et al.*, 2014]. The advance of sugarcane over one of the breadbaskets of Brazil also contributed to this discussion [*Abdala and Ribeiro*, 2011; *Silva and Miziara*, 2011]. The present research considered this topic by considering the two main row-crop productions (soybean single crop and soybean double crop) as alternative uses in the farmers' land allocation decision processes. In the partial-adjustment model, land competition would appear as negative acreage response to acreage allocated to alternative uses. However, the estimate for the Soybean double crop acreage is positive and statistically significant, and for the Soybean single crop, it is negative but not significant. These results indicate a different land dynamic between biofuel and food crop production. Instead of competing, the results show that increases in the soybean double crop acreage are consistent with sugarcane expansion, thus these land uses have complementary behavior. For instance, when farmers increase the area under soybean double crop, in the following year more area will be used for sugarcane production. This interpretation is supported by the cross-price response to soybeans, which is positive but inelastic indicating that an increase in the price of soybeans does not change the land allocated to sugarcane. An explanation for the inelasticity may be due the temporal in the crops rotation with soybeans being annual while sugarcane is a semi-perennial.

The fourth finding is the land dynamics of sugarcane and pasture. The conversion of pasture to sugarcane is another alternative of land use transition. This transition is the one favored by the Brazilian government because of its smaller impact on food production when compared to the conversion of cropland. In the econometric model, three variables are employed to capture the influence of pasture and cattle ranching on the allocation of land to sugarcane: Pasture, Cattle Stockage, and Price of Cattle. Given that previous research had found that sugarcane expanded over pasture [*Rudorff et al.*, 2010; *Aguiar et al.*, 2011; *Adami et al.*, 2012; *Ferreira Filho and Horridge*, 2014], it was unexpected to find the estimate for Pasture acreage not statistically significant (Table 4-2). This result raises the alternative that the pasture acreage does not influence the acreage of sugarcane. An explanation for such result is the difference in the acreage dedicated to each activity, while pasture is present in all counties for all the years in the study, sugarcane is confined to few counties and correspond to less than 10% of the average pasture area. Such difference in average area and spatial distribution diminishes the effect of the variable Pasture. For the variable Price of Cattle, the cross-price acreage response is statistically significant and elastic, implying that an increase in the price of cattle positively impacts the allocation of land to sugarcane. The intensification of pasture and cattle stockage has been proposed as a source of ‘new’ agricultural land and an alternative to reduce deforestation in the Cerrado [*Martha Jr et al.*, 2012; *Mann et al.*, 2014; *Gil et al.*, 2015]. The strong cross-price elasticity demonstrates the importance of cattle ranching on farmers’ decisions. With the increase of cattle price, ranchers can obtain more revenue that in turn can be applied to the intensification of cattle ranching activity, thus freeing land for sugarcane. The process hypothesized is the increase of cattle stockage in the existing pasture (mainly on nondegraded pasture, but reform and correction of degraded pasture is also an alternative) and the degraded areas or nonsuitable to sustain higher cattle density would be allocated to sugarcane [*Cohn et al.*, 2014; *Alkimim et al.*, 2015]. However, our model does not find a correlation between cattle stockage and sugarcane acreage. Hence, more research is needed to understand the dynamic among sugarcane and pasture in Goiás and Mato Grosso do Sul.

4.5 Conclusion

In conclusion, this research uses a new data set for the Cerrado with special attention to pastureland, the main anthropogenic land use in the region. This study applies the partial adjustment framework to the Brazilian Cerrado to understand farmers’ land use decisions regarding sugarcane production. Furthermore, by developing a time-series of land use maps, farmers’ decisions over time can be modeled considering the main agricultural land use in the states of Goiás and Mato Grosso do Sul. The results did not find evidence for a statistically significant relationship between sugarcane acreage and the amount of Cerrado vegetation, which is a major concern in relating biofuel production and its impact on the environment. This research implies the importance of cattle ranching and the intensification of grain production in understanding farmers' sugarcane acreage decisions in the states of Goiás and Mato Grosso do Sul.

Previous studies on sugarcane expansion in Brazil have discussed the relationship between pastureland and sugarcane. The large areas of degraded pasture and the low cattle stockage are frequently listed as factors that could sustain sugarcane expansion without deforestation in new areas. This study used distinct land use classes for pasture and for the Cerrado (native vegetation). Additionally, the variable Price of Cattle Herd had the largest cross-price elasticity with sugarcane acreage. The short- and long-run elasticity are highly elastic, demonstrating that this may be an important dynamic for the farmers' land use allocation.

Furthermore, a new land use dynamic between sugarcane and grain production is found. Intensification from a single crop to a double crop increases sugarcane acreage; thus, these land uses tend to be complementary. This finding lends support to the claim that intensification of grain production can release land for fuel and/or sugar production. However, this result cannot support the claim that this land use change does not affect food production and price.

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Chapter 5 - Land use policy, biodiversity, climate change and the future of sugarcane: the case of Sugarcane Agroecological Zoning and the amphibians in the Brazilian Cerrado

5.1 Introduction

In the last decade, bioenergy has been adopted as a substitute for fossil-based energy and as an initiative to mitigate environmental impacts [*Surendran Nair et al.*, 2012; *Gelfand et al.*, 2013]. The adoption and development of these alternative sources of energy are strongly influenced by governmental policies [*Tilman et al.*, 2009; *Sorda et al.*, 2010; *OECD-FAO*, 2013]. Governments have established policies to stimulate consumption, especially of biofuels. Examples of policies include blending mandates of biofuels with fossil fuels, tax incentives, and import restrictions [*Sorda et al.*, 2010; *OECD-FAO*, 2013]. Projections from FAO estimate that bioenergy will increase threefold by 2050 [*OECD-FAO*, 2013].

Considering this scenario of growing market demand, expanding the production of feedstock becomes an inherent necessity [*Foley et al.*, 2011]. The expansion of a bioenergy crop, nevertheless, adds a new land use to an already pressured agricultural system [*Rudel et al.*, 2009; *Tilman et al.*, 2009]. Competition for land is not the only concern surrounding bioenergy production. Land suitability for biofuel feedstock is still uncertain, especially for new feedstock such as jatropha outside India [*Barney and DiTomaso*, 2011; *OECD-FAO*, 2013]. The concept of land suitability is related to adequate terrain, slope, soil nutrients and structure, and weather (i.e., precipitation, mean temperature), among other factors such as crop varieties and technological packages [*Blanchard et al.*, 2015; *Pugh et al.*, 2016]. Models of land suitability for diverse potential bioenergy crops have been developed, such as corn and sorghum for the U.S. [*Barney* *and DiTomaso*, 2010; *Evans et al.*, 2010], *Jatropha curcas* [*Trabucco et al.*, 2010], a set of nine potential biofuel crops for South Africa [*Blanchard et al.*, 2015], and a global assessment by Barney and DiTomaso [2011].

Additionally, the land transition to bioenergy production is paramount for greenhouse gas (GHG) reduction. Expansion over native vegetation may create a carbon deficit larger than the carbon saving of many decades, or even centuries, of bioenergy consumption [*Fargione et al.*, 2008; *Lapola et al.*, 2010a; *De Figueiredo and La Scala Jr*, 2011; *Egeskog et al.*, 2014]. Thus, a challenge for bioenergy production is to find areas that are suitable for production that will not affect GHG emissions. More recently, research focus has broadened to include the sustainability in relationship to bioenergy, biodiversity and other ecosystem services [*Werling et al.*, 2014; *Chaplin-Kramer et al.*, 2015; *Verdade et al.*, 2015].

Among the countries producing biofuels, Brazil is one of the leaders, being the second largest producer of ethanol in the world. Ethanol based on sugarcane has been used in Brazil since the 1970s, with most of the production taking place in the state of São Paulo [*Goldemberg*, 2007; *Hira and de Oliveira*, 2009; *Rudorff et al.*, 2010]. The surge in ethanol demand motivated by the rise of oil prices and the introduction of flex-fuel cars stimulated the ethanol industry to expand its production. The strategy chosen to meet this new demand was to invest in new mills and incorporate more area to sugarcane production. To implement this strategy, several ethanol companies established new mills but not in traditional growing regions of São Paulo. the ethanol companies decided to expand into the Cerrado biome. Many factors have affected this decision such as cheap land prices in the region and appropriate soil and climatic conditions [*Granco et al.*, 2015]. However, the fast expansion of ethanol demand in the 2000s pushed the Brazilian government to implement a zoning policy known as the Sugarcane Agroecological Zoning (SAZ).

The SAZ has the goal to coordinate sugarcane expansion, defining areas as suitable, nonsuitable, and not allowed to be converted to sugarcane[*Manzatto et al.*, 2009]. The SAZ is a collaborative project between Ministério da Agricultura (Ministry of Agriculture) and Ministério do Meio Ambiente (Ministry of Environment), executed by the EMBRAPA Agroenergy in a framework incorporating environmental, agronomic, and food security concerns. [*Manzatto et al.*, 2009].

The land suitability model created for the SAZ specifically considers soil, slope, and climate conditions; additionally, it incorporates restrictions to the conversion of native vegetation to protect the environment. The SAZ indicates a preference for sugarcane expansion over pastureland instead of sugarcane conversion of cropland to ensure food security [*Manzatto et al.*, 2009]. Even a comprehensive effort such as the SAZ cannot tackle all the concerns surrounding bioenergy production. In this research, we contribute to this effort by focusing on two points. The first point is the analyze climate change scenarios impacts on sugarcane land suitability defined by the SAZ. The SAZ has the power to influence the decision of all agents involved in the sugarcane industry and to not include climate change can increase the risk of those agents. The second point is the conflict between sugarcane and biodiversity. With the SAZ coordinating sugarcane expansion, understanding the species richness affected in the present and in the future is paramount to protect this threatened biome [*Strassburg et al.*, 2017]. Additionally, this new information can make the SAZ more robust.

The approach used to model climate change impact on the land suitability of sugarcane is to develop an Ecological Niche Model (ENM) of land suitability for sugarcane production using

SAZ as the reference. Previous research have used ENM to model land suitability for biofuel crops [*Evans et al.*, 2010; *Trabucco et al.*, 2010; *Blanchard et al.*, 2015] while ENM have been used to estimate the impacts of climate change on species distribution [*Behrman et al.*, 2013; *Machovina and Feeley*, 2013]. In this chapter, ENM will be projected to generate scenarios of land suitability given climate change. The discussion on the conflict with biodiversity will be addressed by investigating the spatial distribution of 68 species of amphibians located in the Cerrado and the exposure of these species to climate change and sugarcane expansion. The use of amphibians as the proxy for biodiversity is supported by the Amphibia class is facing the highest rate of decline in the world and the Cerrado is a global biodiversity hotspot with a significant presence of amphibians [*Becker et al.*, 2007; *Fonseca et al.*, 2013; *Signorelli et al.*, 2016].

5.2 Sugarcane producing areas

Sugarcane (*Saccharum officinarum*) is a commercial crop originally from South Asia (India and China) and cultivated since the twelfth century [*Mukherjee*, 1957]. Sugarcane is a C-4 plant, it has adequate resistance to drought, with a semi-perennial rotation. This plant produces yields of biomass and sucrose content. Traditionally, the economic value was on the amount of sugar content, which was obtained by crushing the cane at mills. Sugarcane has many economical uses, the most important being the production of sugar; more recently, the production of biofuel and bioenergy [*Cheavegatti-Gianotto et al.*, 2011]. The climatic conditions needed for this crop production are mainly found in the Tropics [*Goldemberg*, 2007]. Currently, sugarcane has a wide geographical distribution; it is being grown in more than 100 countries, from 35°N to 35°S including tropical and subtropical regions. The main producers in 2012 were Brazil (35% world's production), India (18%), China (6.5%), Thailand (5%), and Pakistan (3%)

(FAOSTAT) (Food and Agricultural Organization (FAO), FAOSTAT: Crops, FAO Statistics Division, available at http://faostat.fao.org).

Brazil is not only the largest producer of sugarcane, but it is the main producer of sugar, ethanol, and bioelectricity using sugarcane biomass. Sugarcane production in Brazil was started by Portuguese colonizers interested in producing sugar in the sixteenth century. Ethanol production was initiated in the 1930s and completely integrated into the Brazilian energy matrix in the 1970s [*Hira and de Oliveira*, 2009]. Throughout the development of the sugarcane industry, two main producing regions emerged: the northeast region (states of Pernambuco, Bahia, and Alagoas) specialized in sugar and the southeast, especially the state of São Paulo with a mixed production structure (mills able to produce sugar and ethanol). During the 1970s, the Brazilian government invested in the development of the sugarcane ethanol industry as a substitute for imported oil. São Paulo was the main beneficiary of this policy, with a growing dominance of the sector [*Shikida and Bacha*, 1999]. But this concentration of the sugarcane industry in the state has also increased the awareness of its environmental impacts and aggravated the competition for land and sugarcane among the mills [*Martinelli and Filoso*, 2008; *Granco et al.*, 2015]. With the rise in demand for ethanol in the 2000s, several mills sought out new areas to expand their production. This expansion created a new frontier for sugarcane in the Cerrado, especially in the states of Goiás and Mato Grosso do Sul. In the span of a decade, this region became responsible for ~20% of the hydrous ethanol produced in Brazil [*CONAB*, 2016].

From 2000 to 2014, sugarcane producing areas in Brazil increased from 5 million ha to ~9 million ha [*CONAB*, 2016]. This fast-paced expansion called attention to the risk of converting native vegetation to sugarcane fields, and the negative impacts on the food production structure already in place. Aware of land use concerns, the Brazilian government launched the

Sugarcane Agroecological Zoning (SAZ) aiming to ensure sustainable growth of the sugarcane industry [*Manzatto et al.*, 2009].

The SAZ has the goal to coordinate sugarcane expansion, defining areas as suitable, nonsuitable, and not allowed to be converted to sugarcane. The suitability of each area is a combination of sugarcane's ecoclimatic requirements such as climate, soil, and previous land use [*Manzatto et al.*, 2009]. The definition of areas not allowed to convert is a political decision to enhance environmental protection by ruling out any conversion of native vegetation and any area in the Amazon and Pantanal biomes, and Alto Paraguay River Basin. The exception would be for grandfathering areas that were in production before the SAZ allowing these sites to continue their production [*Manzatto et al.*, 2009].

The suitability for sugarcane production is given by a set of climatic and edaphic conditions [*Manzatto et al.*, 2009]. Climate factors are average air temperature, annual hydric deficit, an index for the satisfaction of sugarcane's water necessities, and risk of frost. Areas that need intense irrigation or that had too much rain were considered unsuitable for sugarcane production. Soil factors include deficiencies of fertility, water deficits, water excess or lack of oxygen, erosion prone, restrictions to mechanized harvest, and restrictions to the development of sugarcane's radicular root system [*Manzatto et al.*, 2009]. Land use is not considered as a restriction factor; but it is an expressed desire from the Brazilian government that sugarcane expands over pastureland, thus reducing direct land competition with food production [*Manzatto et al.*, 2009].

Among suitable areas, a three-tier system is implemented (Table 5-1). Areas with the highest suitability (P-Class) are those with the best climate and soil conditions—the SAZ identified 18 million ha in this tier. This class is the most attractive for production. The second tier is composed of areas with regular suitability (R-Class) defined by average soil conditions and good climate conditions—41 million ha belong to this tier. The last tier is low suitability (S-Class), this class has good climate conditions but poor soil—4 million ha in this tier, being the class less attractive for production.

Table 5-1 – Amount of suitable areas for sugarcane production in Brazil, by suitability classes and land use classes (ha)

		Land use classes (ha)			Total, by suitability class
		Pastureland	Mixed use	Agriculture	
Suitability classes	High (P)	10,251,026.90	585,988.94	7,191,387.54	18,028,403.38
	Regular (R)	22,818,769.58	2,015,246.50	16,340,889.74	41,174,905.82
	Low (S)	3,062,028.55	490,027.40	733,151.94	4,285,207.89
Total, by land use class		36,131,825.03	3,091,262.84	24,265,429.22	63,488,517.09

Source: Manzatto et al., (2009).

5.3 Amphibians and the Cerrado

The Amphibia class is the most vulnerable class in the Animalia kingdom [*Becker et al.*, 2007]. The decline of amphibians have been associated with habitat loss due to the conversion of native vegetation, the introduction of alien species, diseases, climate change, and interaction of the above causes [*Beebee and Griffiths*, 2005; *Becker et al.*, 2007]. An important interaction is the defined as the habitat split which is the disconnection between habitats needed in each stage of the amphibians life [*Becker et al.*, 2007; *Fonseca et al.*, 2013]. Elements of amphibians life trajectory supporting this thesis include a small distribution range, local dependence, low dispersion, and connection between water environment and land environment for later stages of life [*Fonseca et al.*, 2013; *Signorelli et al.*, 2016].

The use of species to represent biodiversity is a simplification of this complex concept but it is a valid one given the use of species as indicators of biodiversity and environmental quality [*Dias et al.*, 2016]. For instance, amphibian species are considered to have elements that make it appropriate to model their distribution as a proxy for biodiversity [*Beebee and Griffiths*, 2005].

Analysis of the amphibians' habitat will focus on the Cerrado given that this biome is the new frontier for sugarcane production. Records of amphibian species are available at IUCN (International Union for Conservation of Nature, The IUCN Red List of Threatened Species: Search, available at http://www.iucnredlist.org/search). This selection generated a list with 129 species. The IUCN provides two overall indicators of the species condition. One is the Status of the species concerning its classification in the eight categories of the List of Threatened Species, ranging from Extinct to Least Concern. Our selection has the following species composition: 1 – critically endangered, 1 – endangered, 2 – vulnerable, 6 – near threatened, 76 – least concern, and 43 – data deficient. The other indicator is the population trend. From the 129 species selected, 34 are stable, 1 is increasing, 51 are decreasing, and 43 are unknown. After cleaning repeated data points, and preparing the data to implement the analysis removing data that would be lost given the spatial resolution used in the analysis, the selection was reduced to 68 species. Among these 68 species, 1 is considered near threatened, 1 is vulnerable, 56 are least concern, and 10 are data deficient. For the population trend, 23 species have a stable trend, 1 species is increasing its population, 25 species are facing a decreasing trend, and 19 species have an unknown trend. Amphibians are difficult to study and suffer from lack of data on the number of species and the spatial distribution their habitat [*Becker et al.*, 2007; *Nóbrega and De Marco*, 2011]. The use of Ecological Niche Model has been proposed as a framework to improve the understanding of the amphibian's habitat given this approach ability to operate with restricted data points and generate probability distribution maps [*Elith and Leathwick*, 2009].

5.4 Methods

5.4.1 Ecological niche model

Ecological Niche Models (ENM) are used to estimate the potential range of the species [*Peterson*, 2003; *Phillips et al.*, 2006; *Hirzel and Le Lay*, 2008; *Broennimann et al.*, 2012; *Guillera-Arroita et al.*, 2015; *Akhter et al.*, 2017]. The ENM traces the species' ecological niche by relating data on the occurrence of the species with data on the other elements of the landscape such as climate, physical environment, human population, and land use, among others. These models contribute to answering questions related to the distribution of species and to predicting the distribution shift under a change in the environment, such as climate and/or land use changes [*Anderson et al.*, 2003; *Estes et al.*, 2013; *Silva et al.*, 2014b; *Petitpierre et al.*, 2016]. The ENM's broad adoption can be attributed to three main factors: the good fit of the models' predictions and potential to transferability [*Peterson et al.*, 2007; *Phillips*, 2008]; the user-friendly interface of some ENM software [*Elith and Leathwick*, 2009; *Lozier et al.*, 2009]; and the readily available GIS data layers on species records and landscape factors [*Elith and Leathwick*, 2009; *Lozier et al.*, 2009]. The ENM has been used in a broad range of applications, from modeling exotic species [*Faleiro et al.*, 2015; *Silva et al.*, 2015] and pollinators [*Silva et al.*, 2014a] to invasive species [*Peterson*, 2003; *Barney and DiTomaso*, 2011; *Petitpierre et al.*, 2016]. More recently, ENM started to attract the attention of land change scientists who have used it to model land use suitability [*Heumann et al.*, 2013; *Machovina and Feeley*, 2013], establish potential of new producing regions [*Evans et al.*, 2010; *Trabucco et al.*, 2010], and land cover change and planning [*Zhang et al.*, 2012; *de Souza et al.*, 2014].

ENM has the capability of handling data representing biotic (such as dispersal ability, predation) and abiotic (such as climate and terrain) factors relevant for the study of the potential habitat of a species. Identification of abiotic factors as one of the largest force defining the spatial distribution together with the abundance of GIS layer of climatic and bioclimatic variables stimulated an ENM reliance on abiotic factors [*Pearson and Dawson*, 2003; *Elith and Leathwick*, 2009]. However, the ENM reliance on abiotic factors has been called out as a source of prediction error [*Pearson and Dawson*, 2003; *Araújo and Peterson*, 2012]. Researchers have proposed the use of biotic factors, however, the incorporation of these factors is limited by the specificity of each species and lack of data that can be used as a proxy for the biotic factors [*Elith and Leathwick*, 2009; *Cunningham et al.*, 2016; *Lewis et al.*, 2017].

For this chapter, the influence of biotic and abiotic factors is recognized, however, given our research goals the approach used in this chapter relies on the abiotic factors affecting the species distribution. The first research goal deals with modeling and predicting land suitability for sugarcane which is defined in terms of abiotic factors. The second research goal focuses on the general amphibians vulnerability. The focus of this goal is to be more generalizable and encompassing all species in the same modeling framework. Even though this objective could benefit from the use of biotic variables the identification, data collection, and incorporation of the individuals biotic variables for each species would deviate from our research goal.

5.4.2 Research design

The research design consisted of two experiments. The first experiment is the development of an ENM for crop suitability, more specifically sugarcane suitability. The second experiment is the development of an ENM for 68 species of amphibians present in the Brazilian savanna (Cerrado biome) and the exposition of these species to potential sugarcane expansion.

The first experiment consists of three steps: (1) the development of specific ENM for sugarcane suitability classes defined in the Brazilian SAZ; (2) the transference of the results from (1) to 34 climate change scenarios using the representative concentration pathways (RCP) 4.5 and 8.5 and to 17 global climate models (GCM); (3) the estimation of the distributional shift of sugarcane suitable areas and vulnerability to climate change. To implement (1), three different algorithms previously tested in the literature were used [*Evans et al.*, 2010; *Duan et al.*, 2014; *Silva et al.*, 2014a]: (i) Maxent (MXT) [*Phillips et al.*, 2006]; (ii) Random Forest (RDF) [*Breiman*, 2001; *Howard et al.*, 2014]; and (iii) Support Vector Machine (SVM) [*Drake et al.*, 2006; *Bedia et al.*, 2011]. An ANOVA statistical test assessed the algorithm that produced the best True Skilled Statistics [*Allouche et al.*, 2006; *Garcia et al.*, 2013; *Brun et al.*, 2016] for all the SAZ suitability classes. After the identification of the best algorithm, we proceeded to step (2) using only the selected algorithm to generate the distribution of suitable areas for sugarcane given different GCM. Finally, to identify patterns of change and associated climate change vulnerability of the areas (step 3), the results in (step 2) are compared to the results in (step 1) generating a set of land suitability change maps. In this step, an ensemble of all ENM developed under all GCM is aggregated into an overall map defining the frequency of prediction and the probability of each area given the set of GCM used. The criteria of vulnerability employed in this analysis are related to the frequency that an area is predicted as suitable for sugarcane production. Areas that have a low probability are more vulnerable than areas with high probability of prediction.

The second experiment consists of three steps. The first step is to develop ENM for 68 amphibian species that occur in the Cerrado. The ENM will be consistent with the one for sugarcane land suitability by using the same set of bioclimatic variables and the best algorithm selected in the first experiment. The second step is to model the amphibians' distribution under climate change using the ENM developed in step one. The third step is the assessment of conflict between land suitable for sugarcane and amphibians. This step also makes use of the ensemble procedure described above.

5.4.3 Data

The data for this study comes from the Brazilian SAZ, which classifies the suitable areas for sugarcane expansion into the three-class system (P, R, and S). The SAZ classification is spatially explicit on a scale of 1:250,000 [*Manzatto et al.*, 2009]. The SAZ data was acquired in shapefile format from the Brazilian Enterprise of Agricultural Research (EMBRAPA) [*Manzatto et al.*, 2009]. The original data set was divided into SAZ Classes and converted to a grid format keeping the same resolution. Each SAZ Class was modeled using ENM with the point location represented by the centroid of each cell. After these steps, the P-Class had 724,818 points, R-Class had 1,527,006 points, and S-Class had 160,308 points. This abundance of points is unusual in the use of ENM and may raise two biases in the models. First, the use of all points can lead to overfitting the model, thus threatening the transferability of the model to different climate scenarios [*Peterson et al.*, 2007; *Phillips*, 2008]. Second, the abundance of points can lead to spatial autocorrelation as the SAZ criteria are related to physical factors that exhibit larger spatial dependencies (e.g., soil characteristics and climate) [*Ettema and Wardle*, 2002; *Hijmans et al.*, 2005].

To avoid these biases, a random sampling procedure was implemented using a 10,000-m threshold. For each SAZ Class, 10 random samples were collected, each sample with 3,500 points (except for the S-Class where the sample size was 1,000 points given the smaller area under this class). This procedure has the advantage of avoiding spatial autocorrelation by using a large spatial threshold, hence reducing the odds of overfitting by sampling the original data set [*Howard et al.*, 2014]. Furthermore, it enables statistical validation of the ENM by the use of repeated measures ANOVA.

Data for amphibians species are from the IUCN (International Union for Conservation of Nature, The IUCN Red List of Threatened Species: Search, available at http://www.iucnredlist.org/search). This data is a presence-only data set.

To evaluate the effects of climate change on sugarcane expansion, we developed an ENM using the present climate conditions with interpolated average data for 1960 to 1990 [*Hijmans et al.*, 2005]. To represent the climate in a more meaningful biological manner, 19 bioclimatic variables derived from climate conditions were considered at a spatial resolution of 2.5 arc-min (approximately 4 km at the equator) [*Hijmans et al.*, 2005]. For instance, these bioclimatic variables include the annual mean temperature, mean diurnal temperature, annual precipitation, and precipitation of wettest quarter—variables considered important to model land suitability [*Evans et al.*, 2010; *Trabucco et al.*, 2010; *de Souza et al.*, 2014]. A principal components transformation (PCT) was implemented to reduce collinearity among the variables [*Jiménez-Valverde et al.*, 2008; *Silva et al.*, 2014b; *Martins et al.*, 2015]. The PCT generated 19 principal components (PC) from which we selected the first 6 PC as variables for the ENM. The first 6 PC accounted for more than 97% of the variation in the original bioclimatic data set.

The future climate scenarios data set includes two representative concentration pathways (RCP 4.5 and 8.5) and 17 global climate models (GCM) under each RCP, for a total of 34 climate models (Table 5-2). Data came from the CMIP5 (IPCC Fifth Assessment) with downscaling and calibration done by Worldclim [*Hijmans et al.*, 2005]. For the future climate ENM, the 6-PC transformation rule derived above is used to generate the variables for the ENM. In this way, future ENMs are comparable to the present ENM by using the same environmental variables and the same target species.

Table 5-2 – Name and code for the selected global climate models (GCM) with indication of the variable type for each representative concentration pathway (RCP)

GCM	Code	RCP 4.5	RCP 8.5
ACCESS1-0	AC	bioclimatic	bioclimatic
BCC-CSM1-1	BC	bioclimatic	bioclimatic
CCSM4	CC	bioclimatic	bioclimatic
CNRM-CM5	CN	bioclimatic	bioclimatic
GFDL-CM3	GF	bioclimatic	bioclimatic
GISS-E2-R	GS	bioclimatic	bioclimatic
HadGEM2-AO	HD	bioclimatic	bioclimatic
HadGEM2-CC	HG	bioclimatic	bioclimatic
HadGEM2-ES	HE	bioclimatic	bioclimatic
INMCM4	IN	bioclimatic	bioclimatic
IPSL-CM5A-LR	IP	bioclimatic	bioclimatic
MIROC-ESM-CHEM	MI	bioclimatic	bioclimatic
MIROC-ESM	MR	bioclimatic	bioclimatic
MIROC5	MC	bioclimatic	bioclimatic
MPI-ESM-LR	MP	bioclimatic	bioclimatic
MRI-CGCM3	MG	bioclimatic	bioclimatic
NorESM1-M	NO	bioclimatic	bioclimatic

Both ENM for sugarcane suitability and for amphibians distribution make use of the same data set and share the same spatial resolution. This approach facilitates the comparison and manipulation of the ENM, however, it imposes a limitation to the amphibians distribution. The spatial resolution of 2.5 arc-min used in this chapter may impose a strong assumption on the predictability of the species and their spatial distribution. Commonly, studies on the spatial distribution of amphibians employ a coarser spatial resolution to dilute the uncertainty of the presence of the species in the predicted area [*Silva et al.*, 2014a, 2014b; *Martins et al.*, 2015]. Thus, the interpretation of the amphibians ENM requires attention and recognize the uncertainty associated with the finer spatial resolution.

5.4.4 ENM algorithms

Importantly, several approaches are available to implement ENM [*Stockwell and Peterson*, 2002; *Wisz et al.*, 2008; *Duan et al.*, 2014; *Howard et al.*, 2014]. These approaches differ in the methods to predict the species' distribution and results. Three different approaches are tested: (i) MaxEnt, (ii) Random Forest, and (iii) Support Vector Machine. These approaches were selected given their ability to generate prediction outputs with greater accuracy and more stability [*Evans et al.*, 2010; *Duan et al.*, 2014; *Silva et al.*, 2014a].The MaxEnt is one of the most popular methods with several applications in the literature [*Elith and Leathwick*, 2009; *Evans et al.*, 2010]. This approach is derived from Shannon's information entropy [*Phillips et al.*, 2006]. Random Forest is a machine-learning approach that more recently has been used as an approach to ENM as it is an efficient algorithm for nonlinear and binary classification [*Breiman*, 2001; *Duan et al.*, 2014]. Support Vector Machine is a kernel-based machine-learning approach [*Burges*, 1998; *Muller et al.*, 2001; *Drake et al.*, 2006].

To identify which algorithm generated the ENM that best represented the set of conditions for the SAZ Classes, we employed True Skilled Statistics (TSS) as the assessment tool [*Allouche et al.*, 2006]. This statistic varies from -1 to +1, where negative values and <0.5 are considered no better than random and where a value closer to +1 is considered excellent. The use of TSS has advantages over other metrics for dichotomous presence-absence predictions of species distribution [*Allouche et al.*, 2006; *Garcia et al.*, 2013]. The TSS is a threshold-dependent measure. The receiver-operator curve (ROC) threshold is used in this research. The ROC threshold provides the value in which the model has the same number of omission and commission errors, thus reducing overfitting problems [*Duan et al.*, 2014; *Silva et al.*, 2014b]. This is a more precautionary threshold than the least presence training threshold [*Silva et al.*, 2014a; *Faleiro et al.*, 2015].

Finally, we compare the three algorithms to identify the best one considering the TSS. The comparison uses a repeated measures ANOVA to test the equality of the means for each sample given each algorithm [*Segurado and Araújo*, 2004; *Pearson et al.*, 2006; *Duan et al.*, 2014; *Silva et al.*, 2014a]. Thus, defining the best algorithm is not only the one with the highest TSS, but it also has the highest TSS over all samples for each SAZ Class.

5.5 Results

To calibrate and assess the best ENM for the SAZ Classes for the current climate (ENM-SAZ), we tested the Maxent (MXT), Random Forest (RDF), and Support Vector Machine (SVM) algorithms for each of the SAZ suitability classes (Figure 5-1). The high score for the TSS for the ROC threshold supports our claim that ENM can be used to model land suitability defined by the SAZ. All three algorithms presented a TSS >0.7, which is considered an excellent fit [*Allouche et al.*, 2006; *Garcia et al.*, 2013]; the only exception is the MXT for the SAZ R-Class. The RDF algorithm had the highest TSS values for all SAZ Classes. A repeated measures ANOVA confirms that the RDF is distinct from the other algorithms. Therefore, we focus our research on the analysis of the RDF approach to the ENM.

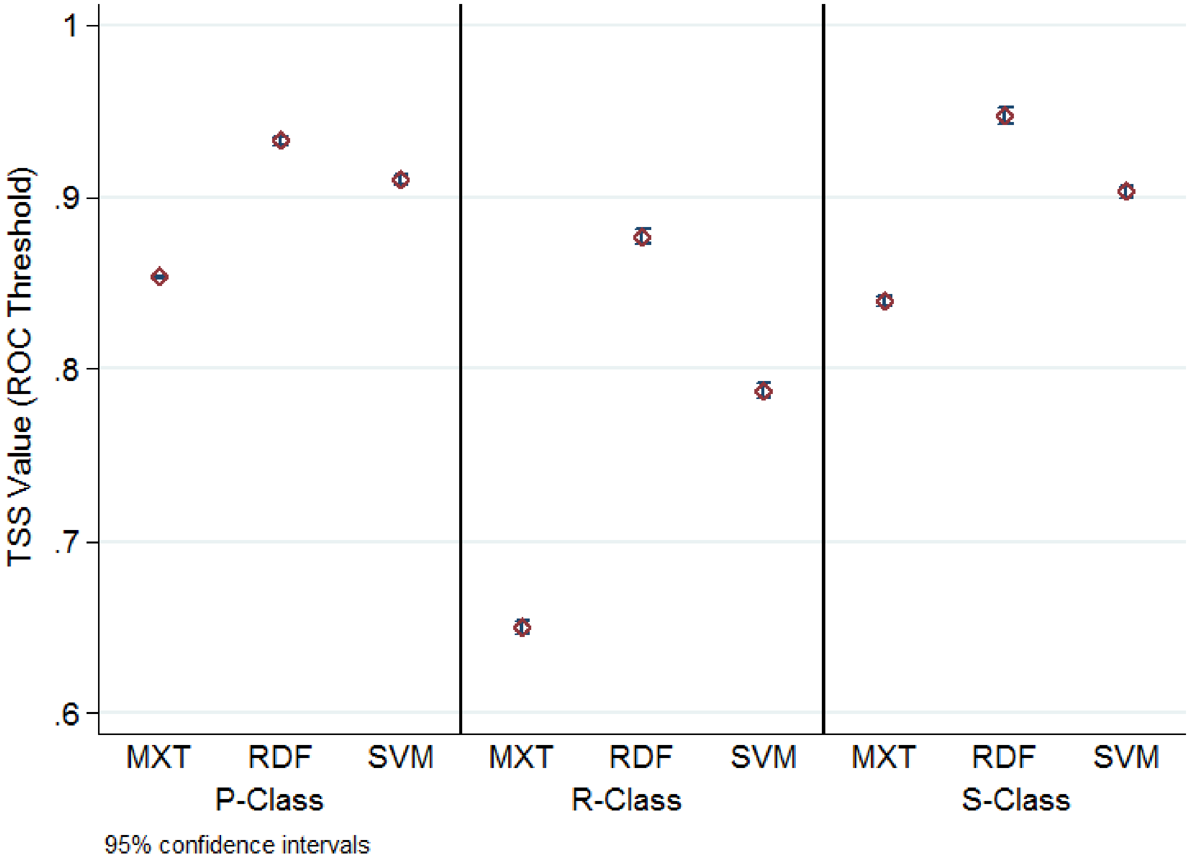

Figure 5-1 – Results of the ENMs developed considering the present climatic conditions. Algorithms are compared against each other for the different SAZ Classes. The evaluation used means (mid-points) and 95% confidence intervals (bars).

Figure 5-2 presents a comparison between the SAZ Classes and the ENMs developed for each of these classes. Given the spatial distribution of each class, the ENM resulted in different levels of accuracy and precision. The ENMs for the S-Class produced the more accurate representation of the original data set; nevertheless, the models for the P- and R-Classes also generated satisfactory output. Using the aggregate output of the ENMs for the 10 samples, the estimates for the SAZ S-Class (Figure 5–2.C) captured 99.95% of the original area with more than 91% of the area estimated by all ENMs. The ENMs for SAZ P-Class (Figure 5–2.A) estimated 99.94% of the area defined by the SAZ with more than 87% accounted by all ENMs.

For the SAZ R-Class (Figure 5–2.B), the ENMs estimated 98.93% of this class area and 62% of the area were predicted by all ENMs.

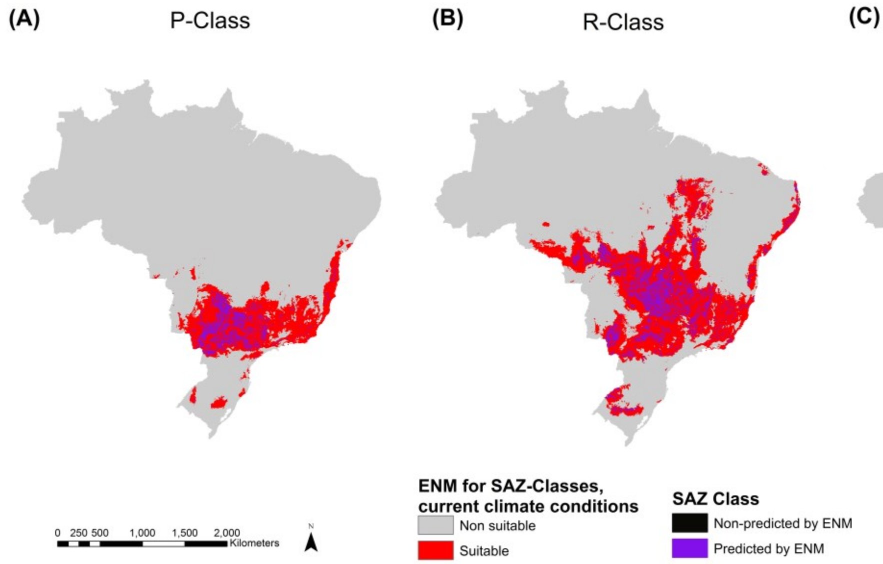

Figure 5-2 – Aggregate distributions for each SAZ Class generated by the RDF algorithm considering the ROC threshold under current climate conditions. Areas defined by the SAZ are overlaid to assist in the visual inspection of the results.

To evaluate the effects of climate scenarios we used 17 global circulation models (GCM) for two representative concentration pathways (RCP 4.5 and RCP 8.5) as the environmental layers for the RDF ENM. Figure 5-3 presents the results for all climate scenarios evaluated. For the ENM developed for the SAZ P-Class (highest suitability areas) under RCP 4.5, the mean value of suitable area for the current climatic conditions is 91 million ha, while the mean value for all models is 64% less at 29 million ha of suitable area (Figure 5–3.A). Under RCP 8.5 (Figure 5–3.D), the average for all models is slightly over 27 million ha. The results for the SAZ R-Class (regular suitability areas) show a smaller reduction than the P-Class, 61% compared to 64%. Under RCP 4.5 (Figure 5–3.B), the average for all ENMs is 48 million ha compared to 157 million ha of the suitable area estimated under the current climatic conditions. Under RCP 8.5 (Figure 5–3.E), the average for all ENMs is 43 million ha. For the SAZ S-Class (lowest suitability areas), the reduction in predicted area is the strongest, on average only 32% of the present area is expected to remain in this class by mid-century. Under RCP 4.5 (Figure 5–3.C), the average for all ENMs is 16.4 million ha compared to 66 million estimated under the current climatic conditions. Under RCP 8.5 (Figure 5–3.E), the average for all ENMs is 16.2 million ha.

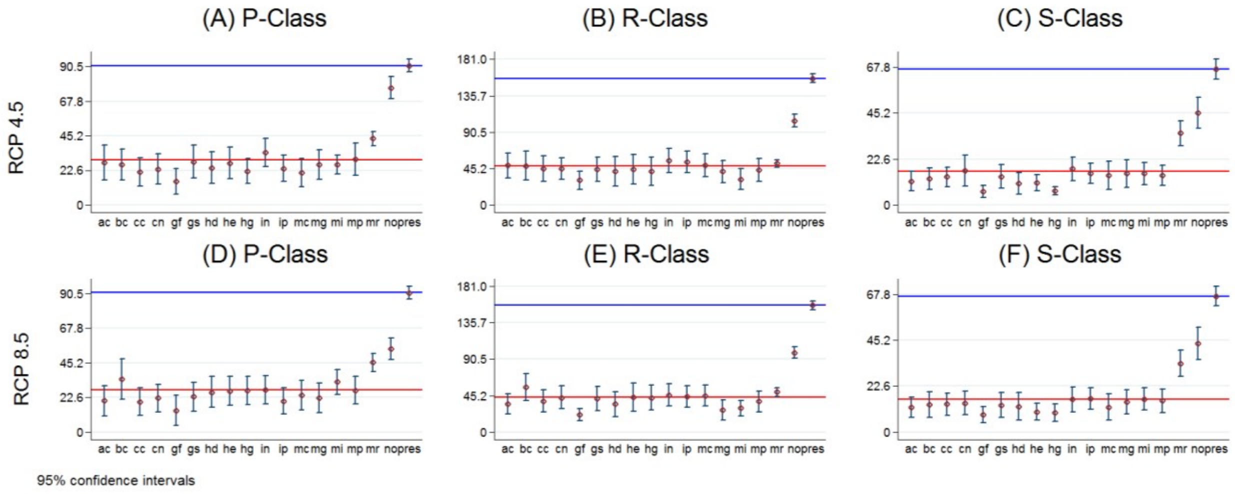

Figure 5-3 – Results for the ENMs giving future climate scenarios. Means are represented by mid-points and 95% confidence intervals are represented by bars, code for each global climate model is presented on the x-axis. The y-axis unit is in million hectares. Blue reference bars indicate the mean for the ENM under present climate conditions and the red reference bars show the average for all ENMs for the specific SAZ Class.

The results in Figure 5-3 indicate that for the case of sugarcane suitability, the difference between the two concentration pathways is small considering the average of all GCM scenarios and the estimates under present condition. However, Figure 5-3 does not present the spatial distribution of the areas predicted as suitable, which is important to consider given the economic and environmental impacts of climate change on land use decisions. To represent the spatial distribution and account for the spatial variability among models, we developed an ensemble of the 17 ENM-GCM using the ROC threshold for each SAZ-Class under RCP 4.5 and 8.5. The ensemble has the advantage of summarizing the results by presenting a probability distribution given the frequency that each pixel is predicted as suitable for sugarcane [*Machovina and Feeley*, 2013].

The ensembles (Figure 5-4) show that most areas have a probability of <0.5 to be predicted as suitable by mid-century. Only a few areas have a probability >0.7; we call these areas hotspots for suitability (on Figure 5–4 the hotspots are the areas in orange, and shades of red). For the P-Class, the ensembles (Figures 5–4.A and 5–4.B) indicate hotspots of suitability in the center-south, with smaller and less intense hotspots in the center-east. These hotspots have an area of 3 million ha for each RCP. Whereas for the R-Class (Figures 5–4.C and 5–4.D), the main suitability hotspots are in the center of Brazil, with smaller hotspots in the neighboring states to the east. For R-Class RCP 4.5 (Figure 5–4.C), the hotspot areas sum up to 2.6 million ha; whereas under RCP 8.5 (Figure 5–4.D), the hotspot areas equals 0.8 million ha. Notably, the probability of R-Class is low in the center-west region of Brazil. For the S-Class (Figures 5–4.E and 5–4.F), the ensembles present a coastal distribution of hotspots, with areas of 1.2 million and 0.6 million under RCP 4.5 and RCP 8.5 respectively.

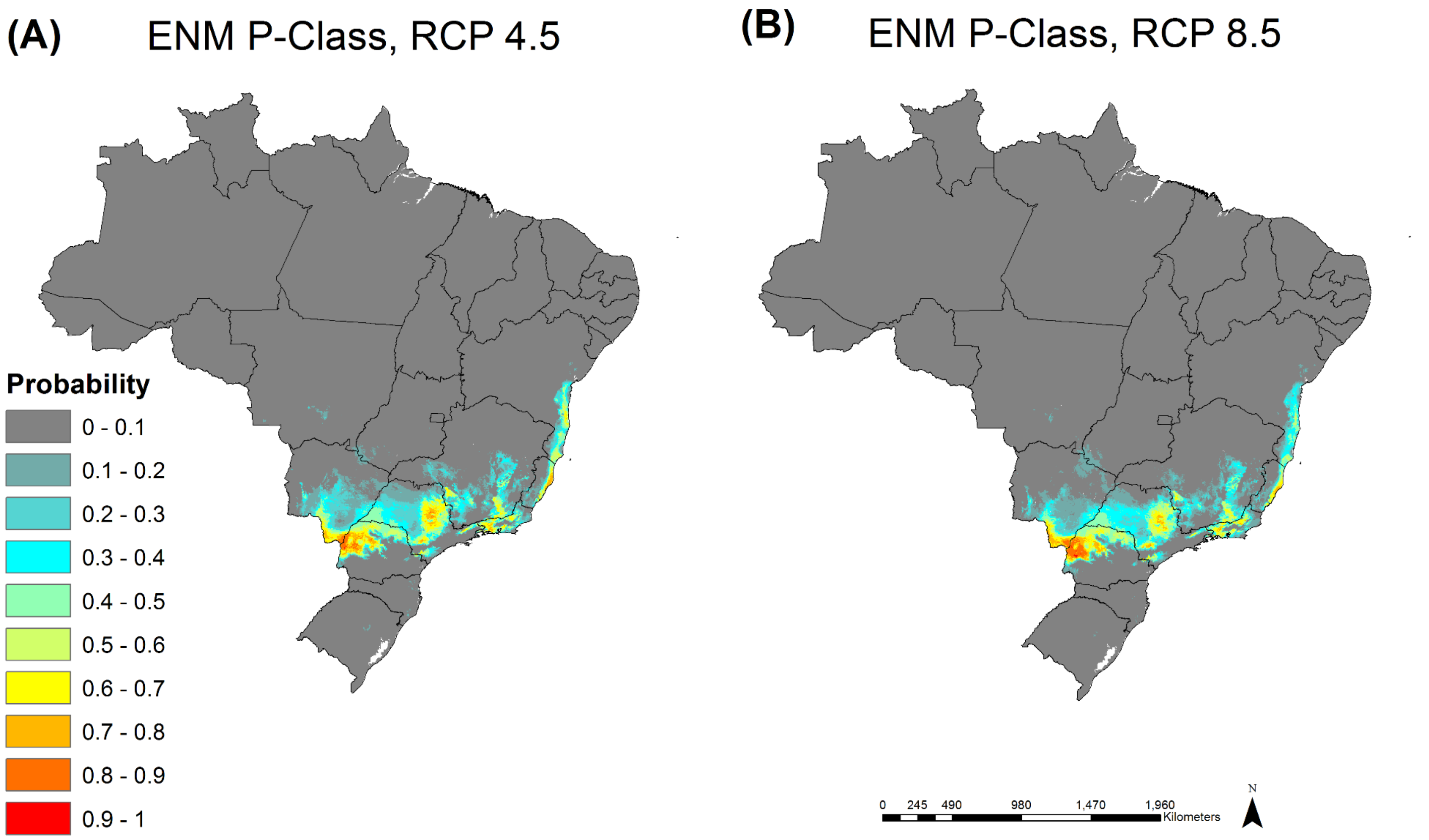

Figure 5-4 – Ensembles of future distribution of suitable areas for sugarcane in Brazil. (A) and (B) are the ensembles for the 17 ENMs for the P-Class under RCP 4.5 and 8.5 respectively. Areas with colder colors have a low probability and areas with warmer colors have a high probability of being suitable.

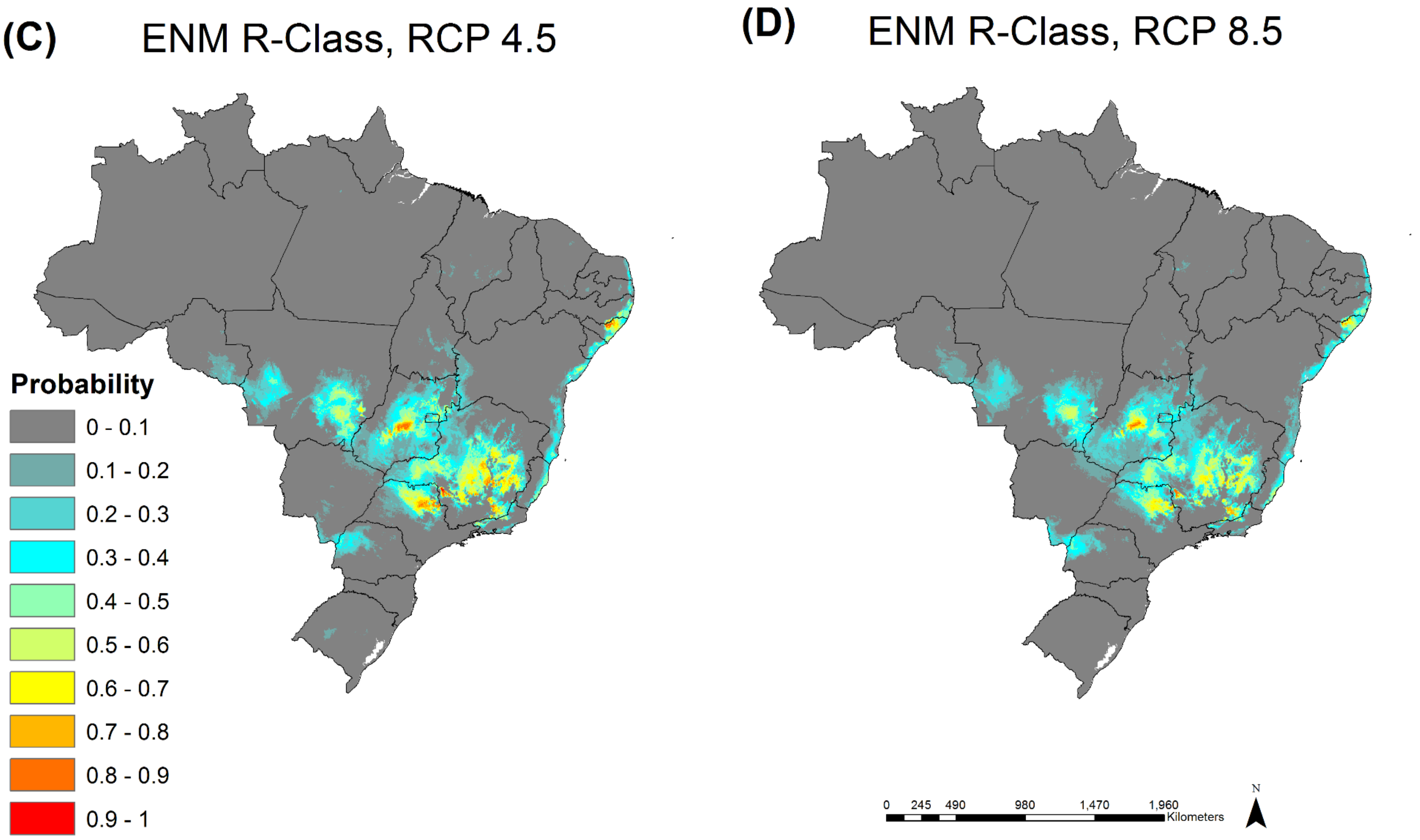

Figure 5-4 (cont.) – Ensembles of future distribution of suitable areas for sugarcane in Brazil. (C) and (D) are the ensembles for the 17 ENMs for the R-Class under RCP 4.5 and 8.5 respectively. Areas with colder colors have a low probability and areas with warmer colors have a high probability of being suitable.

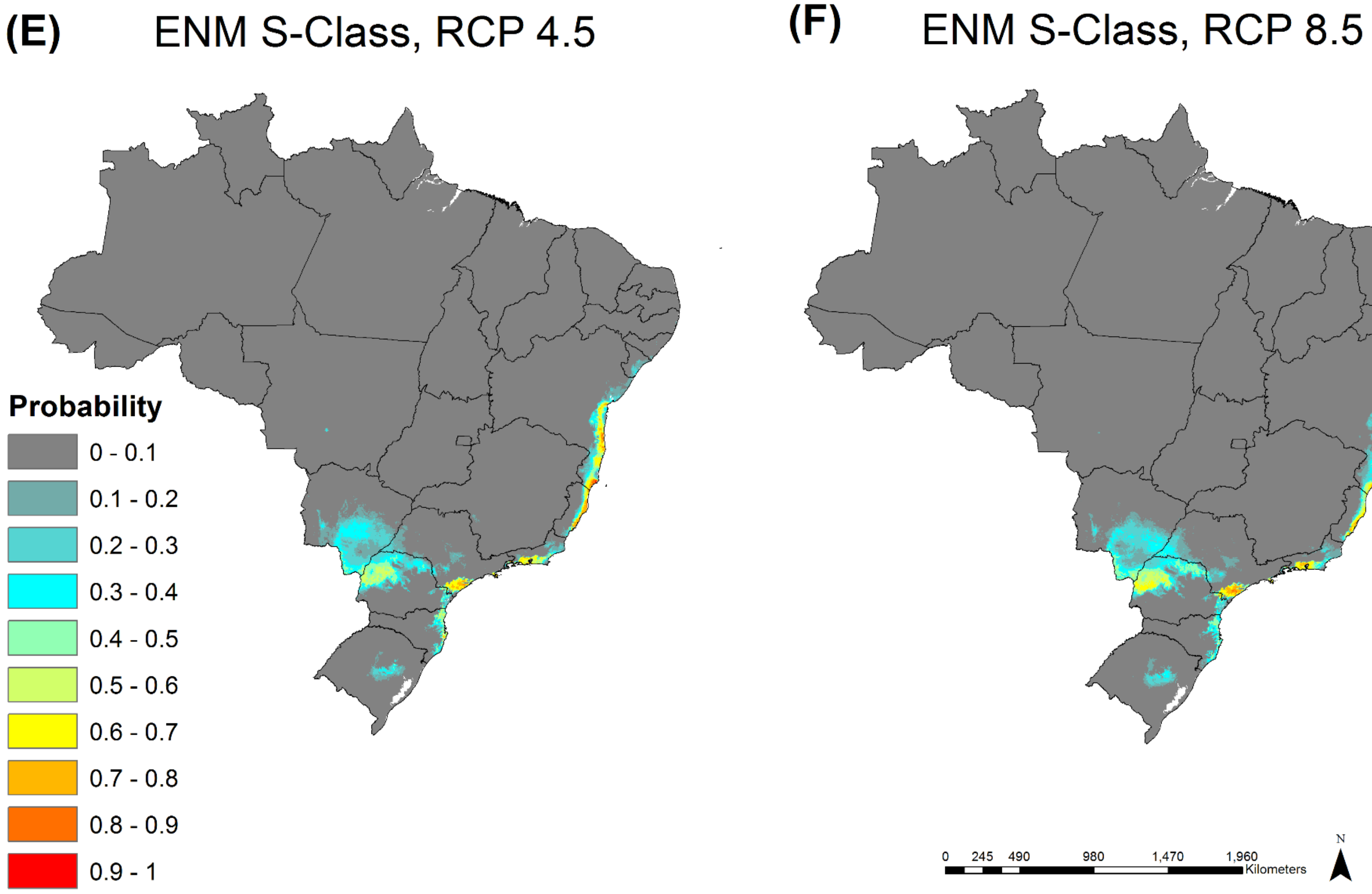

Figure 5-4 (cont.) – Ensembles of future distribution of suitable areas for sugarcane in Brazil. (E) and (F) are the ensembles for the 17 ENMs for the S-Class under RCP 4.5 and 8.5 respectively. Areas with colder colors have a low probability and areas with warmer colors have a high probability of being suitable.

The ensembles can be used to incorporate a new dimension to land use zoning policies, such as the SAZ policy. Currently, the SAZ considers the previous climate information to establish the area's suitability [*Manzatto*, 2008; *Lucon and Goldemberg*, 2010]. We propose that zoning policies can incorporate the climate change scenarios through ENM ensembles. By incorporating the ENM results, zoning can present the uncertainty of each area to maintain its suitability into the future or the risk of losing suitability because of climate change. This information can help agents to incorporate the climate change risk into their decision-making processes [*Rounsevell et al.*, 2013].

To show how the SAZ could incorporate the results from the ENM ensembles, we extracted the suitability probability only for the areas appointed as suitable by the SAZ (Figure 5-5). Currently, the SAZ identifies only the difference between suitable and nonsuitable and among the suitability classes [*Manzatto et al.*, 2009]. By incorporating climate change, areas can also be differentiated by their climate change vulnerability. For instance, the P-Class is considered readily available and the best investment. However, by incorporating the probability of enduring climate change it is possible to differentiate the areas in this class; and assuming that low vulnerability is more desirable, areas with this trait would be the target for sugarcane expansion.

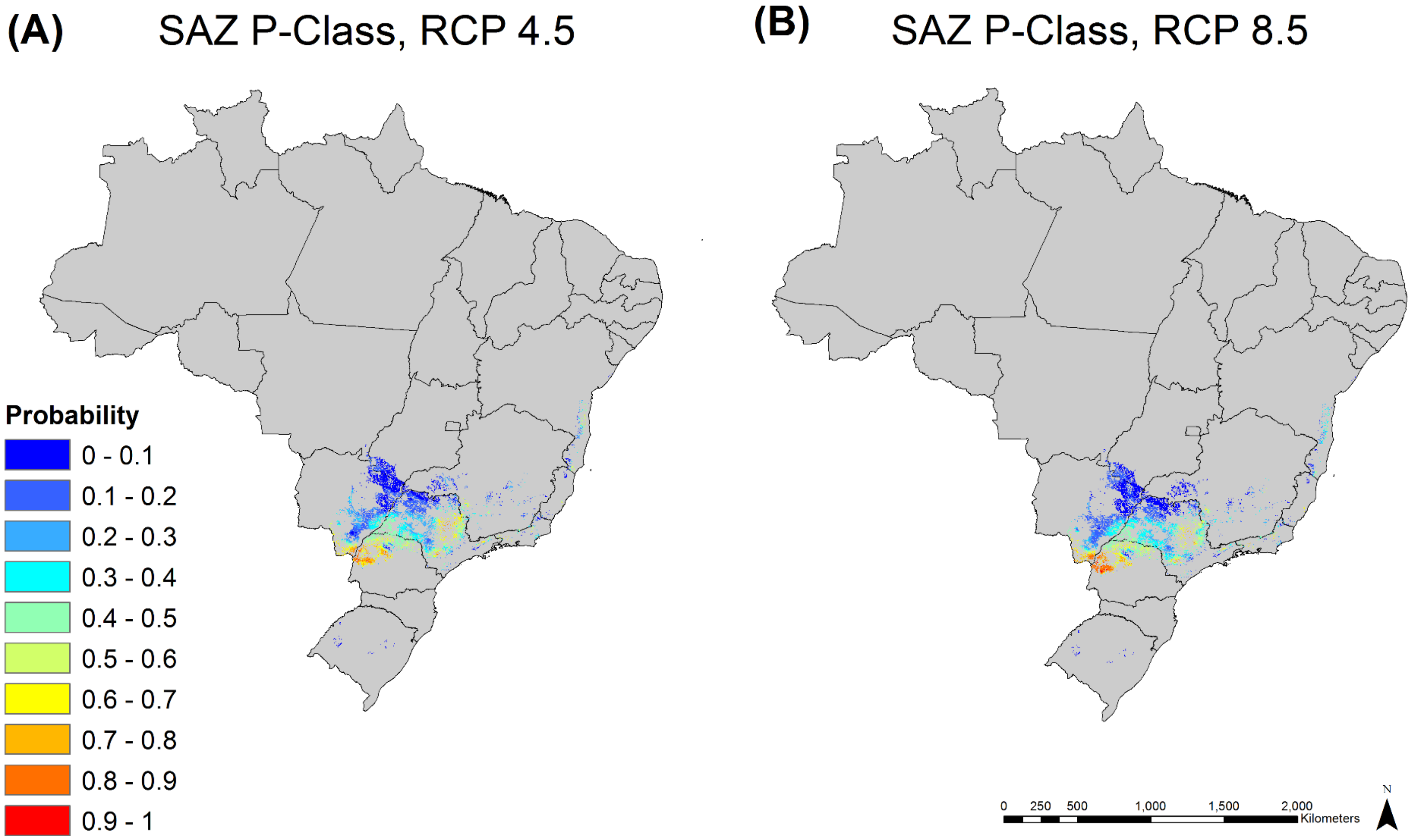

Figure 5-5 – Sugarcane Agroecological Zoning associated with the probability of future distribution of suitable areas. (A) and (B) are the ensembles for the 17 ENM for the P-Class under RCP 4.5 and 8.5 respectively. Areas with colder colors have a low probability; areas with warmer colors have a high probability of being suitable.

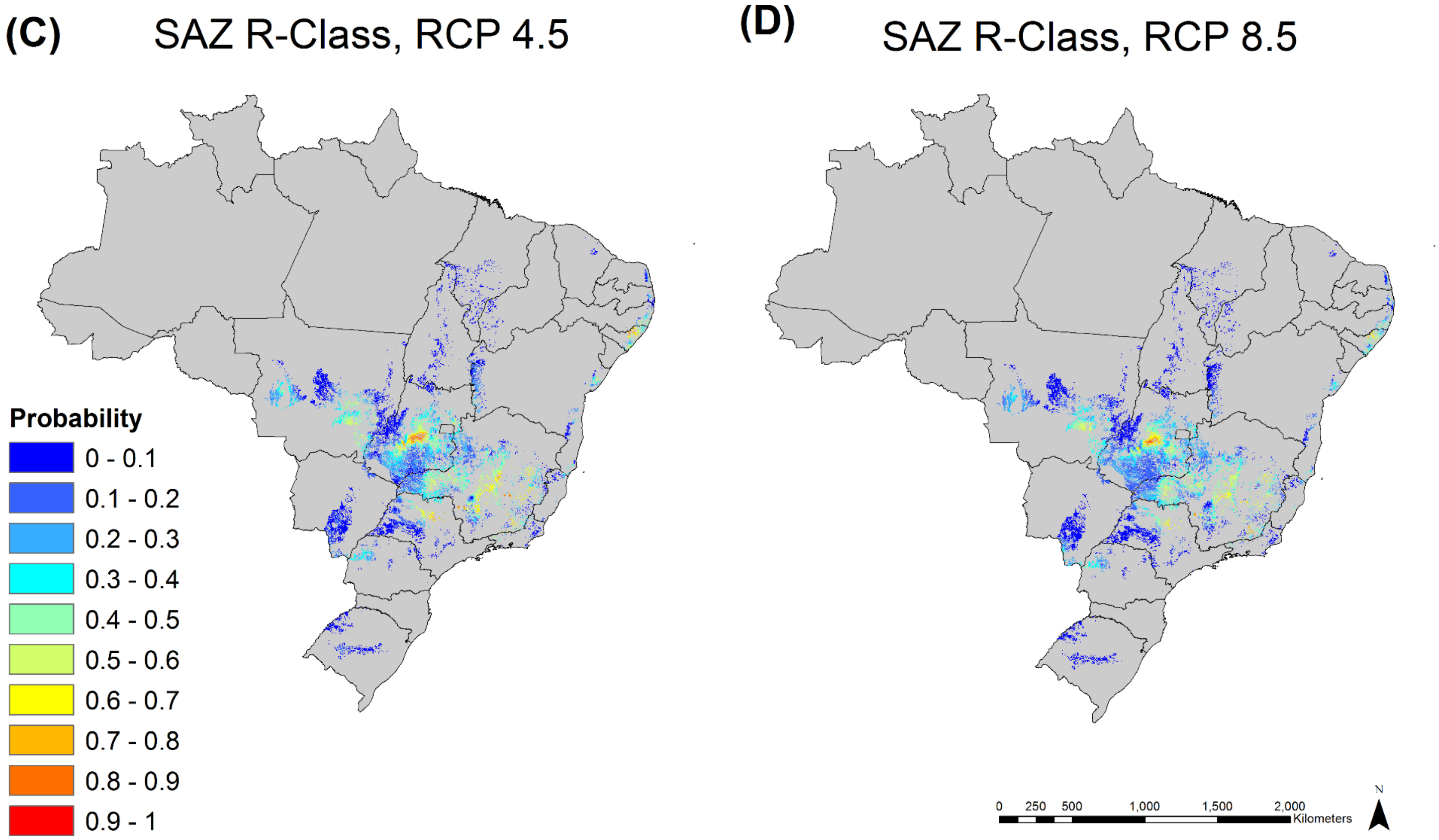

Figure 5-5 (cont.) – Sugarcane Agroecological Zoning associated with the probability of future distribution of suitable areas. (C) and (D) are the ensembles for the 17 ENM for the R-Class under RCP 4.5 and 8.5 respectively. Areas with colder colors have a low probability; areas with warmer colors have a high probability of being suitable.

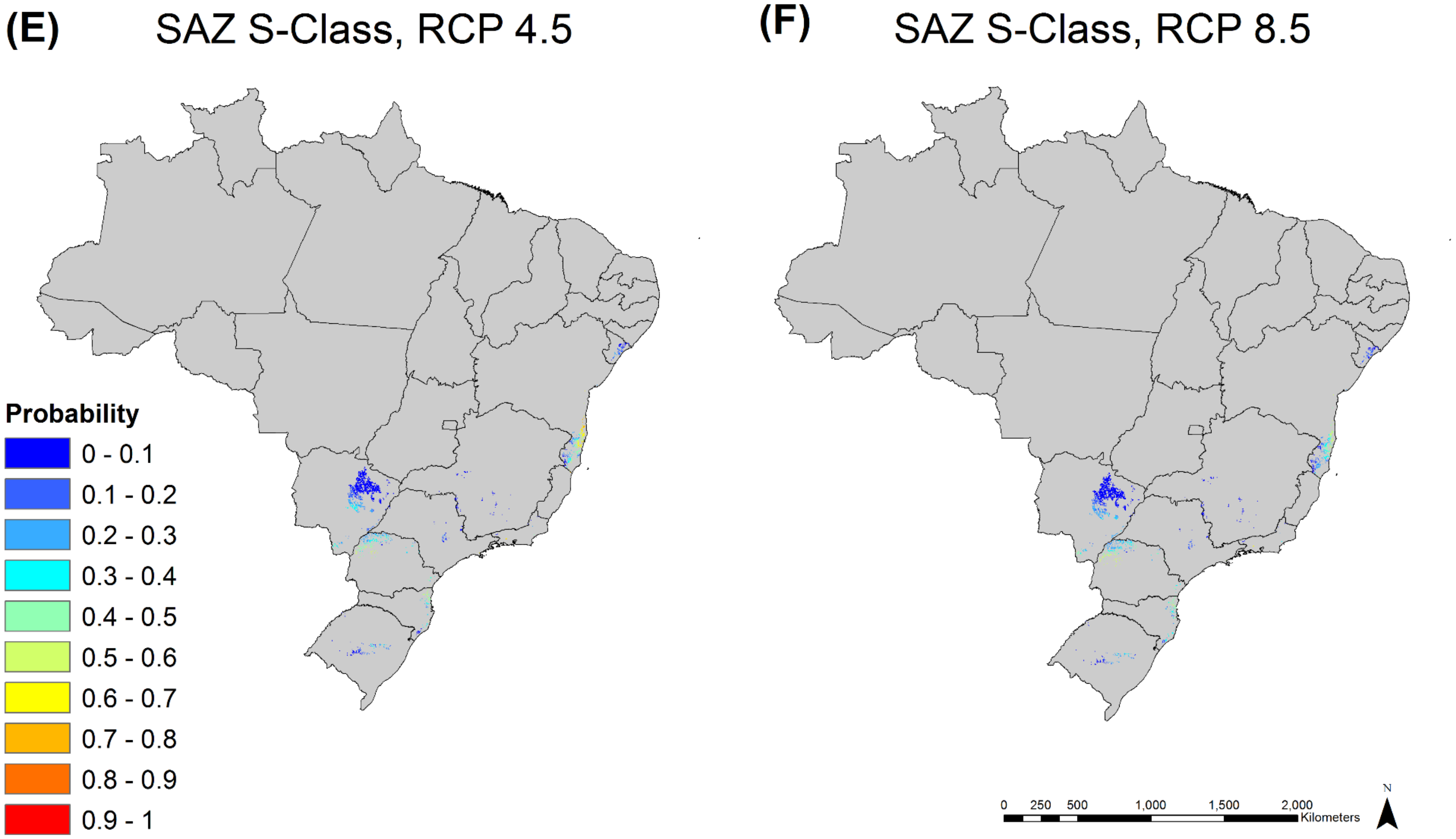

Figure 5-5 (cont.) – Sugarcane Agroecological Zoning associated with the probability of future distribution of suitable areas. (E) and (F) are the ensembles for the 17 ENM for the S-Class under RCP 4.5 and 8.5 respectively. Areas with colder colors have a low probability; areas with warmer colors have a high probability of being suitable.

For instance, Figures 5–5.A and 5–5.B demonstrate that high probability values for SAZ P-Class can be found in the south of Brazil, while areas in the center have a low probability of enduring climate change. For the SAZ R-Class (Figures 5–5.C and 5–5.D), areas to the south and to the north have low probability. This is interesting considering that the center-north region (the region called as Matopiba) is the new agricultural frontier in Brazil, such result indicates that sugarcane should not expand to the Matopiba given the vulnerability to climate change. The areas with the highest probability (low vulnerability) are in the center of Brazil. The SAZ S-Class is the one that may lose the most area because of climate change (Figures 5–5.E and 5–5.F). When only areas indicated by the SAZ are considered, there are no hotspot areas with a probability >0.8, indicating that S-Class is extremely vulnerable to climate change.

5.6 SAZ and conflict with biodiversity

For this study, the focus is on the amphibian species living in the Cerrado biome and its conflict with land suitability for sugarcane. The conflict arises because of the intensity of agricultural activities during harvest and implementation phases of the sugarcane [*Martinelli and Filoso*, 2008; *Verdade et al.*, 2012; *Schiesari and Corrêa*, 2016]. The baseline is the sum of the ENM for 68 species (Figure 5–6.A). The region with the highest concentration of species is the southeast of the Cerrado, with a maximum number of 47 species potentially using the same area. In contrast, the region with the lowest concentration is the north portion of the biome, a drier and warmer region. The lowest potential occupation is 5 species.

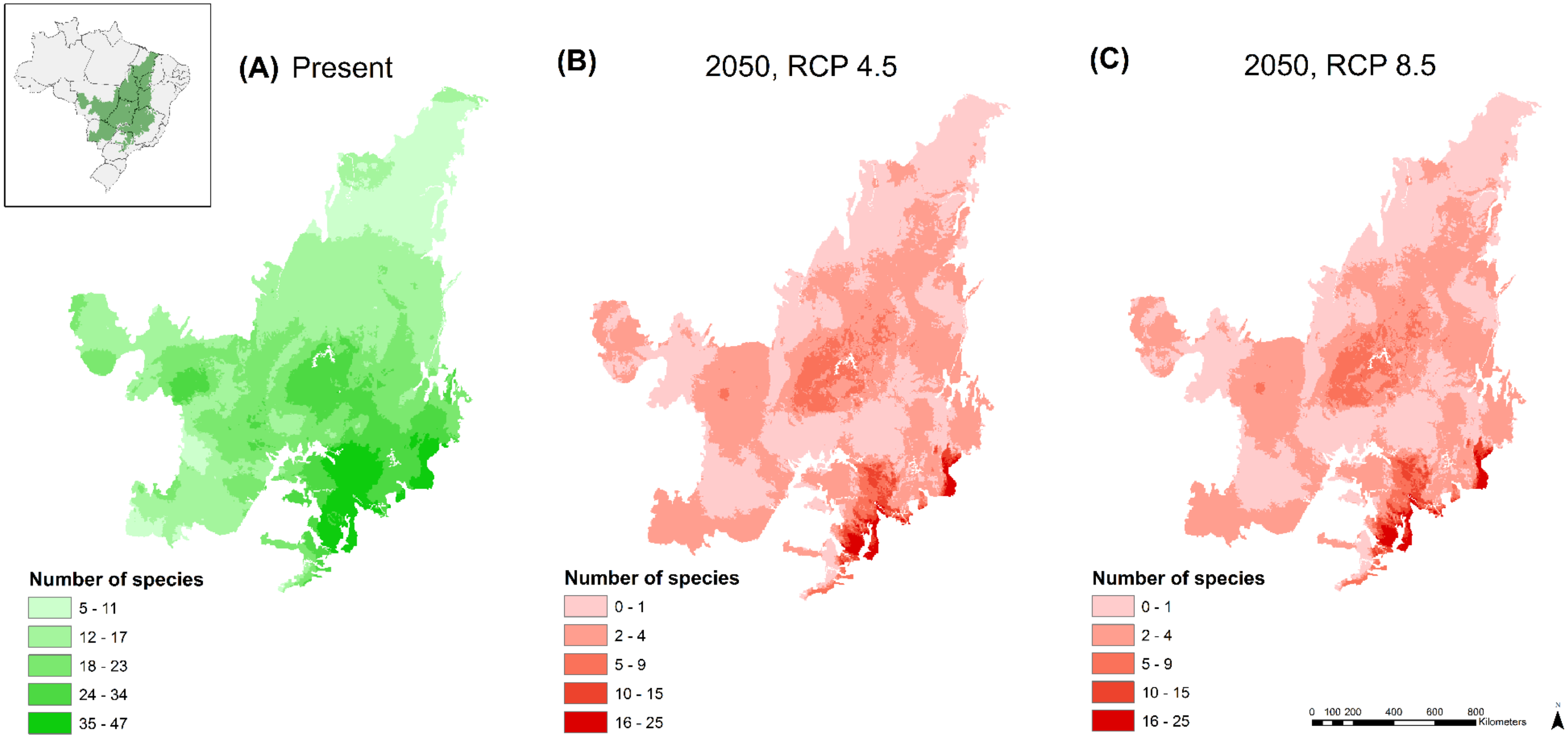

Figure 5-6 – Ensembles of ENM for 68 amphibians species. (A) is the ensemble under climatic conditions for the 2000s. Darker green indicates a larger number of species predicted for the area. (B) is the ensemble of an individual ensemble of each 68 species considering the RCP of 4.5. Darker red indicates a larger number of species predicted for the area. (C) is the ensemble of an individual ensemble of each 68 species considering the RCP of 8.5. Darker red indicates a larger number of species predicted for the area.

When climate change is considered, the spatial distribution of the number of species changes (Figures 5–6.B and 5–6.C). There is a loss of species richness with the highest potential occupation at 25 species in both representative concentration pathways. More than that, the lowest is reduced to "0" showing there will be areas are not suitable for the amphibian species considered in this study.

Notably, climate change is not the only factor influencing the future of amphibians in the Cerrado. It is important to also consider the exposure of amphibians to agricultural land use. Zoning policies may increase pressure on vulnerable species by indicating areas that are more suitable for production without accounting for the biodiversity and ecosystem function of the landscape. Figure 5-7 presents the potential risk of threat to species richness in each area of the SAZ by combining the results of the climate ensemble for the suitability areas in the SAZ (Figure 5-5) with the results of the climate ensemble for the amphibian species (Figures 5–6.B and 5–6.C).

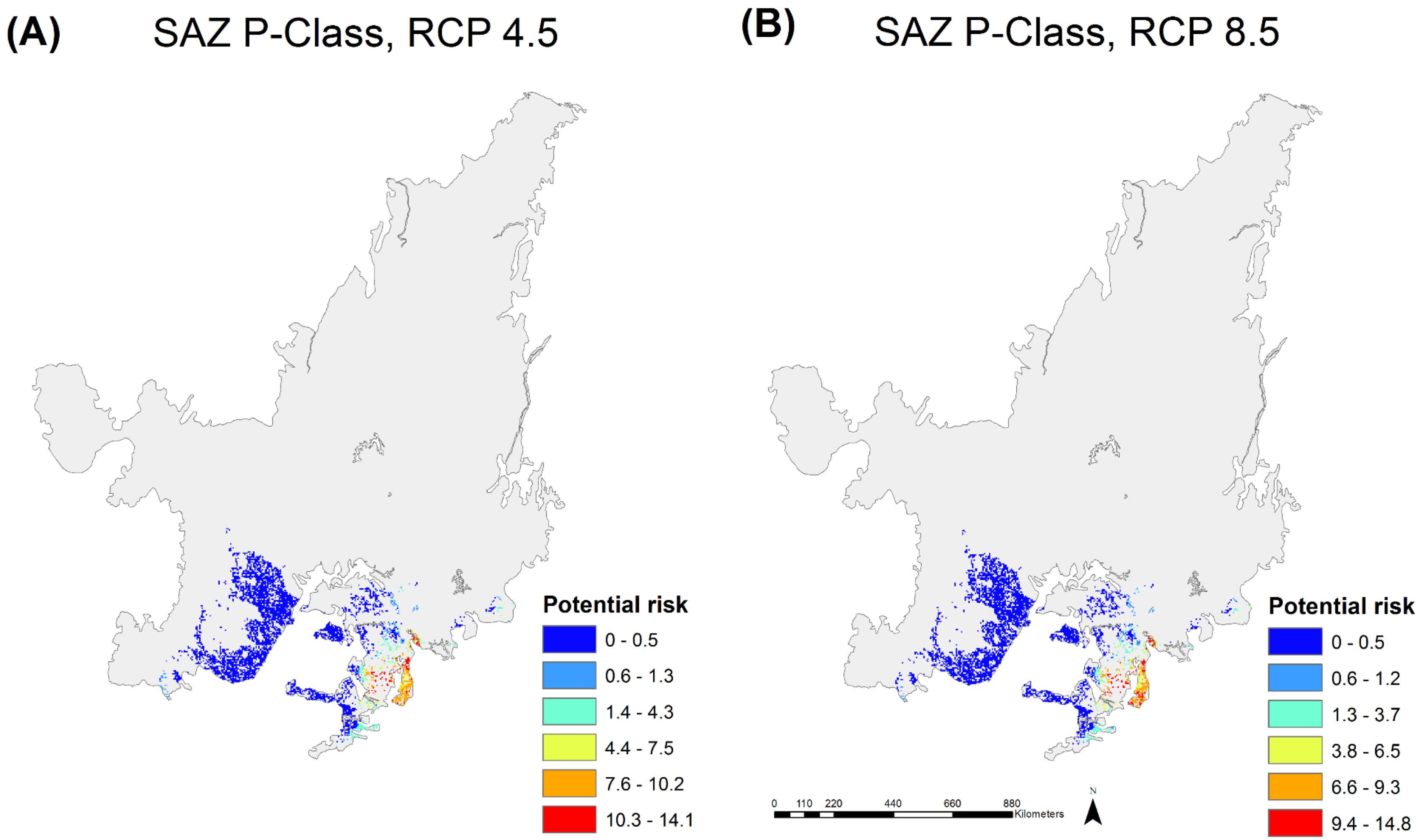

Figure 5-7 – Potential risk for amphibian species given mid-century climatic conditions and the presence of areas suitable for sugarcane production. (A) and (B) are the potential risk for the P-Class under RCP 4.5 and 8.5 respectively. Areas with colder colors have a low risk, and areas with warmer colors have a higher risk.

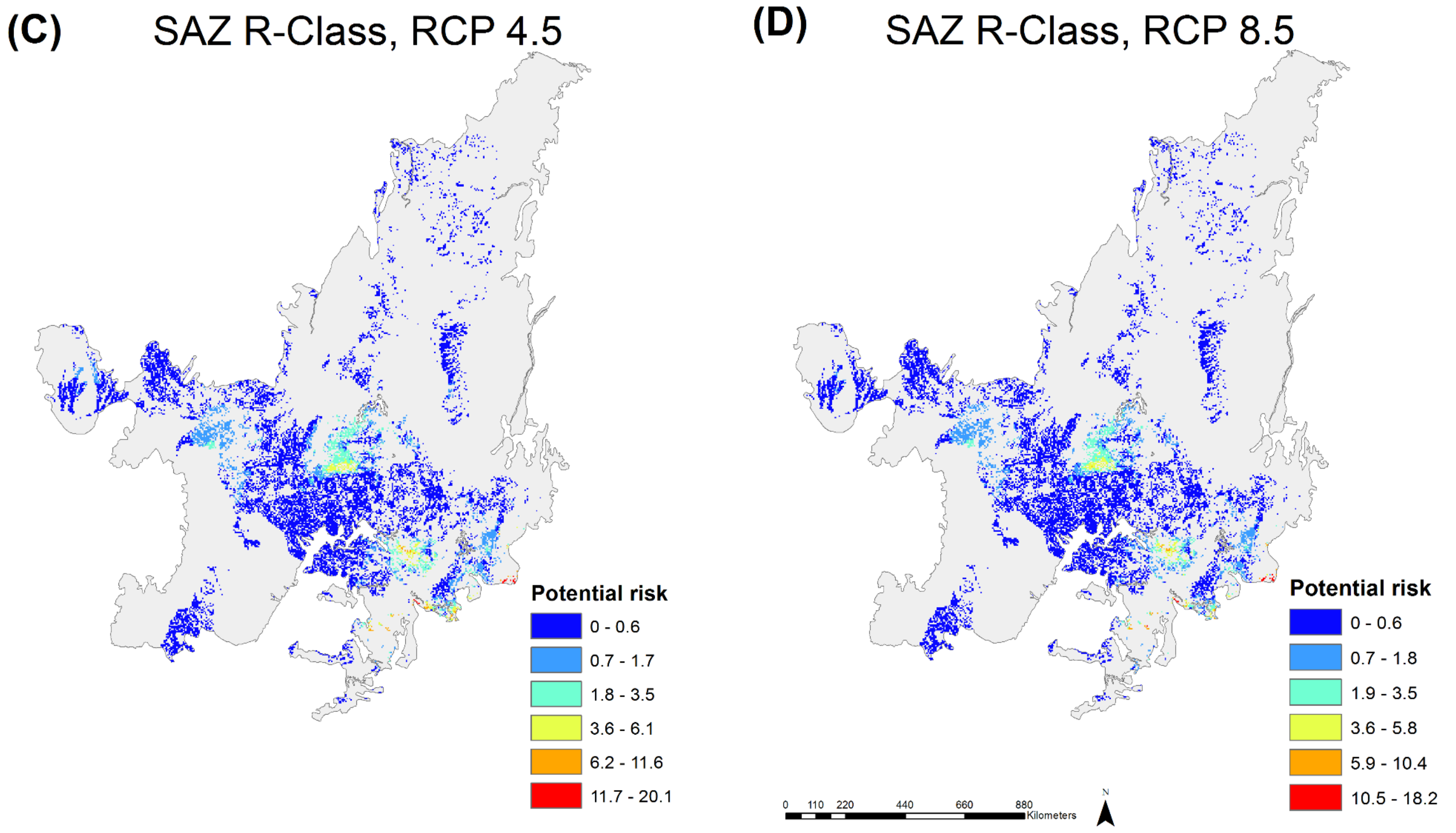

Figure 5-7 (cont.) – Potential risk for amphibian species given mid-century climatic conditions and the presence of areas suitable for sugarcane production. (C) and (D) are the potential risk for the R-Class under RCP 4.5 and 8.5 respectively. Areas with colder colors have a low risk, and areas with warmer colors have a higher risk.

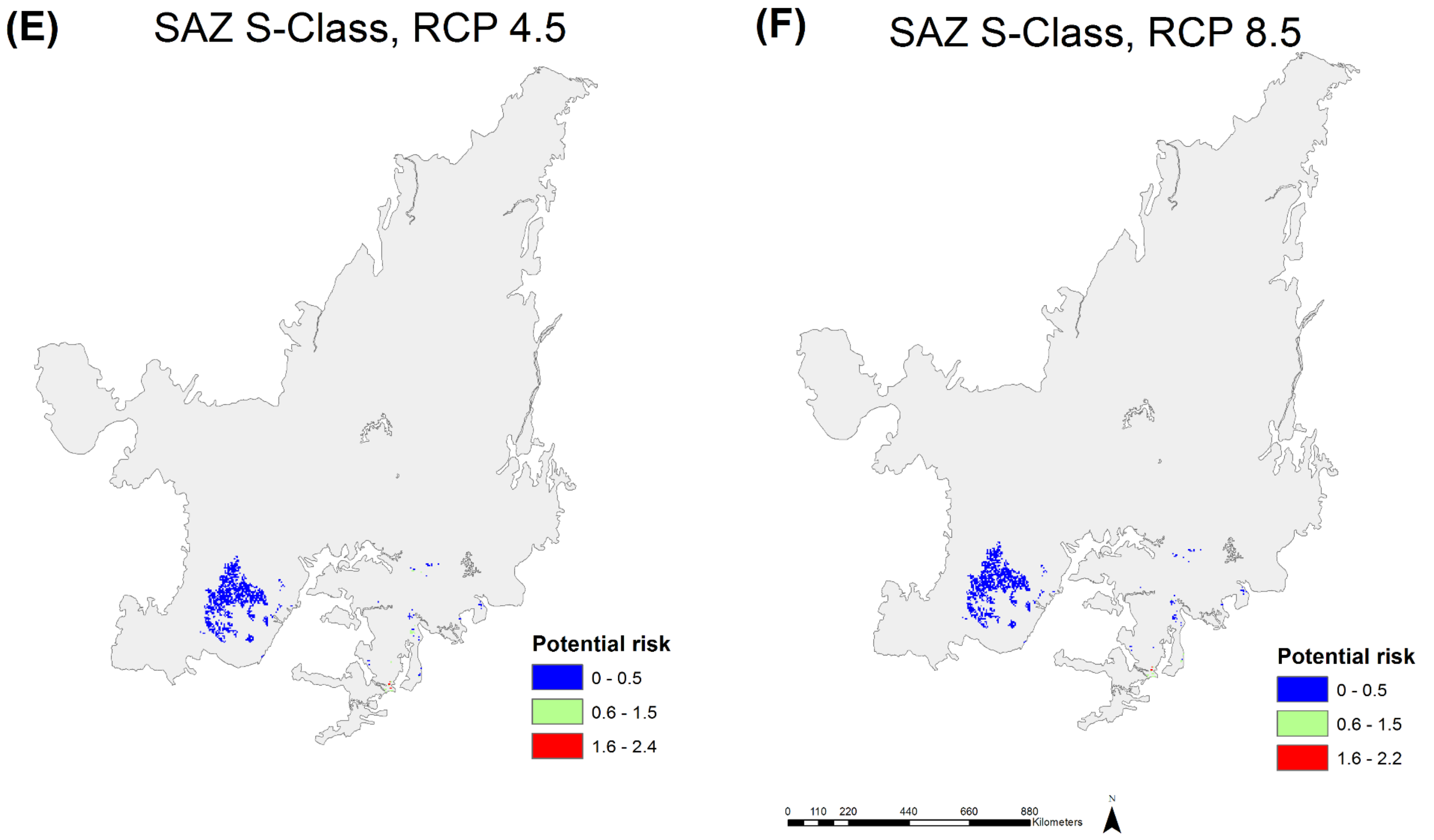

Figure 5-7 (cont.) – Potential risk for amphibian species given mid-century climatic conditions and the presence of areas suitable for sugarcane production. (E) and (F) are the potential risk for the S-Class under RCP 4.5 and 8.5 respectively. Areas with colder colors have a low risk, and areas with warmer colors have a higher risk.

In the context of Figure 5-7, areas with low vulnerability to climate change for both sugarcane suitability and amphibians are the hotspots for conservation (areas in red) because these areas are desired for two competing uses. There is a small number of hotspots: for P-Class (Figures 5–7.A and 5–7.B) the hotspot areas are present in 2% of this class, or 214,000 ha from a total of 8.9 million ha. Hotspots are rare in the R-Class with the presence of only 0.1% of its 30.9 million ha. For the S-Class, hotspots are even rarer: present in 0.5% for RCP 4.5 (Figure 5–7.E) and 0.2% for RCP 8.5 (Figure 5–7.F) from its 2.2 million ha.

This result is conditional on the definition of land suitability resistance to climate change and the assumption that areas with high vulnerability to climate change will not be converted to sugarcane. The literature contains no consensus related to exposure to land use change and loss of species richness. For this discussion, making the assumption that climate vulnerability defines land use and, consequently, the impact on biodiversity was appropriate. This rationale puts forward the importance of incorporating climate change risk in land use policies, such as the SAZ.

5.7 Discussion and conclusions

The expansion of bioenergy production expansion in Brazil has been analyzed through a zoning policy, SAZ, which aims at improving the sustainability of sugarcane expansion. The SAZ is a land use policy that employs a land suitability model to define which areas are suitable and which areas are nonsuitable for the expansion. Considering the increasing demand for biofuel ethanol, and for sugar, the SAZ can play an important role in the future expansion of sugarcane.

Studies on the future of agricultural production have cautioned about severe impacts of climate change on agricultural production leading to changes in the distribution of agricultural areas [*Schlenker and Lobell*, 2010; *Machovina and Feeley*, 2013; *Pugh et al.*, 2016], yield loss [*Nelson et al.*, 2014; *Rosenzweig et al.*, 2014; *Pugh et al.*, 2016], and food security [*Campbell et al.*, 2016; *Kline et al.*, 2016]. However, the SAZ policy does not incorporate any information related to climate change.

The SAZ's lack of information on the impacts of climate change on the land suitability of sugarcane can have consequences for the sugarcane industry and for the environment. Considering the definition of land suitability from the SAZ, an ENM could create a spatial distribution that would meet the conditions for suitability (Figure 5-1). From this model and from bioclimatic variables for 17 CGM, maps of land suitability under climate change were developed to investigate the impacts of climate change on the land suitability of areas defined as suitable by the SAZ. The overall finding is that the SAZ is not resistant to climate change with a reduction of more than 60% of the total area; more importantly, areas defined as suitable by the SAZ are vulnerable to climate change. Considering climate-change-resistant areas with a probability of prediction above 60%, only 11% of P-Class, 4% of R-Class, and 4% of S-Class would be considered resistant. Stricter criteria of 80% of probability, would result in only 3% of P-Class, 0.5% of R-Class, and 0% of S-Class.

Given that the SAZ is influencing agents' decisions, these results claim that the land will not exhibit the expected productivity. Once the impacts of climate change begin to continuously affect farmers and the industry, these agents may lose trust in the coordinating efforts from the government. This consequence can promote an expansion with large environmental impacts, as the expansion that occurred in the state of São Paulo during the period of 1950 to 1980 [*Martinelli and Filoso*, 2008; *Aguiar et al.*, 2011; *Martinelli et al.*, 2011].

The development of land use zoning policies with an assessment of climate change endurance facilitates the coordination of actions between agents. The solution proposed by this research to incorporate climate change into the SAZ is to create an ensemble of the climate change scenarios, identifying the areas that have a higher probability of resisting climate change. For this, the government can update the SAZ and make explicit the climate change risk of each area.

With the SAZ combining land suitability and climate change risk, agents can make more informed decisions. For instance, farmers may incorporate the risk of climate change by selecting different areas to pursue their production or by using different techniques [*Berry et al.*, 2006; *Beck et al.*, 2010; *Rounsevell et al.*, 2013]. Companies can use this information to focus their research to supply technological packages to specific needs [*Lobell et al.*, 2008].

The government can also use this information to consider the SAZ criteria. If the cost of adapting the sugarcane production to the new climate condition is too expensive, certain areas can be reclassified from suitable to nonsuitable. On the other side, areas that currently are nonsuitable but with climate change will have the correct conditions may be reclassified as suitable under the SAZ. However, the update must ensure that the basic conditions imposed by the SAZ continue to be followed, thus avoiding deforestation and competition with food production.

With the exception of avoiding deforestation and expansion to certain biomes, the impact of sugarcane on the environment is not considered in the SAZ. This chapter examined the conflicts between amphibian habitats and sugarcane suitable areas by 2050 in the Cerrado biome. The Cerrado is the new frontier of sugarcane production and a biodiversity hotspot. For this analysis, the impacts of climate change on habitat were significative and later aggravated by the competition with the SAZ. After incorporating the impacts of climate change on habitat (Figure 5-6), species richness diminished from 47 to 25, and areas with <2 species predicted became the most common result. The analysis of the conflict between SAZ and amphibians resulted in the identification of future conservation hotspots (Figure 5-7). These areas have a high climate change resistance for sugarcane suitability and a high number of species using it as potential habitat.

In conclusion, climate change, land use policies, and biodiversity are deeply interwoven. The framework developed in this chapter examined these connections by focusing on the SAZ land use policy. The analysis and results show that the areas defined by SAZ as suitable have a low probability of maintaining this condition by mid-century. The incorporation of climate change resistance is required for the SAZ to fulfill its goals of organizing and to coordinate a sustainable expansion of sugarcane in Brazil.

Furthermore, this research indicates the need to consider a revision of the SAZ criteria and classification of areas, given that areas currently classified as suitable are not suitable under climate change. This mismatch weakens the SAZ and the enforcement of its zonation.

Finally, the second analysis focused on the spatial conflict between sugarcane suitable areas and amphibian habitat in the Cerrado. Amphibia is the class facing the highest rate of decline in the world [*Becker et al.*, 2007; *Fonseca et al.*, 2013], thus it is a good proxy for the biodiversity decline in the Cerrado. The SAZ P-Class, which is the most suitable area, also has the largest area presenting a high potential risk for amphibians.

The SAZ is a policy that needs improvements to remain relevant and to fulfill its purpose. The incorporation of climate change into policies is not a common practice yet [*Lobell et al.*, 2008], but current research [*Olesen and Bindi*, 2002; *Berry et al.*, 2006; *Schlenker and Lobell*, 2010] is proving that it is a pressing need. This is an opportunity for Brazil to continue to have a leadership role in climate politics.

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Chapter 6 - Conclusion

This dissertation focused on the new cash crop that arrived at the Cerrado, sugarcane. Even though sugarcane existed in the region before, it was not a traditional nor a representative crop of the region. This context started to change in 2003 with the rise in demand and a new wave of investments in sugarcane mills. From 2005 to 2013, the Cerrado became the new frontier of the sugarcane industry, expanding its ethanol and sugarcane production faster than any other region in Brazil [*Shikida*, 2013].

The expansion of biofuels and the added pressure to the agricultural system drew the attention of several researchers [*Searchinger et al.*, 2008a; *Rudel et al.*, 2009; *Tilman et al.*, 2009; *Lambin et al.*, 2013; *Leal et al.*, 2013; *Goldemberg et al.*, 2014; *Lossau et al.*, 2015], but few focused on the Cerrado. This gap in the literature proved to be significant, especially considering the high rates of deforestation and agricultural expansion in this biome [*Brasil*, 2015]. The Cerrado, with a unique and rich biodiversity of plants and animals, is under a growing threat given the increasing anthropomorphic use of its land [*Klink and Machado*, 2005; *Carvalho et al.*, 2009]. Thus, more research is needed on land change dynamics occurring in this biome.

Sugarcane is a plant with a highly efficient photosynthesis process, high yield potential per hectare, and as a perennial crop, it is well adapted to tropical climate conditions (Goldemberg and Guardabassi, 2009; Buckeridge et al., 2012). Additionally, there is a spatial constraint to this production as sugarcane starts to lose its content soon after being harvested, consequently reducing the amount of sugar and ethanol obtained. This limitation constrains the location of sugarcane fields to areas close to mill facilities [*Neves et al.*, 1998]. The arrival of new mills in the states of Goiás and Mato Grosso do Sul accelerated sugarcane acreage expansion from 0.3 to 1.4 million ha from 2005 to 2013.

The demand for land has raised concerns on how sugarcane expansion is changing farmers' land use decision processes. Specific concerns included land competition between food and fuel production, the addition of new land to agricultural production (increase in deforestation), and impacts on biodiversity. My contribution is to present an evaluation of sugarcane expansion looking at its drivers, the farmers' decision and land use responses, and the future of this expansion.

The findings in Chapter 2 concerning the drivers of this movement and establishment of the new frontier in the states of Goiás and Mato Grosso do Sul can be divided into three main points: (1) the consolidation of the traditional areas and stronger enforcement of environmental legislation, especially in São Paulo State; (2) the attractive conditions in the Cerrado's states such as good agricultural conditions, affordable land prices, and favorable state-level fiscal incentive policies; and (3) the importance of governmental policies at federal, state, and municipal levels. An important element of the ethanol industry in Brazil is the price difference between hydrous ethanol and the blend of gasoline and anhydrous ethanol because it sets the demand for ethanol. The federal government sets the base price for fuels in Brazil, thus influencing the competitiveness of ethanol and the demand for this fuel. These points are interconnected with federal policies playing a role to stimulate the installation of new mills by reinforcing agricultural conditions in Goiás and Mato Grosso do Sul through the Sugarcane Agroecological Zoning (SAZ).

The conceptual framework presented in Figure 1-2 shows farmers' land use decisions being influenced by some of these drivers. To test this framework, two analyses related to land use change were performed. The first one, presented in Chapter 3, considered the land use response to sugarcane expansion. Because the intensification response is the conversion of cropland to sugarcane production, this chapter is related to the discussion of food vs. fuel. To avoid this dilemma, an ‘extensification’ response (conversion of noncropland to sugarcane) is supported by the Brazilian government and researchers [*Manzatto et al.*, 2009; *Leal et al.*, 2013; *Cohn et al.*, 2014; *Strassburg et al.*, 2014; *Alkimim et al.*, 2015]

This research shows that the extensification response is the most common and that it has an increasing trend, suggesting that direct conversion of food-producing areas is not a major concern for sugarcane production. Moreover, the logit model estimated that increases in soybean yields increased the probability of extensification. Together, these findings indicate that cropland may be able to compete and push sugarcane to expand over noncropland. Another result from the logit model demonstrates the influence of the mills in the LUR process. The variable Distance to Mill had a positive and significant marginal effect resulting in an increase in the probability of extensification the farther an area is to the mill.

The results from Chapter 3 offered insights on what happens to the land once farmers decide to adopt sugarcane. A complementary question is “What is influencing the acreage allocation to sugarcane?”. To study this subject, I implemented a partial-adjustment model, in which the sugarcane acreage is a function of previously owned acreage and other land use acreage, price and yield, and distance to the nearest mill on the previous year (Equation 4-1). The estimation found sugarcane to be inelastic to its own acreage, indicating a spatial inertia response in the short run (Table 4-2). Other variables that have a significant impact are soybean double-crop acreage, sugarcane price and yield, cattle price, and distance to the mill.

Considering the impact of competing for land uses, the results indicate a different land dynamic between biofuel and food crop production. Instead of competition, the results show that intensification of row-crop production is consistent with sugarcane expansion—hence these land uses are complementary. The findings in Chapters 3 and 4 make the case for this counterintuitive view of sugarcane and soybean double crop production as co-occurring rather than directly competing for the same land. If sugarcane is not converting and competing for land previously dedicated to row crops, it is likely advancing over pasture. The acreage response model did not find pasture acreage to be significant, but cattle price was the variable with the largest short-run cross-price elasticity.

As in Chapter 3, distance to the mill has statistical significance to sugarcane acreage (Table 4-2). For sugarcane acreage, distance to mill has a negative relationship where a reduction in the distance increases the sugarcane acreage response. The finding related to the distance to the mills confirms the spatial relation between sugarcane-producing areas and the mill.

From the first three research chapters, some policy guidelines can be suggested. Considering a scenario where the government policy is to promote expansion of biofuel production then it should target at stimulating the mills to move into the region. The influence of fiscal incentives is important, especially to attract mills to the region. Mills are the main market and they have more structure and economic power than most farmers. However, the mills' dependence on sugarcane supply supports the position of the farmers and its relevance for the sugarcane industry. When examining the land change dynamics promoted by the sugarcane expansion, the relationship of mills and land use became even more explicit. The results demonstrate that the mills are affecting the land change dynamics in the region. First, by demanding more land to sugarcane the mill influences in the farmers' decision of allocating more land to sugarcane. Second, by stimulating different land use response favoring intensification (conversion of cropland) response close to the mill and extensification (conversion of noncropland) farther from the mill.

In a scenario where the society desire is to have biofuel expansion without reduction of cropland and food production, the policy must target the relationship between the biofuel crop and the existing land use. In the Cerrado, the competition between sugarcane and soybeans is not causing a direct conversion of cropland. Rather, it is promoting gains in soybeans yield and adoption of double crop rotation, such that the expansion of sugarcane is concomitant with the increase of a more productive soybean system.

While studying the sugarcane expansion to the Cerrado, I was instigated to consider the lasting impacts of this expansion and the influence of climate change on the Brazilian sugarcane sector. The last chapter takes a broader view to incorporate biodiversity and climate change. The need to understand sugarcane vulnerability to climate change is one of the main motivations of this study. The focus is on the impacts of climate change on what SAZ defines as 'land suitability' for sugarcane and how this zoning policy can incorporate the concept of climate vulnerability into land suitability. Adaptation and mitigation of the effects of climate change can be facilitated through prospective planning and incorporation of measures before the full setting of climate change [*Berry et al.*, 2006; *Rosenzweig et al.*, 2014]. A case study relating sugarcane and amphibian species are used to demonstrate the relevance of future implications of sugarcane expansion.

This study found evidence of climate vulnerability for the areas defined as 'suitable' by the SAZ. Additionally, using the definition of land suitability from the SAZ, new areas have been identified as hotspots of suitability with low vulnerability to climate change. Moreover, amphibians are affected by climate change and conflicted with areas suitable for sugarcane in climate change scenarios.

The SAZ needs to incorporate climate vulnerability in order to fulfill its objective of organizing a sustainable expansion of sugarcane in Brazil. I propose the use of climate change ensembles to assess the vulnerability of each area considered by the SAZ. By incorporating the vulnerability of each area, the zoning policy would not be binary (suitable or nonsuitable) but would have a continuous level of suitability given the vulnerability.

This measure also provides an indicator to farmers and mills of the risk they may face by producing in a certain area. Inability to do so can lead to loss of investments and to a threat to the Cerrado biodiversity (through amphibians and other groups). My analysis assumes technology as a constant, hence the definition of suitability is the same as the SAZ [*Manzatto et al.*, 2009]. This strong assumption can be considered a limitation of this study, but it also assists policy makers and the private sector to identify what type of technological improvements will be needed to reduce sugarcane vulnerability to climate change.

This chapter also illustrates the problem with land use policies developed using current climate information but without considering the impacts of climate change. The suggestion of incorporating a vulnerability metric to land use policies such as the SAZ would represent a change in the way policy is made. By given the information of the vulnerability to climate change to farmers, mills, and other stakeholders, the SAZ would be fulfilling its mission of coordinating a sustainable expansion of sugarcane in Brazil

6.1 References

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